THE DECIBEL NOTATION

V. V. L. RAO

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THE DECIBEL NOTATION

Its Application to Radio and Acoustics

V. V. L. RAO

This pioneering book is the first volume in the English language which explains in sufficient detail the origin, development and a wide range of applications of decibel notation, with special reference to radio engineering and acoustics.

The subject has been developed from its principles assuming no high standard of mathematics on the part of the reader; the average student of electrical engineering will not encounter any difficulty in understanding and applying the information given in the book. Many solved problems will prove most helpful to the radio and acoustics engineer and students.

The book is a masterly survey of the development of the logarithmic unit, zero levels and level signs, decibel meter and decibel graphs, sound levels and phon calculations, etc., which will be welcome to technical workers of the radio and acoustics field.

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Its Application to Radio and Acoustics

by

V. V. L. RAO

Radio Engineer

1946

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FOREWORD

For The First American Edition

This up-to-date and critical compilation of widely-scattered data on decibal notation should prove valuable to radio, telephone, and acoustical engineers as well as engineering students, and to all who work with high-frequency electronics and circuits.

The subject is well covered and many examples are given which will facilitate the solution of special problems.

The book was originally published in Madras, India and the American edition corresponds entirely to the original publication. This will account for the use of some British terms, such as *aerial* for antenna, *valve* for tube, *gramo-pickup* for phono--pickup, etc. We assume that the reader is familiar with these terms and will have no difficulty in interpreting the information compiled in this handy volume.

THE EDITOR

FOREWORD

Though the decibel notation has been widely used for a number of years and is becoming increasingly important in the field of Wire and Radio Communication, it has not yet been treated with the thoroughness it deserves in all its essential aspects.

Mr. Lakshmana Rao has made a masterly survey of the development of the logarithmic unit, the associated formulae used in everyday calculation, the idea of "zero levels" and "level signs", the decibel meter and the decibel graphs as well as the various applications of the notation in Radio and Acoustics Engineering. The range of usefulness of the work has been extended by the inclusion of a separate section relating to "phon", sound levels and phon calculations. The modest work is packed with much useful and worthwhile information presented with clarity and economy of words.

Mr. Rao's pioneer effort is very timely and he deserves the thanks alike of students of electrical communication engineering and engineers of Telecommunications and Broadcasting administrations.

S. P. CHAKRAVARTI,
Radio Controller,
Department of Industries
and Civil Supplies,
Government of India.

AUTHOR'S PREFACE

'The growth in popularity of the decibel, since 1929, has been so great that it is now almost a household word throughout all branches of Electrical Engineering and Acoustics'..................
(The Admiralty Handbook of Wireless Telegraphy, Vol. II, 1938.)

1. The present work has been undertaken as, that so far as the author is aware, no book on this subject has been published in the English language, barring a booklet of 57 pages by Morris*. Usually, only a page or two are devoted to this topic in several general text-books on Communication Engineering or Acoustics, and such treatment consequently has been very elementary and scanty. It is the object of this book to explain the origin, development, and a wide range of applications of this notation, with special reference to Radio Engineering and Acoustics, illustrated by a number of worked out examples, and also to give a succinct picture and justification of the notation.

2. The book does not use very high standard of mathematics. It can be followed by an average student of Electrical Engineering as the subject has been developed from the first principles wherever possible. The monograph is so written as to serve as a valuable reference book to any student or engineer in telecommunications. It is divided for convenience into four parts. Part I solely deals with every aspect of the origin and development of the decibel notation; Part II deals with the derivation of the Phon notation, which is being increasingly used in acoustic engineering; Part III deals with a very wide range of applications of the decibel notation; Part IV contains four valuable appendices relating to the importance of log-linear graphs, limitations of a logarithmic unit, the standard cable, and the log-tables.

3. Both DECIBEL and PHON are really of an abstract nature, and it is very difficult to obtain a physical conception of them, which is responsible for the hazy notions regarding these two units. The confusion is aggravated by the lack of a standard zero level (of power, voltage or current) and a

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* Vide item 1 in the BIBLIOGRAPHY at the end of the text of monograph.

standard impedance, and the common, though defective, practice of mentioning as so many db, without mentioning with what zero level the result has been obtained. The author thinks that, unless a standard reference level is internationally agreed upon, it is always worthwhile to specify the zero level.

4. The author is indebted for valuable information to the books listed in the bibliography, and therefore acknowledges his grateful thanks to the authors and publishers of those books. In particular, the author records his grateful acknowledgement to the following, from whose publications several diagrams are reproduced: General Radio Coy., Mass., USA; The Wireless World, London; Philips' Electrical Coy. (India) Ltd., Calcutta; Messrs. Chapman & Hall Ltd., London; Thordarson Elec. Mfg. Coy., Chicago, USA; Weston Elec. Inst. Corporation, Newark, N. J., USA.

5. The author has great pleasure in thanking Messrs. T. N. Seshadri, M.A., J. K. Murty, M.A., and Dr. I. Ramakrishna Rao, Ph.D. (Calcutta), D.Sc. (Lond.), for going through several portions of the manuscript critically and offering constructive criticism, and also reading through the proofs in parts; Mr. S. Sambasivarao, Grad. I.E.E., for assisting the author in scriptural work in preparing the final manuscript. Last but not least, the author is much indebted to Prof. S. P. Chakravarti for readily consenting to write a foreword and for giving several helpful suggestions.

6. Any constructive criticism from the readers is most welcome, and the suggestions will be considered carefully for incorporating in the future editions of this monograph.

V. V. L. R.

NOTATION USED IN THE TEXT

P_o = Output power
P_i = Input ,,
V_o = Output voltage
V_i = Input ,,
I_o = Output current
I_i = Input ,,
A_o = Output amplitude (of voltage, current, pressure or velocity)
A_i = Input ,, ,, ,, ,, ,, ,,
Z_o = Output impedance
Z_i = Input ,,
$\cos \phi_o$ = Output-side power factor
$\cos \phi_i$ = Input-side ,,
N for nepers
B ,, bels
D ,, decibels (db)
m.s.c. for miles of standard cable

Abbreviations of Electrical and Physical Quantities as used in the Text.

1.	Direct current	d-c, DC
2.	Alternating current	a-c, AC
3.	Frequency	f
4.	Audio frequency	AF
5.	Radio frequency	RF
6.	Low frequency	LF
7.	High frequency	HF
8.	Cycles per second	cps
9.	Kilocycles per second	kcs
10.	Megacycles per second	Mcs
11.	Automatic volume control	avc, AVC
12.	Electromotive force	emf
13.	Root mean square	rms
14.	Metre	m
15.	Kilometre	km
16.	Centimetre	cm
17.	Volt	V
18.	Millivolt	mV
19.	Microvolt	μV
20.	Millivolt per metre	mV/m
21.	Microvolt per metre	μV/m
22.	Milliamp	mA
23.	Watt	W
24.	Kilowatt	kW
25.	Milliwatt	mW
26.	Microwatt	μW
27.	Micromicrofarad	μμF

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PART I

THE DECIBEL

1. Introduction.

(1) Of all the units used in telecommunication engineering and electro-acoustics, perhaps the most widely used one is the 'Decibel'. It has come to be more often used than even volts, amperes and ohms. The 'Decibel notation' was first used in about 1924 in telephone engineering. The unit was then called a 'Transmission Unit' (TU), a name which has since been superseded. Strictly, it would be more rational to use the term: 'Decibel notation', rather than 'Decibel Unit'. The decibel notation is a logical consequence of certain natural phenomena, for example, the response of certain human senses to stimuli, but it must be remembered that it is also a mathematical artifice introduced to simplify calculations. As it will be seen later, it has no dimensions, being the logarithm of certain ratios.

(2) There are five human senses: (i) sight, (ii) hearing, (iii) touch, (iv) taste, and (v) smell. Of these, while the first three are more physical than chemical, the last two are predominantly chemical. Each sensation is the result of a stimulus, and according to the 'Weber-Fechner Law' in psychology[2], "the minimum change in stimulus necessary to produce a perceptible change in response is proportional to the stimulus already existing".

Suppose that an initial stimulus produces a sensation, then, increasing the stimulus results naturally in an increased sensation. How far this increase is measurable is a different question with which we are not concerned at the moment, but suffice it to say that the perceived increase in sensation depends on the original stimulus and its sensation. A certain increase in the perceived sensation, depending as it does on the original stimulus, must depend upon the ratio of the change in stimulus, rather than the actual addition to the stimulus. Doubling the stimulus must give rise to an increase in sensation depending upon the intensity of the original stimulus. As the stimulus increases in a geometrical progression, sensation rises in an arithmetical progression. Hence, mathematically, we can take the sensation as proportional to the logarithm of the stimulus. Thus, if (Se) represents sensation and (St) represents stimulus, then (Se) = k log (St). This law holds good between stimulus and sensation in the following 5 well-known cases :—

Stimulus	Sensation
1. Pressure	1. Feeling
2. Temperature	2. Heat
3. Sound Intensity	3. Loudness
4. Frequency change	4. Pitch
5. Intensity of Illumination	5. Brightness

At this stage, it must be remarked that all sensations are comparative and therefore it is usual among psychologists to take the threshold value of stimulus as the datum of reference. It is very difficult to measure sensation, while it is not so with stimulus, which can be measured objectively and with great precision, with the recent advances in the technique of electrical measurements. Both the engineer-physicist and the biologist would be eager to cite exact figures based on readings from the measuring instruments, but it is the physical interpretation of these readings which is most difficult and unsatisfactory. The dealer who sells you a radio set may assure you that it has a uniform response over the entire audio-frequency range, but you are at liberty to ask him with what instruments the tests were made, the significance and the representative character of the overall electrical fidelity curve that he might show. Perhaps, the only apparatus with which one should really judge the fidelity of a radio receiver is one's own ear, but science has not progressed so far as to render the human brain act like a meter-needle kicking over a calibrated scale.

(3) All measurements are necessarily relative to a particular unit of the same nature as the quantity measured. While it is possible to choose any unit for measurement, it is advisable to choose a unit comparable to the quantity measured. Though there can be no objection strictly in expressing the distance between Madras and Calcutta in inches or millimetres, it is preferable to express in miles, a unit, which is comparable to the distance measured. It is a common artifice, therefore, to find a suitable unit, which will reduce the number denoting the measure of a quantity to a reasonable value. The logarithm of any large or small number (or ratio), is naturally a small and convenient value in handling for calculation purposes. This, coupled with the fact that the human ear itself behaves logarithmically, has given special interest in this new and versatile unit for extensive use in radio and acoustic engineering. Several aspects of this unit are dealt with in this monograph.

2. Difference of Power Level.

In any electric circuit power losses occur. In a circuit composed of several individual components, the usual method of evaluating the overall efficiency is by multiplying the individual efficiencies. In certain communication circuits (consisting of amplifiers) power gain also occurs, and, therefore, must be taken into account. Though the final useful power is naturally less than the total power put in, the power of the output signal is greater than the power of the input signal, so that, using the conventional definition of efficiency, values exceeding 100% may be obtained. This apparent discrepancy is not difficult to explain.

Consider the following transmission network :—

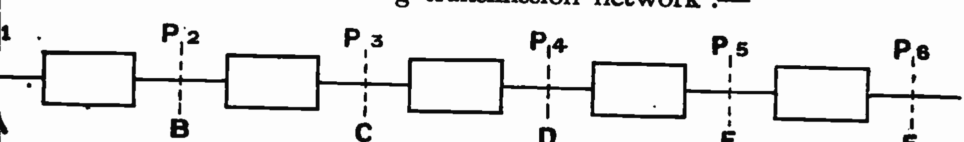

Fig. 1. 1 Block Schematic of a Communication System.

Defining the difference of power level as ratio of two powers[3],

the power level at B, relative to A $= \frac{P_2}{P_1}$;

" " C, " B $= \frac{P_3}{P_2}$;

" " D, " C $= \frac{P_4}{P_3}$;

" " E, " D $= \frac{P_5}{P_4}$;

" " F, " E $= \frac{P_6}{P_5}$;

But, $\frac{P_6}{P_1} = \frac{P_6}{P_5} \times \frac{P_5}{P_4} \times \frac{P_4}{P_3} \times \frac{P_3}{P_2} \times \frac{P_2}{P_1}$;

(*i.e.*), (Level of F referred to A) = (Level of F referred to E) × (Level of E referred to D) × (Level of D referred to C) × (Level of C referred to B) × (Level of B referred to A).

Thus, the total difference in level of the entire system, from the start to the finish, is equal to the product of the difference in level of the individual units of the system. In order to avoid the multiplication of the individual efficiencies, recourse can be had to the logarithms of the efficiencies, because such a system would involve the simple processes of addition and subtraction only. Then,

$$\log \frac{P_6}{P_1} = \log \frac{P_6}{P_5} + \log \frac{P_5}{P_4} + \log \frac{P_4}{P_3} + \log \frac{P_3}{P_2} + \log \frac{P_2}{P_1}$$

i.e., the total difference in power level of any system on the logarithmic basis will now be obtained by adding up the individual differences in level of the various parts of the system.

3. Logarithmic Unit—Its Advantages.

A logarithmic method of measuring power is both convenient and advantageous for the following reasons :

(i) The human ear responds to sound intensities according to a logarithmic law ; hence the comparison of two audio-frequency outputs on a logarithmic basis gives a more natural picture of the relative effects on the ear than a mere statement of the ratio of powers. This may be explained as follows. The human senses of sight and sound, as stated already, do not detect the differences of light and sound in direct proportion to the arithmetical differences. If the intensity of a sound is doubled, the ear does not detect the 100% increase, but only records the impression of a much smaller increase. Consequently, the sound output from a loudspeaker driven by 2 watts is not heard twice as loud as that of another driven by 1 watt, and actually we have to increase the intensity of sound by 10 times, so that it may sound twice as loud as before. If we increase 10-fold again, it would only lead to an apparent increase in loudness similar to the former increase, though the actual intensity of sound has now been increased a 100-fold. Therefore, our realization of loudness of sound varies as the logarithm of the actual sound intensity. So, by using a logarithmic unit we are able to assess the differences in sound level better.

(ii) Attenuation in a line (infinitely long or terminated by its characteristic impedance) carrying power is logarithmic, so that the total attenuation of a composite line is given by the direct addition of the attenuations of its different sections.

4. The Development of the Logarithmic Units : Neper, Bel and Decibel.

At the moment, there are two logarithmic units in general use in the USA and Europe, one based on the Naperian system of logarithms and the other based on the Briggsian or decimal system of logarithms. The Naperian system of logarithms is due to John Napier, Baron of Merchiston in Scotland, who was the inventor of logarithms to the base 'e' (= 2.7183), in 1614. The Briggsian or common logarithms we use, are the invention of Henry Briggs, an Englishman.

If $10^x = N$, then x is called the logarithm of N in this system. This logarithm is said to refer to the base 10.

The International Advisory Committee on Long Distance Telephony (of Europe), has recommended that the two logarithmic units based on the Naperian and Briggsian systems, be standardised. These two units are called the Neper and the Bel and they are defined as follows:—

(i) **The Neper :**

Two powers P_o and P_i are said to differ by N nepers, where $N = \frac{1}{2} \log_e \left(\frac{P_o}{P_i}\right)$. When the output and input impedances are the same, this expression becomes : $\log_e \left(\frac{V_o}{V_i}\right)$ or $\log_e \left(\frac{I_o}{I_i}\right)$.

The unit 'Neper' is named after John Napier.

(ii) **The Bel :**

The Bel is the logarithm to base 10 of the ratio between two powers or intensities, and it is also equal to twice the logarithm of the ratio between the corresponding amplitudes of voltages, currents, pressures or velocities, when the output and input impedances are the same.

$$\log_{10} \left(\frac{P_o}{P_i}\right) = 2 \log_{10} \left(\frac{V_o}{V_i}\right) = 2 \log_{10} \left(\frac{I_o}{I_i}\right) \text{ bels.}$$

The unit 'Bel' is named after Alexander Graham Bell, the inventor of the telephone.

(iii) **The Decibel :**

The 'Bel' being inconveniently large for ordinary practical purposes, a smaller unit, 'Decibel', is in general use in all countries now. This is known as the 'Transmission Unit' in the USA. It is also equivalent to the sensation unit used in acoustic work.

The decibel gets its name from the Latin word, 'decimus', which means 'one tenth', together with 'bel' and therefore a decibel is the tenth part of a bel.

Some of the abbreviated symbols used to denote the decibel or its plural form, decibels, are :

DB, Db, dB, db.

Amongst these, the last one, db, is the one most widely used. A decibel is defined by the following simple relation :

$$\text{Power level} = 10 \log_{10} \left(\frac{Po}{Pi}\right) \text{ decibels.}$$

In the USA the following abbreviations[4] are widely used :

βl unit for the 'Neper';

TU for the 'Transmission Unit';

SU for the 'Sensation Unit';

and db for the 'Decibel'.

(iv) **Definitions in general terms :**

With the usual notation, the bel, decibel and neper will be defined in general terms.

(a) **Bel :**

The difference in level between the output and input is B bels, where $B = \log_{10} \left(\frac{Po}{Pi}\right)$

$$\therefore \left(\frac{Po}{Pi}\right) = 10^B$$

(b) **Decibel :**

The same difference in level is D decibels, where $D = 10 \log_{10} \left(\frac{Po}{Pi}\right)$ $\therefore \left(\frac{Po}{Pi}\right) = 10^{(D/10)}$

(c) **Neper :**

The same difference in level is N nepers, where $N = \frac{1}{2} \log_e \left(\frac{Po}{Pi}\right)$ $\therefore \left(\frac{Po}{Pi}\right) = e^{2N}$

5. Conversion of Nepers to Decibels and vice versa.

Considering an amplifier, whose input and output powers are P_i and P_o respectively, its power gain in

$$nepers = \frac{1}{2} \log_e \left(\frac{P_o}{P_i}\right)$$

$$= 2{\cdot}3026 \times \frac{1}{2} \log_{10} \left(\frac{P_o}{P_i}\right)$$

$$(\because \log_e x = 2{\cdot}3026 \times \log_{10} x)$$

$$= 1{\cdot}1513 \times \log_{10} \left(\frac{P_o}{P_i}\right)$$

$$= 0{\cdot}11513 \times 10 \log_{10} \left(\frac{P_o}{P_i}\right)$$

$$= N, \text{ say.}$$

The same power gain, expressed in *decibels*, $= 10 \log_{10} \left(\frac{P_o}{P_i}\right) = D$, say.

$\therefore$ The power gain of the amplifier $= D$ decibels $= N$ nepers. Hence, 1 decibel $= \frac{N}{D}$ nepers $= 0{\cdot}11513$ neper, as $N = 0{\cdot}11513 \times 10 \log_{10} \left(\frac{P_o}{P_i}\right)$ and

$$D = 10 \log_{10} \left(\frac{P_o}{P_i}\right).$$

$$\therefore 1 \text{ neper} = \frac{1}{0{\cdot}11513} = 8{\cdot}686 \text{ db.}$$

Results :—

1 neper = 8·686 db ;

and 1 decibel = 0·11513 neper.

It is obvious that the neper is a larger unit than the decibel.

The next three tables below give the bels, decibels, and nepers for various power ratios, ranging from 1.0 to 10^9

Table 1.

Power ratio	1·0	1·023	1·047	1·072	1·096	1·122	1·148	1·175	1·202	1·23
Bels	0	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09
db	0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9
Nepers	0	0·0115	0·023	0·0345	0·046	0·0575	0·069	0·0805	0·092	0·1035

Table 2.

Power ratio	1·259	1·585	1·995	2·512	3·162	3·981	5·012	6·310	7·943
Bels	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9
db	1	2	3	4	5	6	7	8	9
Nepers	0·115	0·23	0·345	0·46	0·575	0·69	0·805	0·920	1·035

Table 3.

Power ratio	10^1	10^2	10^3	10^4	10^5	10^6	10^7	10^8	10^9
Bels	1	2	3	4	5	6	7	8	9
db	10	20	30	40	50	60	70	80	90
Nepers	1·15	2·30	3·45	4·60	5·75	6·90	8·05	9·20	10·35

6. Relation between Miles of Standard Cable, Decibels and Nepers.

Sometimes, in communication engineering one comes across "miles of standard cable" (abbreviated: m.s.c.), a transmission unit used formerly. Before 1923, the British Post Office used the m.s.c. as a standard unit to express the ratios in telephone engineering.

A mile of standard cable is defined as that power ratio at 800 cps, that is obtained between the ends of a mile of cable, whose constants[5] per loop mile are :

W, weight = 20 lbs.,
R, resistance = 88 ohms,
L, inductance = 1·0 millihenry,
C, capacitance = 1·054 microfarad,
G, leakance = 1·0 Micro-mho.

The m.s.c. depends on frequency and therefore is not a desirable or absolute unit. It has therefore given place to the unit, decibel, which is not dependent upon frequency. Whenever a new unit is chosen to supersede an old one, it is always preferable that it should numerically have the same value (approximately) as the old one. The decibel satisfies this requirement, being only about 8% higher than the "800-cycle m.s.c."

The conversion constants between nepers, decibels and m.s.c. are tabulated below for ready reference.

Table 4.

Multiply	By	To get
(1) Nepers	8·686	Decibels
(2) ,,	9·420	m. s. c.
(3) Decibels	0·11513	Nepers
(4) ,,	1·084	m. s. c.
(5) m. s. c.	0·10616	Nepers
(6) ,,	0·9221	Decibels

7. Simple Decibel Formulae.

Since power $= I^2R = \left(\frac{V^2}{R}\right)$, in the simplest case when the voltages across, or currents in, equal impedances are measured, the following simple formulæ for the number of decibels, for current and voltage ratios, can be deduced:

If $P_i = I^2_i R_i$ or $\left(\frac{V^2_i}{R_i}\right)$, and $P_o = I^2_o R_o$ or $\left(\frac{V^2_o}{R_o}\right)$,

and, further, if $R_i = R_o$,

then, $10 \log \left(\frac{P_o}{P_i}\right) = 10 \log \left(\frac{I_o}{I_i}\right)^2 = 20 \log \left(\frac{I_o}{I_i}\right)$

(when currents alone are considered),

and $10 \log \left(\frac{P_o}{P_i}\right) = 10 \log \left(\frac{V_o}{V_i}\right)^2 = 20 \log \left(\frac{V_o}{V_i}\right)$

(when voltages alone are considered).

From the above formulæ, $\left(\frac{P_o}{P_i}\right) = \left(\frac{V_o}{V_i}\right)^2$, or $\left(\frac{V_o}{V_i}\right) = \sqrt{\frac{P_o}{P_i}}$.

From Table 2, it is seen that two powers differ by 1 db when their ratio is 1.259.

$\therefore$ If $\left(\frac{P_o}{P_i}\right) = 1.259$, then $\left(\frac{V_o}{V_i}\right) = \sqrt{1.259} = 1.122$.

Thus, two voltages differ by 1 db when their ratio is 1.122.

Power in electricity corresponds to intensity in acoustics, and voltage corresponds to pressure in acoustics.[6]

In the case of intensities of sustained sounds, a change of the order of 1 db is the smallest change in intensity appreciable to the average ear, while in practice a change of 2 db is usually considered the maximum limit of variations that would pass undetected by any human ear.

8. General Expressions for the Power Gain or Loss in Nepers and Decibels.

Power at any point in a single phase a-c circuit is:

$$P = VI \cos \phi = I^2 Z \cos \phi = \frac{V^2}{Z} \cos \phi.$$

When V_o, V_i, I_o, and I_i operate in unequal impedances,

$$P_o = \frac{V^2_o}{Z_o} \cos\phi_o = I^2_o Z_o \cos\phi_o \text{ and,}$$

$$P_i = \frac{V_i^2}{Z_i} \cos\phi_i = I^2_i Z_i \cos\phi_i.$$

(a) in Nepers :—

Since, gain or loss, N nepers, is $= \frac{1}{2}\log_e\left(\frac{P_o}{P_i}\right)$,

$$\therefore N = \log_e\left(\frac{V_o}{V_i}\right) + \frac{1}{2}\log_e\left(\frac{Z_i}{Z_o}\right) + \frac{1}{2}\log_e\left(\frac{\cos\phi_o}{\cos\phi_i}\right)$$

nepers, and also

$$= \log_e\left(\frac{I_o}{I_i}\right) + \frac{1}{2}\log_e\left(\frac{Z_o}{Z_i}\right) + \frac{1}{2}\log_e\left\{\frac{\cos\phi_o}{\cos\phi_i}\right\} \text{ nepers.}$$

This, when converted to decibels $= N \times 8.686$ db.

A separate expression for the gain or loss directly in db will be derived now :

(b) in Decibels:—

$$D = 10\log\left(\frac{P_o}{P_i}\right),$$

$$= 10\log\left(\frac{V_o}{V_i}\right)^2 + 10\log\left(\frac{Z_i}{Z_o}\right) + 10\log\left(\frac{\cos\phi_o}{\cos\phi_i}\right) \text{db},$$

$$= 20\log\left(\frac{V_o}{V_i}\right) + 10\log\left(\frac{Z_i}{Z_o}\right) + 10\log\left(\frac{\cos\phi_o}{\cos\phi_i}\right) \text{db}.$$

If the impedances are pure resistances and are denoted by R_i and R_o respectively,

i.e., if $\cos\phi_i = \cos\phi_o = 1$, then, $10\log\frac{\cos\phi_o}{\cos\phi_i} = 0$.

Then, gain $D = 20\log\left(\frac{V_o}{V_i}\right) + 10\log\left(\frac{R_i}{R_o}\right)$.

In the formula : $D = 10\log\left(\frac{P_o}{P_i}\right)$, if the ratio $\left(\frac{P_o}{P_i}\right)$ is < 1, D becomes negative and denotes a loss.

(c) A simple use of the decibel unit is indicated below :—

If two circuits of ratio of power output to power input of $\left(\frac{Po_1}{Pi_1}\right)$ and $\left(\frac{Po_2}{Pi_2}\right)$ respectively are connected in cascade the power ratio of the combination is :

$$\left(\frac{Po}{Pi}\right)=\left(\frac{Po_1}{Pi_1}\right)\times\left(\frac{Po_2}{Pi_2}\right)=10^{(D_1/10)}\times 10^{(D_2/10)}=10^{(D_1+D_2)/10}$$

where D_1 and D_2 are the transmission equivalents in decibels of the first and second elements respectively.

Taking logarithms of both sides and multiplying throughout by 10, we get $10 \log \left(\frac{P_o}{P_i}\right) = D_1 + D_2$.

Thus, it is seen that any number of transmission equivalents can be added or subtracted to obtain the transmission equivalent of the complete circuit.

9. (a) **Zero Level.**

It should be noted that the decibel is fundamentally a unit of *power ratio* and not of *power*, but it can be used as a unit of power itself, if we define a standard power level and express other power levels in terms of that standard. This standard power level is also called the 'zero level'. If a power level is expressed as D decibels, it is meant that it is D db above the 'zero level'.

(b) **Zero Power Level.**

In England, for communication testing purposes, 1 mW is often taken as the 'zero power level'. The other 'zero power levels' in vogue are the 6 mW and 12.5 mW ; the former is in general use in the USA, barring the RCA Manufacturing Co., Inc., which expresses the gain or loss of its products with respect to a zero power of 12.5 mW only.

If the power in a circuit is P milliwatts, then :

(i) taking 1 mW zero level, the power level

$$(D_1 db) = 10 \log \frac{P}{1};$$

(ii) taking 6 mW zero level, the power level

$$(D_2 db) = 10 \log \frac{P}{6};$$

(iii) taking 12·5 mW zero level, the power level

$$(D_3 db) = 10 \log \frac{P}{12.5}.$$

Since using decibels to indicate the power ratios as well as the absolute values of powers, leads to some confusion, a new unit for expressing the absolute power, called the "Volume Unit" (abbreviated : VU), is slowly coming into use.

(c) **Zero Voltage Level.**

This is defined as that voltage across a 600-ohm resistance, which dissipates the 'zero power'. The zero voltage levels corresponding to three zero power levels in vogue are tabulated below :

Table 5.

Zero Power Levels (1)	Zero Voltage Levels (2)
1 mW.	0·775 volts.
6 mW.	$0{\cdot}775 \times \sqrt{6} = 1{\cdot}898$ volts.
12·5 mW.	$0{\cdot}775 \times \sqrt{12{\cdot}5} = 2{\cdot}739$ volts.

Values in column (2) in the above table are obtained by using the formula :

$$P = \frac{V^2}{R} \quad \text{or, } V = \sqrt{P \times R}$$

(d) **Zero Current Level.**

This is defined as that current flowing in a 600-ohm resistance, which dissipates the zero power. The following table gives the zero current levels corresponding to the three zero power levels in vogue.

Table 6.

Zero Power Levels (1)	Zero Current Levels (2)
1 mW.	1·291 mA.
6 mW.	$1{\cdot}291 \times \sqrt{6} = 3{\cdot}162$ mA.
12·5 mW.	$1{\cdot}291 \times \sqrt{12{\cdot}5} = 4{\cdot}564$ mA.

The values in column 2 are obtained by using the formula :

$$P = I^2 R \text{ or, } I = \sqrt{\frac{P}{R}}$$

(e) **Conversion from One Zero Level to Another.**

One may be required to convert the power (or voltage or current) level from one zero to another.

If P is a power level, which is D_1 db above a power level P_1, and D_2 db above a power level P_2, we have the equations:

$$D_1 = 10 \log\left(\frac{P}{P_1}\right) \text{and } D_2 = 10 \log\left(\frac{P}{P_2}\right),$$

$$\text{Now, } D_2 = 10 \log\left(\frac{P}{P_2}\right) = 10 \log\left(\frac{P}{P_1} \times \frac{P_1}{P_2}\right)$$

$$= 10 \log\left(\frac{P}{P_1}\right) + 10 \log\left(\frac{P}{P_2}\right),$$

$$= D_1 + D', \quad \text{(say)},$$

$$\text{where, } D' = 10 \log\left(\frac{P_1}{P_2}\right).$$

This general formula can be used for converting any power in db referred to one " zero power level " to " any other zero power level ". It will be seen that this conversion involves merely an addition of D' to D_1 to get D_2. The following table gives the db values of absolute powers of 1 mW, 6 mW, 12.5 mW, and 1 watt referred to the three zero power levels in vogue :—

Table 7.

Absolute Power in Watts	db–value		
	"Zero db." = 1 mW.	"Zero db." = 6 mW.	"Zero db." = 12.5 mW
0.001	0	− 7.782	− 10.969
0.006	7.782	0	− 3.19
0.0125	10.969	3.19	0
1.0	30	22.218	19.031

When the zero power level is changed from 1 mW to 6 mW, the db value is lowered by a constant 7.782, since $10 \log_{10} \left(\frac{1}{6}\right) = -7.782$. When the zero power level is changed from 1 mW to 12.5 mW, the db value is lowered by a constant 10.969, since $10 \log_{10} \left(\frac{1}{12.5}\right) = -10.969$. Similarly, when the zero power level is changed from 6 mW to 12.5 mW, the db value is lowered by a constant 3.19, since $10 \log_{10} \left(\frac{6}{12.5}\right) = -3.19$. The conversion constants for voltage and current values are left for the reader to work out.

10. Standard Impedance Terminations.

Voltages and currents expressed in db notation refer to the corresponding standard or zero levels, which have already been defined as those across a 600-ohm resistance dissipating the standard power level. This 600-ohm value is called the standard impedance termination in communication engineering. It must be stated that other standard impedance terminations are also in vogue. 500 and 550-ohm impedance values are commonly used in the USA and the continent of Europe, these values being the common surge or characteristic impedances of transmission lines, filters, attenuators etc.

Still other values of impedance terminations we come across in communication (power transmission) lines carrying power are : 200, 74, 50 and 37-ohms. Of these, 74- and 37-ohm-impedance transmission lines are used only for radio frequency power transmission from transmitter to ærial, and seldom for powers less than 25 watts, while the 50-ohm-impedance transmission line is seldom used for power levels exceeding 6 watts, and even then, mainly for audio applications. 600, 500, and 200-ohm-impedance lines, are used both for RF and AF lines of both high-, and low-power transmission and with overhead lines. Their practical applications will be discussed in Part III of this monograph.

11. The Sign of a Level.

Every decibel rating (or level) has a sign, either positive or negative, unless it is zero db, for the level corresponding to zero watts or volts is minus infinity, since,

$$\log_{10} 0 = -\infty, \textit{i.e.}, \quad 10^{-\infty} = \frac{1}{10^{\infty}} = \frac{1}{\infty} \longrightarrow 0$$

Sometimes, the expressions: so many "db up", or "db down", are also used. Let us examine the significance of these two expressions. When the number of decibels is positive, the result is called "db up", and when the number of decibels is negative, the result is called "db down", with reference to the chosen zero level.

When the number of decibels is positive, we can at once infer that the corresponding ratio (of powers or voltages or currents) is greater than unity, while when the number of decibels is negative, we can at once infer that the corresponding ratio (of powers or voltages or currents) is less than unity. When the ratio is exactly unity, the number of decibels is zero, and it has no sign, for both $\log_{10} 1.0$ and $10 \log_{10} 1.0$, as well as $20 \log_{10} 1.0$, are all zero.

12. Decibel Meter.

If the reader has closely followed the text so far, a doubt will arise in his mind whether decibels can be read on a calibrated meter just as volts are read on a voltmeter, amperes on an ammeter, and watts on a wattmeter. The reader may at once be assured that there are direct reading decibel meters already in the market.

The db-meters are usually employed to indicate the rapidly varying power levels, *e.g.*, those corresponding to speech or music, while monitoring broadcast programmes. The meters are, however, calibrated only for steady power levels and the reading refers to 1 mW zero power level and 600-ohm termination. The Broadcasting industry in the USA has adopted this standard, and the unit is called "Volume Unit", but this is the same as the db referred to already. The readings on such a meter, when power levels are rapidly varying, may not give the true values as they must necessarily depend, in addition, upon the time constants of the meter circuit.

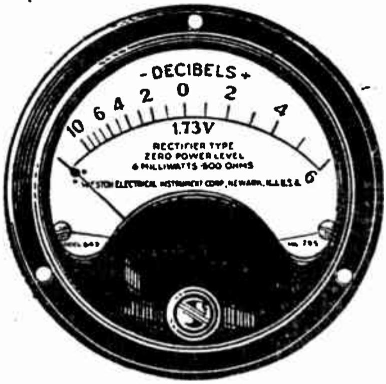

Fig. 1·2 Decibel Meter.
(By courtesy of the Weston Electrical Instrument Corporation, Newark, N. J., U.S.A.)

Note that the scale divisions on this power level meter are logarithmic in spacing, and are therefore unequal. This is because the voltage which the meter reads and equivalent db value are logarithmic in character.

A power level (db) meter[1] manufactured by the Weston Corprn. of USA (Fig. 1.2), is described below.

The direct reading db-meter is nothing but a d-c voltmeter used in conjunction with a copper-oxide rectifier. It is made to measure a-c voltages, but the dial is calibrated in decibels instead of volts. For the purpose of this meter a zero power level of 6 mW in a 500-ohm impedance is assumed. Then, $6 \text{ mW} = \left(\frac{V^2}{500}\right)$ or, V = 1.73 volts,

and, the zero voltage reference level is, therefore, 1.73 volts. This point is marked on the scale (vide Fig. 1.2) as O. A-C voltages greater than 1.73 volts are marked on the dial as so many decibels above the zero level, and are marked $+x$ db. The exact number of decibels above the zero level is determined by the ratio of the higher voltage to 1.73 volts. For example, consider a voltage of 17.3 volts. Then, $20 \log \left(\frac{17.30}{1.73}\right) = 20$ db.

This voltage of 17.3 is considered as having been applied across a 500-ohm load, which must remain constant.

Voltages less than the reference level of 1.73 volts are marked as —db. Consider a voltage of 0.173. Then,

$$20 \log \left(\frac{0.173}{1.73}\right) = -20 \text{ db}$$

Therefore, in a db-meter whose db range is: + 20 db to —20 db, the range of a-c voltages across a 500-ohm load is 0.173 to 17.3 volts.

In some meters, as stated earlier, the zero level may be different, and instead of 500-ohms, 600-ohm impedance may be chosen; but whatever may be the reference level, what the meter actually reads always is the a-c voltage.

The logarithmic relationship between the db-values and the corresponding voltages, explains the spacing of the divisions on the dial—like the divisions on a slide rule or a logarithmic graph paper.

13. Reflection Loss.

Let Z_1 be the impedance of a generator and Z_2 the impedance of the load connected to it. The power consumed by the load, *i.e.*, the power that flows from the generator to the load is a maximum when $Z_2 = Z_1$. When $Z_2 \neq Z_1$, the power that flows from the generator to the load is not the maximum value, the difference being supposed to be reflected by the load back to the source, at the junction of the two. This loss, by reflection, will be larger, the greater the degree of mismatch between the source and the load, and can be expressed by the ratio :

$$\frac{\text{power flowing when matched } (i.e., Z_2=Z_1)}{\text{power flowing when mismatched } (i.e., Z_2=Z_2.)}$$

This ratio, expressed in db, is taken as the reflection loss in communication engineering.

An expression for this loss is derived as follows :—

Case (*i*). Let the source impedance be Z_1 and load impedance Z_2.

First, let us assume $Z_1 = Z_2$ *i.e.*, the load is matched to the source.

Then the current in the circuit $= \dfrac{e}{Z_1+Z_2} = \dfrac{e}{(2\ Z_1)}$, where 'e' is the *emf* of the source.

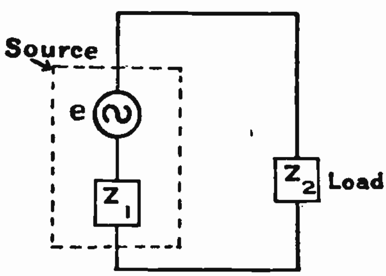

Fig. 1.3 An. ac- Source of Impedance Z_1, feeding a Load Z_2.

P_1, power in the load when $Z_1 = Z_2$,

$$= \left(\frac{e^2}{4\ Z_1^2}\right) \times Z_1 = \left(\frac{e^2}{4\ Z_1}\right)$$

Case (*ii*). Let $Z_1 \neq Z_2$, *i.e.*, the load is mismatched to the source impedance.

Then, current in the circuit $= \left(\frac{E}{Z_1 + Z_2}\right)$

P_2, power in the load, $= \left(\frac{E}{Z_1 + Z_2}\right)^2 \times Z_2$.

$$\therefore \left(\frac{P_1}{P_2}\right) = \left(\frac{E^2}{4 Z_1}\right) \times \frac{(Z_1 + Z_2)^2}{Z_2} \times \left(\frac{1}{e^2}\right) = \left\{\frac{(Z_1 + Z_2)^2}{4 Z_1 Z_2}\right\},$$

and the power loss $= 10 \log \left\{\frac{(Z_1 + Z_2)^2}{(4 Z_1 Z_2)}\right\}$ db or,

$$20 \log \left\{\frac{Z_1 + Z_2}{2 \sqrt{Z_1 Z_2}}\right\} \text{db}.$$

This expression gives the power reflection loss as used in communication engineering.

It must be remembered that Z_1 and Z_2 in the above expression are vector impedances, and two cases need consideration.

(i) If $Z_1 = Z_2$, both in magnitude and phase, the above expression vanishes, *i.e.*, the impedances are perfectly matched and no reflection loss occurs.

(ii) It can be proved that, when the phase angles are opposite in sign, the reflection loss may sometimes be negative, which only means a reflection gain. The necessary condition for maximum negative reflection loss, *i.e.*, maximum reflection gain, is that, when the two impedances are conjugate: their moduli are equal in magnitude and phase angles are again equal in value but opposite in sign :

In other words, when $Z_1 = R_1 + jx_1$,

and $Z_2 = R_1 - jx_1$.

If the impedances are assumed to be pure resistances, *i.e.*, $Z_1 = R_1$ and $Z_2 = R_2$, the condition for zero reflection loss is that $R_1 = R_2$ in magnitude. The reflection loss, when the above condition is not satisfied, is given by the following expression :

Power reflection loss $= 10 \log \left\{\frac{(R_1 + R_2)^2}{4 R_1 R_2}\right\}$ or,

$$20 \log \frac{(R_1 + R_2)}{2 \sqrt{R_1 R_2}}$$

The voltage reflection loss is defined by the ratio:

$$\frac{\text{Voltage across the load when matched } (\textit{i.e.}, R_2 = R_1)}{\text{Voltage across the load when mismatched } (\textit{i.e.}, R_2 = R_2)}$$

Then, the voltage reflection loss can be shown to be $= 20 \log \frac{(R_1 + R_2)}{2\,R_2}$, as proved below :

On substituting R_1 for Z_1, and R_2 for Z_2 in Fig. 1·3, we get V_L, the voltage across the load, to be $\left(\frac{R_2 \times e}{R_1 + R_2}\right)$ When $R_1 = R_2$ (matched condition), V_L becomes $= \frac{e}{2}$. Then, the voltage reflection loss, by definition,

$$= 20 \log \left\{ \frac{\frac{e}{2}}{e.\left(\frac{R_2}{R_1 + R_2}\right)} \right\}$$

$$= 20 \log \left\{ \frac{R_1 + R_2}{2\,R_2} \right\}.$$

(i) If $R_2 < R_1$, the above expression becomes positive denoting a voltage loss, and (ii) if $R_2 > R_1$, the above expression becomes negative denoting a voltage gain.

In order to obtain the true working gain of an amplifier, unless the load is matched to the output impedance, the gain of the amplifier must be corrected for the reflection loss.

14. Expressions for the Gain of Amplifiers in db-notation.

From the point of view of the equality or inequality of the input and output impedances of an amplifier, amplifiers can be classified as symmetrical and unsymmetrical amplifiers.

Three typical cases are considered for evaluating the db gain of amplifiers.

(a) A symmetrical amplifier working between matched impedances (Fig. 1.4);

(b) An unsymmetrical amplifier working between matched impedances (Fig. 1.5);

(c) An unsymmetrical amplifier working into a mismatched impedance (Figs. 1.6 and 1.7).

In what follows the following assumption is made in order to simplify the working :

Impedances are treated as pure resistances, and therefore power factors are ignored.

Case (a). The Decibel Gain of a Symmetrical Amplifier Working between Matched Impedances.

Let the input impedance = output impedance = R

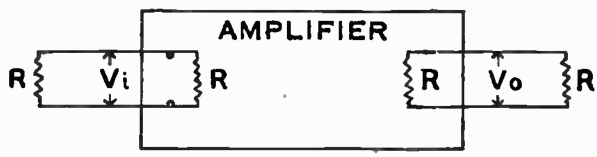

Fig. 1.4 A Symmetrical Amplifier Working between Matched Impedances.

$$\text{Then, gain in db} = 10 \log \left(\frac{\text{Output}}{\text{Input}}\right) = 10 \log \left(\frac{P_o}{P_i}\right)$$
$$= 10 \log \left(\frac{V_o}{V_i}\right)^2 = 20 \log \left(\frac{V_o}{V_i}\right).$$

Case (b). The Decibel Gain of an Unsymmetrical Amplifier Working between Matched Impedances.

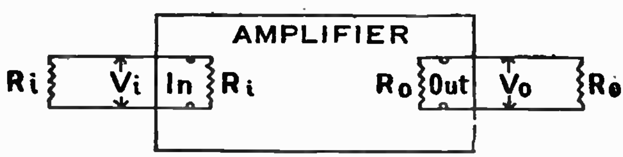

Fig. 1.5 An Unsymmetrical Amplifier Working between Matched Impedances.

$$\text{Then, gain in db} = 10 \log \left(\frac{P_o}{P_i}\right) = 10 \log \left(\frac{V_o^2 R_i}{V_i^2 R_o}\right)$$

$$= 10 \log \left(\frac{V_o}{V_i}\right)^2 + 10 \log \left(\frac{R_i}{R_o}\right)$$

$$= 20 \log \left(\frac{V_o}{V_i}\right) + 10 \log \left(\frac{R_i}{R_o}\right)$$

= Voltage gain + correction due to the unsymmetry of the amplifier.

Case (c). The Decibel Gain of an Unsymmetrical Amplifier Working into a Mismatched Impedance.

First, consider the output circuit of the amplifier. Because of mismatched impedance there will be reflection loss. Expressions for the output power and voltage levels are derived below, using the notation of Fig. 1.6.

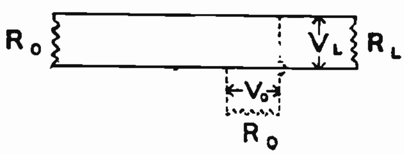

Fig. 1.6

Let P_1 = Power consumed by the load when $R_L = R_O$, and P_L = actual power consumed when $R_L = R_L$.

Power level in R_L (assuming 1mW zero level)

$$= 10 \log \left(\frac{P_L}{1}\right) = 10 \log \left(\frac{P_O}{1}\right) - 10 \log \left\{\frac{(R_O + R_L)^2}{4 R_O R_L}\right\}$$

= sending power level into a matched impedance *minus* power reflection loss.

Voltage level in R_L (assuming 0.775-volt zero level)

$$= 20 \log \left(\frac{V_L}{0\cdot775}\right)$$

$$= 20 \log \left(\frac{V_O}{0.775}\right) - 20 \log \left\{\frac{R_O + R_L}{2 R_L}\right\}$$

= Sending voltage level into a matched impedance *minus* voltage reflection loss.

Note :—

If $R_L > R_o$, voltage reflection loss will be negative, *i.e.*, a reflection gain, and therefore must be numerically added instead of substracted.

Next, considering the case of an unsymmetrical amplifier working into a mismatched impedance, the following expressions for its gain are derived :

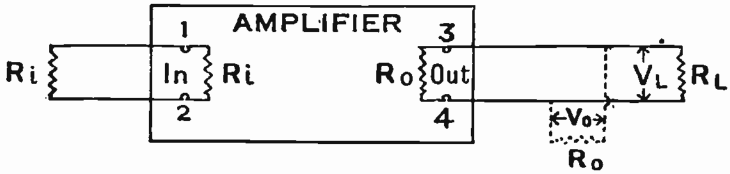

Fig. 1.7 An Unsymmetrical Amplifier Working into a Mismatched Impedance.

$$\left.\begin{array}{l}\text{Working gain in db}\\ \text{(from powers)}\end{array}\right\} = 10 \log \left(\frac{P_o}{P_i}\right) - 10 \log \left\{\frac{(R_O + R_L)^2}{(4R_O R_L)}\right\},$$

the second term being due to the reflection loss as a result of mismatch. The gain can also be expressed as :

$$= \left[20 \log \left(\frac{V_o}{V_i}\right) + 10 \log \left(\frac{R_i}{R_o}\right) - 10 \log \left\{\frac{(R_O + R_L)^2}{4 R_O R_L}\right\}\right]$$

= Gain of amplifier for the matched impedance condition (Case (b)) *minus* output power reflection loss.

$$\left.\begin{array}{l}\text{Working gain is also}\\ \text{(from voltages)}\end{array}\right\} = 20 \log \left(\frac{V_L}{V_i}\right) + 10 \log \left(\frac{R_i}{R_L}\right),$$

where V_L is the actual voltage across the load.

= Voltage gain for the actual working conditions *plus* load impedance correction.

From the last two equations, we get :

$$20 \log \left(\frac{V_L}{V_i}\right) + 10 \log \left(\frac{R_i}{R_L}\right)$$

$$= 20 \log \left(\frac{V_o}{V_i}\right) + 10 \log \left(\frac{R_i}{R_o}\right) - 10 \log \left\{\frac{(R_L + R_O)^2}{4 R_L R_O}\right\},$$

$$= 20 \log \left(\frac{V_o}{V_i}\right) + 10 \log \left(\frac{R_i}{R_L} \times \frac{R_L}{R_O}\right) - 10 \log \left\{\frac{(R_L + R_O)^2}{4 R_L R_O}\right\},$$

$$= 20 \log \left(\frac{V_o}{V_i}\right) + 10 \log \left(\frac{R_i}{R_L}\right) + 10 \log \left(\frac{R_L}{R_O}\right) - 10 \log \left\{\frac{(R_L + R_O)^2}{4 R_L R_O}\right\},$$

i.e., $$20 \log \left(\frac{V_L}{V_i}\right) = 20 \log \left(\frac{V_o}{V_i}\right) + 10 \log \left(\frac{R_L}{R_O}\right) - 10 \log \left\{\frac{(R_L + R_O)^2}{4 R_L R_O}\right\},$$

$$= 20 \log \left(\frac{V_o}{V_i}\right) - 10 \log \left\{\frac{(R_L + R_O)^2}{4 R_L R_O} \times \frac{R_O}{R_L}\right\},$$

$$= 20 \log \left(\frac{V_o}{V_i}\right) - 10 \log \left\{\frac{(R_L + R_O)^2}{4 R_L^2}\right\},$$

$$= 20 \log \left(\frac{V_o}{V_i}\right) - 10 \log \left(\frac{R_L + R_O}{2 R_L}\right)^2,$$

$$= 20 \log \left(\frac{V_o}{V_i}\right) - 20 \log \left(\frac{R_L + R_O}{2 R_L}\right).$$

$$\therefore 20 \log \left(\frac{V_L}{V_i}\right) = 20 \log \left(\frac{V_o}{V_i}\right) - 20 \log \left(\frac{R_O + R_L}{2 R_L}\right).$$

Voltage gain for working conditions = Voltage gain for matched impedance conditions *minus* output voltage reflection loss.

Thus, gain in db (from voltages)=

$$20 \log \left(\frac{V_o}{V_i}\right) + 10 \log \left(\frac{R_i}{R_L}\right) - 20 \log \left(\frac{R_L + R_o}{2 R_L}\right)$$

NUMERICAL EXAMPLE: Consider the following numerical example to illustrate the application of the above derived formulæ in case (c), which may seem a little confusing at first sight.

Problem: An amplifier, working from a 500-ohm line with an input of 6 mW, has an output impedance of 10-ohms. When worked into a matched load, the output is 6 watts, giving a gain of 30 db. What is the gain, when the amplifier works into a 20-ohm load?

Solution: Using the notation in Fig. 1.7, we have the following data:

$$P_i = 6 \times 10^{-3} \text{ watts}; \quad P_o = 6 \text{ watts}; \qquad \begin{array}{|l} R_i = 500 \text{ ohms} \\ R_L = 20 \text{ ,,} \\ R_o = 10 \text{ ,,} \end{array}$$

From this data, we have:

$$V_i = \sqrt{P_i \times R_i} = \sqrt{6 \times 10^{-3} \times 500} = \sqrt{3} \text{ volt};$$

$$V_o = \sqrt{P_o \times R_o} = \sqrt{6 \times 10} = \sqrt{60} \text{ volts};$$

$$V_L = V_o \times \frac{2 R_L}{R_L + R_o} = \sqrt{60} \times \frac{2 \times 20}{20 + 10} = \frac{4}{3} \sqrt{60} \text{ volts};$$

$$\text{and } P_L = \frac{V_L^2}{R_L} = \frac{16}{9} \times \frac{60}{20} = \frac{16}{3} \text{ watts.}$$

$$\left.\begin{array}{l}\text{Gain into the matched load} \\ \text{(from powers)}\end{array}\right\} = \left(10 \log \frac{P_o}{P_i}\right)$$

$$= \left(10 \log \frac{6}{6 \times 10^{-3}}\right) = 10 \log 10^3 = 30 \text{ db.}$$

$$\left.\begin{array}{l}\text{Gain into the matched load} \\ \text{(from voltages)}\end{array}\right\} = \left\{20 \log \frac{V_o}{V_i} + 10 \log \frac{R_i}{R_o}\right\},$$

$$\text{,, \quad ,,} \qquad \Big\} = \left\{20 \log \sqrt{\frac{60}{3}} + 10 \log \frac{500}{10}\right\},$$

$$\text{,, \quad ,,} \qquad \Big\} = \left\{20 \log \sqrt{20} + 10 \log 50\right\},$$

$$\left.\begin{array}{c}\text{Gain into the matched load}\\ \text{(from voltages)}\end{array}\right\} = \left(13 + 17\right) \text{ db,}$$

$$\text{,, ,,} \quad \Big\} = 30{\cdot}0 \text{ db.}$$

$$\left.\begin{array}{c}\text{Gain when working into a mis-}\\ \text{matched load (from powers)}\end{array}\right\} = \left\{10 \log \frac{P_o}{P_i} - 10 \log \frac{(R_L + R_o)^2}{4 R_L R_o}\right\},$$

$$\left.\begin{array}{c}\text{Gain when working into a mis-}\\ \text{matched load (from powers)}\end{array}\right\} = \left\{30 - 10 \log \frac{900}{800}\right\},$$

$$\text{,, ,,} \quad \Big\} = (30-0{\cdot}5) \text{ db,}$$

$$\text{,, ,,} \quad \Big\} = 29{\cdot}5 \text{ db.}$$

The loss due to mismatch $= 0{\cdot}5$ db.

$$\left.\begin{array}{c}\text{Gain when working into a mis-}\\ \text{matched load (from voltages)}\end{array}\right\} = \left\{20 \log \frac{V_o}{V_i} + 10 \log \frac{R_i}{R_L} - 20 \log \frac{R_L + R_o}{{}^{2}R_L}\right\},$$

$$\left.\begin{array}{c}\text{Gain when working into a mis-}\\ \text{matched load (from voltages)}\end{array}\right\} = \left\{20 \log \sqrt{\frac{60}{3}} + 10 \log 25 - 20 \log \frac{30}{40}\right\},$$

$$\left.\begin{array}{c}\text{Gain when working into a mis-}\\ \text{matched load (from voltages)}\end{array}\right\} = (13 + 14 + 2{\cdot}5) \text{ db.}$$

$$\therefore \left.\begin{array}{c}\text{Gain when working into a mis-}\\ \text{matched load (from voltages)}\end{array}\right\} = 29{\cdot}5 \text{ db.}$$

Thus, we see the overall gain is the same whether we work from a consideration of powers or voltages.

From straightforward working also, we get :

$$\left.\begin{array}{c}\text{Gain when working into a mis-}\\ \text{matched load (from powers)}\end{array}\right\} = \left(10 \log \frac{P_L}{P_i}\right).$$

$$\left.\begin{array}{l}\text{Gain when working into a mis-}\\ \text{matched load (from powers)}\end{array}\right\} = \left\{10 \log \left(\frac{16}{3} \times \frac{1}{6 \times 10^{-3}}\right)\right\} = 29{\cdot}5 \text{ db},$$

$$\left.\begin{array}{l}\text{Gain when working into a mis-}\\ \text{matched load (from voltages)}\end{array}\right\} = \left\{20 \log \frac{V_L}{V_i} + 10 \log \frac{R_i}{R_L}\right\},$$

$$\left.\begin{array}{l}\text{Gain when working into a mis-}\\ \text{matched load (from voltages)}\end{array}\right\} = \left\{20 \log \frac{4\sqrt{60}}{3\sqrt{3}} + 10 \log \frac{500}{20}\right\},$$

$$\left.\begin{array}{l}\text{Gain when working into a mis-}\\ \text{matched load (from voltages)}\end{array}\right\} = (15{\cdot}5 + 14) \text{ db},$$

$$= 29{\cdot}5 \text{ db}.$$

15. Decibel Graph.

With the aid of the chart (vide frontispiece), the number of decibels, corresponding to power or voltage or current ratios, can be readily read out; the two graphs in the chart are based on the following simple relations for matched impedance only:—

$$D = 10 \log \left(\frac{P_o}{P_i}\right) = 20 \log \left(\frac{V_o}{V_i}\right) = 20 \log \left(\frac{I_o}{I_i}\right).$$

The graphs are drawn upto 40 db corresponding to a power ratio of 10,000 (or 10^4), and upto 60 db corresponding to a voltage or current ratio of 1,000 (or 10^3).

The graph sheet is a log-linear paper, with linear scale on the X-axis for db, and the ratios of power or voltage or current on the Y-axis (log-scale). The use of the chart should need no further explanation.

16. Decibel Tables.

Like tables of logarithms and antilogarithms, two very useful tables are reproduced here from the catalogue of Messrs. General Radio Company,[8] USA.

The scope of these tables is as follows:

Tables 8 (a) and (b) : These tables enable us to find (the unknown) power and voltage or current ratios corresponding to the known number of decibels.

Table 8 (a).

Given : (+) Decibels ; to find: {Voltage or Current} and Power Ratios.

Table for positive decibels only.

+ *db*	*Voltage Ratio*	*Power Ratio*	+ *db*	*Voltage Ratio*	*Power Ratio*	+ *db*	*Voltage Ratio*	*Power Ratio*	+ *db*	*Voltage Ratio*	*Power Ratio*
0	**1.000**	**1.000**	**5.0**	**1.778**	**3.162**	**10.0**	**3.162**	**10.000**	**15.0**	**5.623**	**31.62**
.1	1.012	1.023	5.1	1.799	3.236	10.1	3.199	10.23	15.1	5.689	32.36
.2	1.023	1.047	5.2	1.820	3.311	10.2	3.236	10.47	15.2	5.754	33.11
.3	1.035	1.072	5.3	1.841	3.388	10.3	3.273	10.72	15.3	5.821	33.88
.4	1.047	1.096	5.4	1.862	3.467	10.4	3.311	10.96	15.4	5.888	34.67
.5	1.059	1.122	5.5	1.884	3.548	10.5	3.350	11.22	15.5	5.957	35.48
.6	1.072	1.148	5.6	1.905	3.631	10.6	3.388	11.48	15.6	6.026	36.31
.7	1.084	1.175	5.7	1.928	3.715	10.7	3.428	11.75	15.7	6.095	37.15
.8	1.096	1.202	5.8	1.950	3.802	10.8	3.467	12.02	15.8	6.166	38.02
.9	1.109	1.230	5.9	1.972	3.890	10.9	3.508	12.30	15.9	6.237	38.90
1.0	**1.122**	**1.259**	**6.0**	**1.995**	**3.981**	**11.0**	**3.548**	**12.59**	**16.0**	**6.310**	**39.81**
1.1	1.135	1.288	6.1	2.018	4.074	11.1	3.589	12.88	16.1	6.383	40.74
1.2	1.148	1.318	6.2	2.042	4.169	11.2	3.631	13.18	16.2	6.457	41.69
1.3	1.161	1.349	6.3	2.065	4.266	11.3	3.673	13.49	16.3	6.531	42.66
1.4	1.175	1.380	6.4	2.089	4.365	11.4	3.715	13.80	16.4	6.607	43.65
1.5	1.189	1.413	6.5	2.113	4.467	11.5	3.758	14.13	16.5	6.683	44.67
1.6	1.202	1.445	6.6	2.138	4.571	11.6	3.802	14.45	16.6	6.761	45.71
1.7	1.216	1.479	6.7	2.163	4.677	11.7	3.846	14.79	16.7	6.839	46.77
1.8	1.230	1.514	6.8	2.188	4.786	11.8	3.890	15.14	16.8	6.918	47.86
1.9	1.245	1.549	6.9	2.213	4.898	11.9	3.936	15.49	16.9	6.998	48.98

2.0	**1.259**	**1.585**	**7.0**	**2.239**	**5.012**	**12.0**	**3.981**	**15.85**	**17.0**	**7.079**	**50.12**
2.1	1.274	1.622	7.1	2.265	5.129	12.1	4.027	16.22	17.1	7.161	51.29
2.2	1.288	1.660	7.2	2.291	5.248	12.2	4.074	16.60	17.2	7.244	52.48
2.3	1.303	1.698	7.3	2.317	5.370	12.3	4.121	16.98	17.3	7.328	53.70
2.4	1.318	1.738	7.4	2.344	5.495	12.4	4.169	17.38	17.4	7.413	54.95
2.5	1.334	1.778	7.5	2.371	5.623	12.5	4.217	17.78	17.5	7.499	56.23
2.6	1.349	1.820	7.6	2.399	5.754	12.6	4.266	18.20	17.6	7.586	57.54
2.7	1.365	1.862	7.7	2.427	5.888	12.7	4.315	18.62	17.7	7.674	58.88
2.8	1.380	1.905	7.8	2.455	6.026	12.8	4.365	19.05	17.8	7.762	60.26
2.9	1.396	1.950	7.9	2.483	6.166	12.9	4.416	19.50	17.9	7.852	61.66
3.0	**1.413**	**1.995**	**8.0**	**2.512**	**6.310**	**13.0**	**4.467**	**19.95**	**18.0**	**7.943**	**63.10**
3.1	1.429	2.042	8.1	2.541	6.457	13.1	4.519	20.42	18.1	8.035	64.57
3.2	1.445	2.089	8.2	2.570	6.607	13.2	4.571	20.89	18.2	8.128	66.07
3.3	1.462	2.138	8.3	2.600	6.761	13.3	4.624	21.38	18.3	8.222	67.61
3.4	1.479	2.188	8.4	2.630	6.918	13.4	4.677	21.88	18.4	8.318	69.18
3.5	1.496	2.239	8.5	2.661	7.079	13.5	4.732	22.39	18.5	8.414	70.79
3.6	1.514	2.291	8.6	2.692	7.244	13.6	4.786	22.91	18.6	8.511	72.44
3.7	1.531	2.344	8.7	2.723	7.413	13.7	4.842	23.44	18.7	8.610	74.13
3.8	1.549	2.399	8.8	2.754	7.586	13.8	4.898	23.99	18.8	8.710	75.86
3.9	1.567	2.455	8.9	2.786	7.762	13.9	4.955	24.55	18.9	8.811	77.62
4.0	**1.585**	**2.512**	**9.0**	**2.818**	**7.943**	**14.0**	**5.012**	**25.12**	**19.0**	**8.913**	**79.43**
4.1	1.603	2.570	9.1	2.851	8.128	14.1	5.070	25.70	19.1	9.016	81.28
4.2	1.622	2.630	9.2	2.884	8.318	14.2	5.129	26.30	19.2	9.120	83.18
4.3	1.641	2.692	9.3	2.917	8.511	14.3	5.188	26.92	19.3	9.226	85.11
4.4	1.660	2.754	9.4	2.951	8.710	14.4	5.248	27.54	19.4	9.333	87.10
4.5	1.679	2.818	9.5	2.985	8.913	14.5	5.309	28.18	19.5	9.441	89.13
4.6	1.698	2.884	9.6	3.020	9.120	14.6	5.370	28.84	19.6	9.550	91.20
4.7	1.718	2.951	9.7	3.055	9.333	14.7	5.433	29.51	19.7	9.661	93.33
4.8	1.738	3.020	9.8	3.090	9.550	14.8	5.495	30.20	19.8	9.772	95.50
4.9	1.758	3.090	9.9	3.126	9.772	14.9	5.559	30.90	19.9	9.886	97.72
									20.0	**10.000**	**100.00**

Table 8 (b)

Given: (—) Decibels; To find: {Voltage or current} and Power Ratios.

Table for negative decibels only.

−*db.*	*Voltage Ratio*	*Power Ratio*	−*db.*	*Voltage Ratio*	*Power Ratio*	−*db.*	*Voltage Ratio*	*Power Ratio*	−*db.*	*Voltage Ratio*	*Power Ratio*
0	**1.0000**	**1.0000**	**−5.0**	**.5623**	**.3162**	**−10.0**	**.3162**	**.1000**	**−15.0**	**.1778**	**.03162**
−.1	.9886	.9772	5.1	.5559	.3090	10.1	.3126	.09772	15.1	.1758	.03090
.2	.9772	.9550	5.2	.5495	.3020	10.2	.3090	.09550	15.2	.1738	.03020
.3	.9661	.9333	5.3	.5433	.2951	10.3	.3055	.09333	15.3	.1718	.02951
.4	.9550	.9120	5.4	.5370	.2884	10.4	.3020	.09120	15.4	.1698	.02884
.5	.9441	.8913	5.5	.5309	.2818	10.5	.2985	.08913	15.5	.1679	.02818
.6	.9333	.8710	5.6	.5248	.2754	10.6	.2951	.08710	15.6	.1660	.02754
.7	.9226	.8511	5.7	.5188	.2692	10.7	.2917	.08511	15.7	.1641	.02692
.8	.9120	.8318	5.8	.5129	.2630	10.8	.2884	.08318	15.8	.1622	.02630
.9	.9016	.8128	5.9	.5070	.2570	10.9	.2851	.08128	15.9	.1603	.02570
1.0	**.8913**	**.7943**	**6.0**	**.5012**	**.2512**	**11.0**	**.2818**	**.07943**	**16.0**	**.1585**	**.02512**
1.1	.8810	.7762	[illegible]	.4955	.2455	11.1	.2786	.07762	16.1	.1567	.02455
1.2	.8710	.7586	[illegible]	.4898	.2399	11.2	.2754	.07586	16.2	.1549	.02399
1.3	.8610	.7413	6.3	[illegible]342	.2344	11.3	.2723	.07413	16.3	.1531	.02344
1.4	.8511	.7244	6.4	.4786	.2291	11.4	.2692	.07244	16.4	.1514	.02291
1.5	.8414	.7079	6.5	.4732	.2239	11.5	.2661	.07079	16.5	.1496	.02239
1.6	.8318	.6918	6.6	.4677	.2188	11.6	.2630	.06918	16.6	.1479	.02188
1.7	.8222	.6761	6.7	.4624	.2138	11.7	.2600	.06761	16.7	.1462	.02138
1.8	.8128	.6607	6.8	.4571	.2089	11.8	.2570	.06607	16.8	.1445	.02089
1.9	.8035	.6457	6.9	.4519	.2042	11.9	.2541	.06457	16.9	.1429	.02042

2.0	**.7943**	**.6310**	**7.0**	**.4467**	**.1995**	**12.0**	**.2512**	**.06310**	**17.0**	**.1413**	**.01995**
2.1	.7852	.6166	7.1	.4416	.1950	12.1	.2483	.06166	17.1	.1396	.01950
2.2	.7762	.6026	7.2	.4365	.1905	12.2	.2455	.06026	17.2	.1380	.01905
2.3	.7674	.5888	7.3	.4315	.1862	12.3	.2427	.05888	17.3	.1365	.01862
2.4	.7586	.5754	7.4	.4266	.1820	12.4	.2399	.05754	17.4	.1349	.01820
2.5	.7499	.5623	7.5	.4217	.1778	12.5	.2371	.05623	17.5	.1334	.01778
2.6	.7413	.5495	7.6	.4169	.1738	12.6	.2344	.05495	17.6	.1318	.01738
2.7	.7328	.5370	7.7	.4121	.1698	12.7	.2317	.05370	17.7	.1303	.01698
2.8	.7244	.5248	7.8	.4074	.1660	12.8	.2291	.05248	17.8	.1288	.01660
2.9	.7161	.5129	7.9	.4027	.1622	12.9	.2265	.05129	17.9	.1274	.01622
3.0	**.7079**	**.5012**	**8.0**	**.3981**	**.1585**	**13.0**	**.2239**	**.05012**	**18.0**	**.1259**	**.01585**
3.1	.6998	.4898	8.1	.3936	.1549	13.1	.2213	.04898	18.1	.1245	.01549
3.2	.6918	.4786	8.2	.3890	.1514	13.2	.2188	.04786	18.2	.1230	.01514
3.3	.6839	.4677	8.3	.3846	.1479	13.3	.2163	.04677	18.3	.1216	.01479
3.4	.6761	.4571	8.4	.3802	.1445	13.4	.2138	.04571	18.4	.1202	.01445
3.5	.6683	.4467	8.5	.3758	.1413	13.5	.2113	.04467	18.5	.1189	.01413
3.6	.6607	.4365	8.6	.3715	.1380	13.6	.2089	.04365	18.6	.1175	.01380
3.7	.6531	.4266	8.7	.3673	.1349	13.7	.2065	.04266	18.7	.1161	.01349
3.8	.6457	.4169	8.8	.3631	.1318	13.8	.2042	.04169	18.8	.1148	.01318
3.9	.6383	.4074	8.9	.3589	.1288	13.9	.2018	.04074	18.9	.1135	.01288
4.0	**.6310**	**.3981**	**9.0**	**.3548**	**.1259**	**14.0**	**.1995**	**.03981**	**19.0**	**.1122**	**.01259**
4.1	.6237	.3890	9.1	.3508	.1230	14.1	.1972	.03890	19.1	.1109	.01230
4.2	.6166	.3802	9.2	.3467	.1202	14.2	.1950	.03802	19.2	.1096	.01202
4.3	.6095	.3715	9.3	.3428	.1175	14.3	.1928	.03715	19.3	.1084	.01175
4.4	.6026	.3631	9.4	.3388	.1148	14.4	.1905	.03631	19.4	.1072	.01148
4.5	.5957	.3548	9.5	.3350	.1122	14.5	.1884	.03548	19.5	.1059	.01122
4.6	.5888	.3467	9.6	.3311	.1096	14.6	.1862	.03467	19.6	.1047	.01096
4.7	.5821	.3388	9.7	.3273	.1072	14.7	.1841	.03388	19.7	.1035	.01072
4.8	.5754	.3311	9.8	.3236	.1047	14.8	.1820	.03311	19.8	.1023	.01047
4.9	.5689	.3236	9.9	.3199	.1023	14.9	.1799	.03236	19.9	.1012	.01023
									20.0	**.1000**	**.01000**

Table 9.

GIVEN: { Voltage or Current } Ratio   TO FIND: Decibels

Voltage Ratio	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
1.0	**.000**	**.086**	**.172**	**.257**	**.341**	**.424**	**.506**	**.588**	**.668**	**.749**
1.1	.828	.906	.984	1.062	1.138	1.214	1.289	1.364	1.438	1.511
1.2	1.584	1.656	1.727	1.798	1.868	1.938	2.007	2.076	2.144	2.212
1.3	2.279	2.345	2.411	2.477	2.542	2.607	2.671	2.734	2.798	2.860
1.4	2.923	2.984	3.046	3.107	3.167	3.227	3.287	3.346	3.405	3.464
1.5	3.522	3.580	3.637	3.694	3.750	3.807	3.862	3.918	3.973	4.028
1.6	4.082	4.137	4.190	4.244	4.297	4.350	4.402	4.454	4.506	4.558
1.7	4.609	4.660	4.711	4.761	4.811	4.861	4.910	4.959	5.008	5.057
1.8	5.105	5.154	5.201	5.249	5.296	5.343	5.390	5.437	5.483	5.529
1.9	5.575	5.621	5.666	5.711	5.756	5.801	5.845	5.889	5.933	5.977
2.0	**6.021**	**6.064**	**6.107**	**6.150**	**6.193**	**6.235**	**6.277**	**6.319**	**6.361**	**6.403**
2.1	6.444	6.486	6.527	6.568	6.608	6.649	6.689	6.729	6.769	6.809
2.2	6.848	6.888	6.927	6.966	7.008	7.044	7.082	7.121	7.159	7.197
2.3	7.235	7.272	7.310	7.347	7.384	7.421	7.458	7.495	7.532	7.568
2.4	7.604	7.640	7.676	7.712	7.748	7.783	7.819	7.854	7.889	7.924
2.5	7.959	7.993	8.028	8.062	8.097	8.131	8.165	8.199	8.232	8.266
2.6	8.299	8.333	8.366	8.399	8.432	8.465	8.498	8.530	8.563	8.595
2.7	8.627	8.659	8.691	8.723	8.755	8.787	8.818	8.850	8.881	8.912
2.8	8.943	8.974	9.005	9.036	9.066	9.097	9.127	9.158	9.188	9.218
2.9	9.248	9.278	9.308	9.337	9.367	9.396	9.426	9.455	9.484	9.513

3.0	**9.642**	**9.571**	**9.600**	**9.629**	**9.657**	**9.686**	**9.714**	**9.743**	**9.771**	**9.799**
3.1	9.827	9.855	9.883	9.911	9.939	9.966	9.994	10.021	10.049	10.076
3.2	10.103	10.130	10.157	10.184	10.211	10.238	10.264	10.291	10.317	10.344
3.3	10.370	10.397	10.423	10.449	10.475	10.501	10.527	10.553	10.578	10.604
3.4	10.630	10.655	10.681	10.706	10.731	10.756	10.782	10.807	10.832	10.857
3.5	10.881	10.906	10.931	10.955	10.980	11.005	11.029	11.053	11.078	11.102
3.6	11.126	11.150	11.174	11.198	11.222	11.246	11.270	11.293	11.317	11.341
3.7	11.364	11.387	11.411	11.434	11.457	11.481	11.504	11.527	11.550	11.573
3.8	11.596	11.618	11.641	11.664	11.687	11.709	11.732	11.754	11.777	11.799
3.9	11.821	11.844	11.866	11.888	11.910	11.932	11.954	11.976	11.998	12.019
4.0	**12.041**	**12.063**	**12.085**	**12.106**	**12.128**	**12.149**	**12.171**	**12.192**	**12.213**	**12.234**
4.1	12.256	12.277	12.298	12.319	12.340	12.361	12.382	12.403	12.424	12.444
4.2	12.465	12.486	12.506	12.527	12.547	12.568	12.588	12.609	12.629	12.649
4.3	12.669	12.690	12.710	12.730	12.750	12.770	12.790	12.810	12.829	12.849
4.4	12.869	12.889	12.908	12.928	12.948	12.967	12.987	13.006	13.026	13.045
4.5	13.064	13.084	13.103	13.122	13.141	13.160	13.179	13.198	13.217	13.236
4.6	13.255	13.274	13.293	13.312	13.330	13.349	13.368	13.386	13.405	13.423
4.7	13.442	13.460	13.479	13.497	13.516	13.534	13.552	13.570	13.589	13.607
4.8	13.625	13.643	13.661	13.679	13.697	13.715	13.733	13.751	13.768	13.786
4.9	13.804	13.822	13.839	13.857	13.875	13.892	13.910	13.927	13.945	13.962
5.0	**13.979**	**13.997**	**14.014**	**14.031**	**14.049**	**14.066**	**14.083**	**14.100**	**14.117**	**14.134**
5.1	14.151	14.168	14.185	14.202	14.219	14.236	14.253	14.270	14.287	14.303
5.2	14.320	14.337	14.353	14.370	14.387	14.403	14.420	14.436	14.453	14.469
5.3	14.486	14.502	14.518	14.535	14.551	14.567	14.583	14.599	14.616	14.632
5.4	14.648	14.664	14.680	14.696	14.712	14.728	14.744	14.760	14.776	14.791
5.5	14.807	14.823	14.839	14.855	14.870	14.886	14.902	14.917	14.933	14.948
5.6	14.964	14.979	14.995	15.010	15.026	15.041	15.056	15.072	15.087	15.102
5.7	15.117	15.133	15.148	15.163	15.178	15.193	15.208	15.224	15.239	15.254
5.8	15.269	15.284	15.298	15.313	15.328	15.343	15.358	15.373	15.388	15.402
5.9	15.417	15.432	15.446	15.461	15.476	15.490	15.505	15.519	15.534	15.549

Table 9—*(continued.)*

Voltage Ratio	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
6.0	**15.563**	**15.577**	**15.592**	**15.606**	**15.621**	**15.635**	**15.649**	**15.664**	**15.678**	**15.692**
6.1	15.707	15.721	15.735	15.749	15.763	15.778	15.792	15.806	15.820	15.834
6.2	15.848	15.862	15.876	15.890	15.904	15.918	15.931	15.945	15.959	15.973
6.3	15.987	16.001	16.014	16.028	16.042	16.055	16.069	16.083	16.096	16.110
6.4	16.124	16.137	16.151	16.164	16.178	16.191	16.205	16.218	16.232	16.245
6.5	16.258	16.272	16.285	16.298	16.312	16.325	16.338	16.351	16.365	16.378
6.6	16.391	16.404	16.417	16.430	16.443	16.456	16.469	16.483	16.496	16.509
6.7	16.521	16.534	16.547	16.560	16.573	16.586	16.599	16.612	16.625	16.637
6.8	16.650	16.663	16.676	16.688	16.701	16.714	16.726	16.739	16.752	16.764
6.9	16.777	16.790	16.802	16.815	16.827	16.840	16.852	16.865	16.877	16.890
7.0	**16.902**	**16.914**	**16.927**	**16.939**	**16.951**	**16.964**	**16.976**	**16.988**	**17.001**	**17.013**
7.1	17.025	17.037	17.050	17.062	17.074	17.086	17.098	17.110	17.122	17.135
7.2	17.147	17.159	17.171	17.183	17.195	17.207	17.219	17.231	17.243	17.255
7.3	17.266	17.278	17.290	17.302	17.314	17.326	17.338	17.349	17.361	17.373
7.4	17.385	17.396	17.408	17.420	17.431	17.443	17.455	17.466	17.478	17.490
7.5	17.501	17.513	17.524	17.536	17.547	17.559	17.570	17.582	17.593	17.605
7.6	17.616	17.628	17.639	17.650	17.662	17.673	17.685	17.696	17.707	17.719
7.7	17.730	17.741	17.752	17.764	17.775	17.786	17.797	17.808	17.820	17.831
7.8	17.842	17.853	17.864	17.875	17.886	17.897	17.908	17.919	17.931	17.942
7.9	17.953	17.964	17.975	17.985	17.996	18.007	18.018	18.029	18.040	18.051
8.0	**18.062**	**18.073**	**18.083**	**18.094**	**18.105**	**18.116**	**18.127**	**18.137**	**18.148**	**18.159**
8.1	18.170	18.180	18.191	18.202	18.212	18.223	18.234	18.244	18.255	18.266
8.2	18.276	18.287	18.297	18.308	18.319	18.329	18.340	18.350	18.361	18.371
8.3	18.382	18.392	18.402	18.413	18.423	18.434	18.444	18.455	18.465	18.475
8.4	18.486	18.496	18.506	18.517	18.527	18.537	18.547	18.558	18.568	18.578

8.5	18.588	18.599	18.609	18.619	18.629	18.639	18.649	18.660	18.670	18.680
8.6	18.690	18.700	18.710	18.720	18.730	18.740	18.750	18.760	18.770	18.780
8.7	18.790	18.800	18.810	18.820	18.830	18.840	18.850	18.860	18.870	18.880
8.8	18.890	18.900	18.909	18.919	18.929	18.939	18.949	18.958	18.968	18.978
8.9	18.988	18.998	19.007	19.017	19.027	19.036	19.046	19.056	19.066	19.075
9.0	**19.085**	**19.094**	**19.104**	**19.114**	**19.123**	**19.133**	**19.143**	**19.152**	**19.162**	**19.171**
9.1	19.181	19.190	19.200	19.209	19.219	19.228	19.238	19.247	19.257	19.266
9.2	19.276	19.285	19.295	19.304	19.313	19.323	19.332	19.342	19.351	19.360
9.3	19.370	19.379	19.388	19.398	19.407	19.416	19.426	19.435	19.444	19.453
9.4	19.463	19.472	19.481	19.490	19 499	19.509	19.518	19.527	19.536	19.545
9.5	19.554	19.564	19.573	19.582	19.591	19.600	19.609	19.618	19.627	19.636
9.6	19.645	19.654	19.664	19.673	19.682	19.691	19.700	19.709	19.718	19.726
9.7	19.735	19.744	19.753	19.762	19.771	19.780	19.789	19.798	19.807	19.816
9.8	19.825	19.833	19.842	19.851	19.860	19.869	19.878	19.886	19.895	19.904
9.9	19.913	19.921	19.930	19.939	19.948	19.956	19.965	19.974	19.983	19.991

Voltage Ratio	0	1	2	3	4	5	6	7	8	9
10	**20.000**	**20.828**	**21.584**	**22.279**	**22.923**	**23.522**	**24.082**	**24.609**	**25.105**	**25.575**
20	26.021	26.444	26.848	27.235	27.604	27.959	28.299	28.627	28.943	29.248
30	29.542	29.827	30.103	30.370	30.630	30.881	31.126	31.364	31.596	31.821
40	32.041	32.256	32.465	32.669	32.869	33.064	33.255	33.442	33.625	33.804
50	33.979	34.151	34.320	34.486	34.648	34.807	34.964	35.117	35.269	35.417
60	35.563	35.707	35.848	35.987	36.124	36.258	36.391	36.521	36.650	36.777
70	36.902	37.025	37.147	37.266	37.385	37.501	37.616	37.730	37.842	37.953
80	38.062	38.170	38.276	38.382	38.486	38.588	38.690	38.790	38.890	38.988
90	39.085	39.181	39.276	39.370	39.463	39.554	39.645	39.735	39.825	39.913
100	**40.000**	—	—	—	—	—	—	—	—	—

To find ratios outside the range of this table, see pages 39 to 44

Table 9 : This table enables us to find (the unknown) number of decibels corresponding to the known voltage or current ratio directly, and the power ratio indirectly. The indirect method of finding out the number of decibels corresponding to a given power ratio is explained later.

It will be seen that these two tables are independent of arbitrarily chosen "zero or reference levels".

(ii) Range of the Tables:—

For ready reference the following table, which covers 10 to 100 db in steps of 10 db, is also specially reproduced below.

Table 10.

—db	Voltage ratio	Power ratio	+db	Voltage ratio	Power ratio
—10	3.162×10^{-1}	10^{-1}	10	3.162	10
—20	10^{-1}	10^{-2}	20	10	10^{2} or 100
—30	3.162×10^{-2}	10^{-3}	30	3.162×10	10^{3} or 1,000
—40	10^{-2}	10^{-4}	40	100	10^{4} or 10,000
—50	3.162×10^{-3}	10^{-5}	50	3.162×10^{2}	10^{5} or 100,000
—60	10^{-3}	10^{-6}	60	1,000	10^{6} or 1,000,000
—70	3.162×10^{-4}	10^{-7}	70	3.162×10^{3}	10^{7} or 10,000,000
—80	10^{-4}	10^{-8}	80	10.000	10^{8} or 100,000,000
—90	3.162×10^{-5}	10^{-9}	90	3.162×10^{4}	10^{9} or 1,000,000,000
—100	10^{-5}	10^{-10}	100	100,000	10^{10} or 10.000.000,000

Table 8 (a) covers a voltage (or current) ratio of 1.0 to 10.0 or power ratio of 1.0 to 100.0, *i.e.*, O to + 20 db, in steps of 0.1 db.

Table 8 (b) covers a voltage (or current) ratio of 0.1 to 1.0 or power ratio of 0.01 to 1.0, *i.e.*, —20 db to O db, in steps of 0.1 db.

Table 9 covers a voltage or current ratio of 1.0 to 9.9 in steps of 0.01, and the corresponding decibel range of 0 to 19.991 db. There is a further table below the main table, covering a voltage ratio range of 10 to 100 in steps of 1, corresponding to the db range of 20 to 40 db.

At this stage one may wonder whether these two tables could be used for decibel values outside the range of the values listed in Tables 8 (a) and (b), and for ratios outside the range of the values listed in Table 9. Fortunately, these two tables can be used for any decibel value and any power, voltage or current ratio. The following rules are given to find the values outside the range of conversion tables:—

(iii) Use of Tables 8 (a) and (b) : Decibels to Voltage and Power Ratios.

(a) For ratios >1, *i.e.*, when the number of decibels is positive.

Subtract + 20 db repeatedly from the given number of decibels until the remainder for the first time comes within the range of Table 8 (a).

To find the voltage ratio :

Multiply the value listed in the voltage-ratio column by 10 for each 20 db subtracted.

To find the power ratio :

Multiply the value listed in the power-ratio column by 100 for each 20 db subtracted.

The application of the above rules will be clear from the following two examples :

Example :—*Given* : + 56.7 db.
To find: (1) Voltage ratio;
(2) Power ratio.

Solution :—

56.7 – 20 – 20 = 16.7 db. After two subtractions of 20 db each time, the result is 16.7 db, which is found to be within the range of Table 8 (a).

(1) To find the voltage ratio :

16.7 db ⟶ 6.839 (from Table 8 (a)).

∴ 56.7 db = 20 + 20 + 16.7 ⟶ 10 × 10 × 6.839

∴ The answer is 683.9

This can be verified by the direct logarithmic method :

Log 683.9 = 2.8350 (from log-tables).

20 log 683.9 = 20 x 2.8350
= 56.70 db.

(2) To find the power ratio :

16.7 db ⟶ 46.77 (from Table (8) (*a*)).

∴ 56.7 db = 20 + 20 + 16.7 ⟶ 100 × 100 × 46.77

∴ The answer is 467700 or 46.77×10^4.

This can be verified by the direct logarithmic method :

Log 467700 = 5.670

10 log 467700 = 10 x 5.670 = 56.7 db.

(b) For ratios < 1, *i.e.*, when the number of decibels is negative :

Add 20 db repeatedly to the given number of db until the total sum for the first time comes within the range of Table 8 (b).

(1) To find the voltage ratio :

Divide the value listed in the left-hand voltage-ratio column by 10 for each addition of + 20 db.

(2) To find the power ratio :

Divide the value listed in the left-hand power-ratio column by 100 for each addition of + 20 db.

The application of the above rules will be clear from the following two examples :

Example :— *Given* : —56.7 db.

To find:—(1) Voltage ratio;

(2) Power ratio.

Solution:—

$$-56.7 + 20 + 20 = -16.7 \text{ db.}$$

(1) To find the voltage ratio:

$$-16.7 \text{ db} \longrightarrow 0.1462 \text{ (from Table 8 (b)),}$$

$$-56.7 \text{ db} \longrightarrow 0.1462 \times \frac{1}{10} \times \frac{1}{10},$$

$$= 0.001462.$$

(2) To find the power ratio:

$$-16.7 \text{ db} \longrightarrow 0.02138$$

$$-56.7 \text{ db} \longrightarrow 0.02138 \times \frac{1}{100} \times \frac{1}{100},$$

$$= 0.000002138$$

Alternative Method :—

A rule for an alternative method of obtaining the voltage or power ratio corresponding to a given number of **negative db** is as follows :—

Add 20 db repeatedly till an excess (+ value) is left over the given number of *negative* db.

Then obtain from Table 8 (a) the ratio for the excess (+) value of db and divide it by 10 for voltage ratios, and by 100 for power ratios, for each 20 db added.

This is illustrated by the following example:

Take again, − 56.7 db.

Solution :—

$$20 + 20 + 20 - 56.7 = 3.3 \text{ db},$$

(1) **To find the voltage ratio:**

$$+3.3 \text{ db} \longrightarrow 1.462 \text{ (from Table 8 (a))}$$

$$\therefore -56.7 \text{ db} \longrightarrow 1.462 \times \frac{1}{10} \times \frac{1}{10} \times \frac{1}{10}$$

$$= 0.001462$$

(2) **To find the power ratio :**

$$+3.3 \text{ db} \longrightarrow 2.138$$

$$-56.7 \text{ db} \longrightarrow 2.138 \times \frac{1}{100} \times \frac{1}{100} \times \frac{1}{100}$$

$$= 0.000002138$$

(iv) Use of Table 9 : Voltage Ratios to Decibels.

(a) Rule for ratios smaller than those in Table 9, *i.e.*, for ratios < 1 :

Multiply the given ratio by 10 repeatedly until the product for the first time can be found in the table. From the number of decibels thus found, subtract + 20 db for each multiplication by 10.

Example :—*Given* : Voltage ratio = 0.0123
To find : the db value.

Solution :—

(1) 0.0123 × 10 = 0.123, which is not found in Table 9.

(2) $0.123 \times 10 = 1.23$, which is found in Table 9.

From Table (9), $1.23 \longrightarrow 1.798$ db.

$\therefore 0.0123 \longrightarrow 1.798 - 20 - 20$ or, $-40 + 1.798$.

$\therefore$ The answer is -38.202 db.

(b) **Rule for ratios greater than those in Table 9, *i.e.*, for ratios > 1 :**

Divide the ratio by 10 repeatedly until the result can be found in the table. To the number of decibels thus found, add 20 db for each division by 10.

Example :— *Given* : Voltage ratio = 345.

To find : the db value.

Solution:— $\frac{345}{10} = 34.5$, which is not found in Table 9,

and $\frac{34.5}{10} = 3.45$, which is found in Table 9.

From Table (9), $3.45 \longrightarrow 10.756$ db.

$\therefore 345 \longrightarrow 10.756 + 20 + 20$ or 50.756 db.

$\therefore$ The answer is 50.756 db.

(v) **Use of Table 9 : Power Ratios to Decibels.**

Rule: Assuming the given power ratio to be a voltage (or current) ratio, find out the corresponding number of decibels from the table. Then, the required result is exactly one half of the number of decibels found previously from the table.

The rule is illustrated by two examples, first when the power ratio is greater than 1, and the second when the power ratio is less than 1.

(a) **Rule for ratios > 1, *i.e.*, when the number of decibels is positive :**

Example :—*Given* : a power ratio of 3.45

To find : the corresponding db value.

Solution :—From Table 9, the number of decibels corresponding to a voltage ratio of 3.45 is 10.756.

From the above rule, $\frac{10.756}{2} = 5.378$ db is the required answer.

(b) **Rule for ratios < 1, *i.e.*, when the number of decibels is negative :**

Example :—*Given* : a power ratio of 0.0123

To find : the corresponding db value.

Solution :—

It has already been found in a previous example the number of decibels corresponding to a voltage ratio of 0.0123 is —38.202 db.

$\therefore$ The required answer $= \frac{-38.202}{2} = -19.101$ db.

PART II
THE PHON

PART II

THE PHON

(1) Introduction.

The decibel notation and its formulæ, involving electrical quantities like power, voltage, and current, have been explained in Part I. Under the head: 'advantages of the db notation', it has been mentioned that it is applicable to the case of sound, because the ear obeys a logarithmic law in its response to the loudness of sound. The decibel is, therefore, used to compare intensities of sounds, and it would be better to understand the equivalents of power, voltage, and current in the field of acoustics.

Sound is produced by the vibration of a body and is propagated as wave motion. The body in motion exerts a force on the particles of the medium, and this force corresponds to emf. The particles of the medium move under this force, and this particle velocity (to be distinguished from the velocity of sound in the medium, which is quite different), corresponds to current in an electrical circuit.

The sound disturbance proceeds from the source as a spherical wave. Where the radius of this sphere is large, it is equivalent to a plane wave. If we now consider a sq. cm. of the wave front, the pressure exerted by it is similar to voltage, and is measured in dynes sq. cm.; the particle velocity corresponds to current, and is measured in cms. sec. The sound power associated with this sq. cm. of the wave front is the sound intensity, and is expressed in watts sq. cm. (1 watt $= 10^7$ ergs/sec.)

On this analogy, we could state Ohm's law for sound[9] thus: "The ratio between the sound pressure and the particle velocity thus produced, is constant for a given medium". This constant is known as the acoustic or mechanical impedance, which is expressed in mechanical ohms.

Sound Pressure = Velocity of Particle × Acoustic Impedance

$$(P_s) = (V_p \times Z_a) \qquad (\text{c.f. } E = I \times Z)$$

The modifications of this law can be easily derived, and are similar to their electrical analogues. The acoustic impedance of air is nearly equal to 40 mechanical ohms.

Just as the electrical power is the product of voltage and current, the sound intensity is the product of pressure and particle velocity:

i.e., $I_s = P_s \times V_p$ (c.f. $P = V \times I$). The other modifications of this equation can be easily derived.

From the foregoing, it is seen that two sounds can be compared, and their differences in level computed in db, using the same laws as have been used in electrical circuits, *i.e.*, from intensities or pressures, or particle velocities.

The ultimate judge of the loudness of sound is the ear, and any measurements made or inferences drawn from experimental data regarding sound, would be incorrect unless the peculiarities of the ear are taken into consideration. Thus, for example, though the ear is logarithmic in its response to loudness of a particular frequency, two sounds of equal power but of different frequencies, do not sound equally loud to the ear. As an example, a sound intensity of 10^{-16} watts sq. cm. at 1,000 cps is just audible to the ear ; the same sound intensity at 30 cps is inaudible, and to make 30 cps just audible we have to increase the intensity by over 60 db, *i.e.*, to 10^{-10} watts sq. cm. Had this at least been a constant difference, matters would not be so difficult. Sound intensities of 10^{-4} watts sq. cm. would appear equally loud approximately at 30 cps and 1,000 cps. These peculiarities are clearly depicted in the curves given in Fig. 2.1.

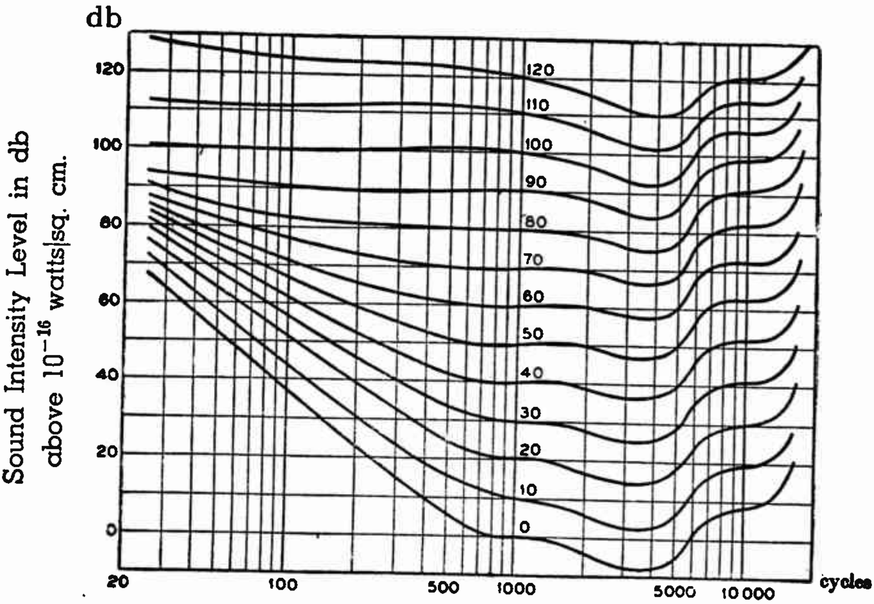

Fig. 2.1. Aural Response Curves.

Curves originally obtained by H. Fletcher and W. A. Munson (Jour. Acoust. Soc. Amer., 5, 82, 1933)
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In Fig. 2.1, the intensity level at constant loudness is plotted as a function of frequency. These are the well-known curves obtained by Harvey Fletcher and Munson. It is seen that a much higher sound intensity corresponds to an equivalent loudness at low frequencies than at medium frequencies. The difference may be as great as 60 db, *i.e.*, a ratio of 1 million. The frequency response of the ear at the threshold of audibility and threshold of pain are shown (approximately) by the bottom and top curves respectively. The bottom curve shows that, though at 1,000 cps the sound is audible at zero level, at 400 cps an increase of about 10 db, and at 50 cps an increase of about 53 db, are required in order to render the sound audible. The top curve shows that the ear is nearly as sensitive to the low-frequency notes as to the 1,000-cycle note. Therefore, if we intend expressing loudness by a unit at various frequencies, this unit must necessarily take care of the peculiarities of the response of the ear to (1) the different frequencies, and to (2) the different intensities of sound.

In Fig. 2.1, a number of curves called loudness contours, all passing through 1,000 cycles at intensity levels rising by 10 db, are shown. On any curve, at any point, the sound will be heard as though of the same loudness as the corresponding 1,000-cycle note, *e.g.*, at 10,000 cycles, an actual intensity of, say 30 db above zero, will sound just as loud as a note of 1,000 cycles at 20 db above zero. In expressing loudness at any frequency in terms of the equivalent loudness at 1,000 cycles, we can specify the degree of loudness for any sound at any particular level and frequency. The Phon is the name of this unit. A sound of loudness of, say 50 phons, is such that it sounds as loud as a 1,000-cycle note of intensity level 50 db above a zero of 10^{-16} watts sq. cm. The actual intensity at any particular frequency can be determined from the curves, as each curve corresponds to equal loudness over the frequency range represented. It is clear from these curves, how the low-frequency notes in music are missed, when the volume control is turned down, as a result of the low-note sensitivity of the ear at low sound pressures, *i.e.*, greater pressures are required with low-frequency notes than with high, or middle-frequency notes before the ear can detect the note at all.

Thus, the Phon is a unit used for the measurement of sensation of loudness and purely a subjective quantity. Expressing loudness of sounds of two different frequencies in db is not quite appropriate. It is to avoid this difficulty that the Phon or the loudness unit has been introduced.

Before we proceed to understand thoroughly what a phon is, it is worth-while to consider the definitions of some important terms in acoustics.

2. Definitions.

The following seven terms are defined, based on American Engineering and Industrial Standards' standard for Noise Measurement[10], or IRE Standards[11] on "Electro-acoustics", or BSS (661 1936).[12]

(a) **Intensity Level :**

The intensity level of a sound is the number of decibels above the zero reference level. The reference intensity for intensity level comparisons is 10^{-16} watts sq. cm. While in England and America, an intensity level of 10^{-16} watts sq. cm. (corresponding approximately to the intensity of sound at the threshold of audibility of the ear), is the zero intensity level of reference, in Germany, a sound intensity of $2{\cdot}5 \times 10^{-16}$ watts/sq. cm., is taken as the zero intensity level of reference.

In a plane or spherical progressive sound wave in air, the intensity level of sound corresponds to an rms pressure P given by, $P = P_o \times \sqrt{\frac{H}{76}} \sqrt{\frac{273}{T}}$, where $P_o = 0{\cdot}000207$. P is expressed in dynes sq. cm., H is the barometric pressure in cms., and T, the absolute temperature. At a temperature of 20° C and a pressure of 76 cms., P is equal to 0.000204 dynes sq. cm. For sound pressure measurements, 0.0002 dynes sq. cm. is taken as reference pressure.

(b) **Pressure Level :**

The pressure level of a sound is $20 \log \left(\frac{P}{P_o} \right)$. The unit of pressure level is the decibel, and $P_o = 0.0002$ dynes sq. cm.

(c) **Loudness Level :**

The loudness level of a sound is the intensity of an equally loud reference tone at the position where the listener's head is situated.

(d) **Reference Tone :**

A plane or spherical sound wave, having only a single frequency of 1,000 cps, is used as reference tone for loudness comparisons.

(e) **Threshold of Audibility :**

The threshold of audibility at any specified frequency is the minimum value of sound pressure of a pure tone of that frequency which is just audible. This term is often used to denote the minimum value of sound pressure of any specified complex wave (such as speech or music), which gives the ear a sensation of sound. The point at which the pressure is measured must be specified in every case. It is expressed in dynes sq. cm. It can also be expressed in terms of intensity. Its value then is 10^{-16} watts sq. cm.

(f) **Threshold of Feeling :**

The threshold of feeling at any specified frequency is the minimum value of the sound pressure of a sinusoidal wave of that frequency, which will stimulate the ear to a point at which there is the sensation of feeling. The point at which there is the sensation of feeling, and the point at which the pressure is measured, must be specified in every case. It is expressed in dynes sq. cm., and can also be expressed in watts sq. cm.

(g) **Equivalent Loudness Level :**

The IRE standards on 'Electroacoustics' define 'Equivalent Loudness, Loudness Level, or Equivalent Loudness Level', as follows :—

"The equivalent loudness of a sound is the intensity level, relative to an arbitrary reference intensity of the 1,000-cycle pure tone, which is judged by the listener to be equally loud. The unit is the decibel.

Note :

The term 'Phon' is used by some writers as the equivalent of the db in specifying equivalent loudness."

3. **The Phon.**

(a) **Definition of Phon :**

Decibel is a relative measure. Two sounds having intensities I_1 and I_2 are said to have a difference in level denoted by $10 \log \left(\frac{I_1}{I_2}\right)$ db. From this definition, which is used only for sound intensity, we have to distinguish clearly 'Phon', the loudness unit, standardised some years ago at an International Acoustic Conference in Paris.

According to BSS No. 661 of 1936, phon is defined thus :—A unit of equivalent loudness : the standard tone shall be a plane sinusoidal sound wave commenced from a position directly in front of the observer and having a frequency of 1,000 cps. The listening shall be done with both ears, the standard tone and the sound under measurement being heard alternately, and the standard tone being adjusted until it is judged by a normal observer to be as loud as the sound under measurement. The zero intensity level of the standard tone shall be taken to be an rms pressure of 0.0002 dynes sq. cm. More accurately, an intensity level of 10^{-16} watts sq. cm. corresponds to a sound pressure of 0.000204 dynes sq. cm. at 20° C and 76 cms. of mercury. These values approximate to the 1,000-cycle threshold pressure for a normal observer.

When, under the above conditions, the intensity level of the standard tone is N db above the stated reference intensity, the sound under measurement is said to have an equivalent loudness of N phons (B.S.).

Decibel is used not only for expressing the intensity of sound, but also its loudness in terms of intensity of an equally loud sound of standard pitch.

(b) **Phon as adopted in different countries :**

The 'Phon' was originated in Germany. The British Phon agrees with that adopted as the unit of equivalent loudness in the USA, but the German Phon differs from the British Phon.

The latter embodies listening with one ear and a reference intensity level of $2{\cdot}5 \times 10^{-16}$ watts/sq. cm. This reference level will work out to 0.000316 dynes sq. cm., if we take 10^{-16} watts sq. cm. as equivalent to a pressure of 0.0002 dynes sq. cm., as cited by the BSS. But, the Philips Tech. Review[13] assumes 0.0002034 dynes sq. cm., as equivalent to 10^{-16} watts sq. cm. Then the German reference pressure level will work out to 0.00032 dynes sq. cm.

Table 1 gives the comparative values for a plane progressive wave: the intensity level (decibels above 10^{-16} watts sq. cm.), phons, the intensity as well as the corresponding effective value of pressure fluctuations, and the sound particle velocity.

The amplitude 'a' is calculated from the effective sound particle velocity 'v' for a specific frequency 'f', using the expression: $a = \frac{v. \sqrt{2}}{2\pi f}$. The amplitudes of the particles are also given in the last column of the table for a frequency of 1,000 cps, which is the reference tone. As an example, if $v = 8 \times 10^{-3}$ cm./sec. and f = 1,000 cps., then a = $1{\cdot}8 \times 10^{-6}$

Table 1.

Relationships between Different Acoustic Magnitudes for Plane Progressive Waves in Air.[13]

DB	PHONS	INTENSITY	SOUND PRESSURE	SOUND PARTICLE VELOCITY IN AIR	AMPLITUDE OF VIBRATIONS IN AIR
Above 10^{-16} watts/sq. cm. (in USA.)	db above 2.5×10^{-16} watts/sq. cm. (in Germany)	10^{-9} watts per sq. cm.	Dynes per sq. cm.	10^{-3} Cm. per second	(at 1,000 cycles, 10^{-6} cm.)
(1)	(2)	(3)	(4)	(5)	(6)
64	60	0.25	0·32	8	1·8
65	61	0·32	0·36	9	2·0
66	62	0·40	0·40	10	2·2
67	63	0·50	0·45	11	2·5
68	64	0·63	0·50	12	2·8
69	65	0·8	0·56	14	3·2
70	66	1·0	0·63	16	3·6
71	67	1·25	0·71	18	4·0
72	68	1·6	0·80	20	4·5
73	69	2·0	0·89	22	5·0
74	70	2·5	1·0	25	5·6
75	71	3·2	1·1	28	6·3
76	72	4·0	1·25	32	7
77	73	5·0	1.4	36	8
78	74	6·3	1·6	40	9
79	75	8	1.8	45	10
80	76	10	2·0	50	11
81	77	12·5	2·2	56	12
82	78	16	2·5	63	14
83	79	20	2·8	71	16
84	80	25	3·2	80	18

4. Sound Levels and Phon Calculations.

Greenlees[14] gives the following sound levels on p. 238 of his book : Amplification and Distribution of Sound.

Table 2.

Intensity level in db above 10^{-16} watts/sq. cm.	Dynes/sq. cm.	Watts/sq. cm.	Effect of sound
(1)	(2)	(3)	(4)
0	·000204 or $2{\cdot}04 \times 10^{-4}$	10^{-16}	Threshold of hearing at 1,000 cps.
130	645	10^{-3}	Threshold of feeling or pain

Morris[15] gives the following sound levels.

Table 3.

Intensity level in db above 10^{-16} watts/sq. cm.	Dynes/sq. cm.	Effect of sound
0	2×10^{-4}	Sound inaudible to the average human ear at 1,000 cps.
7	$4{\cdot}47 \times 10^{-4}$	Threshold of hearing at 1,000 cps.
140	2×10^{3}	Threshold of feeling
145	$3{\cdot}55 \times 10^{3}$	Sensation of pain

Thus, there is a discrepancy between the levels described by Greenlees and Morris for the threshold of hearing and threshold of feeling. Taking Morris' figures the following phon levels can be calculated:—

(i) Zero phon loudness level.

The pressure of 2×10^{-4} dynes/sq. cm. corresponds to $20 \log\left[\frac{2 \times 10^{-4}}{1}\right]$ or –74 db relative to 1 dyne/sq. cm.

This level will be o db when referred to a reference level of –74 db, because–74 – (–74) = 0.

The sound corresponding to 2×10^{-4} dynes sq. cm. is. therefore, defined as zero phon loudness level.

(ii) Loudness level in phons of the threshold of hearing.

The pressure for the threshold of feeling is 4.47×10^{-4} dyne/sq. cm., which corresponds to $20 \log \left[\frac{4{\cdot}47 \times 10^{-4}}{1}\right]$ or –67 db relative to 1 dyne/sq. cm. and this is = –67 – (–74) or + 7 db relative to–74 db (relative to 1 dyne/sq. cm.).

∴ The loudness level of the threshold of hearing is expressed as 7 phons.

(iii) Loudness level in phons of the threshold of feeling.

The pressure for the threshold of feeling is 2×10^{3} dynes/sq. cm. This corresponds to $20 \log \left[\frac{2 \times 10^{3}}{1}\right]$ or + 66 db relative to 1 dyne/sq. cm., which is + 66 – (–74) or 140 db relative to –74 db (relative to 1 dyne/sq. cm.).

∴ The loudness level of the threshold of feeling is expressed as 140 phons.

(iv) Loudness level in phons of the threshold of pain.

The pressure for the threshold of pain is $3{\cdot}55 \times 10^{3}$ dynes/sq. cm., which corresponds to 20 log

$\left[\frac{3.55 \times 10^3}{1}\right]$ or + 71 db relative to 1 dyne/sq. cm. or, + 71−(−74) = + 145 db relative to −74 db (relative to 1 dyne/sq. cm.).

∴ The loudness level of the threshold of pain is 145 phons.

The above results are tabulated below.

Table 4.

Sound	in db rel. to 1 dyne/ sq. cm.	Loudness in Phons
1. Zero phon loudness level	−74 (see Table I)	0
2. Threshold of hearing ...	−67	+ 7
3. " feeling ...	+66	+140
4. " pain ...	+71	+145

Table 5 gives tolerable noise levels (in phons) in different types of buildings,[16] and Table 6 gives the value in phons of some types of noises we come across, as given by Davis.[17]

Table 5.

Table of Tolerable Noise Levels in Buildings.

	Phons
1. Studios for recording sound or broadcasting.	15 to 20
2. Hospitals	15 to 20
3. Music studios	20 to 25
4. Apartments, Hotels and Homes ..	20 to 30
5. Auditoriums, (including theatres, cinemas, churches, class rooms and libraries) ..	20 to 35

		Phons
6.	Private offices	30 to 40
7.	Public offices, banking rooms	35 to 50

Table 6.

A Table of Phons

Threshold of audibility	0
Quiet whisper	20
„ suburban garden	30
Clock ticking briskly	40
Soft radio music	50
Moderate conversation	60
Loud radio speech	70
Loud radio music	80
Near pneumatic drill	100
„ unsilenced æroplane engine	110
Tickling in the ear	130

PART III

APPLICATIONS OF THE DECIBEL NOTATION TO RADIO ENGINEERING AND ACOUSTICS

PART III

Applications of the Decibel Notation to Radio Engineering and Acoustics.

1. POWER LEVEL DIAGRAMS (HYPSOGRAMS).

In the case of heavy electrical engineering the efficiencies of power generators, motors, and transformers, are usually expressed as ratios or percentages of output to input. This is a simple matter since each machine is considered individually, but in telecommunication engineering, calculations involve the combined performance of a whole chain of equipment, *e.g.*, microphone, amplifiers, matching transformers, mixers, cables, lines and feeders, loudspeakers etc., some of which contribute to gains, while others to losses. The overall efficiency of the entire chain can be obtained by multiplying together the efficiency ratios of the individual members. But, the same overall gain is obtained more easily by a simple algebraic addition of the individual gains, when such gains (both for the members of the chain and for the whole chain) are expressed in decibels. If the input power is expressed in decibels above an agreed zero level, the output power can be worked out in decibels above the same zero level. The following example illustrates the method of calculations. Let the communication network consist of the following:

(1) A microphone, whose output level is—45 db (with reference to a zero level of 6 mW).

(2) Preamplifier whose gain is 20 db.

(3) One mixer which introduces a loss of 6 db.

(4) Power amplifier which contributes a gain of 70 db.

(5) Transmission line which introduces a loss of 2 db.

Required to find the output level of the loudspeaker.

Solution :

The overall gain of the system from the microphone to the loudspeaker is obtained merely by adding the decibel gains, and subtracting the decibel losses or, in other words, an algebraic addition of the decibel values given above. The output level of the system $= -45 + 20 - 6 + 70 - 2 = +37$ db. Therefore, the reproduction level for the loudspeaker is $+ 37$ db.

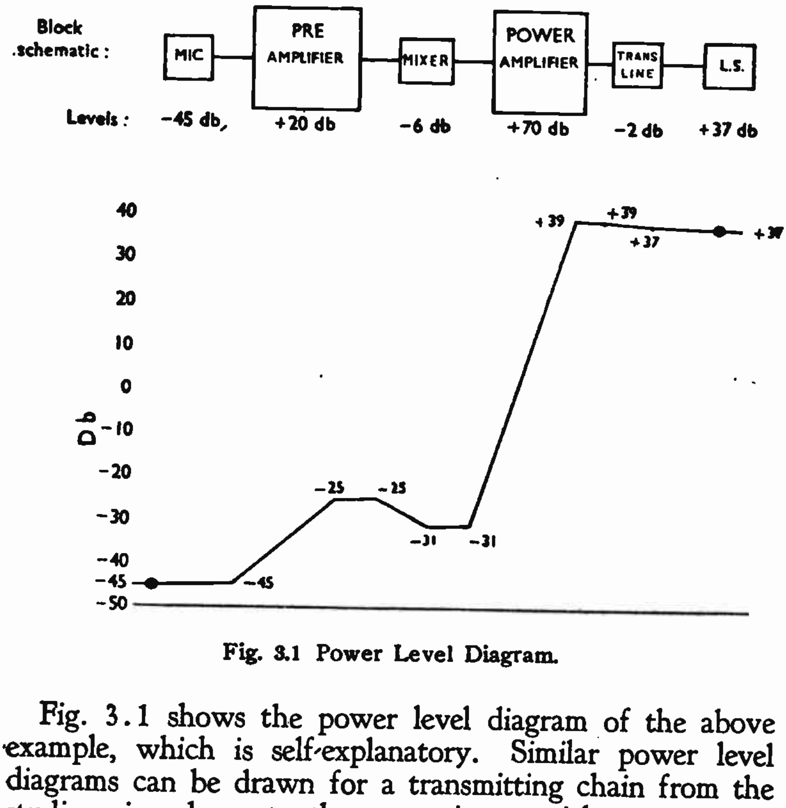


Fig. 3.1 Power Level Diagram.

Fig. 3.1 shows the power level diagram of the above example, which is self-explanatory. Similar power level diagrams can be drawn for a transmitting chain from the studio microphone to the transmitter aerial.

2. THE OUTPUT-POWER METER.

An output-power meter is one which measures directly the amount of absolute power (in milliwatts or decibels, with reference to a chosen zero level) delivered by an audio-frequency system into a variable external load, which is also incorporated in the meter.

(2) Use :—This instrument is used in finding (1) the audio power delivered to a load of a known impedance; (2) the effect of load impedance on the output power; (3) the characteristic impedance of telephone lines, gramo-

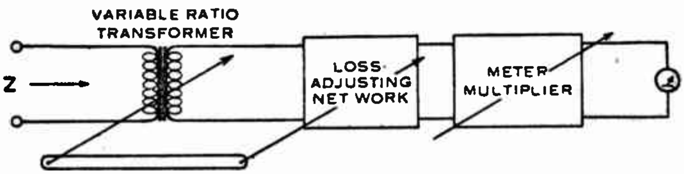


Fig. 3.2. Schematic Diagram of an Output-Power Meter.

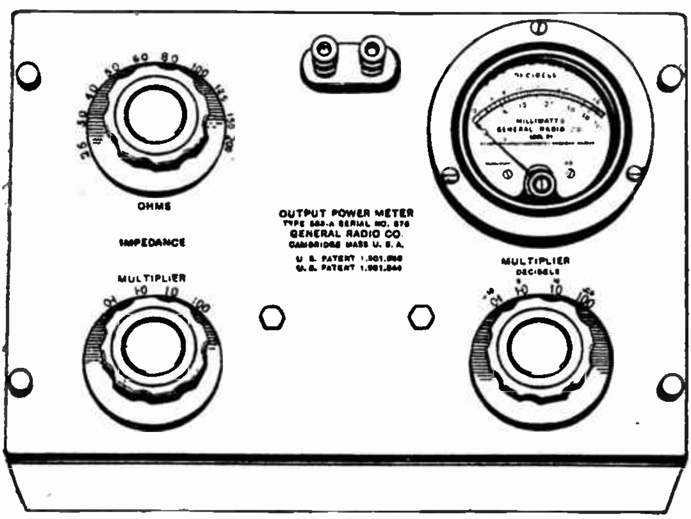


Fig. 3.3. G. R. Coy's Output-Power Meter.
(By Courtesy of Messrs. General Radio Company, USA.)

pick-ups, oscillators, etc., by noting the impedance which gives the maximum reading on the instrument; (4) as an output indicator (read in db) for conducting the standard tests on radio receivers (like sensitivity, selectivity, bandwidth and fidelity, (vide Part III Sec. 5), amplifiers, filters, transformers, vacuum tubes etc.

(3) **Design** :—Fig. 3.2 shows the schematic diagram of the instrument. Fig. 3.3 shows the actual photograph of the front panel of the instrument. The instrument is an adjustable-load impedance connected across which is a constant-impedance, rectifier-type voltmeter, calibrated to read directly the watts dissipated in the load.

There are two standard instruments on the market:—

(1) G. R. Company's[18] (USA) output-power meter: Type 583-A (vide Fig. 3.3)

& (2) Marconi-Ekco's[19] (British) output-power meter: Type TF. 340.

The general design and purpose of both these instruments is the same. The specification of the former instrument is given below (taken from the G. R. Company's catalogue).

(i) Power range :—0.1 to 5,000 milliwatts in four ranges :

(a) 0—5; (b) 0—50; (c) 0—500; (d) 0—5,000 milliwatts for full scale, *i.e.*, the power range covered by the meter is $\frac{50,000}{1}$.

The copper-oxide rectifier voltmeter is calibrated 1 to 50 mW, with an auxiliary scale, reading from 0 to 17 db. (above a zero reference level of 1 mW), besides —10 db, + 10 db, or 20 db, as required.

(ii) Error in decibel-scale :—The maximum error in full-scale power reading does not exceed:

(1) 0.5 db between 150 and 2,500 cycles,
or (2) 1.5 db „ 20 and 10,000 „

The average error is 0.3 db at 30 and 5,000 cps, and 0.6 db at 20 and 10,000.

(iii) Input-impedance range :—2.5 to 20,000 ohms, *i.e.*, a range of $\frac{20,000}{2 \cdot 5}$ or 8,000:1. Forty impedance steps, each step being only about 25% increase, are provided. Thus, logarithmically distributed impedances are obtained, chosen by a 10-step ohms-dial, and a four-step multiplier.

The markings on the impedance dial are:—
25, 30, 40, 50, 60, 80, 100, 125, 150 and 200 ohms.
Impedance Multiplier settings are: 0.1, 1, 10, and 100.

(4) **The meter and its dial calibration** :—From the above description, it is seen that the output-power meter is nothing but an a-c voltmeter, calibrated in db with reference to the power passed into a load of known impedance, contained within the instrument itself, and substituted for the normal one, *e.g.*, as a substitute for the loudspeaker speech-coil impedance in conducting tests on radio receivers.

If impedance of the load = 1,000 ohms, and zero level is 1 mW, then the voltage = $\sqrt{0 \cdot 001 \times 1{,}000} = 1$ volt (rms).

For the purpose of tests on receivers, a standard output has been chosen—(Vide Sec. 5, Part III). 50 mW is considered as the lowest, useful-power output from a receiver to be of any practical value to the listener. Hence, 50 mW is calibrated as 17 db, and powers less than 1 mW are given negative readings in db, as will be explained presently.

On the multiplier-scale dial the following two sets of readings are found:—

Table 1.
Multiplier Dial.

Multiply meter reading in milliwatts by	Add to the meter aux. scale reading in db.
× 0·1	— 10 db.
× 1·0	0 db
× 10·0	+ 10 db
× 100	+ 20 db

It will be seen that the figures in column (2) of the above table are merely 10 × log of the values in column (1), since multiplying the value in milliwatts is equivalent to adding algebraically the corresponding number of decibels.

If the multiplying factor is < 1, the number of db to be added is negative;

if the multiplying factor is = 1.0, the number of db to be added is 0; and

if the multiplying factor is > 1.0 the number of db to be added is positive.

The dial of the meter is calibrated thus:—

Table 2.

Reading in mW.	Reading in db (approx.)
1	0
4	6
5	7
6.5	8
10	10
12.5	11
15.5	12
25	14
31.5	15
40	16
50	17

It will be seen that the db scale is calibrated by evaluating $10 \log \frac{\text{mW (rdg.)}}{1 \text{ mW}}$, *i.e.*, with reference to a zero level of 1 mW.

Hence, when the multiplier setting is against 1.0, no more decibels need be added to, or subtracted from, the reading on the auxiliary decibel-scale, on the meter face itself. Further, it is seen that 0 db is marked against 1 mW, since $10 \log \frac{1 \text{ mW}}{1 \text{ mW}} = 0$; and no value in db is marked against 0 mW, since the corresponding value in db would be 10 log 0 = $-\infty$, which is not easy to determine. That explains why any readings on db scale below 0 db, or corresponding to 1 mW, are not marked.

5. Maximum Power Reading.

For the maximum output-power reading of 5 watts or 5,000 milliwatts, the multiplier-switch should be against 100, since 100 × 50 = 5,000 and the main meter dial is calibrated 0-50 mW only, corresponding to + 17 db.

Hence 100 × 50 mW correspond to: + 20 + 17 or 37 db, which can be verified by evaluating the formula.

---

3. AUDIO AMPLIFIERS.

The specification for a typical amplifier is given below:

(a) Power output:—with 8% distortion + 31.25 db (reference level: 6 mW).

(b) Frequency response:—Within ± 1 db from 45 cps to 6,000 cps; tone control in treble position.

(c) Gain:— Microphone input: 111 db based on 100,000 ohms.

Phono input: 66 db (0.1 megohm) input impedance.

(d) Hum:—61.5 db below maximum output.

The meanings of these statements are to be understood as follows:

(a) **Power Output:**

The power output of an amplifier is specified as so many db, at a rated percentage distortion with reference to a specified zero-power level. The tolerable distortion is anything from 5 to 10%, and 8% may be taken as a representative figure for the so-called "undistorted output".

In the example the undistorted output of the amplifier should be 8 watts (with 8% distortion) for, only then the output in db relative to 6 mW zero = 10 log $\frac{8}{0.006}$ = + 31.25 db.

The set-up of apparatus, as in Fig. 3.4, is used for the measurement of power. If R is a load that matches the amplifier, and V_0 the voltage across it (measured with a suitable a-c voltmeter), then V_0^2 R gives the power-output.

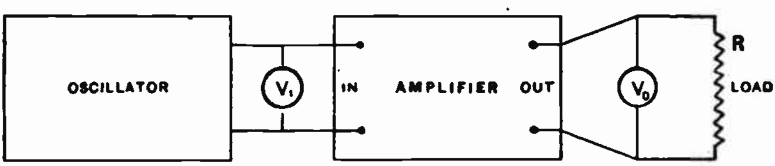


Fig. 3.4. Set-up for Obtaining the Power Output of an Amplifier.

(b) Frequency Response:

The frequency response of an amplifier is illustrated by a 3-cycle, log-linear graph (Fig. 3.5), of which the logarithmic X-axis is the frequency scale, and linear Y-axis is used for representing the frequency response in decibels.

The function of an amplifier is to amplify all frequencies between, say, 30 cps to 10,000 cps or more, and it is the variation in amplification of the different frequencies that is specified in decibels with respect to an arbitrarily chosen zero, *i.e.*, the amplification at 400 or 1,000 cycles per second. It is usual to specify that an amplifier should have a frequency response within ± 3 db from 40 to 10,000 cps. Fig. 3.5 satisfies this specification, though at 40 cps as well as at 10,000 cps, the response falls 6 db below the level at 1,000 cycles. In this connection, Greenlees [20] rightly remarks that a better specification would be to define the departures as so many db from the level at 1,000 cycles, where the response is generally maximum and constant over a fairly wide range.

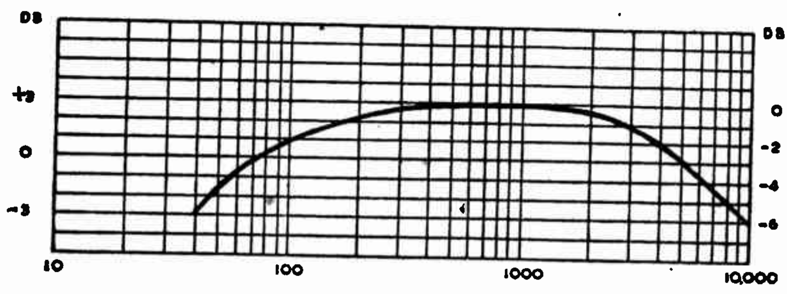


Fig. 3.5. Frequency Response of an Amplifier.

Measurement of amplification in decibels throughout the range of frequencies :—

The set-up of the apparatus is the same as in Fig. 3.4. A non-inductive load R, to match to the output impedance of the amplifier, is connected. V_i measures the input voltage of the amplifier, and V_o the output voltage from the amplifier to the load. If valve-voltmeters are not available, at least high-impedance, rectifier-type a-c voltmeters should be used. Inputs of various frequencies are applied to the amplifier at a constant voltage, and the varying output voltages for the different frequencies fed in, are measured and converted to decibels, relative to the output at some arbitrarily chosen level, usually 400 or 1,000 cps. The following example will make this clear:

Amplifier Data:—Input impedance =0.5 megohm.
„ volts =0.75 volt.
Output Impedance =10 ohms.
Rated undistorted output (5% distortion) =10 watts.

The load resistance should be 10-ohms and at least of 10 watts rating. If a voltmeter (V_o) of 0 to 25 volts range having a sensitivity of 1,000-ohms per volt is connected, making a total internal resistance of 25,000-ohms, it will have negligible effect on the output circuit conditions. With this meter, the high-impedance input cannot be measured. Experimental details of two methods will be described.

Method I:—

(1) Set volume control on the amplifier at the maximum position;

(2) Adjust frequency of the oscillator to 1,000-cycles;

(3) Set the volume control on the oscillator so that V_i reads 0.75 volt;

(4) Read V_o; it should read: $\sqrt{10 \times 10} = 10.0$ volts;

(5) Keeping input V_i constant at 0.75 volt, read V_o for the different frequencies.

From this data, the decibel gain for each frequency, can be calculated and plotted with decibel gain at 1,000-cycles taken as zero reference db level. A method of calculation, say for 1,000-cycles, is shown below:

Input volts = 0.75 volts; Input impedance = 500,000 ohms.

$$\therefore \text{ Input power, } P_i = \frac{V_i^2}{Z_i} = \frac{(0.75)^2}{5 \times 10^5} = 0.112 \times 10^{-5} \text{ watts.}$$

Output power, P_o = 10.0 watts (given).

$$\therefore \text{ Amplification at 1,000-cycles} = \frac{P_o}{P_i} = \frac{10.0}{0.112 \times 10^{-5}}$$

$= 8.93 \times 10^6$.

$$\therefore \text{ Db gain} = 10 \log \frac{P_o}{P_i} = 10 \log 8.93 \times 10^6$$

$$= 69.508 \text{ db or, say, } 70 \text{ db.}$$

Method II:—

In order to avoid overloading of the valves (even at some frequencies), which will make the response curve appear better than the actual response curve, it is safe to measure the frequency response curve at about one half the full, rated-output of the amplifier. The volume control should be turned, so that V_o reads $\sqrt{5{\cdot}0 \times 10} = 7.07$ volts, which correspond to 5.0 watts output = ½ the maximum output. Keeping this output voltage constant, the oscillator may be swept over the frequency range of 50 to 10,000 cycles, and the input volts read at each frequency. A typical test data is furnished in the table below. The input-, and output-impedances used in the calculation are, of course, 0.5 megohms and 10-ohms respectively.

Table 3.

Output V_o constant at 7.07 volts.

Cps. (f)	Input volts. (V_i)	$\frac{V_i \text{ at } 1{,}000 \text{ cps.}}{V_i \text{ at } f}$	db relative to 1,000 cps.
50	9.43	0.75	—2.5
70	8.04	0.879	—1.12
100	7.68	0.920	—0.724
200	7.40	0.955	—0.4
400	7.33	0.965	—0.31
600	7.33	0.965	—0.31
800	7.23	0.978	—0.194
1,000	7.07	1.00	0
2,000	7.00	1.01	+0.086
4,000	6.93	1.02	+0.172
6,000	7.00	1.01	+0.086
8,000	7.40	0.955	—0.4
10,000	8.40	0.841	—1.51

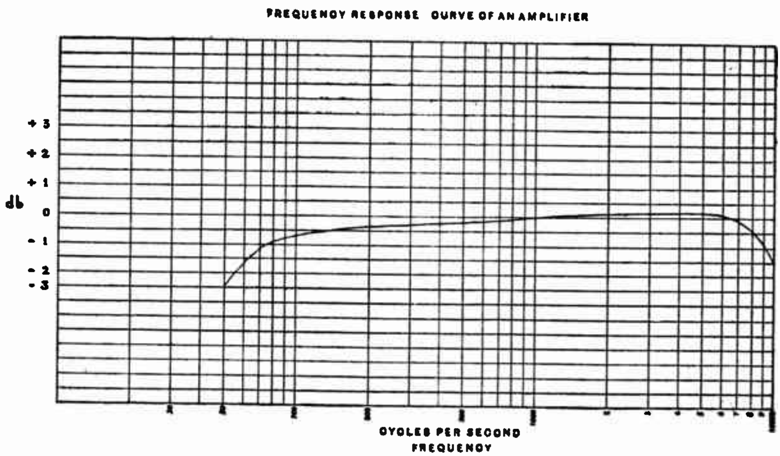


Fig. 3.6. Frequency Response Curve of an Amplifier.

Fig. 3.6. shows the frequency response curve of the amplifier in question.

(c) **Gain or Amplification of a Channel:**

The overall gain or power amplification of an amplifier is expressed in decibels, but a mere statement that an amplifier has a gain of 40 db is no indication of the actual power output of the amplifier, unless some additional information is also furnished. By saying that a power amplifier has a gain of 40 db, all that we can infer is that its output audio power is 10,000 times its input audio power, since $40 = 10 \log \frac{P_o}{P_i}$, or $\frac{P_o}{P_i} = 10^4$.

This is true irrespective of the actual magnitude of the input power, and it may so happen that the output may still be too small to be audible. If, for instance, we are given, that the amplifier delivers its full output with an input of 1 volt across its input impedance of 1 megohm, and has a gain of 80 db, then the output power can immediately be calculated as follows:

Solution :—

80 db corresponds to a power amplification of $10^8 = \frac{P_o}{P_i}$. $P_i = \frac{V_i^2}{Z_i} = \frac{1 \times 1}{10^6}$ watts.

$\therefore$ P_o, actual output power $=$ Input power $\times$ amplification $= \frac{1}{10^6} \times 10^8 = 10^2 = 100$ watts.

Decibel gains or losses cannot be calculated directly from the input and output voltages only, unless input and output impedances are identical, which seldom happens in the case of audio amplifiers used in public address systems. Otherwise, the corrections mentioned in Sec. 8 of Part I of this monograph, must be applied for the mismatch.

Consider the following example:—

An amplifier has an input impedance $R_1 = 1$ Megohm, and an output impedance of 1,000 ohms—(generally, the output impedance of an audio amplifier is much less than the input impedance). If V_i and V_o be the input and output voltages of the amplifier, then the real gain of the amplifier is not merely $20 \log_{10}\left(\frac{V_o}{V_i}\right)$, but $20 \log_{10}\left(\frac{V_o}{V_i}\right) + 10 \log_{10}\left(\frac{R_i}{R_o}\right)$. The extra factor of $10 \log_{10}\left(\frac{R_i}{R_o}\right)$ in the present example is responsible for the extra 30 db = $\left\{10 \log_{10} \frac{1{,}000{,}000}{1{,}000}\right\}$.

No rating is more abused than the decibel gain of an audio amplifier, because of the nature of the measurements involved. Decibel being a unit of power measurement, the impedances across which voltage measurements are made will vitiate the mathematical result, as has been illustrated in the preceding example.

To assess the overall gain of a channel, a carefully measured input voltage is applied to the input terminal of the amplifier (channel), and the output voltage measured. Such measurements are made with the aid of a valve voltmeter (because of its high, input-impedance). The decibel gain is given by $10 \log_{10}\left(\frac{P_o}{P_i}\right)$.

Hence, P_o and P_i have to be calculated from V_o and V_i, and Z_o and Z_i. V_o, the output voltage, is read across the load resistor, substituted for the impedance that would normally be connected to the secondary of the output transformer. The input voltage is fed into the normal input terminals of the amplifier across which will be found a high resistance, for example, a 5 megohm resistor, in the case of the well-known range of Thordarson[21] amplifiers of the USA. It is this input resistor, that is the real trouble in the gain measurements. Though its value is 5 megohms (a large value to prevent over loading of the microphone), in practice, such a value is never met with. 5 megohms, when shunted by the microphone, or other source of input, the resultant impedance is less than the lower of the two parallel impedances. Therefore, the secondary impedance of the usual microphone transformer (say, 100,000-ohms), the generally accepted figure, is used in the amplifier gain calculations. An input impedance of 5 megohms would spoil the high-frequency response of the stage involved. The db gain calculated with 100,000-ohms, will be less than that with 5 megohms, but the former result will be more representative of the usable gain. In Thordarson catalogue of their amplifiers, it will be found that 100,000-ohms has been used as input impedance in specifying the gain of the microphone and phono-input channels.

For example, a typical specification is as follows:—

Gain: Microphone input: 111 db; phono-input: 66 db, (based on 100,000-ohms input impedance):

It is therefore apparent that one should never express the db gain without specifying the constants used.

It is seen from the above specification that the gain for the different input channels in a public address amplifier is different: more gain (due to more stages) being provided for microphone channels, and less gain for the gramophone-input channels. This difference is due to the fact that the level of output from any microphone is always considerably less than that from a gramophone pickup. For specific information on the exact levels of the various gramo-pick ups and microphones, the reader is referred to Sections 7 and 9 of the present Part.

(d) **Internal Noise Level or Hum :**

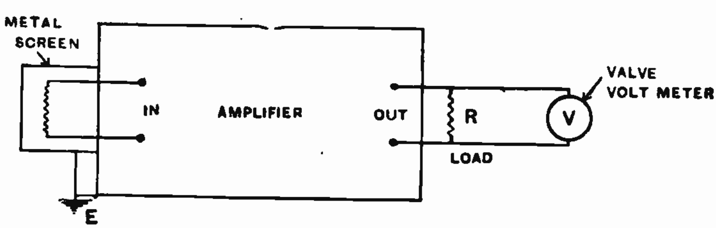


Fig. 3.7. Set-up for Measuring Internal Noise Level of Amplifiers.

An amplifier will deliver a small noise output even when no signal is applied. It is usual to specify this hum output as so many db below the rated output, *e.g.*, as 60 db below the rated or maximum output.

Fig. 3.7 shows the set-up required for measuring the internal noise level or hum of the amplifier. The ratio of the noise volts to the full output volts is expressed in db, and the noise level is then expressed as so many db below the full output rating.

The following example will illustrate the meaning further :

Amplifier output	=	20 watts.
Output impedance	=	500 ohms.
Output volts on noise test.	=	0.03 volts.

Calculation of noise level :—

$$20 \text{ watts} = \frac{V_o^2}{Z_o};$$

$$\therefore V_o = \sqrt{20 \times 500} = 100.$$

$$\text{Noise level in db} = 20 \log_{10} \frac{(\text{Noise volts})}{(\text{Output volts})}.$$

$$= 20 \log_{10} \frac{(0.03)}{(100)} = -70.5 \text{ db}$$

∴ Noise level is 70.5 db below the maximum output. A noise level of 50 or more db below rated output is considered satisfactory for most purposes, although 60 db would be essential in installations where general noise level is very low. –70 db is considered to be very good.

4. SIGNAL TO NOISE RATIO.

In any communication system, the degree of freedom from interference will depend upon the relative strength of the desired signal and the undesired signal, otherwise called the noise or disturbance. The ratio of these two quantities is called the "Signal|noise ratio" and is of fundamental importance in all communication systems. It is expressed in the db notation by x db, where $x = 10 \log_{10} \frac{p_s}{p_n}$, where p_s and p_n represent the signal and noise powers respectively. Alternatively, if V_s and V_n represent the signal and noise voltages respectively, then $x = 10 \log_{10} \left(\frac{V_s}{V_n}\right)^2 = 20 \log_{10} \frac{V_s}{V_n}$.

Atmospherics and man-made noises are invariably heard as background noises while listening to a radio receiver. In order that a radio programme may be of value to a listener, the IEE,[22] London, specified that the signal noise ratio should not be less than 40 db.

The following four examples will illustrate the above formulæ :

(i) for a signal/noise ratio of 60 db and a signal *power* of 2.5 mW, the noise power is:

$$60 = 10 \log \frac{2.5}{n_p},\ \textit{i.e.},\ n_p = \frac{2.5}{\text{antilog of } 6} = 2.5 \times 10^{-6}\ \text{mW}.$$

(ii) for a signal/noise ratio of 60 db and a signal *voltage* of 1.25 volts, the noise voltage is:

$$60 = 20 \log \frac{1.25}{V_n}\ \textit{i.e.},\ V_n = \frac{1{\cdot}25}{10^3} = 1.25\ \text{mV}.$$

(iii) for a signal/noise ratio of 40 db and a signal field *strength* of 1 mV/m the noise field strength is:

$$40 = 20 \log \frac{1}{V_n}\ \textit{i.e.},\ V_n = \frac{1}{\text{antilog of } 2} = 10^{-2}$$

$= 0.01$ mV/m.

(iv) for a radio listener, there are two kinds of noises, which are to be considered : (1) the atmospheric (noise) field strength, and (2) the man-made static (noise) field strength. It is usual to express the intensity of the field strength of the signal at the listening point due to a broadcasting station relative to the total noise strength, in the decibel notation, by the formula :

$$20 \log \frac{\text{radio signal field strength}}{\text{total noise field strength}}.$$

This is best illustrated by the following numerical example :—

When a refrigerator is working at a distance of 50 ft. from a radio receiver, the signal strength of a medium-wave station, the listener is listening to, is 120 mV m, while at the same place the atmospheric and man-made static noise field strengths are 3 and 16.2 mV m respectively.

Then, the total noise field strength equals $\sqrt{(3)^2+(16.2)^2}=$ 16.48 mV m (assuming both are vertically polarised) and the signal total noise ratio equals : $20 \log \frac{120}{16.46} = 17.27$ db.

5. RADIO RECEIVERS.

Application: Decibel notation is used with radio receivers in expressing the results of the following tests:

(a) Selectivity,
(b) Image ratio,
(c) AVC characteristics,
(d) Overall electric fidelity characteristic (popularly styled the frequency response).

(a) **Selectivity Test:**

The radio receiver is accurately tuned to the test frequency (usually 1,000 kcs). The RF signal generator is then detuned each side of the resonance, and the RF input voltage required for the normal test output* noted. Such observations are to be made for every few kcs upto either of the following limits, whichever requires the least departure from resonance.

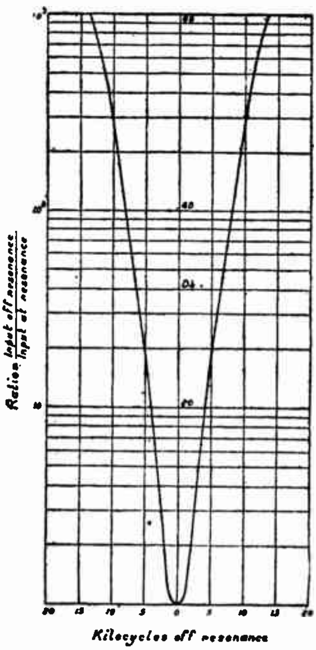


Fig. 3·8. Selectivity curve 1,000 kcs, modulated 400 cps, 30%, AVC paralysed.

(1) The ratio of input at x kcs off resonance exceeds 10,000 or 80 db (= 20 log 10,000), or (2) input exceeds 1 volt.

A typical selectivity curve of a receiver is shown in Fig. 3.8 (reproduced from Fig. 5 of the author's paper[25]

* *Foot Note*:—50 milliwatts according to IRE Standards[23], New York (1938), for sets having an undistorted output between 0.1 and 1 watt and 500 mW for sets capable of delivering at least 1 watt maximum undistorted output. 50 milliwatts according to the British RMA Specifications[24] (1936).

"Standard Tests on Broadcast Receivers"). The figure is drawn on a log-linear graph paper.

In the curve, the x-axis is used for kilocycles off the resonant frequency (positive and negative, 0 being the resonance frequency or the desired station frequency, *viz.*, 1,000 kcs in the test), the y-axis is log-scale representing db $= 20 \log \left(\frac{\text{Input at } x \text{ kcs off resonance}}{\text{Input at resonance}}\right)$ for a constant output.

From the curve it will be seen that, at $\pm$ 5 kcs off resonant frequency the selectivity is 20 log 20 = 20 × 1.3010 = 26 db, and at $\pm$ 10 kcs off resonant frequency the selectivity is 20 log 300 = 20 x 2.4771 = 49.542 or, say 49.5 db. The significance of these results is as follows :—

(1) That a station working on 1,005 or 995 kcs should induce a voltage 20 times that of the station working on 1,000 kcs, in order that the stations on 1,005 or 995 kcs give same output from the radio receiver under test, as it gives when tuned to a station on 1,000 kcs.

A standard specification is that the selectivity of the receiver should be at least 40 db *down* at 20 kcs, and at least 6 db down at 8 kcs off resonance. It is seen that the receiver under test does satisfy these specifications, since even at about 8 kcs off resonance it is about 40 db down. (The significance of db "down" and "up" have already been explained in Part I).

(b) **Image Ratio:**

In a superheterodyne receiver the local oscillator frequency, f_{lo}, is normally designed to exceed the desired signal frequency, f_s, by the intermediate frequency, f_{if}, *i.e.*, $f_{lo} - f_s = f_{if}$ ——(1). But, even when a station working at a frequency : $f_{lo} + f_{if}$, is present then also the i.f. amplifier responds.

In other words, if f_i is the interfering station

$$f_i - f_{lo} = f_{if} \qquad \text{——(2)}$$

∴ By adding (1) and (2) $f_i - f_s = 2f_{if}$.

Therefore, the interfering station and the desired station are separated by twice the intermediate frequency. So, in a superhet unless the response to the interfering station is much lower than that to the desired station, the desired programme is marred by the undesired one, and this is known as the image (or second channel) interference.

The image or second channel ratio is measured and expressed in db thus :—

Suppose the receiver is tuned to 1,000 kcs, and its sensitivity is 15 μV. If the IF is 110 kcs, the image frequency is 1,220 kcs (= 1,000 + 2 x 110). The RF signal generator is then tuned to this frequency, and the input to the radio is increased, until 'Standard output' is once more obtained from the receiver. Suppose the signal is now 27,000 μV or 27 mV, then the ratio of this to the first channel sensitivity is $\frac{27,000}{15} = 1,800$.

The best way of expressing this result is in db form:
$20 \log 1,800 = 20 \times 3.2553 = 65$ db nearly.

If the IF is in the neighbourhood of 465 kcs (as is common in those sets incorporating short-wave bands), the image frequencies (which exceed the desired frequencies by 2 x 465 kcs) fall largely outside the broadcast band, and the ratio is so high that interference even from a local station is absolutely unlikely in the medium-wave band, but the ratio should be measured on the long-wave band, as there is a possibility of interference from a very powerful station of 1,100-1,200 kcs. Whatever the IF may be, the image ratio should be measured and expressed in db on all short-wave bands. With a low IF (say, about 100) and a badly aligned receiver, the ratio may be less than unity!

(c) AVC **characteristic :**

AVC or, more accurately, the automatic gain control of a radio receiver, is intended to keep the output of the receiver constant within narrow limits over a wide range of input of RF signal.

Usually, the avc characteristic is conducted at 1,000 kcs, the signal being modulated at 400 cps to a depth of 30%. The test is performed as follows :

The receiver is tuned to the desired RF (say 1,000 kcs). The input to the receiver is adjusted to a value of 1 volt, and the volume control so adjusted, that the receiver delivers ¼ of its nominal undistorted output. The input is then reduced in suitable steps to, say, 10 μV, and the output read in mW or db at each step.

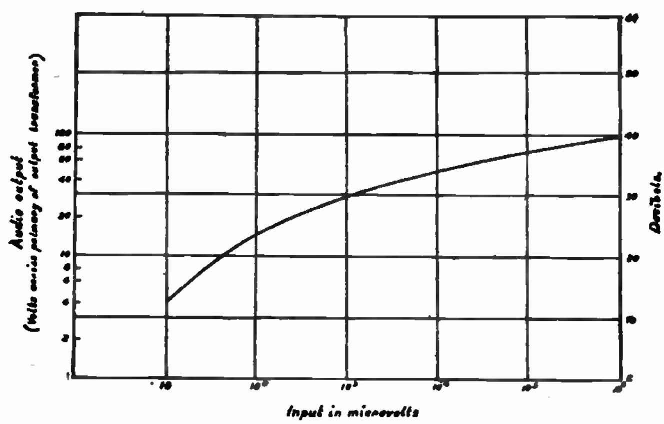


Fig. 3 9. AVC Characteristic of a Receiver.

Fig. 3.9 is a reprodu tio of Fig. 7 in the author's paper.[26] From it the following information is gathered.

Table 4.

Actual variation in input	Change in input ratio	Change in input in db	Change in output in db
10^3 to 10^6 μV	10^3	60	10
10^4 to 10^6 μV	10^2	40	7

A standard specification for the constancy in output is, that the change in output corresponding to a 40 db change in input (between $10^4\,\mu V$ to $10^6\,\mu V$), should not exceed 7 db.

(d) Overall Electric Fidelity of a Receiver :

The capacity of the receiver (excluding the loudspeaker) to reproduce the different modulation frequencies (usually 50 cps to 10 kcs) without frequency distortion is represented by the overall electric fidelity curve. The curve is plotted on a log-linear graph paper—x-axis is of logarithmic type, while the y-axis is of linear scale to represent response in db.

The value of the test lies in the ease and accuracy with which it can be performed, and its usefulness for comparative purposes. It is usual to conduct this test at 1,000 kcs with audio frequencies (50 to 10,000 cps) modulated to a depth of 30%. Usually, this test is also performed for at least two different positions of the 'tone control'. The procedure of the test is as follows :

The receiver is tuned to the desired RF signal (say 1,000 kcs) modulated 30% at 400 cps, so that a reasonable

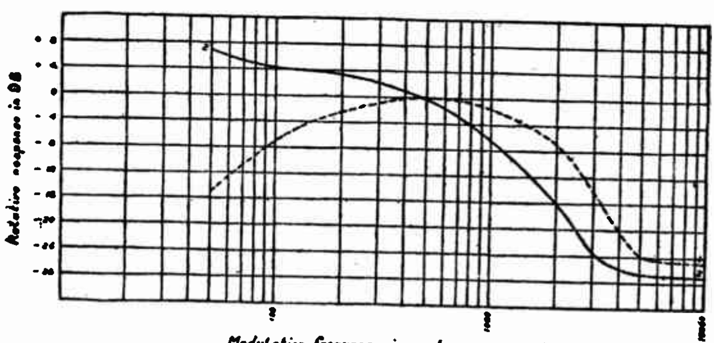


Fig. 8.10. Overall Electric Fidelity Curves of a Receiver.

output, say, ¼ of the full, rated output is delivered. The volume control is at maximum, and the tone control at a chosen position, *e.g.*, 'treble maximum' or 'bass maximum.' Then, the AF generator is made to deliver the same strength of signal to the RF generator at various frequencies (50 to 10,000 cps), and the output in db obtained for each of these audio-frequencies.

Fig. 3.10 is a reproduction of Fig. 6 in the author's paper.[27] Curve 1 is for 'treble maximum' position, and curve 2 for 'bass maximum position' of the tone control. Best fidelity is, of course, when the curve is as flat as possible. The drooping of the curve at both ends is inevitable.

6. AUDIO TRANSFORMERS

As stated already, the decibel, being directly related to the effect of sound on the ear, is useful in expressing the fidelity-rating of a transmission chain, or any of its components—*e.g.*, the fidelity of reproduction of audio transformers. Consider the following example: In a certain (1:1 ratio) audio transformer, 1 volt across the primary winding produces the following voltages in the secondary at the stated frequencies.

Table 5.

Cps	Voltage
30	0.2
50	0.6
100 to 8,000	1.0
10,000	0.85

The above information does not mean much unless converted into decibels. Hence, giving the arbitrary value of 0 db to 1 volt, the following results are obtained:

This can be written as:

$$\text{at 30 cps the db– response} = 20 \log \frac{0.2}{1} = 20 \log 0.2$$
$$= 20 \times \bar{1}.3010$$
$$= 20 \times -0.6990$$
$$= -13.98 \text{ db or, say,} -14 \text{ db.}$$

At 50 cps, loss is 4.4 db (—4.4).

At 10,000 cps, loss is 1.41 db (—1.41).

A fidelity curve can be plotted on a 3-cycle, log-linear graph paper with the above data.

7. GRAMOPHONE RECORD CUTTERS AND PICK-UPS

The db-notation is used in connection with gramophone record cutters and pick-ups for recording their frequency response characteristics, and to denote the operating levels.

(i) RECORD CUTTERS:

(a) Requirements of Frequency Response :—

For high fidelity, all frequencies between 30 and 10,000 cps should be reproduced uniformly. A cutting-head converts electrical energy into mechanical energy with a poor conversion efficiency. An examination of the frequency characteristics of an average cutter reveals the deficiencies at the low-, and high-frequency ends. The LF loss is deliberately introduced. The comparative hardness of the coated disc relative to wax, is partly responsible for the HF loss, but the main reason is the design of the cutter itself—the amount of play between the cutting needle and needle holder.

By using an audio equalizer (vide Sec. 16, Part III), the loss at the HF-end can be compensated. When using an equalizer, a high gain amplifier is to be used, as the equalizer introduces an appreciable loss in gain.

(b) Operating Level:—

A good cutter operates at a level of 16 db, equal to 0.24 watt, if referred to 6 mW zero. At this level the surface noise is 40 db below the level of the recorded sound, and is about 10 db better than the surface noise of a shellac pressing, and approximately the same as that of the best acetate disc. A level of + 16 db is considered low, and any recording amplifier, with an output of at least 2 watts, can handle the recording head easily.

(c) Measurement of Frequency Response:—

The frequency response of a cutting head can be obtained by two well-known methods:

(i) Deflection method.

(ii) Calibrated pick-up method, for which the reader is referred to Sterling's Radio Manual.[28]

(ii) PICK-UPS :

(a) Response Curve :—

The response curves of pick-ups are plotted on a 3-cycle, log-linear, graph paper, with response on the Y-axis (linear scale) and frequencies on the X-axis (logarithmic scale).

Nilson and Hornung[29] give the following data regarding the output levels and frequency ranges of four common types of gramophone pick-ups :

Table 6.

Type	Output in db (relative to 6 mW zero)	Frequency Range cps.
Standard magnetic	–35	80—3,000/5,000
Oil–damped	–35	60—5,000
Astatic (crystal)	–78	30—8,000

Fig. 3.11 shows the response curve of a good pick-up of modern design.[30] The curve shows that the response approximates very closely to the ideal—a positive response between 60 and 1,000-cycles (relative to response at 1,000-cps as zero), and falling after about 4,000 cps, the loss at 7,000 cps being —15 db.

As most pick-ups have a rapidly falling characteristic after about 5,000 cps, the response above that frequency is cut out by means of a low-pass filter (cut-off at 5,000 cps). Further, this also serves to cut down the noise due to needle scratch, which becomes noticeable when frequencies beyond 5,000 cps are attempted to be reproduced.

(b) Output of the Pick-up :

The output of a good pick-up should be well over 1 volt rms, in order to get ample input for even the smallest

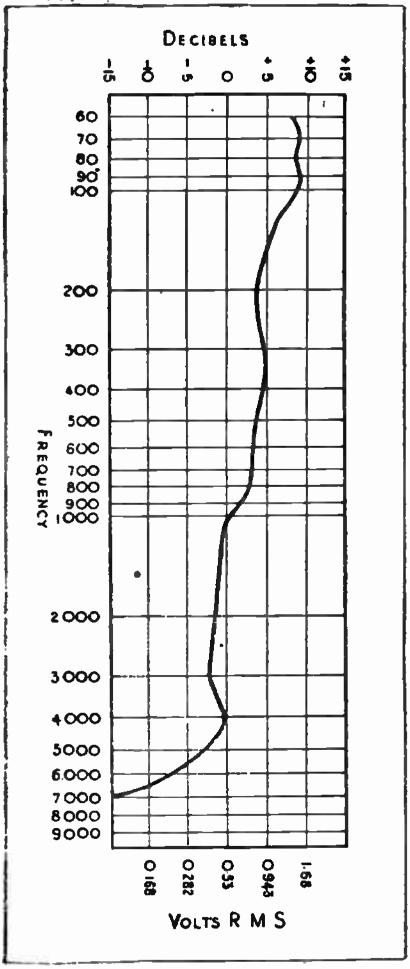


Fig. 3.11. Response curve of a Modern Pick-up.
(By Courtesy of PHILIPS Electrical Co. (India) Ltd.

amplifier. The volts (rms) and the corresponding db scale, are also indicated in the Fig. 3.11.

$$\because \frac{V^2}{Z} = P, \text{ if } V = 0.53 \text{ volts and } P = 0.006 \text{ watts,}$$

then, $Z = \dfrac{(0.53)^2}{.006} = 46.8$ ohms, which is about the value of an average dynamic pick-up.

8. OUTPUT VALVES

The decibel can be conveniently used for expressing the output of the power valves relative to 6 mW zero. It will now be possible to get a truer comparison of the relative usefulness of output valves regarding their merit as acoustic-power producers.

This is a better method than merely giving the power output of the valve in milliwatts or watts with corresponding percentage distortion. The following table classifies the power output of three well-known pentode output valves, working under class A conditions.

Table 7.

Output Valves.

Single-Tube (Pentode) Class A operation.

Valve	Volts (V_a)	Distortion (%)	Power Watts (W)	Power db (6 mW zero)
6 F 6	250	8	3.2	+ 27.27
6 L 6	250	10	6.5	+ 30.35
6 V 6	250	8	4.5	+ 28.75

Considering the case of two 6L6 valves in pushpull in class A-1, for the same anode voltage, the pushpull connection delivers 14.5 watts with a distortion of 2% ; 14.5 watts correspond to $10 \log_{10} (14.5|0.006) = 33.832$ db. A single 6L6 valve can give 6.5 watts with 10% distortion, but when two of these are connected in parallel they give only 13 watts or 33.357 db with 10% distortion. Thus by connecting in pushpull the distortion is reduced from 10% to 2%. Next, consider two 6L6 valves operating in class AB 2 with anode voltage of 360. Then the output of

Table 8.

Push-Pull (Pentodes)—(Two valves). Values of Power Output.

Valve	Class A 1				Class A B 1				Class A B 2			
	V_a	% distortion	Power		V_a	% distortion	Power		V_a	% distortion	Power	
			Watts	db			Watts	db			Watts	db
6 F6	315	4	11	+32.63					375	3.5	18.5	+34.89
6 L6	250	2	14.5	+33.83	360	2	26.5	+36.45	360	2	47	+38.94
6 V6					250	5	10	+32.21				

two valves in pushpull is 47 watts with 2% distortion. 47 watts correspond to 38.94 db. That is, by increasing the anode voltage from 250 to 360 volts, we have been able to increase the power output from 14.5 to 47 watts, or an increase of about 5 db for the same percentage distortion. The increase is due not only to the difference in anode voltage but also to the method of operation. Also, we may compare the increase to 47 watts, obtained from two 6L6 valves in pushpull working in class AB 2, with a single 6L6 valve operating in class A 1, giving only 6.5 watts. The difference in db between these two outputs is only 8.6 db, which gives a better idea as far as the appreciation of the ear is concerned as a result of increasing the power, though the figures in watts: 6.5 and 47, look really a vast jump. Thus, though the increase in output may appear very large, yet when expressed in db, it is only small. The increase may not make much difference to the loudness sensation.

9. MICROPHONES

The db notation is used in connection with microphones for two purposes :

(1) Sensitivity rating,
and (2) Response curves

(1) Sensitivity Rating :

The output of any microphone is less than 1 volt, and therefore it is conveniently specified as so many decibels below an arbitrarily chosen zero level. The sensitivity of a certain microphone is given as follows :—

"—62 db relative to 1 volt per dyne sq. cm., measured on open circuit, across the secondary of the matching transformer, and with sound introduced along its axis, at a frequency of 1,000 cps". This, besides the impedance of the microphone and the step-up ratio of the matching transformer, provides the information required for determining the required amplification. To evaluate the 'open circuit voltage' specified above, the impedance of the microphone and the load to which it is connected must be considered. Let us consider the sensitivity calculations in the case of some common microphones.

Case I. Moving Coil Microphone :

Consider a moving coil microphone of 50-ohms impedance connected to a 500-ohm line via a line-matching transformer.

If the sensitivity of the microphone on open circuit is —62 db relative to 1 volt|dyne|sq. cm., the voltage generated is calculated thus :

$$20 \log \frac{x}{1} = -62, \text{ or } x = 0.0008 \text{ nearly.}$$

$x = 0.0008$ volt/dyne/sq. cm.; and the ratio of the matching transformer $= \sqrt{\frac{500}{50}} = 3.162.$

The transformer must present an impedance of 50-ohms towards the microphone (source impedance = load impedance). Since a generator giving 0.0008 volt feeds two impedances of 50-ohms each, the voltage across the microphone is equal to the voltage across the primary terminals of the matching transformer, i.e., equal to $\frac{.0008}{2} = 0.0004$ volt.

If the transformer step-up ratio is 1:3.162, then the voltage in the line = 3.162 x 0.0004 =0.001265 volt/dyne|sq. cm. Actually, the line voltage will be less than this value (due to the load reflected by the current in the moving coil); the line voltage will, therefore, be of the order of 1 mV.

Case II. **Ribbon Microphone :**

Next, consider a ribbon microphone. The sensitivity of a certain ribbon microphone is given as —76 db for a sound pressure of 1 dyne|sq. cm. Let us examine the above statement in detail in order to understand its significance.

The power W of the source of sound is given by

$$W = \frac{4 \pi r^2 p^2}{\rho c} \text{ ergs/second,}$$

$$= \frac{4 \pi}{\rho c} \times r^2 p^2 \times 10^{-7} \text{ watts,}$$

where,

p = sound pressure in dynes/sq. cm,

r = distance between the microphone and the speaker in cms,

ρ = density of air = 0.001225 grams/cu. cm. at 15° C and 76 cm,

c = velocity of sound in air at 15° C = 34140 cms./sec.

At a distance of r = 100 cm, p, the sound pressure = 1.8 dynes/sq. cm., for the maxima of the spoken word. Let r = 100, p = 1.8, and $\rho \times c = 41.8$ or, say, 42.

Then, $W = \frac{4\pi}{42} \times 10^4 \times (1.8)^2 \times 10^{-7} = 10^{-3}$ watt or, 1 mW, *i.e.*, the maximum energy of the spoken word is about 1 mW.

A ribbon (velocity) microphone gives 0.28 mV at the secondary terminals of a matching transformer. Its sensitivity at a distance of 3 feet along its axis, is —76 db with zero level of 12.5 mW; the adapting impedance in the microphone is given as 250 ohms.

Calculations :

$$10 \log_{10} \frac{P_1}{P_2} = -76 \text{ db, or } \frac{P_1}{P_2} = 10^{-7.6}$$

If $P_2 = 12.5$ mW (zero level),

then, $P_1 = 12.5 \times 10^{-7.6}$, or 0.0003139 mW.

$V = 0.28 \times 10^{-3}$ volts, but $P_1 = \frac{V^2}{Z}$.

$$\therefore Z = \frac{0.0784 \times 10^{-6}}{0.0003139 \times 10^{-6}} = 250 \text{ ohms, which agrees}$$

with the adapting impedance of the microphone, already stated. 12.5 mW and 250 ohms, correspond to 1.77 volts (for $V^2 = 250 \times 12.5 \times 10^{-3}$).

$$D \text{ db} = 20 \log_{10} \frac{V_1}{V_2}, \text{ where } V_1 = 0.28 \times 10^{-3} \text{ volts,}$$

and $V_2 = 1.77$.

$$\therefore D = 20 \log_{10} \frac{0.28 \times 10^{-3}}{1.77} = -76 \text{ db.}$$

Case III. **Crystal Microphone :**

Loss in level due to capacity in leads may be computed from the formulæ[31] :

$20 \log_{10} \left\{1 + \frac{C_1}{C_2}\right\}$, where C_1 represents the capacity of the lead,

and C_2 the capacity of the microphone.

The capacity of a good, special microphone cable is about 30$\mu\mu$f per foot. The internal capacity of an average crystal microphone will be about 0.01 μf, the load impedance 1 to 3 Megohms, and the output level about —66 db relative to 12.5 mW zero.

(2) The Rating of Sensitivities :

In rating the sensitivities of microphones, unfortunately there is no standard zero level. Actually, both '6 milliwatt' and '12.5 milliwatt' zero levels are used. The comparative sensitivities of some common microphones, as given by Greenlees[32] are shown in the table below.

Table 9.

No. Type of microphone	Impedance at 1,000-Cycles (Ohms)	Open circuit voltage in *db.* below 1 volt per dyne/sq. cm.	Output power in db relative to 6 mW zero level at 1 dyne/sq. cm.	Output power in db level relative to 12.5 mW zero level at 1 dyne/sq. cm.
1. Carbon ...	2,000	—38	—45	—48
2. Condenser ...	500,000	—50	—90	—93
3. Moving coil...	20	—63	—60	—63
4. Ribbon ...	200 (with transformer)	—73	—80	—83
5. Crystal ...	50,000	—72	—103	—106

(3) Response Curves of Microphones :

A 3-cycle, log-linear, graph paper is used to represent the response curves. The X-axis is used for representing the frequency, usually from 50 to 10,000 cps, and the

Y-axis for the response in db. Fig. 3.12 shows the output of microphones corresponding to various frequencies of sound waves at a fixed intensity for the following types of microphones :

A. carbon,
B. condenser,
C. moving coil,
D. ribbon,
E. crystal.

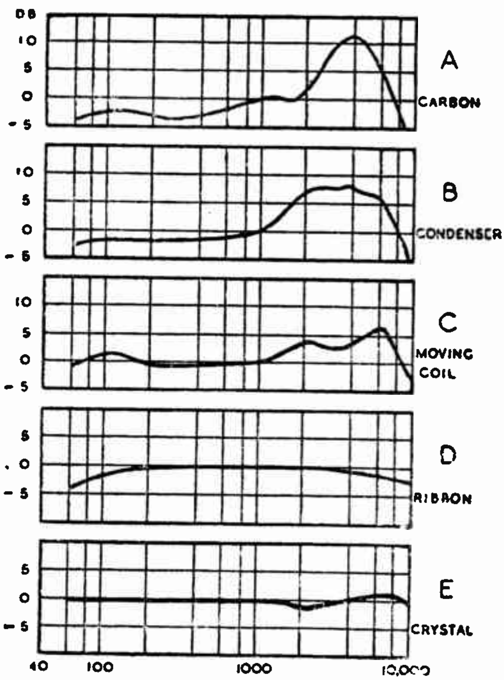


Fig. 3.12. Response curves of Five Different Types of Microphones (By courtesy of Messrs. Chapman & Hall Ltd., London.)

For any microphone, response curves can be drawn for sounds arriving at angles off the axis, vide Fig. 3.13, which gives response for sounds arriving at angles : 0, 30, 60 and 90, with the axis for a certain microphone.

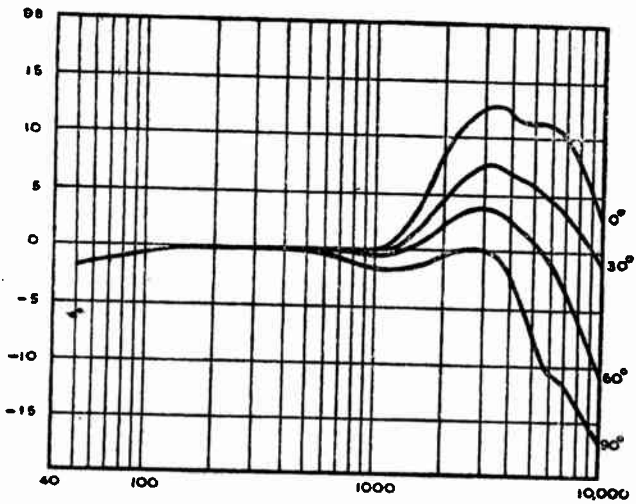


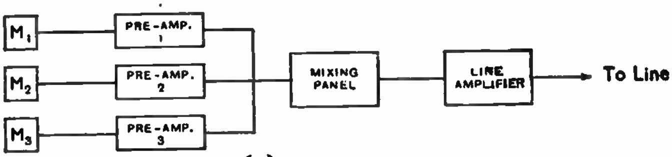
Fig. 3.13. Directional Response Curves.
(By courtesy of Messrs. Chapman & Hall Ltd., London.)

It is seen from the different curves in this graph, that the frequency response to sound waves arriving at an angle to the axis of the microphone, differs from that for sound waves coming along the axis, and that the high-frequency response falls rapidly as the angle with the axis increases (c.f. curve for $\theta = 90$, with that for $\theta = 0$, where θ is the angle which the arriving sound wave makes with the axis).

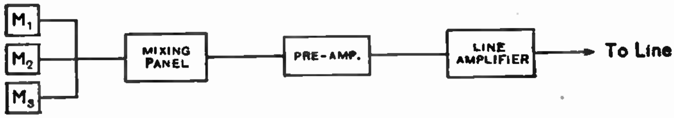
(4) High-Level, and Low-Level Mixing.

It will be seen from Table 9 that the output of any microphone is several tens of db below the zero level. Hence, before the output of a microphone is fed to a line-amplifier, usually there will be the amplification by pre-amplifiers as well as a 'mixer', for mixing the outputs of several microphones.

There are two methods of mixing the outputs of several microphones, called (1) the high-level mixing, and (2) the low-level mixing. These two methods are illustrated in the Fig. 3.14 below :



(1) High Level Mixing



(2) Low Level Mixing

Fig. 3.14.

In the case of low-impedance microphones, *e.g.*, ribbon or velocity microphone, and moving coil or dynamic microphones, whose output level is between —60 and —85 db, low-level mixing is resorted to, and in the other types, high-level mixing.

The fundamental difference between the two methods of mixing is that, in the high-level mixing, the mixing is done at a level of —30 db (approx.), subsequent to the amplification by pre-amplifiers, while in the case of low-level mixing, the mixing is done first and then amplified by the pre-amplifier. High-level mixing is advantageous from the point of view of the higher signal|noise ratio. In general, it may be expected that the total noise level at the first valve of an amplifier using a low-level mixing system to be about 10 db higher than in a high-level mixing system.

10. LOUDSPEAKERS.

According to the IRE Standards on Electroacoustics,[33] decibels appear in describing the following characteristics of a loudspeaker :

(1) Response-Frequency characteristic,
and (2) Directional characteristic.

(1) Response-Frequency Characteristic.

The response of a loudspeaker is a measure of the sound produced at a designated position in the medium with the electrical input, frequency, and acoustic conditions, specified.

$$\text{The absolute pressure} = p\frac{\sqrt{Z}}{V},$$

where, p = measured sound pressure in dynes sq. cm.,
V = effective voltage applied to the voice coil in volts,
and Z = absolute value of the impedance of the voice coil—(Z is a function of the frequency).

It is usual to express the response in decibels, relative to an arbitrary value of response corresponding to one volt, one ohm, and one dyne|sq. cm.

$$\text{Then, response in db} = 20 \log_{10} \frac{\dfrac{p}{V/\sqrt{Z}}}{\dfrac{1}{1/\sqrt{1}}}.$$

$$= 20 \log_{10} \frac{p.}{(V/\sqrt{Z})}$$

$$= 20 \log_{10} \frac{p\sqrt{Z}}{V}$$

It is not proposed to describe here the actual method of measuring the sound pressure (p), Z, etc., as Part III of the IRE standards[33] headed: 'Methods of testing loudspeakers', gives detailed information on the subject, and the reader interested in the actual method of obtaining the response-frequency characteristic of a loudspeaker either by automatic, semi-automatic, or point-to-point methods, can readily obtain information from there.

Response curves of loudspeakers can be drawn for (1) response along the axis of the speaker, or (2) for any angle off the axis of the speaker (c.f. corresponding curves for microphones).

(2) **Directional Characteristic.**

The directional characteristic of a loudspeaker is the response as a function of the angle with respect to the normal axis of the system, and the characteristic may be plotted as a system of polar curves for various frequencies, or as response-frequency curves for various angles with respect to the axis. Fig. 3.15 (A & B) shows two frequency-response curves of a projector type of loudspeaker.[34] In it, curve A relates to the response along the axis of the loudspeaker, while curve B relates to the response 45° off the axis.

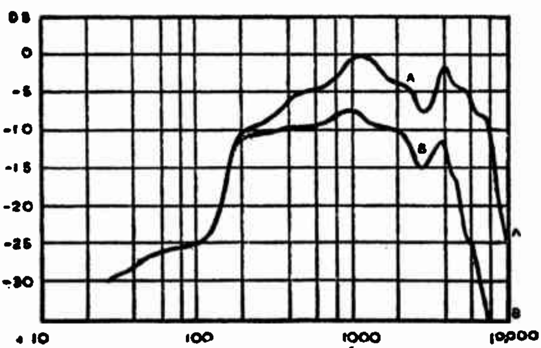


Fig. 3.15. Frequency Response Curves of a Projector Type of Loudspeaker. (By courtesy of Messrs. Chapman & Hall Ltd., London.)

From Fig. 3.15, it is seen that the response at 45° off the axis is —25 db for 6,000 cps, and only —8 db at 1,000 cps. The result is that a relative difference of 25—8 = 17 db exists between 6,000-, and 1,000-cycle response at 45°, compared with the response along the axis.

The quality of reproduced sound from a loudspeaker varies with the angle of distribution. The higher-audio frequencies, more than the lower-audio frequencies, concentrate around the axis, leading to sound at the limiting edge of the cone of the reproduced sound being woolly and indistinct.

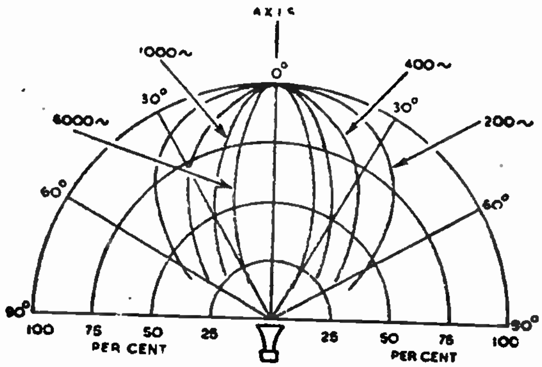


Fig. 3.16. Polar Response Curves of a Loudspeaker.
(By courtesy of Messrs. Chapman & Hall Ltd., London.)

Consider Fig. 3.16, which shows the polar curves of a loudspeaker[34] for four different frequencies. A polar curve can be obtained from a series of frequency-response (linear) curves similar to those in Fig. 3.15 taken at a number of angles off the axis. The frequency response at any angle from the axis can be read off directly from the polar curve.

The method of converting the percentage response to db-loss is best illustrated by the following table :

Table 10.

% response	Response (in decimals)	log of value in col. (2)	Column 3 evaluated	db loss = 20 log of Column 4
(1)	(2)	(3)	(4)	(5)
25	0·25	$\bar{1}.3979$	−0.6021	−12.0
50	0·50	$\bar{1}.6990$	−0.3010	− 6.0
75	0·75	$\bar{1}.8751$	−0.1249	− 2.5
100	1·00	0.0000	0.0000	0

The values in column 5 of the above table explain the db values in Fig. 3.16.

From Fig. 3.16, it is seen that, at 6,000 cps for 30°, the response is only 25%, *i.e.*, has fallen by 75%. In db, this response will be —12 db relative to the axial response for the same 30°.

For the same 30°, the responses of the three other frequencies shown in the Fig. 3.16 are as follows :—

at	200 cps	88%	*i.e.*, fallen by	12%	from	the	response	at 0°
,,	400 ,,	70%	,,	30%	,,	,,	,,	,,
,,	1,000 ,,	50%	,,	50%	,,	,,	,,	,,

Thus, the effect of angle of distribution on response is well brought out by the polar response curves.

11. TRANSMITTERS.

In connection with transmitters, the db-notation is used in expressing the performance or specification of the following items :

(1) Strength or intensity of a signal at a point,
(2) Overall-frequency response,
and (3) Carrier noise.

These items will be examined in detail below.

(1) Strength or Intensity of a Signal at a Point due to a Transmitter.

The power or strength of a transmitter can be judged by the AF power delivered by a distant radio receiver, when tuned to the transmitter in question. Let us suppose that the power of a broadcast transmitter is 1 kW and a certain receiver, when tuned to this transmitter, gives an audio output of 10 db (reference level of 6 mW). Then, let us increase the power of the transmitter to 10 kW. What is the audio output from the radio receiver with increased power of the transmitter?

Solution :—

Assuming (for simplicity) that the audio-power output from the receiver varies directly as the power rating of the transmitter, if P_r and P_t be the two powers in question, then for the same percentage modulation, $P_r = k\ P_t$, where k is a constant.

The increase in signal strength at the receiver in db due to the increase in transmitter power from P_{r1} to P_{r2}.

$$= 10 \log \left(\frac{P_{r2}}{P_{r1}}\right)$$

$$= 10 \log \left(\frac{10}{1}\right)$$

$$= 10 \text{ db}$$

If the receiver output was originally only 10 db, the new output from the receiver will be 10 + 10 = 20 db.

(2) Overall Frequency Response.

It is usual practice to specify the departure in db level, at chosen frequencies in the frequency-response curve, which is similar to that of an AF amplifier. The response curve is drawn on a 3-cycle, log-linear graph paper. In broadcasting, the range of frequencies we are interested in is 30 to 10,000 cps.

A typical specification is as follows :—

With a constant voltage at the input terminals of the pre-amplifier, the LF components of the rectified aerial currents should not exceed, at 80% modulation, the following deviations with regard to the reference frequency of 1,000 cps :

(i)	100–5,000 cps	1.5 db
(ii)	50–8,000 cps	2.0 „
(iii)	30–10,000 cps	3.0 „

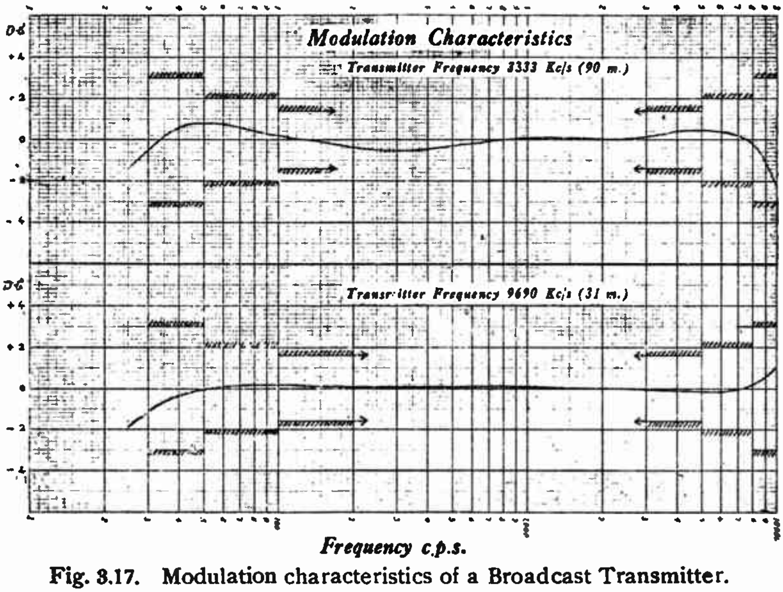


Fig. 3.17. Modulation characteristics of a Broadcast Transmitter.

Fig. 3.17 shows the actual response curves of a short-wave transmitter at two different carrier frequencies, with the specified limits indicated hatched.

(3) Carrier Noise.

The carrier of a transmitter has always some inherent noise associated with it. In order that such noise may not effectively drown the signal (in non-suppressed carrier systems, as in ordinary broadcasting), the carrier noise is often specified to be as so many db below the level of power at 100% modulation—(c.f. the rating of hum level in AF amplifiers, as so may db below the full, rated output of the amplifier).

A typical specification for a transmitter is as follows :—

(a) **Unweighted :** The noise level on the carrier should be at least 60 db below the level of the 100% modulation,

(b) **Weighted :** The figure will be below 60 db as indicated for the 100% modulation.

The significance of the words : 'unweighted' and 'weighted,' is explained as follows.

It has already been pointed out that loudness response of the human ear is different for different frequencies. Therefore, to take into account this peculiarity of the ear in interpreting the audio-frequency response of electrical systems, a weighted network, consisting of a filter designed to attenuate each audio frequency in proportion to the sensitivity of the ear at that frequency, is employed.

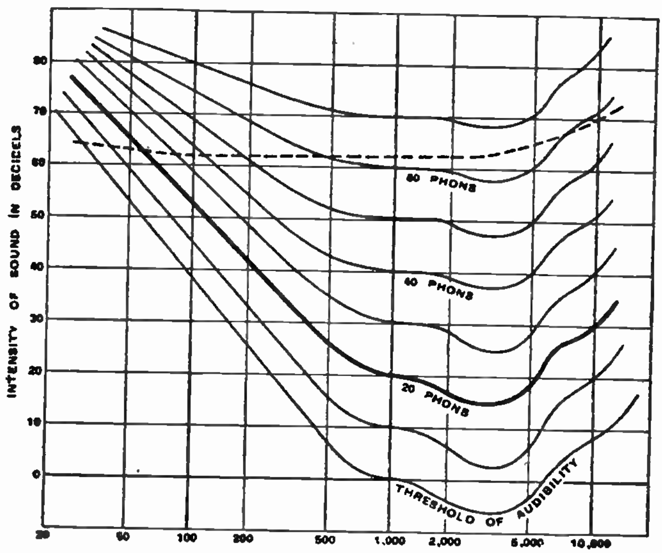


Fig. 3.18. Average characteristics of the Human Ear.
(By courtesy of the *Wireless World*, Messrs. Iliffe & Sons, Ltd., London.)

Fig. 3.18 shows the average characteristics of the human ear. 'Curves of Equal Loudness' (Phons) are quite different from the horizontal straight lines corresponding to equal intensities of sound. Consider the 20-phon loudness curve. Its slope is about 12 db per octave up to 800 cps. Noise of 20-phon loudness is considered objectionable. An increase of about 6 db per octave is obtained by taking the voltages developed across an inductance in the anode circuit of a constant current device (a pentode), whose internal impedance is much higher than the maximum-load impedance.

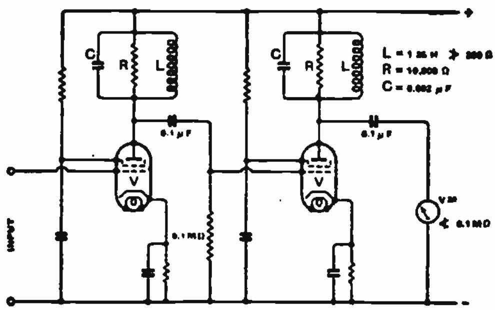


Fig. 3.19. Circuit of a weighted Amplifier to compensate for the characteristics of the Average Ear, as shown in Fig. 3.18. (By courtesy of Messrs. Iliffe & Sons Ltd., London.)

The circuit of an amplifier described by Scroggie[34], to reduce the 20-phon loudness curve to that shown in the dotted line in the Fig. 3.18, is shown in Fig. 3.19. For details of design the reader is referred to "weighting of an amplifier" in Scroggie's 'Radio Laboratory Hand book'.[35]

Thus, by using the weighted amplifier the 20-phon line is raised up to the level of the dotted line, thereby enabling an ordinary meter to deflect in proportion to loudness.

12. TRANSMISSION LINES & FEEDERS.

(1) Application.

The db-notation is used in connection with transmission lines and feeders of different characteristic impedances, for expressing the power transmitted as well as evaluating the power losses in such lines and feeders.

It is common practice to install transmitters or special receivers in a building remote from the ærial systems. Hence feeders or transmission lines are required to convey the high-frequency output of the transmitters to the corresponding aerial, or to convey the energy intercepted by the aerial to the corresponding receiver, as for example, in the case of diversity-reception centres. The energy in each case is transferred by means of a feeder system. These high-frequency feeders may be either of overhead parallel wires or two concentric tubular conductors, laid a few inches over the earth or buried in the earth itself. In audio-frequency power transmission also transmission lines, as overhead or underground cables, (as is common in telephone engineering), are used. The characteristic impedances of the various transmission lines and feeders will be first discussed before considering the various losses which occur in them.

(2) Characteristic Impedance.

(a) Overhead Lines.

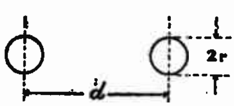


Fig. 3.20.

For twin parallel wire feeders (Fig. 3.20), the characteristic impedance $Z_o = 276 \log_{10}\left(\frac{d}{r}\right)$ ohms, where, d = spacing between wires, and r = radius of the wire.

This formula is accurate down to a ratio of $\left(\frac{d}{r}\right) = \left(\frac{4}{1}\right)$.

The following table gives values of Z_o corresponding to various $\left(\frac{d}{r}\right)$ values. It is seen that over a wide range of practical value for $\frac{d}{r}$ (5/1 to 500/1), the characteristic impedance varies between 200 and 750-ohms. In fact, we are mostly interested in $Z_0 = 200$, 500 and 600-ohms only. An example will illustrate how this table is constructed with the above formula.

Table No. 11.

$\frac{d}{r}$	Z_0 Ohms
5 : 1	200
15 : 1	300
30 : 1	400
60 : 1	500
100 : 1	550
150 : 1	600
350 : 1	700
500 : 1	750

Example :—A telephone line is constructed with a pair of 14 SWG copper conductors ($r = 0.04''$) spaced 6.0 inches apart. Find out Z_0.

Solution :—$d = 6''$, $r = 0.04''$

$$\therefore \frac{d}{r} = \frac{6}{\cdot 04} = \frac{150}{1}$$

$$Z_0 = 276 \log_{10} 150 = 600\text{-ohms.}$$

In Table 13 (on pages 110 and 111), power in watts and the corresponding power levels in db relative to (a) 1 mW zero, (b) 6 mW zero, and (c) 12.5 mW zero level, for $Z_0 = 200$, 500 and 600-ohms, are evaluated over a power range of 6×10^{-9} watts to 100 kW.

(b) **Underground Feeders or Concentric Cables.**

For short waves, concentric tubular feeders can be used. These feeders are such that one conductor is fitted inside another (bigger tube), with suitable insulators acting as spacers between the two conductors. (Fig. 3.21).

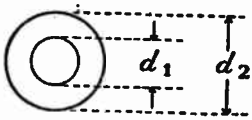


Fig. 3.21.

Characteristic Impedance (Z_0) for such a feeder $= 138 \log_{10} \left(\frac{d_2}{d_1}\right)$,

where, d_2 = Inner diameter of the outer tube,
and d_1 = Outer diameter of the inner tube.

The following table gives some (d_2/d_1) ratios and the corresponding values of Z_0.

Table No. 12.

$\frac{d_2}{d_1}$	Z_0 (Ohms) approx.
2 : 1	40
2.5 : 1	50
3.5 : 1	74
4 : 1	84
5 : 1	100
10 : 1	140

The characteristic impedance most widely used is 70 to 74-ohms.

Example :—Find out Z_0 for a concentric tubular feeder, if $d_2 = 3.5''$, $d_1 = 1''$.

Solution :—

$$\frac{d_2}{d_1} = \frac{3.5}{1} = 3.5.$$

$$Z_0 = 138 \log_{10} \frac{d_2}{d_1} = 138 \log_{10} 3.5$$
$$= 74\text{-ohms.}$$

The accompanying Table 13 gives power in watts and the corresponding db-levels with (a) 1 mW zero, (b) 6 mW zero, and (c) 12.5 mW zero level, for $Z_0 =$ 37, 50 and 74-ohms.

(i) As 37-, and 74-ohm-impedance feeders are used for the transmission of RF power greater than 25 watts, the power range evaluated is : 25 watts to 100 kW only.

(ii) As the 50-ohm-impedance-line feeder is used for the transmission of AF power below 6 watts, the power range evaluated is : 6×10^{-9} to 6 watts only.

(3) **Losses in Feeders.**

The losses in feeders comprise the following :

1. Attenuation, as energy flows along the line, due to
   (i) conductor losses,
   (ii) dielectric ,, ,
   and (iii) radiation ,, .

(i) Conductor losses can be calculated accurately and easily.

(ii) It is not very easy to calculate dielectric losses.

(iii) Radiation loss is of importance in the case of overhead parallel feeders and may be ignored in the case of concentric feeders.

Table 13.

Table of Power and Power Levels in db (relative to Three Different Zero Levels) and RMS Voltage Levels (for Six Different Impedances).

POWER				VOLTAGE					
In watts	In db			RMS Volts across Surge Impedance Z_0 ohms					
Absolute Power	1mW Zero	6mW Zero	12.5mW Zero	600	500	200	74	50	37
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
6×10^{-9}	−52.22	−60	−63.19	0.0019	0.0017	0.0011		0.00055	
6×10^{-8}	−42.22	−50	−53.19	0.006	0.0055	0.0034		0.00173	
6×10^{-7}	−32.22	−40	−43.19	0.019	0.0173	0.0109		0.0055	
6×10^{-6}	−22.22	−30	−33.19	0.06	0.0548	0.0346		0.0173	
6×10^{-5}	−12.22	−20	−23.19	0.19	0.1732	0.1095		0.0548	
6×10^{-4}	−2.22	−10	−13.19	0.60	0.5478	0.346		0.173	
.000755	−1.22	− 9	−12.19	0.673	0.614	0.386		0.194	
.000951	−0.22	− 8	−11.19	0.755	0.689	0.433		0.218	
.001197	+0.782	− 7	−10.19	0.848	0.774	0.487		0.244	
.001507	1.782	− 6	− 9.19	0.952	0.868	0.546		0.275	
.001897	2.782	− 5	− 8.19	1.07	0.974	0.613		0.308	
.002388	3.782	− 4	− 7.19	1.19	1.09	0.687		0.344	
.003007	4.782	− 3	− 6.19	1.35	1.23	0.775		0.389	
.003786	5.78	− 2	− 5.19	1.51	1.38	0.870		0.436	
.004766	6.78	− 1	− 4.19	1.69	1.54	0.971		0.487	

.006000	7·78	0	−3.19	1.89	1.73	1.095		0.546	
.007553	8.78	+1	−2.19	2.13	1.94	1.22		0.614	
.009509	9.78	2	−1.19	2.39	2.18	1.37		0.679	
.01197	10.78	3	−0.19	2.72	2.48	1.56		0.784	
.01250	10.97	3.19	0.	2.74	2.5	1.57		0.792	
.01507	11.78	4	+0.81	3.02	2.75	1.73		0.870	
.01897	12.78	5	1.81	3.38	3.08	1.94		0.975	
.0239	13.78	6	2.81	3.79	3.46	2.18		1.095	
.0301	14.78	7	3.81	4.26	3.89	2.45		1.23	
.0379	15.78	8	4.81	4.76	4.35	2.74		1.38	
.0477	16.78	9	5.81	5.35	4.88	3.08		1.54	
.06	17.78	10	6.81	6.0	5.47	3.45		1.73	
.6	27.78	20	16.81	19.0	17.32	10.9		5.48	
6.0	37.78	30	26.81	60.0	54.77	34.5		17.3	
25.0	43.97	36.19	33.0	122.2	111.8	70.3	42.3		30.4
50	46.99	39.21	36.02	173.5	158.2	99.5	60.8		43
75	48.48	40.10	36.90	212	193.5	121.9	74.5		52.7
100	50.00	42.22	39.03	244	222.6	140.5	86.0		60.8
150	51.76	43.98	40.79	300	274	172.5	105.0		74.5
200	53.01	45.23	42.04	346	316	199	121.5		86.0
250	53.98	46.20	43.01	388	354	223	136.		96.3
500	56.99	49.21	46.02	548	500	315	173.		136.0
1,000	60.00	52.22	49.03	775	707	446	272.		192.3
2,500	63.98	56.20	53.01	1,222	1,118	703	423.		304.
5,000	66.99	59.21	56.02	1,735	1,582	995	608.		430.
10,000	70.00	62.22	59.03	2,440	2,226	1,405	860.		608.
25,000	73.98	66.20	63.01	3,880	3,540	2,230	1,360.		963.
50,000	76.99	69.21	66.02	5,480	5,000	3,150	1,730.		1,360.
100,000	80.00	72.22	69.03	7,750	7,070	4,460	2,720.		1,923.

2. Copper Losses in Feeders.

The power efficiency of a kilometre length of a concentric tubular feeder taking into account copper losses only and neglecting the other two, is given by the formula[36] :

$$\log_{10} \eta = -1.30 \times 10^{-5} \frac{\sqrt{f}\left(\frac{1}{r_1} + \frac{1}{r_2}\right)}{\log_{10}\left(\frac{r_2}{r_1}\right)},$$

while the loss itself per km in db is :

$$1.30 \times 10^{-4} \frac{\sqrt{f}\left\{\frac{1}{r_1} + \frac{1}{r_2}\right\}}{\log_{10}\left(\frac{r_2}{r_1}\right)},$$

where, η = efficiency,

f = frequency (cps),

r_1 = radius of inner tube in cms.

and r_2 = radius of outer tube in cms.

The efficiencies per km length, and loss in db per km of some typical concentric tubular feeders, calculated from the above formulae, are given in Table 14 (reproduced from Ladner and Stoner).[35]

Table 14.

Losses in Feeders at f = 20 Mcs. (15 metres).

Type SWG	Outer radius of inner tube (cms).	Inner radius of outer tube (cms).	Ratio $\left(\frac{r_2}{r_1}\right)$	Percentage efficiency per km.	Attenuation per km in db.	Z_0 (ohms).
No. 0	3.30	13.0	4	81.3	0.95	83
„ 1	1.11	4.4	4	77.8	1.09	83
„ 2	0.875	3.17	3.6	70.5	1.52	77
„ 3	0.238	0.795	3.34	24.8	6.05	72.2

Corresponding table of losses for parallel-wire feeders is given in Table 15 shown below, (also reproduced from Ladner and Stoner).[36] The calculation ignores the losses due to earth currents as well as the effect due to the presence of other wires on the distribution of currents.

Table 15.

Losses in Feeders at f = 20 Mcs (15 metres).

SWG No.	Radius of wire (cms).	Distance between wires (cms)	Ratio (d/r)	Percentage efficiency per km.	Attenuation db per km	Z_0 (ohms).
6	0.243	10	41.1	71.1	1.48	445
		20	82.2	75.0	1.25	530
		30	123.0	76.9	1.14	578
8	0 203	10	49.3	67.8	1.69	468
		20	98.6	72.8	1.43	551
		30	148.0	73.8	1.32	600
12	0.132	10	75.7	58.3	2.34	519
		20	151.0	63.0	2.01	602
		30	227.0	65.2	1.86	650

The attenuation at any other frequency f_1 may be found, as equation shows, by multiplying the results given for 20 Mcs by the factor : $\sqrt{\frac{f_1}{20 \times 10^6}}$. For further information on the testing of HF cables and measurement of losses, the reader is referred to an interesting paper on this subject by Smith and O'Neill.[37]

13. AERIALS

In the case of aerials, the decibel notation is used to express the gain of a directional aerial array. As the decibel is a relative unit, a standard for comparison is required. In expressing the gain of a directive array, generally the reference standard chosen is the $\left(\frac{\lambda}{2}\right)$ half-wave vertical aerial having the *same input power* as the directive aerial under consideration.

Thus, if $P_r =$ power radiated by a certain aerial in the desired direction,

$P_s =$ power radiated by a $\left(\frac{\lambda}{2}\right)$ vertical aerial (standard), and if $p =$ input power to each of the two aerials, then the gain in db, of the aerial radiating Pr watts in the desired direction, is: $10 \log_{10}\left(\frac{P_r}{P_s}\right)$, and we need not have to know p.

Example :—

Let us, therefore, examine what is meant by saying: "The gain of a directive antenna or aerial system is 6 db".

It means $10 \log \left(\frac{P_r}{P_s}\right) = 6$ db ; $\therefore \left(\frac{P_r}{P_s}\right) = 4$.

The directive aerial, therefore, radiates 4 times the power a half-wave vertical reference aerial radiates, under the condition that the input powers to both these aerials are equal.

For an interesting discussion on the application of the db-notation to aerials, the reader is referred to the Admiralty Hand-book, Vol. II.[38]

14. ACOUSTICS

The decibel notation is used in the science of acoustics in connection with the following:—

(1) Studio acoustics ;
(2) Architectural acoustics;
(3) Noise abatement ;
and (4) Sound films.

Out of the four topics listed above, in radio engineering we are interested only in studio acoustics and so treatment is confined to this aspect only in this monograph.

STUDIO ACOUSTICS

(i) Reverberation Time.

The reverberation time of an enclosure, for sound of a given frequency, is the period of time required for the average sound energy density in the enclosure, initially in a steady state, to decrease, after the source is stopped, to one millionth of its initial value, *i e.*, by 60 db. It is to be noted that the sound energy density corresponds to electrical power; hence the formula : $10 \log \frac{P_1}{P_2}$, is used.

(ii) Degree of Silence in Broadcast Studios.

The degree of silence necessary for good broadcasting is 10 db above the threshold of hearing. It is difficult to appreciate how quiet such a noise level is, without having first-hand experience in the measurement of sound intensity. An idea of this degree of silence (+ 10 db) is obtained by imagining the sound of rustling leaves caused by a gentle breeze, in a very quiet spot, at night, on a non-rainy day !

(iii) Sound Intensity in Broadcast Studios.

The average sound intensity in most of the BBC studios was said to be only between 10 and 20 db. The sound intensities were specified by the BBC as follows :

"That all sound intensities referred to in db are measured on the 'Fletcher scale'. This scale divides the range of intensities of a pure note having a frequency of 700-cycles per second, between the threshold of audition and feeling into 120 parts, while the db value corresponding to any intensity E_1 is given by the following formula :

Decibels $= 10 \log \frac{E_1}{E_0}$, in which $E_1 =$ sound energy per unit volume, *i.e.*, intensity at the point of observation, and $E_0 =$ sound energy per unit volume (*i.e.*, intensity corresponding to threshold of audition.) The intensity of sound, due to a pure tone of any other frequency or mixture of frequencies or noises, is to be taken to be equal to that of a pure note having a frequency of 700-cycles per second, which is judged by the normal ear to be equally loud. This is to be interpreted in practice (and has been confirmed by experiment), as meaning that the above formula may be for any pure note when E_1 and E_0 are intensities corresponding to the actual sound and threshold of audition at that particular frequency."[39]

(iv) **Sound Intensity Levels in Speech and Music.**

The upper limit for speech in studios is about 60 db, and that for music about 90 db, above noise level. It is necessary to maintain the strength of a programme within certain limits. The maximum to minimum ratio of the volume of sound due to an orchestra in a studio, when expressed in db, is about 60 db, whereas for satisfactory broadcast transmission and reception the maximum to minimum signal intensity should be within 30 db. Therefore, it is obvious that some form of control for reducing the strength of the strong passage and strengthening the very weak one, is necessary. This is often done by the operator by frequent adjustment of the main potentiometer in the control room.

(v) **Sound Insulation of Studios.**

Sound is transmitted through rigid partitions by forced vibrations in walls. These partitions are used to insulate sound from one studio or room to another, and the sound insulation is expressed in decibels.

The following table gives data on the insulation of rigid partitions.[40] It is based on the formula :

$$\text{Insulation in db} = 14.3 \log_{10} \text{wt./sq. ft.} + 22.7 \text{ db.}$$

Table 16.

Mass/sq. ft. in lbs.	Insulation in db (at 512 cps).	Remarks.
10	37	The transmission loss in db is the arithmetical mean of the transmission losses at the frequencies of 128, 256, 512, 1024 and 2048 cps.
20	41	
40	45	
60	48	
100	51.3	
400	60	

From the above equation which is of the form: $y = k \log_{10} x + c$, it is seen that the relation between the sound transmission loss in db and the logarithm of the weight sq. ft. of the rigid partition is linear so that, if on a log-linear graph paper insulation in db along the Y-axis is plotted against the weight sq. ft. on the X-axis, the graph is a straight line, from which any other desired data can be interpolated or extrapolated.

The two basic design principles in sound insulation are:

(1) losses due to absorption of sound by porous, flexible acoustic materials;

and (2) losses due to inertia (mass) in rigid partitions. While a concrete wall, nearly 4 ft. thick, can give a sound insulation of 60 db, 2 or 3 rigid but thin partitions, separated from each other by felt, etc., can give the same sound insulation. Again, consider the case of thin brick-wall partitions separated by air space between them. While a single 9″ brick-wall gives an insulation of 50 db, two separate 4½″ brick-walls with air-space between, give a joint sound insulation of nearly 90 db. Hence the latter construction is much more effective and cheaper than the former type, and is consequently widely used in studio design practice.

15. ATTENUATORS

(1) Application.

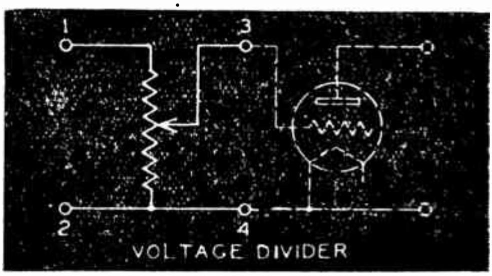
An attenuator is a type of resistance pad providing predetermined diminution in power or voltage, *i.e.*, the output power or voltage from an attenuator is a known fraction of the input power or voltage. It may, therefore, be viewed somewhat as the converse of an amplifier. Decibel serves well as a unit of attenuation or loss. If the output voltage is V_o and input voltage V_i, then the attenuation or loss expressed in decibels, due to the "attenuator network", is given by :

$$20 \log \left(\frac{V_o}{V_i}\right).$$

(2) Methods of Attenuation.

There are two methods of obtaining an output signal, which is a known fraction of the input signal : with the aid of (a) the potential divider ; and (b) the attenuator.

(a) Fig. 3.22 shows a simple potential divider. This is of use when its output is connected to the grid circuit of



(By courtesy of General Radio Coy., USA)
Fig. 3.22

a valve, which is a voltage-operated device. The output impedance is assumed to be infinite. Then the voltage attenuation per tap in db, can be calculated by the formula:

$20 \log_{10} \left(\frac{R_i}{R_o}\right)$, where R_i is the input resistance between the terminals 1 and 2, and R_o is the output resistance between the terminals 3 and 4. The following table gives data for the design of a potentiometer giving variable attenuation from 0 to 50 db in steps of 1 db, with an input impedance $R_i = 100{,}000$ ohms.

Table 17.

db.	Output Resistance tap R_o in ohms.	db.	Output Resistance tap R_o in ohms.
0	100,000	26	5,012
1	89,130	27	4,467
2	79,430	28	3,981
3	70,790	29	3,548
4	63,100	30	3,162
5	56,230	31	2,818
6	50,120	32	2,512
7	44,670	33	2,239
8	39,810	34	1,995
9	35,480	35	1,778
10	31,620	36	1,585
11	28,180	37	1,413
12	25,120	38	1,259
13	22,390	39	1,122
14	19,950	40	1,000
15	17,780	41	891
16	15,850	42	794
17	14,130	43	708
18	12,590	44	631
19	11,220	45	562
20	10,000	46	501
21	8,913	47	447
22	7,943	48	398
23	7,079	49	355
24	6,310	50	316
25	5,623		

This type of attenuator, called a potentiometer, has two defects. When the impedance into which it works is finite and small, (1) the actual attenuation differs from the value calculated by the formula: $20 \log \left(\frac{R_i}{R_o}\right)$, and (2) the input impedance itself is altered.

These defects are counteracted by a network of resistances, mounted in a box called the attenuator box and provided with a pair of input and a pair of output terminals.

(b) **Attenuator Box.**

Three essential requirements of this type of attenuator are :

(i) that the effective resistance of the whole network is always constant or nearly so,

(ii) that the calibration is constant even at high frequencies. (From the point of view of frequency of operation, attenuators are classified into two classes :—

1. Special RF attenuators suitable for a frequency range of 10 Mcs to 150 Mcs.

2. Ordinary attenuators suitable up to a frequency of 100 kcs. In a good attenuator of this type even at 100 kcs, the error normally should not exceed 10% of the reading.)

(iii) that the input impedance of the attenuator is sensibly constant since the frequency of the oscillator (to the output of which the input terminals of the attenuator are usually connected), depends to a certain extent on the resistance, which is connected across the output coupling coil of the oscillator, and consequently, if the input impedance of the attenuator varies widely, then the oscillator frequency will also drift considerably. Special care in design is needed to meet the requirements in designing a good attenuator, especially at high frequencies.

An attenuator widely used, is a special form of a filter network, terminated in a load resistance equal in value to the characteristic impedance.

(3) **Types of Attenuator Networks.**

McElroy,[41] in an exhaustive paper in the IRE gives design data for the following types of attenuator networks :—

(1) T-type
(2) π-type
(3) H-type
(4) Balanced H-type
(5) O-type
(6) Balanced O-type
(7) L-type
(8) U-type
(9) Balanced U-type
(10) Bridged T-type
(11) „ H-type
(12) Bridged-balanced H-type.

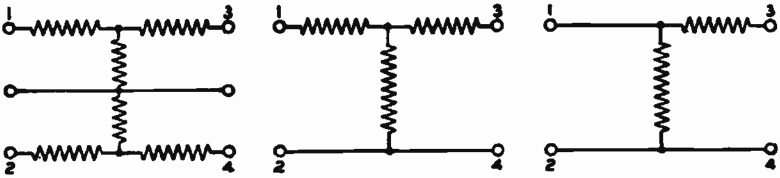
From the point of terminating impedances, they are of two types:

(1) unequal; and (2) equal.

Attenuators can also be classified as :

(1) fixed pads; and (2) adjustable pads.

Continuously variable type of attenuators are widely used in the communication testing equipment.



Balanced-H-section networks are used when impedances must be matched in both directions and balanced to ground. T-type sections maintain constant impedance in both directions, but they are not balanced to ground. L-type section maintains constant impedance at the 3-4 terminals.

(By courtesy of General Radio Coy., USA)

Fig. 3.23

In the present section, design of the following three common types of attenuators, to give a prescribed attenuation in db, is dealt with in detail:

(a) T-Type; (b) H-type; and (c) Ladder type.

(a) Simple T-type Attenuator.

Fig. 3.24 shows a simple T-type attenuator.

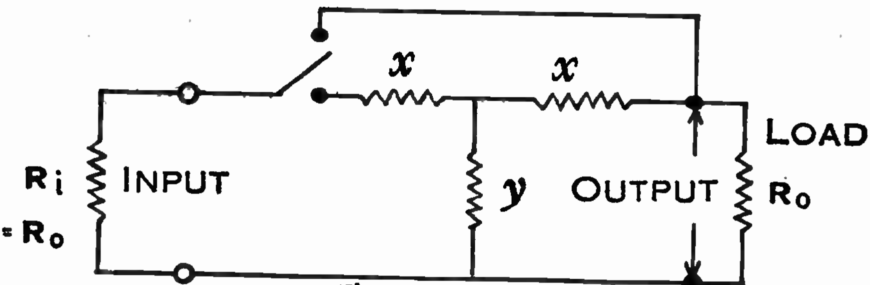


Fig. 3.24

If V_i = input voltage, and V_o = output voltage, then, $k = \frac{V_i}{V_o} = \frac{R_o + x}{R_o - x}$, and $R_o = \sqrt{[x(x + 2y)]}$, whence, $x = R_o\left(\frac{k-1}{k+1}\right)$, and $y = R_o\left(\frac{2k}{k^2-1}\right)$.

Example :—Design a single T-section attenuator to give a loss of 20 db. Given R_o = 600-ohms.

Solution :—

$$20 \log \frac{V_i}{V_o} = 20 \text{ db.} \quad \therefore \frac{V_i}{V_o} = 10.$$

$$\therefore k = 10; \ R_o = 600\text{-ohms.}$$

Then, $x = 600\left\{\frac{10-1}{10+1}\right\} = 600\left(\frac{9}{11}\right) =$ 490.9-ohms,

and $y = 600\left\{\frac{2 \times 10}{100-1}\right\} = \frac{12000}{99} =$ 121.2-ohms.

(b) Simple H-type Attenuator.

Fig. 3.25 shows a simple H-type attenuator.

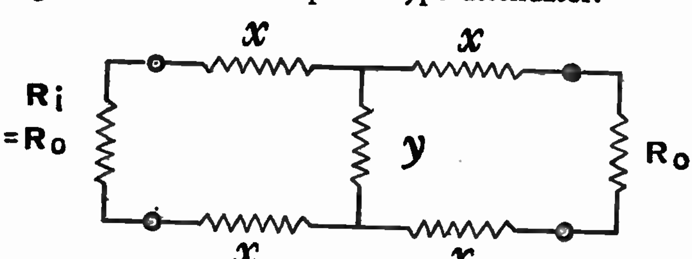


Fig. 3.25

$$\text{If } k = \frac{\text{initial voltage or current}}{\text{attenuated voltage or current}},$$

$$\text{then, } x = \frac{R_o}{2}\left\{\frac{k-1}{k+1}\right\}; \text{ and}$$

$$y = R_o\left\{\frac{2k}{k^2-1}\right\}.$$

Example :—Design a single H-type attenuator to give a loss of 20 db. Given $R_o = 600$-ohms.

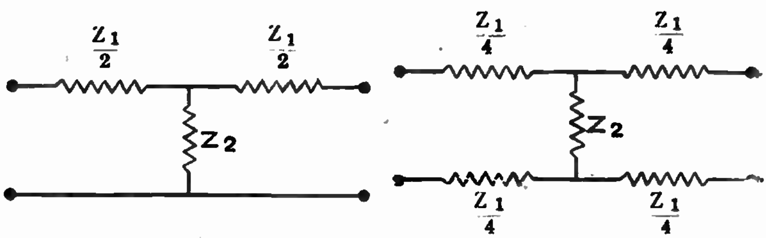
Solution :—

$$20 \log \frac{V_i}{V_o} = 20 \therefore k = 10 \quad (\because k = \frac{V_i}{V_o})$$

$$\therefore x = \frac{600}{2}\left\{\frac{10-1}{10+1}\right\} = 300 \times \frac{9}{11} = 245\text{-ohms},$$

$$\text{and } y = 600 \times \frac{20}{99} = 121\text{-ohms.}$$

The following table gives data for designing either of the above two types with the notation in Figs. 3.26 (a) and (b), having $R_o = 200$, 500, or 600-ohms and for a db-loss ranging from 1 to 165 db, in steps of 1 db.



(a) T-type attenuator (b) H-type attenuator

Fig. 3.26

Table 18.

Attenuation in db	200-ohm line		500-ohm line		600-ohm line	
	Z_1	Z_2	Z_1	Z_2	Z_1	Z_2
1	22.6	1760.0	56.5	4400.0	67.95	5280.0
2	46.0	858.0	115.0	2145.0	138.0	2575.0
3	68.0	571.0	170.0	1427.5	204.0	1714.0
4	89.9	422.0	224.75	1055.0	269.7	1266.0
5	112.0	328.0	280.0	820.0	336.5	986.0
10	207.5	140.6	518.75	351.5	624.0	421.0
20	327.0	40.4	817.5	101.0	982.0	121.4
30	380.0	13.5	950.0	33.75	1140.0	40.5
40	396.0	2.0	990.0	5.0	1180.0	6.0
50	400.0	1.274	1000.0	3.185	1200.0	3.822

To determine the values of Z_1 and Z_2 for a line of any other impedance, we have to multiply the values given for a 200-ohm line by the ratio of the desired impedance of the new line to the 200-ohm impedance, *e.g.*, 500-ohm line values are only $\frac{500}{200}$ (= 2.5) times the 200-ohm-line values.

In actual design, values of resistance to the nearest ohm, or 5-, or 10-ohms only are used, for the sake of convenience in construction.

(c) The Ladder Attenuator.

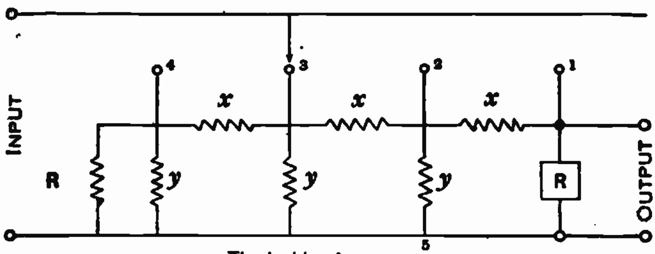
For both AF-, and RF- testing gear, an attenuator, simple in design but quick and easy in operation, and cheap in production, is required, even if it does not maintain perfectly constant resistance when the rotating switch arm is near one of its ends. Such an attenuator is called the 'ladder attenuator', which is made up of a series of inverted-'L' sections (Γ) or their reflections (˥), so designed as to offer a constant resistance to one end only. Its chief field of use is in the output circuit of the standard signal generators, where perfect matching is not important. Its great advantage is the cheapness in manufacture.

Consider Fig. 3.27, which represents a typical ladder attenuator widely used in radio work. It consists of a series of inverted-L sections.

On the following assumptions, its design will be considered :—

that (1) the source impedance = load impedance,

and (2) viewed from the input terminals, the impedance is constant.



The Ladder Attenuator

Fig. 3.27

If the source and load resistances (R_s and R_L) are equal and denoted by R, and $k = \frac{V_i}{V_o}$,

$$\text{then, } x = R\,(k - 1);$$

$$\text{and, } y = R\left\{\frac{k}{k-1}\right\}.$$

R_i is called the surge, characteristic, or iterative resistance, since it is equivalent to having an infinite number of sections towards the left.

$$R_i = k\,R.$$

Consider the following typical example taken from Scroggie.[42]

Assume: (1) $R_s = R_L = R =$ 10-ohms, and (2) each step is to give 5 db attenuation.

Then, $20 \log \frac{V_i}{V_o} = 5$; or, $\log \frac{V_i}{V_o} = 0.25$

$$\therefore \frac{V_i}{V_o} = \text{antilog of } 0.25$$

i.e., $\frac{V_i}{V_o} = 10^{0.25} = 1.778$ $\qquad \therefore k = 1.778$

$x = 10\,(1.778 - 1) = 7.78$-ohms;

$y = 10\,\frac{(1.778)}{(0.778)} = 23$-ohms;

$R_i = 1.778 \times 10 = 17.78$-ohms.

R_i and y are in parallel and their effective resistance:

$\left\{\frac{17.78 \times 23}{17.78 + 23}\right\} = 10$-ohms, is in series with x, making a total resistance of $10 + 7.78 = 17.78$, which is the value of R_i. Thus, R_i and the first stage (Γ) consisting of y and x have the same value as R_i, and can be proved to hold good for any number of (Γ) stages.

Consider the effective resistance between terminals 1 and 5. $R_L = 10$ and this, in series with x (between terminals 1 and 2) = 7.78, comes to 17.78. This value is in parallel with a resistance of 23-ohms between studs 2 and 5, giving again an effective resistance of 10-ohms $\left(= \frac{17.78 \times 23}{17.78 + 23}\right)$.

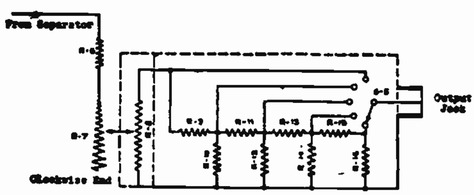
Thus, the resistance through all the paths from any stud to which the source may be connected is 17.78-ohms in parallel with either 10 or 6.4-ohms, which, though not equal to 10, is at least constant for all positions of the switch.

By working from the load-end, it can be easily verified that the attenuation per stage is 5 db.

The output resistances on the various studs are :—

6.4-ohms on stud No. (1),
12.75 „ „ „ (2),
and 16 .0 „ „ „ (3), tending to 17.78-ohms at an infinite number of studs away.

Fig. 3.28 shows the elements and complete circuit of a common ladder attenuator—the G. R. Company's (USA) Standard Signal Generator Model No. 605-B.



(By courtesy of General Radio Coy., USA)
Fig. 3.28

Table 19.

List of values of the elements in the network :—

(1) $R_6 = 450$-ohms.	(5) $R_{11} = R_{13} = R_{15} = 99$-ohms.
(2) $R_7 = 50$ „	(6) $R_{12} = R_{14} = 12.2$ „
(3) $R_8 = R_9 = 95$ „	(7) $R_{16} = 11$ „
(4) $R_{10} = 11.7$ „	(8) $R_{34} = 500$ „

This is a four-section ladder network designed to attenuate in 4 steps, with a ratio of 10 to 1 between steps.

The output impedance of the signal generator is independent of the microvolts-dial setting and constant at 10-ohms, (with the exception of the last step), from 10,000 to 100,000 μV (position of the multiplier = × 1), where the impedance is 50-ohms. This information is summarised in the table below :

Table 20.

Position of the stud	Multiplier value	Range	Internal output Impedance in ohms
1	1	0 - 10 μV	10
2	10	10 - 100 μV	10
3	100	100 - 1,000 μV	10
4	1,000	1,000 - 10,000 μV	10
5	10,000	10,000 - 100,000 μV	50
1 volt output (Jack B)			500

16. EQUALIZERS AND FILTERS.

(1) **Application.** The decibel notation is used in connection with equalizers and filters in plotting the attenuation *versus* frequency curves. The unit of attenuation is the decibel.

(2) **Equalizers.** Certain types of filters, called equalizers, are used to compensate for the non-linearity in a transmission line, *e.g.*, the HF response of a programme line or a similar circuit—(vide Fig. 3.29).

Line Equalizer

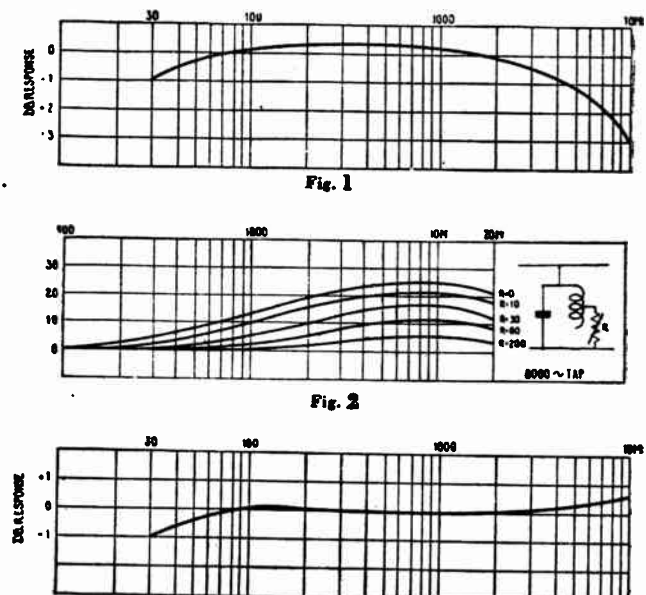


Fig. 3.29. (By courtesy of the Thordarson Elec. Mfg. Coy. USA)

Figs. 1, 2 and 3 in Fig. 3.29 show (1) the response of a transmission line, (2) the response of a line equalizer, and (3) the combined response of the line with the equalizer. By comparing the top and bottom curves, the effect of the equalizer in flattening the response between 100 and 2,000 cps, and raising substantially the drooping characteristic of the top curve between 2,000 and 10,000 cps, is evident.

(3) **Filters.** An electric wave filter is a corrective device to alter the transmission characteristic of a communication system. Wave filters, by virtue of their superiority over tuned circuits, have, of recent years, been widely used in all branches of communication engineering for separating electric waves characterized by a difference in frequency. An ideal, dissipationless filter, when connected in a circuit, should introduce zero attenuation in the pass-band and very high attenuation in the stop-band.

The total transmission loss, when a filter is introduced in a circuit, is composed of the following :—

(1) L_t = transfer loss;

(2) L_a, L_b = terminal losses;

(3) L_r = the interaction loss.

Thus, if L_T denotes the total transmission loss, then, $L_T = L_t + L_a + L_b + L_r$; and the relative importance of these losses is in the order given.

Zobel[43] remarks thus on these losses :

'As a first approximation the transmission loss of a composite filter is given by the transfer loss L_t, but the error due to the omission of the other losses is often considerable. A second approximation is obtained by including the terminal losses L_a and L_b, and for many purposes this is sufficiently accurate. The final step for accuracy is the further addition of the interaction loss L_r, whose effect on the total transmission loss is usually appreciable in the transmission band of a wave filter near the cut-off frequencies'.

Thus, of these three losses, transfer loss is by far the biggest, while items (2) and (3) may be even "gain" (negative losses), at certain frequencies, but it is usual practice to neglect (2) and (3) in comparison with (1), except at the cut-off frequencies. In the portion of the transmitting range where the terminating impedances match or nearly match the impedance of the filter terminal and interaction effects may be neglected. In the attenuating range of the filter, the interaction factor drops out quickly as the attenuation increases. As remarked already, the reflection effect may be a transmission gain, but this gain never exceeds a maximum of 3 db at each end of the filter. At those frequencies where the image impedances of the filter are either small or large as compared with the terminating impedances, the reflection effect does provide an extra loss. Calculation of terminal and interaction losses, is very laborious.

(4) **Kinds of Filters.** Filters are of 4 kinds and are defined as follows :

(i) Low-pass filter, which introduces negligible attenuation at all frequencies below a certain frequency, called the cut-off frequency, and relatively large attenuation at all higher frequencies.

(ii) High-pass filter, which introduces negligible attenuation at all frequencies above a certain frequency, called the cut-off frequency, and relatively large attenuation at all lower frequencies.

(iii) Band-pass filter, which introduces negligible attenuation at all frequencies within the range between two frequencies, and relatively large attenuation at all other frequencies.

(iv) Band-rejection filter, which introduces negligible attenuation at all frequencies outside a certain range, and relatively large attenuation at all frequencies inside that range.

The normal filter characteristics are obtained only when the filter is properly terminated in its characteristic impedance.

Fig. 3.30 (a) : is the attenuation curve of a 400 cps LP-filter for maximum attenuation of 75 db at 800 cps (2nd harmonic), for use on a 500-ohm line.

Fig. 3.30 (b) : is the attenuation curve of a 80 cps HP-filter for maximum attenuation of 40 db at 60 cps, for use on a 500-ohm line.

Fig. 3.30 (c) : is the attenuation curve of a 1,020 cps band rejection filter (for aircraft or other applications where it is desired to eliminate a 1,020 cps signal and still allow speech passage), for use on a 500-ohm line.

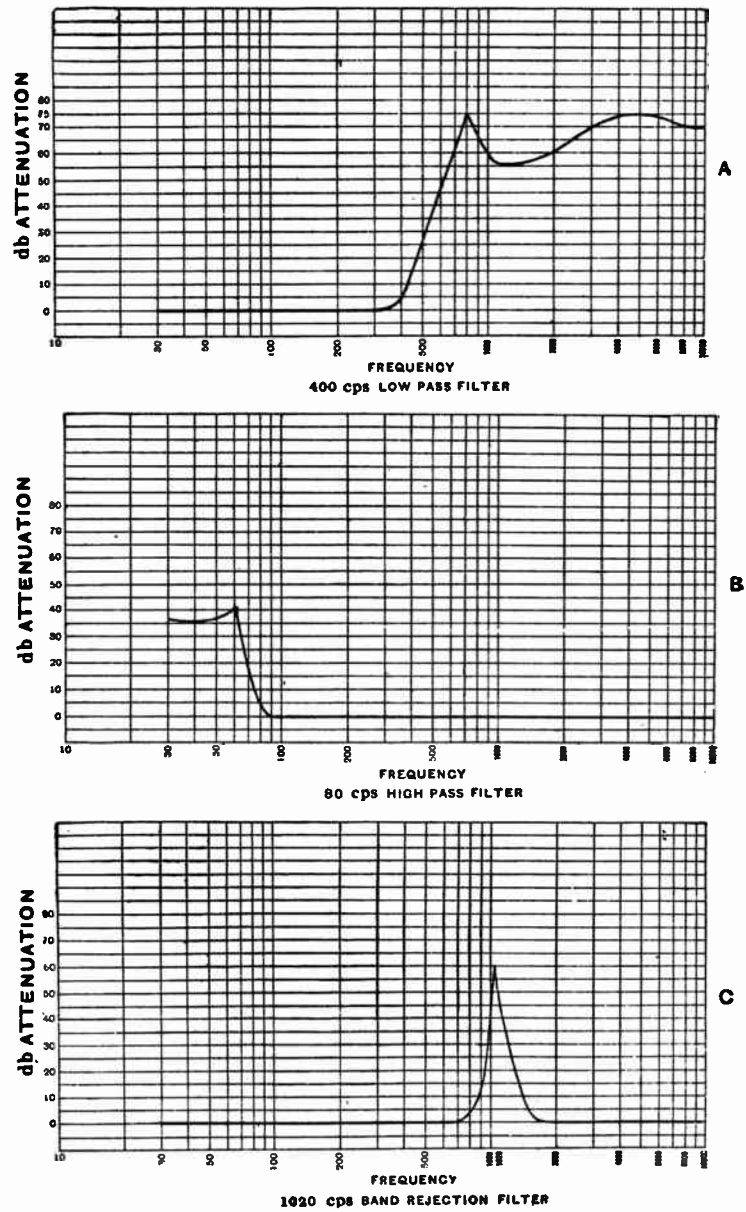


Fig. 3.30

(The above graphs are reproduced in a modified form from Thordarson Elec. Mfg. Coy.'s Catalogue.)

(5) **Methods of Obtaining Attenuation Curves of a Filter.** There are two standard methods of obtaining data for the attenuation-frequency curve of a filter : calculated, and experimental. These will be described presently.

Philips' Technical Review[44] gives complete formulae and graphs for evaluating the data for the attenuation curves of the low-, high-, and band-pass filters. The reader will find detailed information on the subject in Terman[45], Starr[46], Guillemin[47], Shea[48], and Johnson[49].

(i) The Composite Filter.

Detailed treatment for evaluating theoretically and obtaining practically, the attenuation (in db) versus frequency curve of a composite, band-pass filter, which the author designed, constructed and tested, is given below as a typical example[50].

The composite band pass filter is composed of a single constant- k, m $_{\pi}$ derived section divided into two end-halves (Fig. 3.32 (a)), with one mid-shunt derived half section (Fig. 3.32 (b)). The complete filter is shown in Fig. 3.31 and the values of the elements are given below this figure.

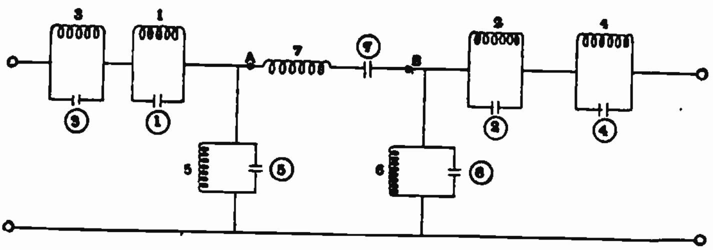
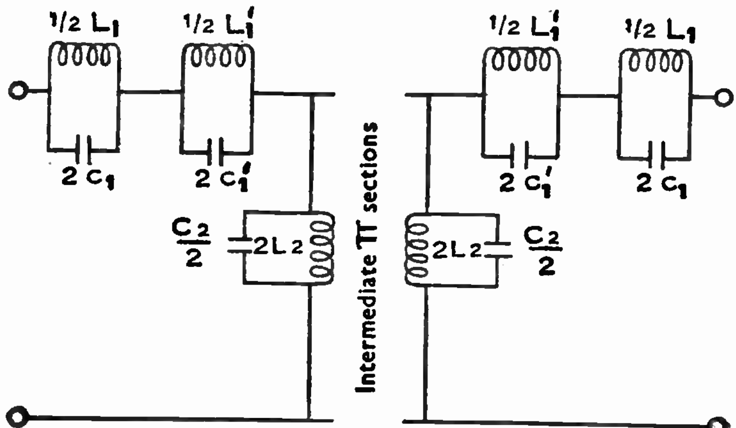


Fig. 3.31. A Composite Band-Pass filter.

Calculated values of the filter elements shown in Fig. 3.31 for $f_1 = 30$ kcs; $f_2 = 40$ kcs; and R = 1,000 ohms, are tabulated below.

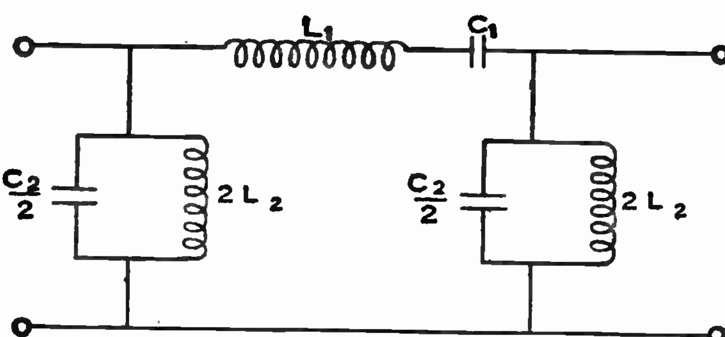
Table 21.

No. on diagram	Inductances (L) Value	No. on diagram	Condensers (C) Value
1.	0.5115 mH	(1)	0.0288 μF
2.	,, ,,	(2.)	,, ,,
3.	0.733 ,,	(3.)	0.04124 ,,
4.	,, ,,	(4.)	,, ,,
5.	0.8287 ,,	(5.)	0.02546 ,,
6.	,, ,,	(6.)	,, ,,
7.	31.83 ,,	(7.)	0.0006631 ,,



End-half sections

Fig. 3.32 (a)



Intermediate section (TT TYPE) Constant – K,m – derived

Fig. 3.32 (b)

Two methods of obtaining the data for attenuation-frequency curve are described below.

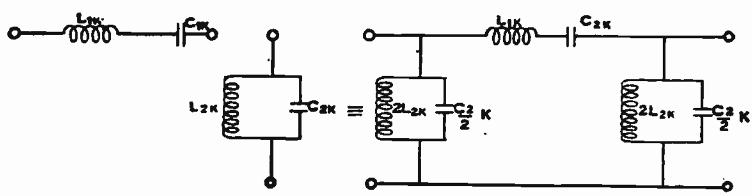
(ii) Method I: Theoretically calculated values.

Calculations were confined to transfer loss only, though this is to a first approximation, leaving aside the other two losses (terminal losses and interaction losses). The transfer loss is given by the attenuation function (α), the real part of the propagation function; $\lambda = \alpha + j\beta$, where α. β and λ, are the attenuation, phase shift, and propagation constants respectively.

The overall attenuation of the composite filter is the sum of the attenuations of the individual sections: $\alpha = \sum \alpha_1$, where α is the overall attenuation and α_1, α_2, α_3, etc.; are the attenuations of the individual sections. If λ_{1k} denotes the attenuation of a constant-k section, and λ_{1km} denotes the attenuation of the constant-k, m-derived section, then the attenuation function of the composite filter is (λ_{1k} + λ_{1km}). Figs. (a) and (b) in Fig. 3.33 represent the two sections of the filter.

The method of calculating the attenuation function of these two filter sections is as follows :—

(i) Constant- k type BP filter :—



(a) Fig. 3.33 (b)

If Z_1 and Z_2 are inverse networks with respect to any value of resistance R, then $Z_1 Z_2 = R^2$, and it follows that :

$$\frac{L_1}{C_2} = \frac{L_2}{C_1} = R^2.$$

Following the standard notation in filter-theory, we get :

$$\frac{Z_1}{4Z_2} = -\frac{\left(\frac{f}{f_m} - \frac{f_m}{f}\right)^2}{\left\{\left(\frac{f_2}{f_m}\right) - \left(\frac{f_m}{f_2}\right)\right\}^2},$$ for the non-dissipative case, (1)

and $$\frac{Z_1}{4Z_2} = \frac{\left[d_L \frac{f}{f_m} + j\left(\frac{f}{f_m} - \frac{f_m}{f}\right)\right]^2}{(1-j\,d_L)\left(\frac{f_2}{f_m} - \frac{f_m}{f_2}\right)^2},$$ for the case with dissipation in coils alone. (2)

(ii) Constant k, double m π transformation :—

This is of the configuration shown below.

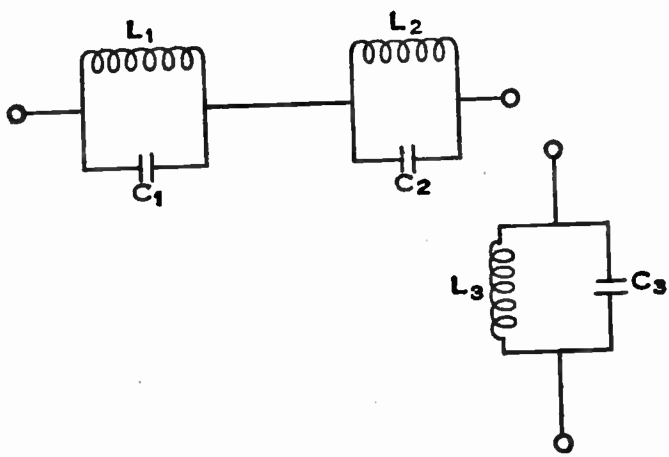


Fig. 3.34

But the attenuation function for this is the sum of the attenuation functions of the following two simpler sections.

(i) Type IV.3 (ii) Type IV.4

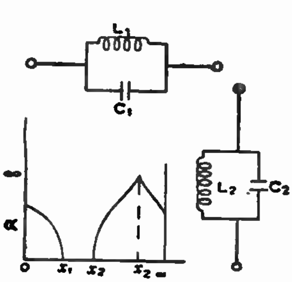


Fig. 3.35

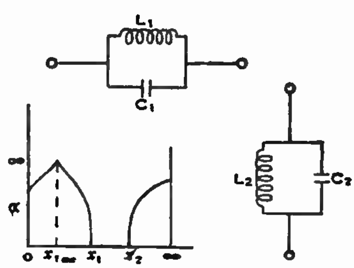


Fig. 3.36

$x_1 = \frac{f_1}{f_m}$; $x_2 = \frac{f_2}{f_m}$; $x_{1\infty} = \frac{f_{1\infty}}{f_m}$, $x_{2\infty} = \frac{f_{2\infty}}{f_m}$.

(i) for type IV_3

(without dissipation in filter elements),

$$Z_1/4Z_2 = \frac{\left[\left\{\left(\frac{f_2}{f_m}\right)^2 - \left(\frac{f_{2\infty}}{f_m}\right)^2\right\}\left\{\left(\frac{f}{f_m}\right)^2 - \left(\frac{f_1}{f_m}\right)^2\right\}\right]}{\left[\left\{\left(\frac{f_2}{f_m}\right)^2 - \left(\frac{f_1}{f_m}\right)^2\right\}\left\{\left(\frac{f_{2\infty}}{f_m}\right)^2 - \left(\frac{f}{f_m}\right)^2\right\}\right]}; \quad (3)$$

and with dissipation in coils alone,

$$\frac{Z_1}{4Z_2} = \frac{\left\{\left(\frac{f_2}{f_m}\right)^2 - \left(\frac{f_{2\infty}}{f_m}\right)^2\right\}\left[\left\{\left(\frac{f}{f_m}\right)^2 (1-j\,d_L)\right\} - \left(\frac{f_1}{f_m}\right)^2\right]}{\left\{\left(\frac{f_2}{f_m}\right)^2 - \left(\frac{f_1}{f_m}\right)^2\right\}\left[\left(\frac{f_{2\infty}}{f_m}\right)^2 - \left\{\left(\frac{f}{f_m}\right)^2 (1-j\,d_L)\right\}\right]}. \quad (4)$$

(ii) for type IV_4

(without dissipation in filter elements),

$$\frac{Z_1}{4Z_2} = \frac{\left\{\left(\frac{f_1}{f_m}\right)^2 - \left(\frac{f_{1\infty}}{f_m}\right)^2\right\}\left\{\left(\frac{f}{f_m}\right)^2 - \left(\frac{f_2}{f_m}\right)^2\right\}}{\left\{\left(\frac{f_1}{f_m}\right)^2 - \left(\frac{f_2}{f_m}\right)^2\right\}\left\{\left(\frac{f_{1\infty}}{f_m}\right)^2 - \left(\frac{f}{f_m}\right)^2\right\}}; \quad (5)$$

and with dissipation in coils alone,

$$\frac{Z_1}{4Z_2} = \frac{\left\{\left(\frac{f_1}{f_m}\right)^2 - \left(\frac{f_{1\infty}}{f_m}\right)^2\right\}\left[\left\{\left(\frac{f}{f_m}\right)^2 (1-j\,d_L)\right\} - \left(\frac{f_2}{f_m}\right)^2\right]}{\left\{\left(\frac{f_1}{f_m}\right)^2 - \left(\frac{f_2}{f_m}\right)^2\right\}\left[\left\{\left(\frac{f_{1\infty}}{f_m}\right)^2 - \left(\frac{f}{f_m}\right)^2 (1-j\,d_L)\right\}\right]}. \quad (6)$$

Each one of these expressions : (1) to (6) above, have been evaluated and the modulus and argument of $Z_1/4Z_2$ have been found in the form $A\,\underline{/\theta}$ for different frequencies. The value of the attenuation constant α, in nepers, corresponding to $A\,\underline{/\theta}$, was taken from the curves given by Shea[48], and α, corresponding to equations 1, 3 and 5 added up, gives the total attenuation in nepers for the dissipationless case—vide Table 22. Again, α, corresponding to equations 2, 4 and 6 added up, gives the total attenuation in nepers for the filter with coil dissipation case—vide Tables 23 (a) and (b). Then this total attenuation is converted into db by multiplying nepers by the constant 8.686.

It is more for theoretical interest than practical utility that the attenuation in the dissipationless case was considered. The total loss in db for the dissipationless case (values in column (9)) are obtained by adding the values in columns (4), (6), and (8) of Table 22.

It was considered unnecessary to include here all the steps involved in evaluating functions (1) to (6) but a sample calculation is given below.

Data :—

f_1 and f_2 are the band-pass frequencies,

$$f_m = \text{mid-frequency} = \sqrt{f_1 f_2}\,;\ d = \frac{1}{Q} = \frac{R}{wL}.$$

The average Q for the 7 coils in the filter designed was found to be 40.

$$\therefore\quad d = \frac{1}{40} = 0.025$$

$$f_1 = 30 \text{ kcs}, \qquad f_2 = 40 \text{ kcs}, \qquad f_m = 34.64 \text{ kcs}.$$

$$f_{1\infty} = 28.96 \text{ kcs, and } f_{2\infty} = 41.45 \text{ kcs}.$$

$$\frac{f_1}{f_m} = \frac{30}{34.64} = 0.866\,;\ \frac{f_2}{f_m} = \frac{40}{34.64} = 1.154.$$

$$\therefore\quad \left(\frac{f_1}{f_m}\right)^2 = x_1^2 = 0.7499\,;\ \left(\frac{f_2}{f_m}\right)^2 = x_2^2 = 1.332.$$

$$(x_{1\infty})^2 = \left(\frac{f_{1\infty}}{f_m}\right)^2 = (0.836)^2 = 0.6988\,;$$

$$(x_{2\infty})^2 = \left(\frac{f_{2\infty}}{f_m}\right)^2 = (1.201)^2 = 1.432.$$

$$(1-jd)\left(\frac{f_2}{f_m} - \frac{f_m}{f_2}\right)^2 = (1-j\,0.025)\,(1.154-0.866)^2$$

$$= (0.08294 - j\,0.0020735) = 0.08316\ \backslash 1°26'$$

$$\frac{\left\{\left(\frac{f_2}{f_m}\right)^2 - \left(\frac{f_{2\infty}}{f_m}\right)^2\right\}}{\left\{\left(\frac{f_2}{f_m}\right)^2 - \left(\frac{f_1}{f_m}\right)^2\right\}} = \frac{1.332 - 1.432}{1.332 - 0.7499} = -0.1718$$

$$\frac{\left\{\left(\frac{f_1}{f_m}\right)^2 - \left(\frac{f_{1\infty}}{f_m}\right)^2\right\}}{\left\{\left(\frac{f_1}{f_m}\right)^2 - \left(\frac{f_2}{f_m}\right)^2\right\}} = \frac{0.7499 - 0.6988}{0.7499 - 1.332} = -0.08778$$

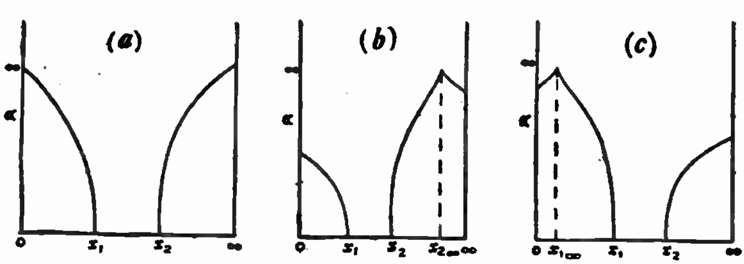
(a) Attenuation constant in db for a filter with elements of no losses. Table 22 below gives the required data.

Table 22.

No.	f (kcs)	Equation (1)		Equation (3)		Equation (5)		Total attenuation in db
		$Z_1/4Z_2$	db	$Z_1/4Z_2$	db	$Z_1/4Z_2$	db	Col.(4)+(6)+(8)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	20	−16.07	35.79	+0.0651	4.43	0.2397	8.164	43.384
2	28	− 2.26	16.50	+0.02119	2.519	1.311	17.02	36.04
3	28.96					∞	∞	∞
4	29	−1.544	11.9	0.01149	1.911	−27.69	40.83	54.64
5	30	−1.0	0	0	0	−1.00	0	0.0
6	31	−0.5998	„	between O & −1	„	between O & −1	„	„
7	32	−0.3692	„		„		„	„
8	33	−0.1144	„		„		„	„
9	34	−0.01694	„		„		„	„
10	35	+0.00497	„		„		„	„
11	36	+0.07278	„		„		„	„
12	37	+0.2091	„		„		„	„
13	38	+0.4145	„		„		„	„
14	39	+0.6817	„		„		„	„
15	40	+1.0	„	−1	„	O	„	„
16	41	+1.387	10.25	−3.493	23.89	.008547	1.65	35.79
17	41.45			∞	∞			∞
18	42	+1.816	14.07	3.253	23.45	.01569	2.301	39.82

We see in the above table the fundamental relationship in elementary filter theory, *viz.*,

$$-1 < \frac{Z_1}{4Z_2} < 0$$



Constant-k Basic Type Type IV_3 Type IV_4

m_{π} transformation.

Fig. 3.36

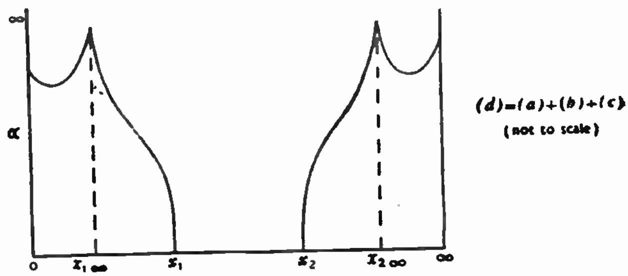


Fig. 3.37

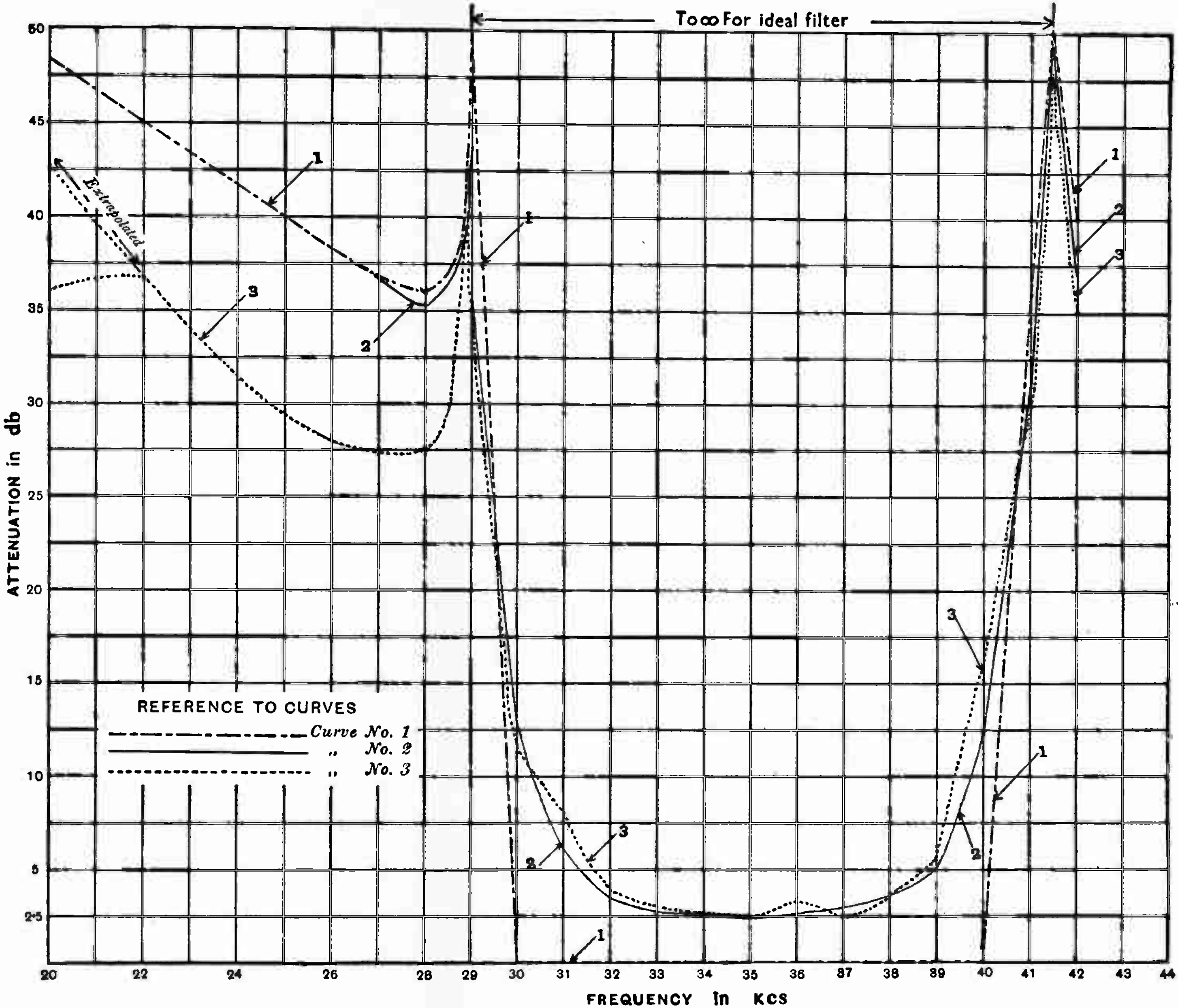
Attenuation characteristic of the composite filter (Fig. 3.37) = sum of the characteristics of (a), (b) and (c) of Fig. 3.36 above for a dissipationless filter.

(b) Attenuation constant in db for the filter with dissipation in coils only. Tables 23 (a) & (b) below give the required data.

Table 23 (a).

Values of $Z_1/4Z_2$

f kcs	Constant— k part		Double m π Type IV_3		Transformation Type IV_4	
	A	/θ	A	/θ	A	/θ
(1)	(2)	(3)	(4)	(5)	(6)	(7)
20	16·05	−180°	0·06469	0° 34′	0.2397	− 0°50′
28	2·215	−173° 10′	0·0215	8° 25′	1·234	− 18°25′
29	1·545	−171° 54′	0·0122	18° 22′	3·142	− 95°
30	1·003	−168° 46′	0·00472	88° 34′	0·9388	−158°
31	0·604	−167° 10′	0·01496	157° 50′	0·4482	−166° 44′
32	0·3745	−163° 40′	0·028	164° 4′	0·3052	−169° 5′
33	0·121	−152° 24′	0·05215	168° 24′	0·1777	−170° 45′
34	0·02415	−112° 10′	0·0787	170° 43′	0·1219	−171° 6′
35	0·01261	78° 52′	0·1138	171° 5′	0·08469	−170° 59′
36	0·08072	144° 26′	0·1614	170° 57′	0·05817	−169° 50′
37	0·2173	158° 31′	0·2305	170° 14′	0·0381	−167° 48′
38	0·4225	164° 34′	0·3376	168° 44′	0·02317	−163° 31½′
39	0·6895	167° 56′	0·5274	165° 37′	0·01003	−147° 43½′
40	1.007	169° 59′	0·9510	158° 18′	0·004609	− 88° 6′
41	1.395	171° 26′	2·394	128° 18′	0·00959	− 24° 16½′
42	1·822	172° 26′	2·344	41° 8′	0·01622	− 11° 73′



Attenuation – frequency Characteristic of a Composite BP Filter Obtained by three Different Methods

Table 23 (b).

f kcs	Attenuation in nepers			Total attenuation in nepers	Total attenuation in db
	Constant k	Type IV_3	Type IV_4		
(1)	(2)	(3)	(4)	(5)*	(6) †
20	4.12	0.50	0.94	5.57	48.39
28	1.9	0.28	1.88	4.06	35.265
29	1.4	0.22	2.5	4.12	35.79
30	0.61	0.10	0.76	1.47	12.76
31	0.275	0.05	0.38	0.705	6.124
32	0.23	0.05	0.12	0.40	3.474
33	0.185	0.045	0.08	0.31	2.693
34	0.18	0.055	0.07	0.305	2.65
35	0.16	0.06	0.06	0.28	2.43
36	0.18	0.078	0.05	0.308	2.675
37	0.20	0.11	0.04	0.35	3.04
38	0.24	0.14	0.045	0.425	3.692
39	0.28	0.27	0.05	0.60	5.212
40	0.57	0.76	0.10	1.43	12.42
41	1.24	2.18	0.20	3.62	31.45
42	1.64	2.37	0.24	4.25	36.92

* Col. (5) = columns (2) + (3) + (4).
† Col. (6) = 8.686 × col. (5).

(c) **Remarks on curves (1) & (2).**

The calculated curves for the dissipationless filter (curve No. 1), and for the filter with dissipation in coils alone (curve No. 2), are plotted on the same sheet—vide Fig. 3.38.

Curve No. 1 : This is the ideal filter curve, and the following facts are noticed from it :

1. it is seen that the attenuation in the pass-band is zero (as it should be), and also the attenuation is infinite at the two frequencies, $f_{1\infty}$ and $f_{2\infty}$ (= 28.96 and 41.45 kcs, respectively).

2. it is also seen that, to the left of $f_{1\infty}$ and to the right of f_{∞}, the curve has a 'U' shape, *i.e.*, from zero to $f_{1\infty}$ the attenuation, starting with a high value falls to a minimum (though high relative to the attenuation in the pass-band) at f = 28 kcs, and then rises to infinity at $f_{1\infty}$. Similar variation in the attenuation for the curve beyond $f_{2\infty}$ can be traced.

Curve No. 2.

This is also from the calculated values.

1. The first point to be remarked about this curve is that the attenuation in the pass-band is a few db as compared with 0 db in the same region for curve (1).

2. Also, due to dissipation in the coils at the cut-off points, the curve is rounded off, unlike the sharp corners of curve (1). Further it is seen that the sides of the curve around the cut-off frequencies are less steep than those of curve (1); *i.e.*, the fall (or rise) in attenuation on the approach of (or departure from) the pass-band is more gradual.

(3) In the attenuating band, it is noticed that the attenuation is less than that for the dissipationless filter, though there is the general resemblance in the shape of the two curves in this band.

4. Another important consequence of the coil dissipation is that at $f_{1\infty}$ and $f_{2\infty}$, the value of attenuation instead of being infinite, is finite, though high (about 50 db).

(iii) Method II: Experimental Method of Measuring the total Insertion Loss of a Filter in db.

(a) Set-up.

The Standard Signal generator could be put to good use by reading the filter attenuation directly on its decibel-calibration dial by using a circuit as shown below. This naturally does away with the decibel-attenuator, which might introduce two sources of error, *viz.*, (i) due to the change in its calibration, and (ii) that it may not be quite accurate for the frequencies in question.

The circuit used is shown below.

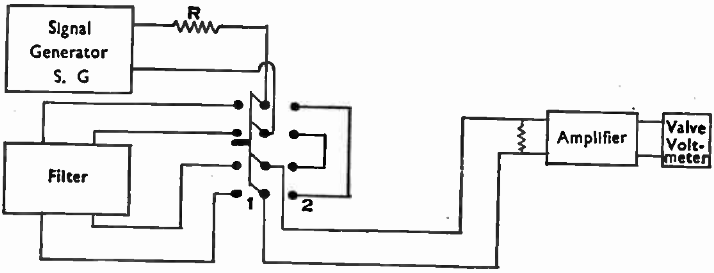


Fig. 3.39

(b) Method of Measurement.

In position 1 of the switch, the filter is connected to the signal generator on the input side, and to the amplifier and valve voltmeter on the output side. In position 2 of the switch the signal generator was directly connected to the voltmeter through the amplifier. Thus, if we choose a definite reading on the voltmeter and then note the readings on the signal generator for the two positions of the switch, when the valve voltmeter reads the same value, this provides a method of finding the insertion loss.

Actually, both the db-scale and the voltage-scale on the attenuator can be read for each frequency for the two positions of the 4-pole, double-throw switch. Thus, the following two sets of readings were obtained in an experiment. These should be identical, if the db-scale calibration could be correctly interpolated and read. But, actually, the divisions on the db-scale were rather too far apart and considerable judgment had to be used to read the db correctly by interpolation. The measurement covered a range from 20 to 42 kcs. This was considered sufficient, as the pass-band was 30 to 40 kcs only.

Table 24.

	Method 'A'				Method 'B'			
f kcs	Input mv V_1	Output mv V	20 log $\left(\frac{V_1}{V_2}\right)$	$\frac{V_2}{V_1}$	Zero rdg. (db)	Rdg. (db)	Loss in db.	$\frac{V_2}{V_1}$
20	520	8.2	36.04	.01577	78.4	114.2	35.8	.01622
22	610	8.85	36.77	.01451	78.8	115.5	36.7	.01462
24	345	9.1	31.58	.02637	79.2	110.8	31.6	.0263
26	225	9.0	27.96	.03999	79.0	106.5	27.5	.04217
28	222	9.48	27.42	.04256	79.5	106.4	26.9	.04519
29	530	9.8	34.662	.01686	79.8	114.5	34.7	.01841
30	38	10.0	11.6	.2631	80.0	91.6	11.6	.2630
31	25.5	10.0	8.13	.3922	80.0	88.2	8.2	.389
32	15.7	10.1	3.83	.6433	80.2	83.9	3.7	.653
33	14.6	10.3	3.03	.7053	80.3	83.4	3.1	.6998
34	13.9	10.25	2.65	.7374	80.2	83.0	2.8	.7244
35	14.2	10.7	2.46	.7536	80.4	83.1	2.7	.7328
36	15.7	10.8	3.25	.6879	80.6	84.0	3.4	.6761
37	17.2	12.9	2.5	.7501	82.2	84.7	2.5	.7499
38	16.8	11.1	3.6	.6607	80.9	84.6	3.7	.6531
39	21.8	11.3	5.7	.5183	81.0	86.7	5.7	.5188
40	73.0	11.5	15.9	.1575	81.2	97.4	16.2	.1549
41	365.0	11.6	29.96	.03178	81.2	111.2	30.0	.03162
42	661.0	11.65	35.1	.01763	81.2	116.4	35.2	.01738

The two methods 'A' and 'B', are essentially the same, the only difference being the greater accuracy to which the voltage scale on the signal generator can be read in method 'A' as compared with that of the db-scale in method B. Curve No. 3 in the graph (Fig. 3.38), shows curve obtained with method 'A' in the usual practice—attenuation in db vs. frequency. This gives a good idea of the steep cut-off at 30 and 40 kcs and we see that the minimum attenuation in the pass-range occurs at about 35 kcs (=2.46 db), which is, as it should be.

(c) Remarks on Curve No. 3.

The attenuation curve No. (3) consists of three distinct sections.

The very sharp rise in attenuation at the cut-off points is remarkable.

at f=29 kcs, α= 34.66 db; at f=30 kcs, α= 11.6 db;
,, f=41 kcs, α= 29.96 db; ,, f=40 kcs, α= 15.9 db.

1. This is the experimental curve and it agrees very closely with the curve (2), which means that the assumption, of the average value of "Q" of the coils = 40, made in calculating curve (2), is nearly correct.

2. It should be remarked here that there is this fundamental difference between curves (2) and (3)—the curve (2) is merely the attenuation-constant vs. frequency, while the curve (3) gives the total insertion loss due to the filter. The latter actually includes the attenuation-constant, and the reflection and interaction losses.

3. The close agreement between these two curves justifies our considering the reflection and interaction losses, as being of no moment in comparison with the attenuation-constant loss.

4. In curve (3), the shape of the curve between frequencies 20 and 22 kcs is peculiar, and the nature of the curve one would expect to get in this region is shown in dotted line.

5. The close similarity between the experimental curve (No. 3) and its corresponding theoretical curve (No. 2) is quite satisfactory. In particular, it is interesting to note that the minimum attenuation in the pass-band in these two curves is 2.46 db and 2.43 db respectively, both occurring at the same frequency (f = 35 kcs) which is as one would expect, since f_m = 34.64 kcs.

PART IV

APPENDICES

1. Types of Graphs in Radio & Acoustic Engineering.
2. Logarithmic Unit—Its Limitations.
3. The Standard Cable.
4. Logarithms and Log-Tables.

APPENDIX I

Types of Graphs in Radio and Acoustic Engineering.

(1) Graph Papers.

All graph papers can be classified under two heads:—

(1) Using cartesian co-ordinates: (a) X-axis or abscissa, (b) Y-axis or ordinate;

(2) Using polar co-ordinates: (a) molulus (r), and (b) angle θ — (vide Secs. 9 & 10 of Part III).

Both these types of graph paper are ed in radio and acoustic engineering, (as the reader will ·ve noticed in the preceding pages), the former type being much more widely used than the latter.

(2) Cartesian Co-ordinates Graph Paper.

Type (1) can again be broadly classified into the following groups from the point of view of the type of scale divisions on the two axes:

Table 1.

X-axis (abscissa).	Y-axis (ordinate)	Common nomenclature
(1) Linear	Linear	Ordinary.
(2) Linear	Logarithmic	Linear-log.
(3) Logarithmic	Linear	Log-linear.
(4) Logarithmic	Logarithmic	Double-log.

There is not much difference between types 2 and 3; if the graph sheet is rotated through 90°, the X-axis becomes the Y-axis and *vice-versa.* While in general engineering and mathematics type (1) is extensively used, types 2 and 3 are widely used in radio engineering and acoustics—*i.e.*, one axis is logarithmic, and the other axis linear. Usually, the X-axis will be the logarithmic, where a range of frequencies covering from, say, 10 to 10,000 cps (audio range) will be marked, and on the Y-axis, db-response to a linear scale will be plotted.

This is the well-known, 3-cycle, log-linear graph paper. 3 cycles referred to are the 3 octaves which the frequency scale covers: *viz.*,

Octave	Ratio
10 to 100 cps;	100|10 or 10: 1;
100 to 1,000 cps;	1,000|100 „ 10: 1;
1,000 to 10,000 cps;	10,000|1,000 „ 10: 1.

Therefore, the 3 cycles occupy equal spaces, for they denote the same (or equal) ratio of 10:1.

Since $\log_{10} O = -\infty$, O cannot be represented on the abscissa, the frequency scale, while it is still possible to denote zero on the ordinate scale.

(3) **Logarithmic Scale.**

(i) **Description:**

Logarithmic scale used for the abscissa to represent 3 cycles of frequency (10—100, 100—1,000, and 1,000—10,000 cps) in the usual response curves is calibrated thus (Fig. 4.1):

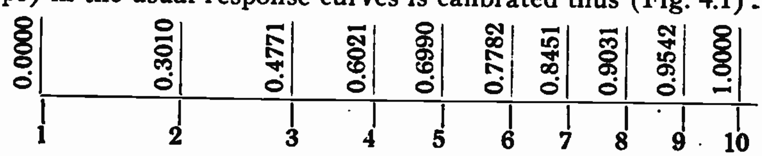


Fig. 4.1. Marking of Divisions on a Log-scale.

The logarithmic scale is made by taking some convenient length, as a unit of length, to represent one octave such as 10 to 100 cps. The space for each of the other two octaves, 100 to 1,000 and 1,000 to 10,000 cps, will also be equal to that for the first octave. Then, on the convenient unit length chosen, the following fractional lengths commencing from the left-end are marked off:

Table 2.

Log 1 = 0	Log 6 = 0.7782
Log 2 = 0.3010	Log 7 = 0.8451
Log 3 = 0.4771	Log 8 = 0.9031
Log 4 = 0.6021	Log 9 = 0.9542
Log 5 = 0.6990	Log 10 = 1.0

Since the mantissa parts of:

(1) 10, 100, 1,000 are the same,
(2) 20, 200, 2,000 „ „ „

(3)	30,	300,	3,000	are the same,
(4)	40,	400,	4,000	„ „ „
(5)	50,	500,	5,000	„ „ „
(6)	60,	600,	6,000	„ „ „
(7)	70,	700,	7,000	„ „ „
(8)	80,	800,	8,000	„ „ „
(9)	90,	900,	9,000	„ „ „
(10)	100,	1,000	10,000	„ „ „ ,

that explains why the spaces marked as 10, 20,....100 on one band, correspond to those marked 100, 200,....1,000, and 1,000, 2,000,....10,000, on the other two bands.

The number designating any one of these fractions is designated with the number having this particular fraction as its logarithm. Thus, after finding the length represented by $\log_{10} 2 = 0.3010$, the mark made on the X-axis at this point is designated 2 (and not log 2), and so on for other divisions. Fig. 4.1 shows such a scale with the logarithms of all integers from 1 to 10 properly marked off on it. In a 3-cycle, log-scale abscissa, the end-point of the first cycle, becomes the starting-point of the second cycle, and the end-point of the second cycle becomes the starting-point of the third cycle. With this explanation the several, 3-cycle, log-linear response curves shown in this monograph will be clearly understood.

(ii) **Advantages:—**

A logarithmic scale has the following four advantages:—

(a) A very wide range of values (*e.g.*, 10 to 10,000 cps), which would normally require a very large space or necessitates the jointing of several linear graph papers, can be compressed into a very small space.

(b) By plotting data on a log-scale, we can easily note the peaks and troughs of the graph to enable drawing conclusions from data covering large ranges or periods of time for statistical purposes.

(c) In graphs like the selectivity curve of a radio receiver (Fig. 3.8 of Part III), the curve will be symmetrical, which will not be the case, were the results plotted on a linear scale.

(d) Certain curves which observe a logarithmic law, *e.g.*, given by the equation $y = \log_{10} x$, will be a straight line, which is easy to plot and extrapolate for obtaining further values, instead of drawing a complicated curve of varying curvature, which cannot be safely extrapolated. Adjoining Figs. 4.2 and 4.3 show the curve of the function $y = \log_{10} x$, when plotted on (a) log-linear and (b) plain graph papers.

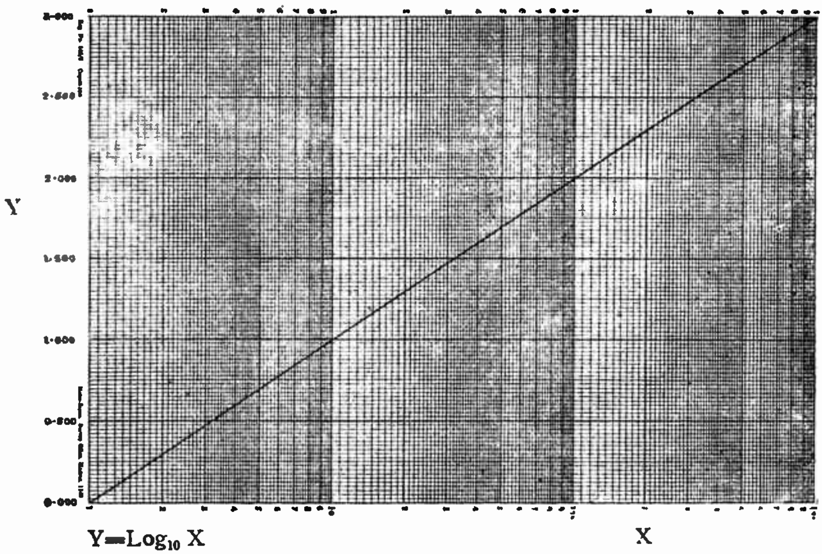


Fig. 4.2

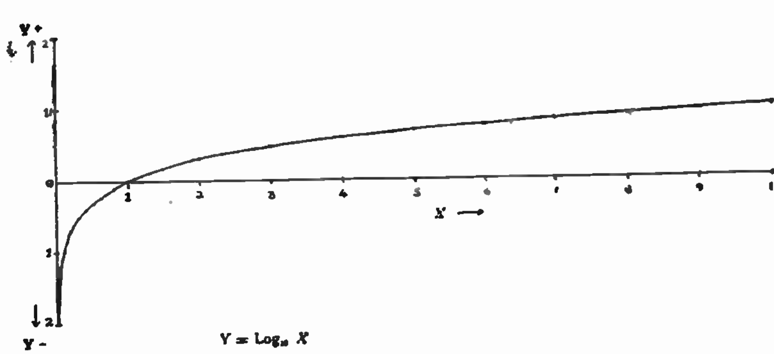


Fig. 4.3

The process of predicting the values of a function beyond the range of observation or available experimental data is called extrapolation. This process may be used cautiously for a short range beyond the known data but beyond that, extrapolation may lead to false inferences. This fear is entirely removed, if the graph is known to be a straight line, which will be the case when a logarithmic function is plotted on a log-linear graph paper.

(iii) **Disadvantages:—**

(a) Zero of the logarithmic scale is not accessible and hence negative values cannot be plotted.

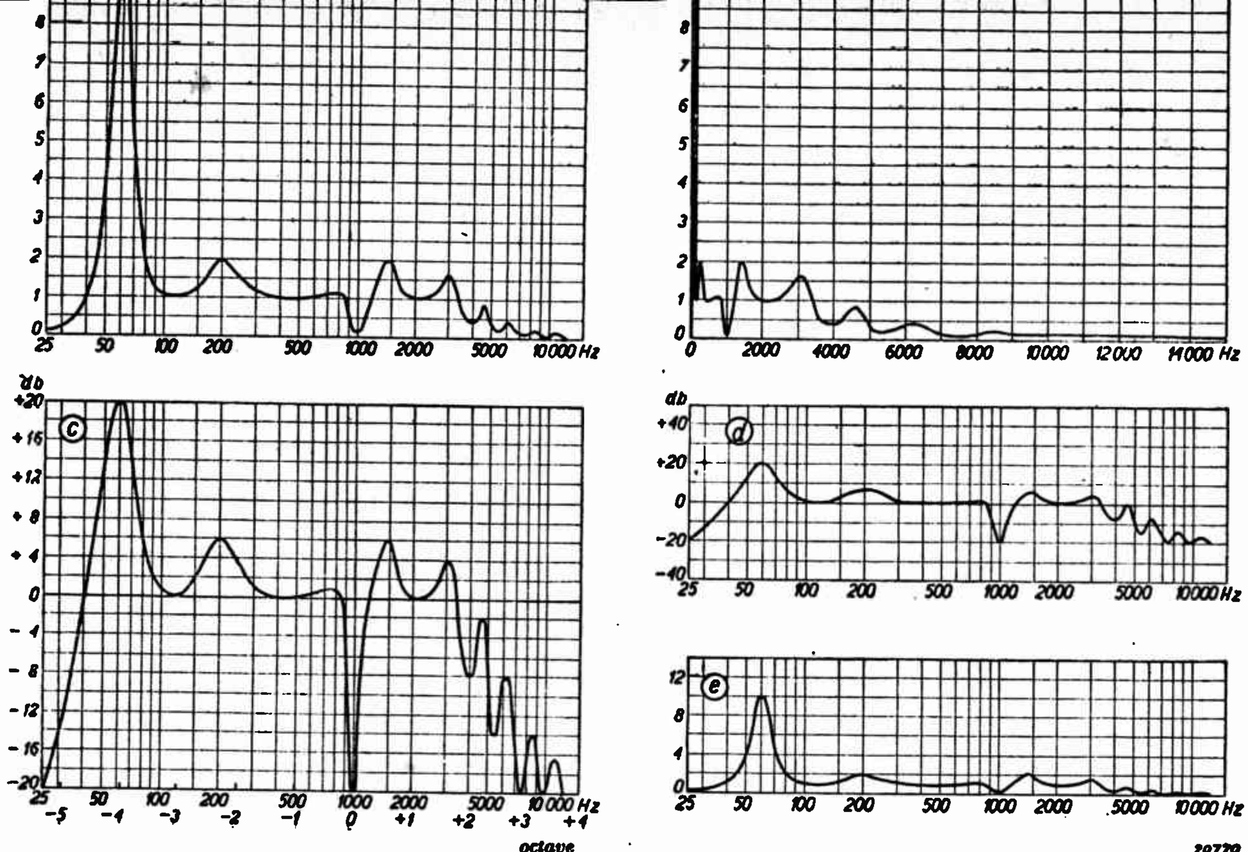
(b) Graph is compressed into a very small space and hence not of much use when only a small range of values is involved, *e.g.*, in the immediate vicinity of the resonance frequency, in a resonance curve. Hence a log-scale can be used only when a very large range of values is to be plotted on a graph sheet of reasonable dimension—(**c.f.** Figs. 4.2 and 4.3).

(c) Crests are reduced in size as compared with troughs.

(d) With a linear scale the numerical value of the intensity of a complex sound wave, equals the sum of the numerical values of its components. With a log-scale it is not so, though on this scale the total gain or attenuation can be computed directly by expressing the corresponding components in decibels and then adding them algebraically. In several cases in electroacoustics and communication engineering, this latter fact alone is so significant as to justify the choice of decibels or nepers (logarithmic units) plotted to a linear scale.

(4) **Comparison of Graphs with Linear and Logarithmic Scales:**

In order to bring out clearly the differences between the linear and logarithmic scales used for graphical representa-



(By courtesy of Philips Elec. Coy. (India) Ltd.)

tion, *The Philips' Technical Review*[51] gives the same characteristic, *viz.*, the variation of sound intensity of a loudspeaker, plotted in five different ways, as a function of frequency (X-axis). Details of these five graphs are given in Table 3.

Table 3.

Ref. to Fig. 4.4.	X and Y axes scales	Nomenclature
(a)	X-axis : log scale ; Y-axis : linear scale.	Log-linear.
(b)	X-axis : linear scale ; Y-axis : linear scale.	Ordinary.
(c)	X-axis : log scale ; Y-axis : db on linear scale.	Log-linear.
(d)	Same as for (c) but reduced scale on the Y-axis (db scale).	,,
(e)	Same as for (a) but reduced scale on the Y-axis.	,,

These five graphs are reproduced in Fig. 4.4. They also show the effect on the graph by reducing the scale on the linear axis (db scale). The following amplified inferences, mainly taken from the source cited above, can be drawn by comparing these graphs critically:—

(i) c.f. (a) and (b): On the X-axis, the log-scale, all octaves occupy equal spaces, while on the corresponding axis of (b), the band of frequencies below 1,000 cps, (the most important from the point of view of audibility), has been so much compressed as to obscure the results of this band, which now occupies an insignificant width. Again, the band between 5,000 to 15,000 cps (1½ octaves), occupies a disproportionately large part of the graph.

(ii) c.f. (a) and (b): The widths of the crests and troughs of the curves are equal on the log-scale of (a), where they are the same percentage fractions of the frequency. This gives a better idea of the damping of the different resonant frequencies which, under certain conditions, contribute to abnormalities.

(iii) c.f. (a) and (c): The linear intensity scale of (a) brings out the crest at 60 cps more prominently than the trough at 1,000 cps, while the amplitudes of the response on the logarithmic scale of (c), are of the same size.

(iv) c.f. (b) and (c): In (b) the curve beyond 5,000 cps is nearly flat on the absolutely linear scale, while the log-scale of curve (c) still shows very marked crests and troughs that will certainly influence the quality of the loudspeaker output.

(v) If the power input to the loudspeaker is reduced to, say, ¼ of the former power, then the response also reduces. This reduction will not influence the shape of the curve if a logarithmic scale is used, the only effect being an overall displacement of the curve downwards by 6 db ($=10 \log 0.25$). With a linear-intensity scale as in (a) and (e), the latter, with lower output, appears less distorted as compared with that of the former; and (e) also appears to be much smoother.

(vi) c.f. (a) and (c): In (c), by plotting log-response in db on the linear Y-axis, we find that the peaks appear less, and troughs more, than those in (a), where the linear Y-axis represents linear response. But, from the acoustic considerations (c) is to be preferred to (a), as the former represents in true proportion to the appreciation of the ear. The exact magnitude by which the crest (or trough) in (c) falls below (or goes beyond) that in (a), is governed entirely by the choice of unit of the scale: c.f. (c) and (e), where the log-scale of (c) shows greater irregularities; and c.f. (a) and (d), where, by plotting the log-response in db on the Y-axis, the crests seem to have become much smaller than in (a).

(vii) c.f. (c) and (d): Both these are log-linear graphs, with log-response plotted in db along the ordinate, but with the difference that the ordinate scale for (d) is ½ of that in (c), resulting in the marked irregularities brought out in (c) being fairly smoothened or shown considerably suppressed in (d).

(viii) From a general survey of the above curves, it is seen that the frequency and intensity range which can be covered conveniently in a single graph is practically unlimited when using a log-scale, while with a linear-scale one has to be limited to a ratio of 1: 10 (approximately)—vide Fig. 4.3.

(ix) Though it has been cited already under the disadvantages of a log-scale, (1) that zero is not available and (2) that negative values cannot be plotted, these are not serious defects since the ear itself, as stated in Part II of the text, has a definite threshold value. Hence a log-scale is eminently suitable for acoustic work.

In conclusion, for a response curve in communication and acoustic work, a log-linear graph paper, with frequencies 10 to 10,000 cps plotted on the logarithmic X-axis and response in db along the linear Y-axis, is the most suitable. The justification for using logarithmic scale for the abscissa is that it covers in a small space the frequencies 10 to 10,000 cps, and the fact that zero cannot be represented is no disadvantage, since practically the lowest audible frequency is between 20 and 50 cps and in most response curves, data below 30 or 50 cps will not be available (vide Fig. 2.1). As for the ordinate, because db is itself a logarithmic unit, we can plot it on a linear scale resulting in the graph being either a straight line or symmetrical curve, both of which are easy to plot. This also gives the following advantages: (1) that both + and — db (vide graph (c)) can be plotted; (2) that zero is available; and (3) the best representation of the crests and troughs is obtained. The position of 0 db solely depends on the arbitrarily chosen 'zero level' for the purpose in question. This explains the choice of this type of graph paper for the several response curves shown in this monograph.

APPENDIX II

Logarithmic Unit—Its Limitations.

It must be clearly understood that the logarithmic notation is not suitable for all classes of work in communication systems. Its limitations are as follows:

(1) It is of use only in calculating the gain or loss of a system whose noise level does not vary between very wide limits.

The meaning of this statement can be best understood by considering the following three cases:—

(a) An amplifier circuit may pick up considerable amount of noise, whereby the latter drowns the desired signal itself. Then, though the amplifier shows a large output apparently, it is not entirely due to the signal but largely due to the noise and, hence, the gain of the amplifier computed in db by the use of the usual formulæ, does not give the gain of the signal in which we are interested. In fact, due to overloading, the output of the amplifier may fall considerably. Whatever may be the result in db in such cases, whether an apparently high gain, moderate gain, or even loss, is of no interest.

(b) Actually, when an amplifier is overloaded, not only does its output drop but it leads to distortion also. Distortion can be best expressed as the rms value of the amplitudes of the voltages of the undesired frequencies, and it is usual to express this as a percentage of the amplitude of the fundamental frequency. Distortion cannot be adequately expressed in db; nor the loss expressed in db, *after the overload point is passed,* can have any significance.

(c) In the case of short waves, owing to fading the signal strength varies considerably from instant to instant. In such a case, it is not worthwhile to express, *e.g.,* the strength in db at any one moment, as this information is of no practical value, owing to the frequent variation of the input to the system and hence its lack of representative character.

(2) It is not convenient when dealing with electrical apparatus or machinery handling large amounts of power, as in heavy electrical engineering. For example, consider an electrical system, which receives 100 kW but delivers only 75 kW. Then, its efficiency $= \frac{\text{output}}{\text{input}} = 75\%$, the loss being ¼ of the input. If we express this in db notation, we get $10 \log \frac{75}{100} = -1.25$ db, which gives an impression of a very small loss while, actually, considerable amount of power (25 kW), ¼ of the input power, is being wasted away!

(3) As most communication circuits (*e.g.*, a wireless transmitting circuit, from the microphone to the ærial) are a combination of both high and low power apparatus, having variable noise level, the logarithmic notation should be used with great discretion and rejected as unsuitable whenever it is likely to give false ideas.

The db-notation is useful only for judging those facts or results which are judged by our senses, since these senses respond to a logarithmic (The Weber-Fechner) law. But, all the other results, which are judged only by direct mental processes, will have to be expressed in the direct-proportion law instead of the logarithmic law, as it is a fact that we are mentally accustomed to compare directly, viewing arithmetical differences instead of ratios, in our daily calculations of several physical quantities like: length, mass, time, etc. Therefore, all comparisons by mind, if expressed in the db-notation, will generally lead to wrong appreciation or incorrect conclusions.

APPENDIX III

The Standard Cable.

The standard cable is defined by the British Standards Institution[52] thus:

"An arbitrary uniform line in terms of which the attenuation of a line or network at a particular frequency may be specified."

The standard cable formerly used in Great Britain has been defined on page 10, Part I of this monograph, and the conversion constants of the British m.s.c. and other modern transmission units, like neper and decibel, have been given already in Table 4, Part I.

The standard cable formerly used for telephone measurements in America, had the following constants per loop mile.

Resistance:	88 ohms
Capacitance:	0.054 microfarad
Inductance:	Nil
Leakance:	Nil

It will be seen that the only difference between the British m.s.c. and the American m.s.c. is that in the latter both inductance and leakance are ignored, while in the former these two constants are 1 millihenry and 1 micromho respectively. The conversion constants of the American m.s.c. and other modern transmission units are tabulated below for reference (c.f. Table 4, Part I).

Table 4.

Multiply	By	To get
(1) Decibels	1.056	m.s.c.
(2) m.s.c.	0.947	Decibels
(3) Nepers	9.175	m.s.c.
(4) m.s.c.	0.109	Nepers

In general, the decibel is the modern unit widely used in Great Britain and America, superseding both the British and American standard cables. Neper is used in certain countries on the continent of Europe and by the C.C.I.T. (Comité Consultatif International Téléphonique) only. There is also a unit, one tenth of a neper, called the decineper (abbreviated: dn), which is very rarely used.

APPENDIX IV

Logarithms and Log-Tables

(1) Bases of Logarithms.

As stated in Part I, there are two sets of logarithms in vogue:

(1) The Naperian system with 'e' as base, where $e = 2.718281828....$,

and (2) The Briggsian System with 10 as base.

In the Naperian or 'natural logarithms', the logarithm of a number N is x, if $e^x = N$, while in the Briggsian or 'Common logarithms', the logarithm of a number N is x, if $10^x = N$.

Naperian system logarithmic tables, *i.e.*, $\log_e N$, will be found useful in calculating Nepers (vide Sec. 4 of Part I) directly, while the common logarithms will be useful in all decibel calculations directly.

(2) Laws of Logarithms.

Irrespective of the base, it is worthwhile to remember the following simple algebraic results, while doing calculations involving logarithms :

$$\log (a \times b) = (\log a + \log b).$$

$$\log \left\{\frac{a}{b}\right\} = \left(\log a - \log b\right).$$

$$\log \left\{a^{n}\right\} = \left(n \log a\right).$$

$$\log \left\{a^{(m/n)}\right\} = \left\{\frac{m}{n} (\log a)\right\}.$$

$$\log \left\{\sqrt[n]{a}\right\} = \left\{\frac{1}{n} (\log a)\right\}.$$

$$\log \left\{\sqrt[n]{a^{m}}\right\} = \left\{\frac{m}{n} (\log a)\right\}.$$

$$\log \left\{\sqrt[n]{\frac{a}{b} \times \frac{c}{d}}\right\} = \frac{1}{n} \Big\{ (\log a + \log c) - (\log b + \log d) \Big\}.$$

To find the natural logarithm from the common logarithm, it is useful to remember that :

$$\left(\log_e{}^x\right) = \left(\log_e{}^{10}\right) \times \left(\log_{10}{}^x\right)$$

$$= 2.3026 \times \log_{10}{}^x \quad (\because \log_e{}^{10} = 2.3026).$$

(3) Tables of Logarithms and Antilogarithms.

The following tables are included here for ready reference :

(1) Table of Natural Logarithms of Nos. from 1.00 to 10.00 (Table 5).

(2) Table of Common Logarithms (Table 6).

(3) Table of Antilogarithms (Table 7)

Table 5.

Natural Logarithms of Nos. 1 to 10

The base of natural Logarithms is $e = 2.718281828$

No.	Nat log.	No.	Nat log.	No.	Nat log.	No.	Nat log.	No.	Nat log.
1.00	0.0000	2.25	0.8109	3.50	1.2528	4 75	1.5581	6.00	1.7918
1.05	0.0488	2.30	0.8329	3.55	1.2669	4.80	1.5686	6.10	1.8083
1.10	0.0953	2.35	0.8544	3.60	1.2809	4.85	1.5790	6.20	1.8245
1.15	0.1398	2.40	0.8755	3.65	1.2947	4.90	1.5892	6.30	1.8405
1.20	0.1823	2.45	0.8961	3.70	1.3083	4.95	1.5994	6.40	1.8563
1.25	0.2231	2.50	0.9163	3.75	1.3218	5.00	1.6094	6.50	1.8718
1.30	0.2624	2.55	0.9361	3.80	1.3350	5.05	1.6194	6.60	1.8871
1.35	0.3001	2.60	0.9555	3.85	1.3481	5.10	1.6292	6.70	1.9021
1.40	0.3365	2.65	0.9746	3.90	1.3610	5.15	1.6390	6.80	1.9169
1.45	0.3716	2.70	0.9933	3.95	1.3737	5.20	1.6487	6.90	1.9315
1.50	0.4055	2.75	1.0116	4.00	1.3863	5.25	1.6582	7.00	1.9459
1.55	0.4383	2.80	1.0296	4.05	1.3987	5.30	1.6677	7.20	1.9741
1.60	0.4700	2.85	1.0473	4.10	1.4110	5.35	1.6771	7.40	2.0015
1.65	0.5008	2.90	1.0647	4.15	1.4231	5.40	1.6864	7.60	2.0281
1.70	0.5306	2.95	1.0818	4.20	1.4351	5.45	1.6956	7,80	2.0541
1.75	0.5596	3.00	1.0986	4.25	1.4469	5.50	1.7047	8.00	2.0794
1.80	0.5878	3.05	1.1151	4.30	1.4586	5.55	1.7138	8.20	2.1041
1.85	0.6152	3.10	1.1314	4.35	1.4701	5.60	1.7228	8,40	2.1282
1.90	0.6419	3.15	1.1474	4.40	1.4816	5.65	1.7317	8.60	2.1518
1.95	0.6678	3.20	1.1632	4.45	1.4929	5.70	1.7405	8.80	2.1748
2.00	0.6931	3.25	1.1787	4.50	1.5041	5.75	1.7492	9.00	2.1972
2.05	0.7178	3.30	1.1939	4.55	1.5151	5.80	1.7579	9.25	2.2246
2.10	0.7419	3.35	1.2090	4.60	1.5261	5.85	1.7664	9 50	2.2513
2.15	0.7655	3.40	1.2238	4.65	1.5369	5.90	1.7750	9.75	2.2773
2.20	0.7835	3.45	1.2384	4.70	1.5476	5.95	1.7834	10.00	2.3026

Tables of Common Logarithms and Antilogarithms (Tables 6 & 7)

Table 6.
Logarithms

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3858	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13

30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7

Logarithms—(*continued*)

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5

75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9352	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	4	4

Table 7.
Antilogarithms

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1	1	2	2	2
01	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1	1	2	2	2
02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1	1	2	2	2
03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1	1	2	2	2
04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1	2	2	2	2
05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1	2	2	2	2
06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1	2	2	2	2
07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1	2	2	2	2
08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1	2	2	2	3
09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1	2	2	2	3
10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1	2	2	2	3
11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2	2	2	2	3
12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2	2	2	2	3
13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2	2	2	3	3
14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2	2	2	3	3
15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2	2	2	3	3
16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2	2	2	3	3
17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2	2	2	3	3
18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545	0	1	1	1	2	2	2	3	3
19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2	2	3	3	3

20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2	2	3	3	3
21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	2	2	2	3	3	3
22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2	2	3	3	3
23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2	2	3	3	4
24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2	2	3	3	4
25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2	2	3	3	4
26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858	0	1	1	2	2	3	3	3	4
27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2	3	3	3	4
28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2	3	3	4	4
29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2	3	3	4	4
30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2	3	3	4	4
31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2	3	3	4	4
32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2	3	3	4	4
33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2	3	3	4	4
34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3	3	4	4	5
35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3	3	4	4	5
36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3	3	4	4	5
37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3	3	4	4	5
38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3	3	4	4	5
39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3	3	4	5	5
40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3	4	4	5	5
41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3	4	4	5	5
42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3	4	4	5	6
43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	3	3	4	4	5	6
44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812	1	1	2	3	3	4	4	5	6
45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3	4	5	5	6
46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3	4	5	5	6
47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3	4	5	5	6
48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	4	4	5	6	6
49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4	4	5	6	6

Antilogarithms—(*continued*)

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1	1	2	3	4	4	5	6	7
51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304	1	2	2	3	4	5	5	6	7
52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1	2	2	3	4	5	5	6	7
53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1	2	2	3	4	5	6	6	7
54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1	2	2	3	4	5	6	6	7
55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1	2	2	3	4	5	6	7	7
56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1	2	3	3	4	5	6	7	8
57	3715	3724	3733	3741	3750	3758	3767	3676	3784	3793	1	2	3	3	4	5	6	7	8
58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1	2	3	4	4	5	6	7	8
59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1	2	3	4	5	5	6	7	8
60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1	2	3	4	5	6	6	7	8
61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1	2	3	4	5	6	7	8	9
62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1	2	3	4	5	6	7	8	9
63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1	2	3	4	5	6	7	8	9
64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1	2	3	4	5	6	7	8	9
65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1	2	3	4	5	6	7	8	9
66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1	2	3	4	5	6	7	9	10
67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1	2	3	4	5	7	8	9	10
68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1	2	3	4	6	7	8	9	10
69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1	2	3	5	6	7	8	9	10

70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1	2	4	5	6	7	8	9	11
71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236	1	2	4	5	6	7	8	10	11
72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1	2	4	5	6	7	9	10	11
73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1	3	4	5	6	8	9	10	11
74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1	3	4	5	6	8	9	10	12
75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1	3	4	5	7	8	9	10	12
76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1	3	4	5	7	8	9	11	12
77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012	1	3	4	5	7	8	10	11	12
78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1	3	4	6	7	8	10	11	13
79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1	3	4	6	7	9	10	11	13
80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1	3	4	6	7	9	10	12	13
81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2	3	5	6	8	9	11	12	14
82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2	3	5	6	8	9	11	12	14
83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2	3	5	6	8	9	11	13	14
84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2	3	5	6	8	10	11	13	15
85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2	3	5	7	8	10	12	13	15
86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2	3	5	7	8	10	12	13	15
87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2	4	5	7	9	10	12	14	16
88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2	4	5	7	9	11	12	14	16
89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2	4	5	7	9	11	13	14	16
90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2	4	6	7	9	11	13	15	17
91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2	4	6	8	9	11	13	15	17
92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2	4	6	8	10	12	14	15	17
93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2	4	6	8	10	12	14	16	18
94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2	4	6	8	10	12	14	16	18
95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2	4	6	8	10	12	15	17	19
96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2	4	6	8	11	13	15	17	19
97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2	4	7	9	11	13	15	17	20
98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2	4	7	9	11	13	16	18	20
99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2	5	7	9	11	14	16	18	20

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