Transactions of the I·R·E Professional Group on Audio

A Group of Members of the I. R. E. devoted to the Advancement of Audio Technology

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The Institute of Radio Engineers

IRE PROFESSIONAL GROUP ON AUDIO

The Professional Group on Audio is an organization, within the framework of the IRE, of members with principal professional interest in Audio Technology. All members of the IRE are eligible for membership in the Group and will receive all Group publications upon payment of prescribed assessments.

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World Radio History

COMMENT ON FLUTTER STANDARDS*

Edward W. Kellogg
RCA Victor Division
Camden, New Jersey

This invited technical editorial, by a pioneer in the development of loudspeakers and sound recording, and reproducing equipment, is related to a standard published in the March, 1954 issue of PROCEEDINGS of the IRE, pp. 537-541. However it is a plea for futher fundamental research on the subject. – *Editorial Committee.*

The March 1954 issue of the IRE PROCEEDINGS carries a set of definitions and specifications, under the title "I.R.E. Standards on Sound Recording and Reproduction: Methods of Determining Flutter Content." This standard, designated at the time as Z57.1/68 of the American Standards Association, was approved October 15, 1953 by the Standards Committee of the I.R.E. It had received the approval, earlier in 1953, of the Society of Motion Picture and Television Engineers, and on March 16, 1954 was approved as an American Standard.

The need for standards with respect to use of terms related to flutter, methods of measurement, and manner of specification, was recognized by the Sound Committee of the S.M.P.E. (Now S.M.P.T.E.) which in 1947, under the chairmanship of Dr. John G. Frayne, drew up proposed standards, which were published in the Journal of that Society in August 1947.

That Fall a committee of the American Standards Association, designated as Z57, was formed to work out standards in the entire field of sound recording and reproduction. Mr. George Nixon of NBC was chairman. The undertaking was sponsored jointly by S.M.P.E. and IRE. At a meeting of the Z57 committee in October 1947, the writer, who was one of the members representing the S.M.P.E., was asked to act as chairman of a subcommittee to recommend standards for measurement of distortion in sound recording and reproduction. Flutter would obviously come within this assignment. One of the first results of the undertaking was that, as thoughts on various phases of the subject of distortion measurement began to crystallize, the writer prepared a paper for the S.M.P.E., setting forth his reflections. The paper was published in the November 1948 Journal, under the title, "Proposed Standards for the Measurement of Distortion in Sound Recording." In that paper are given proposals for measurement of signal-to-noise ratio, which it is still hoped will eventually receive consideration and be used, with modification if need be. The part of the paper dealing with flutter is a statement of the considerations justifying the choice of a "root-mean-square" figure for per cent flutter, rather than peak or average. There was also a comment on the proposed "Flutter Index."

Unaware, at the time, of the manner in which a proposed standard would have to be handled before it could be adopted by A.S.A., the writer prepared a new draft of "Flutter" specifications, based on the Sound Committee proposal, but departing wherever a change would more nearly represent his own ideas and those of members of his A.S.A. subcommittee. It then developed that for acceptance by S.M.P.E. the concurrence of the original Sound Committee would be needed. To that end, a special committee, Dr. Frayne, Messrs. R.R. Scoville and J. K. Hilliard, was appointed to represent the Sound Committee. There followed a protracted correspondence and a number of revisions, but all around approval was finally reached, with the specifications as given in the Z57.1/68, the one considered and approved recently by the I.R.E. Standards Committee.

The item about which there was most correspondence is that which appears in Appendix 1 of Z57.1/68, namely "Flutter Index." This term, with definition, and the formulas essentially as they now appear, were included in the proposed standards published in the August 1947 Journal, with the purpose of giving readers the benefit of what had been learned about flutter perception thresholds, in an important series of tests in the Bell Telephone Laboratories. The results of those tests had been published previously in a paper on "Analysis of Sound Film Drives" by Alberscheim and MacKenzie in the November 1941 S.M.P.E. Journal. They were reprinted in the August 1947 Proposed Standards, and are shown here as Fig. 1.

In the Standards Z57.1/68, the definition states that "Flutter Index is a measure of the perceptibility of frequency modulation of a single tone." But the suggested formulas are required to complete the definition. The formulas given under Flutter Index in effect describe it as the measured flutter, multiplied by a factor which varies inversely as the threshold, using as threshold the values shown in the curves of Fig. 1. For simplicity's

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*Manuscript received April 5, 1954.

sake, only approximations to the inverse threshold relations are attempted.

In the tests on which these curves are based, the observers were in what has been described as a moderately live room, and each observer indicated (as the magnitude of the frequency variations was changed) when he could just distinguish the frequency-modulated tone from a steady tone of the same average frequency.

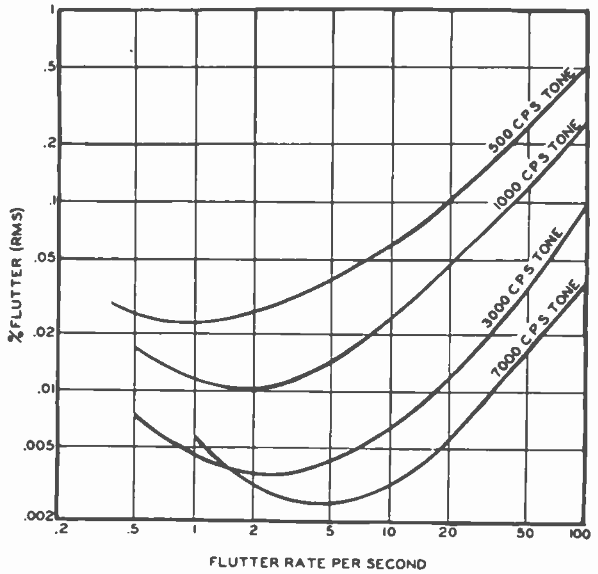

Fig. 1 Minimum perceptible per cent flutter for oscillator tones in small auditorium.

The thresholds were determined for 500, 1000, 3000 and 7000 cycle tones and for modulation or flutter rates from one-half to 100 cycles per second. Each of the family of curves in Fig. 1 shows the perception threshold, for the test tone indicated, plotted as rms per cent frequency modulation, against rate of repetition of the modulation cycle. It will be noticed that all of the curves reach minimum somewhere within the range 1 to 5 flutter cycles per second, and that in the range above 5 cycles the threshold rises almost in direct proportion to the flutter rate. The threshold was found to occur at about the same number of cycles of deviation from average frequency for the various tones, and therefore if expressed as percent flutter, varies about inversely as the frequency of the tone. Another way of describing the relations above 5 flutter cycles per second, is to say that threshold was reached at about the same total phase shift for all of the tones and flutter rates.

The ratio of the measured flutter to the threshold is taken as a "measure of perceptibility," as in the definition, and the formulas are designed to make the calculated Flutter Index directly proportional to this ratio. This is done by multiplying the measured flutter by a factor which corrects for the difference in threshold under the conditions in question (tone frequency and flutter rate) and threshold under conditions chosen as reference. The reference conditions are with a 3000 cycle test tone (the tone which is standard for flutter testing) and at a flutter rate between 1 and 5 cycles per second in which range the threshold is lowest. For these conditions the multiplying factor is unity, which makes the flutter index simply equal to the measured flutter. With a flutter rate at which the threshold is twice that at reference, the Flutter Index would be half the measured flutter.

Those who questioned the desirability of including the material on Flutter Index did not doubt the validity or significance of the tests for the conditions they represented, but feared that they might be misconstrued, as applying to flutter perception in general, as for example when listening to music. To forestall any such misinterpretation some changes in the definition and explanatory note were made, to make clear the conditions of the tests. The fear that any major error would be made was scarcely justified by any material which appears in the Standard under "Flutter Index" for no indication is there given of the absolute magnitudes of the flutter thresholds shown in Fig. 1, but only the general shape of the curves. There is some support in practical experience for the belief that with actual music the threshold is lowest for slow flutter or "wow", and is higher for rapid flutter. Therefore the effect of rate on threshold is very likely at least roughly similar to that indicated by the curves of Fig. 1. A much greater error might result if any one were to assume that the absolute values of the experimental thresholds from which the Flutter Index formulas were derived were generally applicable to program material. However nothing is said in the adopted Standard which gives any support for such an assumption, nor which indicates absolute values, so whatever misgivings may have been felt on this score, as to the desirability of publishing the material on Flutter Index, were probably groundless.

The Flutter Index relations should be helpful to those who are judging flutter by listening to test tones, to better interpret what they hear, especially if their test tones are not standard (1000 cycles, for example, is sometimes used) or if the predominant flutter is rapid. It is hoped that the presentation of this information will also serve to draw recurrent attention to the need for more information about flutter threshold.

The only other published data on frequency modulation thresholds so far as our committee knew was that given by Shower and Biddulph in a paper on the "Differential Pitch Sensitivity of the Ear," in the October 1931 Journal of the Acoustical Society of America. Shower and Biddulph were seeking only to find the rate at which the ear would be sensitive to the smallest changes, and having found a definite minimum threshold at about two cycles and a rapid rise (ear less sensitive to change) at rates above four or five cycles, they did not carry their tests much beyond that. They worked with a 1000 cycle tone using headphones. The interesting point is that the thresholds so found were about ten times higher than those shown in Fig. 1 for the same tone frequency and modulation rates.

One of the members of our A.S.A. subcommittee was Dr. Harry Schechter, at the time working at the Acoustics Laboratory at the Massachusetts Institute of Technology on a project for the U.S. Air Material Command, as part of which he had made extensive tests on flutter thresholds with monaural listening, using a group of subjects, and several test frequencies. For the frequency and range of modulation rates covered by Shower and Biddulph, the agreement was as near as would be expected, and the Schecter data constitutes an extension of the headphone investigation of flutter thresholds. Insofar as it is permissible to draw general conclusions, it appears that compared with loudspeaker listening, in addition to much higher thresholds, the headphone listening gives a less rapid rise in threshold with increase of flutter rate above 5 per second, and (based on a comparison of tests at 250 cycles and 1000 cycles) the threshold is found at about the same per cent frequency modulation for both tones; whereas with loudspeaker listening the threshold was found at a per cent frequency modulation which varies inversely as the frequency of the test tone.

It is well known that sustained tones in a moderately live room build up standing wave patterns, with regions of strong maxima and minima, and that very slight changes in frequency cause radical shifts in the positions of these regions. This, in conjunction with the much higher thresholds with earphones, gives grounds for believing that the very low thresholds found in the tests with a loudspeaker in a live room, may represent observations by intensity changes rather than actual sensitivity to frequency changes.

It would seem on first thought, that since the tests with loudspeakers were for acoustic conditions similar to those under which most music is reproduced, they would constitute a better guide as to the flutter tolerances and the manner in which the tolerance is related to flutter rate, than would tests with earphones. On the other hand it is not established that intensity fluctuations of themselves are objectionable. Certainly they do not make music sound "sour" as do slow flutter or "wows." The music of orchestras, organs and choruses comes from numerous sources at once, which are not exactly synchronized, and so must produce beats or intensity fluctuations of great complexity. Therefore when listening to such musical notes, intensity fluctuations caused by shifting standing wave patterns must, if perceived at all, be perceived in the presence of other fluctuations having what we may call "legitimate causes." Can there be much question that the threshold for the unwanted fluctuations would be considerably raised by the presence of the normal ones? It can hardly be thought that the intensity fluctuations arising from flutter would have a different quality (owing to their origin as frequency changes) and therefore be distinguishable, if the frequency changes themselves are well below thresholds for frequency changes when these are not magnified by transformation into intensity changes. The threshold without such transformation is indicated by the headphone tests.

Even the musical tones of solo instruments or voices are extremely complex. Whereas in loudspeaker listening the standing waves of a single or pure tone would establish a definite pattern of maxima and minima, the pattern for each component of a complex tone would differ from the patterns of the others, and since with the frequency changes due to flutter, the component tones would not rise and fall together, what might be expected would be a cycle of changes in quality, with perhaps little change in loudness. That threshold for such a quality cycle would be as low as the rise and fall of intensity in one component alone is doubtful. Only tests can show how much the difference might be.

When a steady tone is produced, the standing wave patterns are not established until the tone has continued for a time comparable with the reverberation time of the room. Even though in certain musical compositions notes or chords may be sustained this long, the probability of a listener's observing variations within such duration are much less than when he is given as much time as he wants. Assuming that a listener is concentrating his attention on whether there is or is not a detectable effect of flutter, his perceptive faculties must be readjusted every time the note or chord changes.

For all these reasons it seems clear that the relation between flutter thresholds under the three conditions: (a) with pure tones from a loudspeaker in a representative listening room, (b) with music in such a room, and (c) with pure tones with headphones, are largely a matter of speculation and guesswork. The writer's personal guess is that (b) will be found to be much closer to (c) than to (a). Much more experimental work is needed before we can state with confidence what amount of flutter at various rates is barely perceptible and what tolerable.

Such knowledge would be valuable to manufacturers and users of audio recording or reproducing equipment, in writing specifications with respect to flutter more intelligently, in interpreting and judging the significance of flutter measurements, and in designing and building equipment which will be acceptable but not unnecessarily expensive. It would put the control of flutter more nearly on a scientific and engineering basis, in place of the system of trying a product on the public and repenting if it is unacceptable.

In arguing that practical thresholds for flutter are probably much higher than those for steady tones, the writer is by no means seeking to relax standards. As a matter of fact the extremely low figures for threshold indicated in the steady tone and loudspeaker tests (Fig. 1) are far below the flutter values attained in even very high-grade commercial equipment. (We understand that they have recently been approached or equaled in certain tape equipment built to meet very exacting requirements not directly related to sound reproduction).

Since the one way in which reliable information can be obtained, on actual flutter threshold, with speech and various types of music, would be by a comprehensive series of tests, it is very much to be hoped that such investigations will be undertaken. They could be research projects of some of the larger companies interested in audio equipment, or they could be university projects, financed jointly by a group of interested companies. One such investigation is being carried on by the Bureau of Ships*. Publication of findings will be awaited with great interest. It is still very desirable, in view of the complexity of this important problem and the large number of observations needed for drawing reliable conclusions, that similar projects be undertaken by other organizations.

The normal approach to such an investigation would be to introduce flutter into a recording-reproducing system which is otherwise free from flutter. The last stipulation is of course unattainable. but at least the flutter must be well below threshold, and the quality must be particularly clean, and low in distortion.

Precautions would be needed to be sure that the operation which introduces the flutter does not introduce some other cyclic variation. For example, if a disk is driven at fluctuating speed, there must be no vibration to affect the pickup, or make periodic variations in pressure. If a magnetic tape system is not used it would be essential to make tests to prove that the speed modulating system does not affect the evenness of contact nor the contact pressure between tape and reproducing magnet. A photographic sound system (which is a pure amplitude system) would have the advantage that changing speed would cause no amplitude modulation, and if a deep-focus optical system is used, the scanning would be in small danger of being affected by other than longitudinal movements of the film. However, it may turn out that some of these precautions are unnecessary, and it may be possible to prove by tests with pure amplitude modulation that the accidentally introduced output voltage changes are far below threshold and can safely be neglected. If that is true, the choice of system can rest more on convenience.

Either friction drives or thread-belt systems can probably be made to give sub-threshold flutter when the modulating system is inactive. It might prove desirable to cover low flutter rates with one mechanism, and high rates with another.

Judgements will be difficult, and the number of types of program material could easily be formidable. Therefore the schedule would need to be reduced to short basic types, and flutter rates limited to a few discrete values. Something significant would be revealed, for example, if under normal listening conditions the thresholds were determined for intermittent pure tones with various off-on intervals, then with no silent periods but a sequence of several tones, the test being repeated at different note lengths. Then a similar series of tests could be made with complex tones. In a set of tests such as this, the sources could be electronic, with purely electronic (instead of mechanical) methods of modulation.

It would certainly not be in order to try to make determinations with any great precision until work has progressed to the point of proving that significant results are possible, and greater refinement justified.

The foregoing thoughts are offered in the hope that they will help interested persons to visualize what such a project might be like. It seems to the writer that even a very incomplete investigation of thresholds for music and speech would be so much better than the present sporadic observations and guesswork that an effort to get such a project started would be amply justified.

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* Navy Research Project NSS-683-034(10), Bureau of Ships (Code 565).

"HIGH-FIDELITY" in MUSICAL TONE PRODUCTION?

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The tremendous surge of interest in "high-fidelity" sound during recent years has attracted the attention of many manufacturers in commercial fields peripheral to the manufacture of sound equipment. Recently (and somewhat paradoxically) several manufacturers of musical instruments have attempted to capitalize on "hi-fi" interest. For example, electronic organs are sometimes advertised as having high-fidelity amplification equipment, and the magic of the term "high-fidelity" has even been borrowed by advertisers to describe the design of a piano soundboard. Before this trend in loose terminology develops further in the field of musical tone *production*, the origin and meaning of "high-fidelity" in relation to the *re*production of musical sound should be carefully examined.

In the minds of typical discriminating consumers of both tone *production* and *re*production equipment, the term "high-fidelity" is something relatively new and rather mystic. Actually, twenty-five years ago "High-Fidelity" originated as a registered trade-mark of a loudspeaker manufacturing company which, incidentally, is one of the present commercial leaders in the "hi-fi" field. Only a few years later there were several manufacturers producing sound equipment which, in many electrical and acoustical characteristics, equalled the best sound equipment available today! This equipment was used chiefly for reproduction of sound-on-film recordings for motion pictures, and to a lesser extent in the radio broadcasting industry. Such equipment was not mass-produced in the usual sense. The lack of a mass market and the high cost of equipment production were inter-dependent, and one can hardly say which was cause and which was effect. The disc recordings available to music lovers at that time contained non-linear distortion and noise, in amounts which discouraged the use of sound equipment which was capable of reproducing the entire audio-frequency range.

During the early and middle nineteen-forties the use of magnetic recording and playback equipment, and the development of improved record manufacturing techniques and materials, completely changed the picture. Through these means the general public could then obtain recorded music which was potentially of much higher quality than before. However, full appreciation of this potential required the use of electrical and electro-acoustic equipment possessing greater frequency range, better transient response, less non-linear distortion, and greater freedom from system noise. Fortunately for the new types of records, such equipment was already developed, and the major problems of the new audio equipment industry were largely the development of mass production methods and associated simplifications in design for systems and components already available. There have been, of course, further improvements in components and in technique, within the several years since the audio "boom" began. Research and development in the audio and acoustical fields continue, with renewed interest and financial support.

The public appreciates the new musical *re*production, and interested people typically ask: "What is high-fidelity? Who invented high-fidelity? Why can one buy high-fidelity equipment at so many different price levels?" These questions reflect a belief that high-fidelity is a "thing", which a piece of equipment either has or has not.

High-fidelity is a relative term. Probably this is not easy to explain to a prospective purchaser of high-fidelity equipment. Much has been said and written on the necessity for standards in high-fidelity equipment. The difficulty (perhaps impossibility) in standardization for "hi-fi" equipment is that various engineers and manufacturers have progressed along different paths towards the achievement of improved sound fidelity. Actually progress along any one of these lines can truly be termed a step toward "high-fidelity."

One enterprising audio engineer may push along a particular path of improvement farther than anyone else has gone. In doing so, he may have had the necessity of compromise on performance factors related to other paths of improvement. Other audio engineers at the same time are developing equipment in which the compromise is made in favor of other performance factors. Superficial examination of the problem might lead to the conclusion that "high-fidelity" is a combination of all of the possible improvements which have been made individually Such all inclusive standards would probably result in a design impossibility. At the other extreme, standardization upon the minimum performance now permitted in each of the so-called "high-fidelity" reproducing equipments would degrade the term to a meaningless level. This is why it is difficult to define "high-fidelity" for sound *re*production equipment.

There is no similar problem of ambiguity with regard to "high-fidelity" in the original production of musical sound because, by definition, the original is the highest fidelity possible. This is not to say that it is impossible to improve upon the original (although this seldom occurs in the recording and reproduction process), but Gertrude Stein's classic statement "A rose is a rose is a rose..." applies equally well to a violin or to a trumpet.

To the extent that an electronic instrument is intended to *simulate* a different instrument, the fidelity of simulation does have meaning. However, in this usage the term "fidelity" should be applied to the instrument as a whole, and not to the amplification equipment alone (as has been the case). For example, the use of amplification equipment designed for high-fidelity reproduction of recorded music on one type of electronic organ which generates no signal components at frequencies above 5000 cps, will add nothing but noise to the upper range of the spectrum. By contrast a different electronic instrument, which generates an abundance of high-frequency harmonics, may advantageously employ a "roll-off" in high-frequency response of the amplification system as part of the overall voicing of the instrument. Moreover, fidelity of simulation is by no means the sole goal in electronic musical instrument development. In the sense that an electronic instrument is a new instrument, "fidelity" has no meaning at all.

Similarly statements concerning a "hi-fi" piano sound-board should be examined carefully. Do they mean that the sound radiated by the board corresponds exactly to the vibration of the strings which excite it? A person who has listened to the vibrations of a struck string, over an amplifying system having uniform response-frequency characteristics, will understand that the resulting tone is hardly identifiable as a piano. A soundboard is part of the instrument, and helps to create the tonal effect desired. To identify it simply as a sound transmission channel is an oversimplification. To term a soundboard "high-fidelity" is misleading, in this writer's opinion. Any part of a manufactured product may be modified or improved, but this has little to do with "high-fidelity" unless the product is part of a sound *re*producing system.

Improved fidelity of musical sound reproduction can be expected to broaden popular interest in original instruments and in the music they produce. Moreover many of the scientific principles and techniques, and engineering practices and procedures, discovered and developed for sound reproduction, can advantageously be adapted to the solution of musical tone-research problems and to the engineering of new music production equipment. Indeed, this has been occurring quietly for some time, beginning even before "high fidelity" was popularized. Similarly, knowledge gained from research in the field of musical tone has benefited musical sound reproduction, and ultimately will affect it greatly. Although the purposes of these two distinct fields (development of means for *creating* music and for *re*creating music) are similar, they should not be confused.

In summary it can be said that the goal of sound reproducer research and development has been to attempt to *re*create the original sound. Presumably one-hundred per cent fidelity would be the achievement of perfect reproduction of the original sound. Manufacturers of musical instruments should think this through before paying the high compliment of imitation to their own imitators. A music *production* system has inherent advantages in quality of performance over music *re*production systems (lower system noise and distortion, for example). Surely exploitation of such inherent advantages is a more positive and lasting policy for producers of music production equipment than borrowing publicity generated by producers of music reproduction equipment.

PHILADELPHIA CHAPTER ACTIVITIES

Murlan S. Corrington, Chairman
Philadelphia Chapter, PGA

At the regular meeting on March 16, 1954, Mr. Stephen A. Caldwell, Electronics Products Division, Radio Corporation of America, Camden, N.J., gave a lecture with demonstrations on "Multichannel Sound Reproduction." It was explained how multichannel sound systems increase the listening pleasure from recorded music. He discussed the effect of the directional characteristics of the loudspeaker and of the acoustical environment of the recording and reproducing setups. Several systems were demonstrated to show how the fidelity of reproduction, the amount of reverberation, and the relative time delays are all important in the design of a high quality system.

The final meeting of the year was held on April 22, 1954 with Dr. Winston E. Kock and Mr. Floyd K. Harvey of the Bell Telephone Laboratories, Murray Hill, N.J., giving a talk and demonstration on "Polarized Airborne Sound Waves." Although sound waves have generally been considered to be purely longitudinal and therefore not polarizable, it is possible to generate transverse sound waves having a definite "plane" of polarization. Such waves should be confined in hollow tubes to remain polarized. A demonstration of these properties was given, which included the rotation of the plane of polarization by "half-wave plates," the production of circularly polarized sound waves by "quarter-wave plates," acoustical filters, and converging lenses.

The new officers who were elected at the Annual Meeting are:

Mr. H. E. Roys, Radio Corporation of America, Chairman
Mr. Edwin C. Gulick, Philco Corporation, Vice-Chairman
Mr. William L. ten Cate, Custom Sound Associate, Secretary.

CINCINNATI FIELD TRIP TO DAYTON

E. M. Jones, Chairman
Cincinnati Section, PGA

The Cincinnati Chapter IRE-PGA for its final meeting of the season made a field trip to Dayton, Ohio to hear the Sunday evening concert in Carillon Park. Members of the chapter and their families enjoyed a picnic at a nearby park before the concert. The first half of the concert was played on the large carillon. A 5500-watt audio system called the "Celestron" is installed in the same tower as the carillon. The second half of the concert was recorded music played on the Celestron system. After the concert the PGA group was given an inspection trip through the tower installation.

At an earlier meeting on April 20, the Cincinnati Chapter heard a talk on "Wow in Recordings and Measurement Thereof" by Mr. Meredith L. Young of the

General Industries Co., Elyria, Ohio. Common causes of frequency variations in phonograph turntables were discussed. The circuits of "Wow" meters for measurement of these variations were presented. A demonstration accompanied the paper in which measurements were made upon phonograph turntables having various amount of frequency fluctuation. This gave the audience an opportunity to correlate audibility of "Wow" with precise measurements made on the meters.

The new officers of the Cincinnati Chapter IRE-PGA for 1954-55 are as follows:

Chairman: Wynne W. Gulden, Cincinnati & Suburban Bell Tel. Co.
Vice-Chairman: J. Park Goode, National Sound Service
Secretary-Treasurer: Richard Lehman, The Baldwin Piano Co.

PGA BRIEFS

Members of the IRE Section in Washington, D.C. have recently petitioned for the formation of a Chapter of the Professional Group on Audio. The Chapter formation has been approved by the Executive Committee of the Washington Section, by the Administrative Committee of the Professional Group on Audio and by the Executive Committee on the Institute. A hearty welcome to this new Chapter.

The Acoustical Society of America celebrated its twenty-fifth anniversary on June 23-26 in New York City. The Acoustical Society is a part of the American Institute of Physics. Although the Professional Group on Audio and the Acoustical Society of America are organizationally separate and have only a small overlapping membership, there naturally exists a strong bond of "first-cousin" relationship between the two. Congratulations for a quarter-century of fundamental contributions to acoustics and audio.

Inadvertently in the March-April issue the primary affiliation of Professor A. B. Bereskin, author of the paper "A High-Efficiency High-Quality Audio-Frequency Power Amplifier" was omitted. Mr. Bereskin is a Professor of Electrical Engineering at the University of Cincinnati, and a part-time consultant in electronics to The Baldwin Piano Company, where he performed the research reported in this paper.

The Administrative Committee of IRE-PGA met in New York City on June 26th, in order to discuss publication methods, schedules and costs, changes in bylaws, an interchapter memo service, joint meetings, increased cooperation with IRE technical committees, and formation of new chapters.

IRE-PGA Chairman, Dr. Vincent Salmon, announces that the following appointments have been accepted for the 1954-55 period:

Secretary-Treasurer—Benjamin B. Bauer,
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The Baldwin Piano Company
Chairman Program Committee—Philip B. Williams,
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Chairman Awards Committee—John Hilliard,
Altec Lansing Corporation
Chairman Papers Procurement Committee—John Kessler,
Massachusetts Institute of Technology

This is the time of year when the use of tapescripts should be scheduled for coming Chapter meetings. For listings of available tapescripts, refer to the January-February issue of TRANSACTIONS of the IRE-PGA, page 2. One additional tapescript, entitled "How Much Distortion Can You "Hear," described in the March-April issue, has been added to the available tapescripts list.

The IRE-PGA Program Committee made an effort to stimulate audio papers for the October 4-6, 1954 conference of National Electronics Conference, Inc. This effort was partially successful, resulting in several audio papers on the program, but not enough for a special audio session. Commitments for papers for this conference must be made months in advance, at a time of year when authors are planning vacations. Our thanks to the Program Committee for its effort. The Administrative Committee of IRE-PGA will hold its annual fall meeting in Chicago at the time of the NEC. Members of IRE-PGA interested in presenting matters for consideration of the Administrative Committee, are invited to do so by correspondence with the Chairman or Secretary-Treasurer.

RECORDING AND REPRODUCING COMMITTEE

Murlan S. Corrington
Vice-Chairman, Committee 19

Technical Committee 19, which is working on IRE Standards for Recording and Reproducing, met at IRE Headquarters in New York on April 9, 1954. Three new members were appointed: Ellis W. D'Arcy, Marvin Camras, and Alvin H. Willis.

The revised Scope and new name of Committee 19 is as follows:

RECORDING AND REPRODUCING COMMITTEE

1. The selection of terms and the preparation and maintenance of standard definitions for complete systems for mechanical, optical and magnetic recording, and their components which include: the recording device, the reproducing device, the recording medium, and the drive mechanism.
2. The preparation and maintenance of standards covering methods of measurement in the above fields.
3. The coordination of activities with other IRE committees, other professional societies and liaison with technical organizations engaged in allied work.

Consideration was given to cooperation with the Standards Committee of the Audio Engineering Society, which has a Subcommittee on Disk Recording. They are working on: (a) Specifications for a test record, (b) Methods for calibration of test records, and (c) Production problems and quality control. Since both committees are working on similar problems, Committee 19 is to work with them whenever possible.

A new Subcommittee will be established to deal with problems relating to (a) Magnetic Record Media, and (b) Measurement of the State of Magnetization of Magnetic Record Media as a Function of the Recorded Signal.

A letter has been received from the Department of the Navy, Bureau of Ships, dated March 29, 1954 which indicates that the Materials Laboratory of the New York Naval Shipyard, Brooklyn 1, N.Y. is studying flutter in recording systems. They have proposed several minor changes in the "Methods for Determining Flutter Content, 1953" which were published in Proc. I.R.E., vol. 42, pp. 537-541; March, 1954.

NATURAL SOUND REPRODUCTION*

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There are many factors which affect the fidelity of reproduction of voice and music. The purpose of this article is to collect some of the important considerations in such reproduction. Reasonable approximations have been used in order to have definite numerical figures to make comparisons and to establish the general order of each factor. Two sets of reported listening tests have had a definite bearing on these considerations of overall fidelity.

A most interesting series of basic listening tests was performed by Dr. Harry F. Olson[1] of the RCA Laboratories at Princeton, New Jersey. He demonstrated that the complete frequency range was preferred by listeners to a frequency range limited by an acoustic curtain cutting off above 5,000 cps. Live sources of music were provided behind this curtain in one corner of a room and the audience listened in the normal (binaural) manner. During these tests the audience was at no time informed of the exact mechanism of the test. Comparisons were made of fidelity with the hidden acoustic curtain being either arbitrarily opened or closed. Almost invariably the listeners chose the full frequency range. A conclusion reached by Dr. Olson was that other listener preferences for a restricted frequency range in *reproduced music* were probably accounted for by the distortion and deviations heard with extended frequency range in the reproducing system.

The RCA test used no reproducing equipment between the listeners and the orchestra. However, in the case of binaural reproduction, where two channels are used with two microphones separated at approximately the distance between the ears, there are important advantages over a single channel system. One of these advantages is the apparent reduction of reverberation in the studio. A pair of ears also has the characteristic of virtually eliminating distortion of certain types which may exist in the two channels separately. Further, a binaural reproducing system allows the apparent angular separation of instruments of the orchestra, so that the listener can focus his attention deliberately on a particular instrument

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*Manuscript received April 15, 1954.

[1] H.F. Olson, "Frequency range preferences for speech and music," Electronics, p. 80; August, 1947.

which is angularly separated from others, even by but a few degrees. By the same token, a binaural listener is capable of discriminating against a moderate amount of noise when it originates at an angle different from the desired sound. The sum result is that binaural listening, whether directly or through binaural microphones and amplifiers, has a naturalness which is very apparent after short experience. Numerous such tests have been made with experienced musicians, who react very favorably to even poor frequency-range recordings when made on a true binaural system.

The most extensive information available on listener preference with a reproducing system was reported by Howard A. Chinn and Philip Eisenberg of the Columbia Broadcasting System.[2,3] They made a series of careful listening tests with public participation. High-quality, specially-prepared program material was employed, which was reproduced on excellent equipment in a quiet room. Audiences voted on the frequency range preferred. The results showed a definite preference for a "medium range" from approximately 75 to 7,500 cycles, rather than a wider or narrower range. The narrowest range was limited in the high-frequency direction at about 5,000 cps. The results of Olson's work compared directly with the Chinn and Eisenberg results in that the audiences desired a range *exceeding* 5,000 cps in both cases. However, because the Olson experiments were not performed with a second curtain cutting off at 7,500 cps, it cannot be predicted what the result would have been. Presumably there would still have been some preference for the unlimited range.

TABLE I

Frequency Range Comparisons

Comparison of:	Usual Receiver (*75-3500 cps)	High Fidelity (30-15000 cps)	Medium Fidelity (75-7500 cps)
Quality loss of each range	7% loss lows 45% loss highs	Virtually no loss	8% loss lows 8% loss highs
Network program fed directly to each audio amplifier	12% loss lows 35% loss highs	4% loss lows 25% loss highs	8% loss lows 25% loss highs
Local program through selective receiver	12% loss lows 45% loss highs	6% loss lows 45% loss highs	8% loss lows 45% loss highs
Phonograph records-average pickup	10% loss lows 45% loss highs	5% loss lows 45% loss highs	8% loss lows 45% loss highs
Phonograph records-good pickup	8% loss lows 40% loss highs	4% loss lows 8% loss highs	8% loss lows 8% loss highs
Local program—wider selectivity receiver	— —	6% loss lows 6% loss highs	8% loss lows 8% loss highs

*But does not cut off sharply below 75 cps as does the 75-7500 system.

There are a number of factors which help to explain the results for preference of a medium-frequency range in reproducing systems. In order to explain this, the expected results from three types of equipment will be compared as follows:

A. A typical radio-phonograph, called the "usual receiver," which has a frequency range of approximately 75 to 3,500 cps with a 10" loudspeaker. Such a receiver does not cut off sharply below 75 cps, although the acoustic efficiency is dropping rapidly with decrease in frequency.

B. A "high fidelity" amplifier covering a frequency range of approximately 30 to 15,000 cps with a 14" loudspeaker with conventional baffle, and a tweeter.

C. A "medium fidelity" amplifier covering from 75 to 7,500 cycles with *three* conventional, dynamic speakers of about 16", 4" and 1" in diameter, respectively, mounted on conventional baffles. (Such a system was in constant use for comparison purposes.)

Table I shows frequency-range comparisons with respect to the loss of low and high frequency due to the system. The percentage loss in quality of the reproduction of orchestral music is a concept used in an investigation by Snow.[4]

The figures used throughout this article have been taken from many sources, with some estimates where no data was found, or where data does not agree. Reproducing systems corresponding to the three systems below have been compared at various times, but the three systems were not constructed for direct comparison as one experiment.

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[2] H.A. Chinn and P. Eisenberg, "Tonal-range sound-intensity preferences," Proc. I.R.E., vol. 33, p. 571; September, 1945.

[3] H.A. Chinn and P. Eisenberg, "Influence of reproducing system on tonal-range preferences," Proc. I.R.E., vol. 36, p. 572; May, 1948.

[4] W.B. Snow, in: Jour. Acoust. Soc. Amer., vol. 3, no. 1, pt. 1, p. 155.

The first line of Table I shows the estimated quality loss of each range due to frequency-range restriction alone. The second line concerning a network program shows such additional loss of each system if the network program line were fed directly through each audio amplifier and speaker. The loss of high frequencies in this case for the high fidelity and medium fidelity amplifiers is due to the usual practice of limiting most network programs to about 5,000 cps as their highest frequency. The next line involves a local program received by radio through a selective receiver and shows the high frequency loss contributed by conventional selectivity. This effect is minimized in the last line where the program has been received through a wider selectivity receiver on AM and this also applies to a local program received by any reasonably good FM receiver.

So far, it can be concluded that the medium fidelity amplifier is more than adequate for most network programs (assuming an upper limit at 5,000 cps). It is certainly adequate for all local programs (upper limit 10,000 cps) and for phonograph records (upper limit about 10,000 cps on carefully made records). Actually little music is available through any of the usual sources at frequencies much above 7,500 cps, except for some local FM programs which extend to 15,000 cps or on good transcriptions or live programs.

Unfortunately, there are certain noises which disturb listening. During the Chinn and Eisenberg experiments it was found that any slight noise in the reproducing system was immediately objectionable to the listeners. Noise can be classified as hum, turntable rumble, record scratch and electrical interference (such as static, pops, and clicks).

It is very interesting to observe the high-fidelity growth in popularity through 1952, 1953, and 1954 which is probably as much due to reduction of background noise as extension of frequency range. Time and again musicians have reacted very favorably to limited range reproduction free of background noise, and unfavorably to extended range with some, even slight, background noise. The satisfaction of clean silence during pauses in music must not be underestimated.

TABLE II

Intensity of High Frequency Noises

Comparison of:	Usual Receiver (75-3500 cps)	High Fidelity (30-15000 cps)	Medium Fidelity (75-7500 cps)
Network program directly to amplifier	Noise reduced to two-thirds	Noise tripled	Noise increased 50%
Local program through selective receiver	Noise reduced to one-third	Noise reduced to one-third	Noise reduced to one-third
Phonograph records-good pickup	Noise reduced to one-half	Noise doubled	Noise normal
Local program — wider selectivity receiver	— —	Noise increased 50%	Noise normal
Record scratch	Scratch reduced to one-third	Scratch doubled	Scratch normal

Table II shows the relative intensity of high frequency noises in amplitude for the same three amplifier and speaker arrangements. The table refers to the amount of noise which will be reproduced in comparison to the noise present within the program frequency range. It will be noted that the "usual receiver" reduces noise considerably since its frequency range is less than that of the program range in every case. However, Table I shows the frequency range penalty for so doing. It is no accident that the usual receiver is designed in this way, because noise is so objectionable. The high fidelity amplifier will produce noise outside of the program frequency range as shown in Table II. Of course, this assumes that noise does exist with the program as is usually the case. Record scratch at each frequency actually increases with frequency increase. Thus, the amounts of scratch reduction in the "usual receiver" is more than the frequency range reduction alone would indicate, and conversely the high fidelity unit has more than proportional scratch.

The reception of radio programs from AM radio stations, within a few miles of a receiver, is such that little high-frequency noise will be heard. FM reception will usually render noise-free programs for a greater distance, particularly under summertime conditions. Recorded music depends upon the type of record and will have clicks, pops and scratch, which on only the quietest records will be wholly acceptable.

There are other types of noise at the low frequencies and these are principally hum and turntable rumble. The harmonics of power line hum will give trouble in any case. Table III shows the effect of the 60 cycle power hum alone. Naturally, the best turntables are better than cheaper ones with respect to rumble.

Let us review the situation thus far. As far as frequency range is concerned, the medium fidelity amplifier was almost equal to the high fidelity amplifier for most available programs. High-frequency noise was much less in evidence on the medium fidelity amplifier in comparison to the high fidelity amplifier. The usual receiver was best of all for noise, but its frequency range is very limited from the standpoint of high fidelity. Lastly, the effect of hum and turntable rumble do favor the use of a medium fidelity amplifier.

TABLE III

Audibility of Hum and Turntable Rumble

Comparison of:	Usual Receiver (75-3500 cps)	High Fidelity (30-15000 cps)	Medium Fidelity (*75-7500 cps)
Power hum in receiver	some present	Negligible	Negligible
Power hum with program	Will be heard	Will be heard	Almost none
Turntable rumble	Some present	Considerable present	Almost none

*Cuts off sharply below 75 cps.

Now, let's examine the problem of reproduced distortion in Table IV. The figures for the usual receiver were taken from an average of measurements on a number of home receivers commercially produced during the year 1950. Included in the distortion is that part contributed by the loudspeaker which is very important, particularly at the low-frequency region of the spectrum. This is not generally realized, but is well substantiated.[5] It is interesting to note that the usual microphone adds very little distortion to the program, entirely unlike the loudspeaker which, with its higher amplitude of motion, is so often neglected in making distortion measurements. Amplifier distortion alone is no criterion for overall performance in reproduction.

TABLE IV

Effect of Harmonic Distortion
(especially at lower frequencies)

Comparison of:	Usual Receiver (75-3500 cps)	High Fidelity (30-15000 cps)	Medium Fidelity (75-7500 cps)
Distortion tolerable – entire system (1000 cps)	10%	3% (hard to achieve)	5% (possible with care)
Distortion present (2 watts) at lowest note reproduced	25% (or more)	30% (even with care)	3% (or less)
Lowest note heard as fundamental – quiet residence	85 cps	60 cps	75 cps
Lowest note apparently heard due to distortion	60 cps	30 cps	Little bass distortion
Lowest note due to harmonic reconstruction	30 cps (approx.)	20 cps (approx.)	40 cps (approx.)

The low-frequency threshold of hearing is about 50 cps in a quiet residence with ordinary levels of reproduction. Frequencies lower than 50 cps will not be heard at ordinary levels. For this reason, also, little can be heard between 50 and 75 cps except distracting power noise at 60 cps and turntable rumbles extending up to about 70 cps. When one listens to a series of harmonics, the fundamentals will be recreated in the mind. The next to the last line of Table IV shows that the lowest notes apparently heard are often created by distortion due to the unloaded, loudspeaker-diaphragm flopping. When one listens to a series of harmonics in the music itself, the fundamentals will be recreated in the mind by this same process. The last line of Table IV shows the lowest frequency which will probably be so created by the natural harmonics in the music itself. Thus, the medium fidelity amplifier will apparently produce notes down to roughly 40 cps, which is ample. Furthermore, because it cuts off below 75 cps the cone is prevented from excessive travel which otherwise produces a serious amount of distortion. Parenthetically it may be said that the exponential horn is almost a necessity for distortionless reproduction below about 150 cps as it keeps the speaker cone properly loaded above its cutoff.

Push-pull output is especially good for eliminating *even* harmonics but *not* the objectionable odd ones. Therefore, the use of a single output tube with proper caution (feedback, etc.) in design may be equally acceptable to the much touted push-pull amplifier. One of the best expensive commercial radio receivers in times past used a single output tube with very superior results.

For reasons that will be explained, it is well to divide the musical range into at least two, or possibly three

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[5] H.F. Olson, "Elements of Acoustical Engineering," McGraw-Hill Book Co., p. 167; 1947.

parts. One output tube and its associated loudspeaker can be used for each part of the range. A suggested division for the 75 to 7500 cps range is 75-350, 350-1600 and 1600-7500 cps. Each range would thus cover a frequency ratio of about 4½ to 1. Thus, it is difficult for a fundamental in any one range to produce much fifth harmonic and much more difficult to produce higher harmonics.

The three ranges are beneficial in another important detail.

"Intermodulation" is probably the most prolific source of audible distortion. This is a much more sensitive criterion of performance than harmonic generation.[6] When the voices of a choir seem to blur unnaturally in reproduction, this is almost a sure sign of intermodulation. A very simple listening test will show the presence of distortion very strikingly. Stand about four feet from another person some ten feet from the loudspeaker. Talk in a low to moderate conversational tone to him before turning up the volume of some orchestral selection. Then stop talking and raise the volume until he signifies by raising his hand, or some other prearranged signal, that the loudness is adequate for *good* volume, neither soft nor very loud. Now try to converse in the same tones as before. If the conversation now becomes very difficult to hear, it is an indication that there is very *little* distortion. In other words, the level of the clean reproduction is actually quite high in intensity. However, if there is considerable distortion, the volume level will actually be quite low, thus interfering but little with the conversation. Several trials with various reproducing systems will show the validity of this simple test.

If a low frequency is being produced from a loudspeaker, and, at the same instant, some very much higher tone is being reproduced, there is a special type of distortion because the high tone is taking off from a moving "springboard". This causes a wobbling of the high frequency note leading to "frequency modulation" distortion.[7] With the range divided into three parts, this distortion should not exceed one per cent in any range. A large loudspeaker for the entire range, as is usual, may cause ten per cent of this type of distortion with simultaneous reproduction of 100 and 7500 cps, for example.

The matter of loudspeaker efficiency is important.[8] The efficiency of a 16" loudspeaker is best between about 60 and 800 cycles. A 4" loudspeaker works well between 150 to 2,000 cps. A 1" loudspeaker works well between 800 and 10,000 cps. The highest frequency usable is inversely proportional to the mass of the cone. The low-frequency limit is based on distortion requirements, because the amplitude of the cone becomes greater with decrease in frequency.

The three loudspeaker diameters mentioned are approximate, and could be modified without serious difficulty, such as using a 2" diameter for the high frequencies, a 6" diameter for the medium frequencies, and two 12" units for the low frequencies. If the two 12" loudspeakers are used, it is highly preferable to provide a small exponential horn to load them properly. In fact, the use of a moderate horn, such as a simple corner loudspeaker, has great advantage from the low-frequency standpoint in maintaining loudspeaker efficiency at the lowest frequency, and also in limiting excessive cone travel to prevent distortion.

TABLE V

Summary of Other Considerations

Comparison of:	Usual Receiver (12" speaker)	30-15000 (*14" & tweeter)	75-7500 (3 speakers)
Intermodulation at 2 watts	10% (3% is tolerable)	5% or less	2% (or less)
Low frequency "springboard"	10% (or more) distortion	7%	1%
Angular coverage	Poor at highs	Reasonable with expensive spkrs.	Good with inexpensive spkrs.
Efficiency	Falls off at highs	Reasonable	Good
Record storage in medium size cabinets	Space available	Some space	No space

*Conventional baffle and high frequency speaker in simple form — neither with exponential horns as in high-priced two-way systems.

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[6] J.K. Hilliard, "Intermodulation testing," Electronics, p. 123; July, 1946.

[7] H.F. Olson, "Elements of Acoustical Engineering," McGraw-Hill Book Co., p. 171; 1947.

[8] H.F. Olson, "Elements of Acoustical Engineering," McGraw-Hill Book Co., p. 126; 1947.

The directional characteristics of the loudspeakers are quite important because a large loudspeaker is very directional at high frequencies.[9] A 16" loudspeaker emits sound of higher frequencies in an increasingly narrowing beam. This is not serious below 500 cps. A 4" loudspeaker has an upper non-directional limit of some 2,000 cps. A 1" loudspeaker is quite nondirectional up to 8,000 cps. Thus, the use of three conventional loudspeakers will result in a wide angle of coverage throughout the range without special horns or dispersion systems.

Table V gives a summary of the various other effects considered.

If the three loudspeakers with the medium fidelity amplifier in a living room, within the ranges suggested, produce 4, 4 and 0.1 watts maximum output respectively, they will reproduce an equivalent sound heard by a listener in the fourteenth row orchestra seat or ten feet from a piano, in fortissimo passages.[10] There is much less acoustic power available from the orchestra in the 1600 to 7500 cps range than in the two lower ranges. The method[10] of computing this is shown in Table VI. The power per cycle in each range for an orchestra is multiplied by the number of cycles in the range to arrive at the total average acoustic power in each range. The ratio of maximum average power to normal power is then multiplied times the total average to obtain the maximum acoustic power for each range. Because the loudspeakers have an efficiency of approximately five per cent, the electrical input power necessary for each loudspeaker is then computed.

Thus, 8.1 watts peak is the maximum audio power needed for a three-speaker system, which will remain within the bounds of economic design. Actually, program monitoring will reduce these peaks so that it will be safe to run such an amplifier up to one-quarter watt on average power passages. The peak passages will be at 8.1 watts which is very loud in the normal living room.

Finally, it might be said that treble tone controls are generally useful to reduce noise and should be regarded as such. In systems with distortion or noise, the treble tone control will always be used by the average listener.

The combination of reasons given helps to explain the public preference for the 75 to 7500 cps range as reported by Chinn and Eisenberg. The "usual receiver" design is also explained, in which noise and distortion compel the user to prefer a range limited to 3500 cps or less and lead him to reduce the treble response still further for normal listening.

TABLE VI

Intensity from Symphony Orchestra at 14th Row Seats

Comparison of:	Lower Range (75-350 cps)	Middle Range (350-1600 cps)	Upper Range (1600-7500 cps)
Average power per cycle in range	7.3 microwatts	1.6 microwatts	0.04 microwatts
Band width in cycles	275 cycles	1,250 cycles	5,900 cycles
Total average acoustic power in range	2 milliwatts	2 milliwatts	0.25 milliwatts
Ratio of maximum to average power	100 times	100 times	20 times
Total maximum acoustic power	0.2 watts	0.2 watts	0.005 watts
Power necessary for loudspeaker (5% efficiency)	4 watts	4 watts	0.1 watts

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[9] K. Henney, "Radio Engineering Handbook," McGraw-Hill Hill Book Co., 3rd Ed., p. 895.

[10] H.F. Olson, "Elements of Acoustical Engineering," McGraw-Hill Book Co., pp. 412, 481-482; 1943.

EQUIVALENT CIRCUIT ANALYSIS OF MECHANO-ACOUSTIC STRUCTURES*

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I. INTRODUCTION

To comprehend the new, the unknown, we often fall upon the old, the known. Thus, in the time of Volta and Ohm (circa 1800) many of the conceptions of electricity were based upon similarity with the older arts, i.e., hydraulics, mechanics and heat. Volta was among the first to recognize that the phenomena grouped under the name of galvanism were a manifestation of "electricity in motion" – as contrasted with the older electrical phenomena which represented "electricity in tension." Since there was no evidence of accumulation of electricity at any point in a circuit it followed that the current could be represented figuratively by the flow of an incompressible fluid along rigid and inextensible pipes. Ohm used Fourier's analyses of the conduction of heat to derive electrical laws and he was instrumental in developing the concepts of "current" and "electromotive force."[1] Thus since the earliest days of electrical theory, electro-motive force became endowed with the attributes akin to a mechanical force of hydraulic pressure, and electric current has been thought of as being of similar nature as mechanical velocity or the velocity of fluid flow. Undoubtedly, these classical concepts form the historical basis for equivalent circuit analysis as it is known today.

The early analogies became especially important during the end of the 19th century when ac electricity was still in its infancy while the theory of vibrations and sound had been already highly developed by Rayleigh and others. It was discovered that certain differential equations developed for use with vibrating mechanical bodies were equally applicable to electrical quantities. Rayleigh was among the first to bring the subject of alternating current electricity within the scope of acoustics and to prove that similar mathematical principles were applicable to both phenomena.[2]

Much has happened during the half century which followed Rayleigh's writings to change the relative technological positions of electricity, acoustics and mechanics. The improvement in electrical circuit elements, oscillators, amplifiers, oscillographs and meters – and indeed the perfection of the "analogy" computer – have made of the electrical network a most useful and flexible analytical tool. Therefore, we find an ever-increasing tendency to turn to the analogous electrical circuits for solution of mechanical, acoustical and other problems.

After having been introduced to a subject as old and venerable as this, the reader might wonder what there is new to be said about it. Surprisingly enough, the study of analogies has had a recent spurt in activity. New uses as well as limitations of analogies are being discovered almost daily. Complex physical organizations are being put into form manageable by analogies. Definitions and terminology are being brought in line with the new developments. The object of this paper is to attempt to give the reader a broad view of the subject to acquaint him with some of the new thinking regarding analogies.

II. THE EFP AND THE IFP ANALOGIES

The reader should be cautioned at this time that the traditional concept of similarity between voltage-force-pressure and current-velocity-fluid velocity is not the only one upon which a system of analogies can be based. During the past quarter century, through the efforts of Firestone[3] and others, it has become known that it is possible to establish another consistent system of analogies based upon certain mathematical similarities between electrical current, force, and pressure on the one hand, and voltage, velocity, and fluid flow on the other. The older "classical" analogy is currently being spoken of as the "voltage-force-pressure" analogy while the newer analogy (originally called "mobility" analogy by Firestone) is often referred to nowadays as the "current-force-pressure" analogy. For brevity we call them the EFP and the IFP analogies, respectively.

It seems feasible to apply either analogy about equally well to the solution of various problems, although it is generally recognized that the EFP analogy is the more advantageous with respect to acoustic devices and electrostatic (condenser, piezoelectric) transducers, while the IFP analogy is the more adaptable to mechanical devices and electromagnetic (magnetic, magnetostrictive) transducers. (Incidentally, equivalent circuits for transducers are a field in themselves and they are not treated here.) Almost everyone doing much equivalent circuit work eventually becomes conversant with both analogies. The casual user will avoid confusion by choosing a single analogy.

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* Manuscript received June 1, 1954.

[1] Firestone, "A new analogy between mechanical and electrical systems," Jour. Acoust. Soc. Amer., vol. 4, pp. 239-267; 1933.

[2] Lord Rayleigh, "The Theory of Sound," Dover Publications, N.Y., vol. 1, p. 433, etc.; 1945.

[3] W. Dampier, "A History of Science," The MacMillan Company, N.Y., p. 232, etc.; 1944.

In the writer's opinion, the classical EFP analogy is to be preferred because electrically-trained people find it the easiest to comprehend and because it has decided advantages in connection with acoustic devices which, after all, are the principal domain of the audio technologist. However, there are differences of opinion on this matter, and some authors prefer to use the IFP analogy.

The relationships which are the basis of the EFP and the IFP analogies are shown in Table I. In this table it is assumed that all circuit elements are constant and all variables are steady-state RMS values. In each box under the Electrical, Mechanical and Acoustic elements are shown the term and its commonly used symbol, name of the unit (if available) and the unit in cgs and mks systems. Before World War II practically all work in acoustics was done in the cgs system and many acousticians prefer to continue using this system. Lately, however, the mks system has gained recognition and is used by several writers.

TABLE I

ACOUSTICAL QUANTITY	MECHANICAL QUANTITY	ELECTRICAL QUANTITY EFP ANALOGY	IFP ANALOGY
Sound Pressure (p) microbar newton per sq. m	Force (F) dyne newton	Voltage (E) volt	Current (I) ampere
Volume velocity (U) cu. cm per sec cu. m per sec.	Velocity (v) cm. per sec. m per sec.	Current (I) ampere	Voltage (E) volt
Volume displacement (V) cu. cm cu. m	Displacement (D) cm m	Charge (Q) coulomb	Impulse volt-sec.
Acoustic Resistance (R_A) rayl (dyne-sec-cm^{-5}) mks-rayl (newton-sec-m^{-5})	Mechanical Resistance (R_M) mech. ohm (dyne-sec-cm^{-1}) mks-mech. ohm (newton-sec-m^{-1})	Resistance (R) ohm	Conductance (G) ohm
Inertance (M_A) gram-cm^{-4} kg-m^{-4}	Mass (M) gram kg	Inductance (L) henry	Capacitance (C) farad
Acoustic Compliance (C_A) cm^5-dyne^{-1} m^5-newton^{-1}	Mechanical Compliance (C_M) cm per dyne m per newton	Capacitance (C) farad	Inductance (L) henry
Acoustic Impedance (Z_A) $Z_A = p/U$	Mechanical Impedance (Z_M) $Z_M = F/v$	Impedance (Z) $Z = E/I$	Admittance (Y) $Y = I/E$

III. ACOUSTIC STRUCTURES

Acoustic structures consist of volumes of air which, in accordance with the EFP analogy, comprise the "springy" or capacitive elements. These may be connected together by conduits such as pipes, apertures, slits, etc. Flow of air through a pipe is accompanied by an increase in kinetic energy because of the acceleration of the mass of air as it flows from the volume into the pipe and vice-versa. Therefore, a pipe or aperture defines a mass-type or inductive element. Acoustic resistance or damping is obtained through the use of capillaries, slits, or crevices, such as the interstices between the threads of cloth through which the air is caused to flow, with the accompaniment of viscous friction. Additionally, when the openings connect to the atmosphere, sound is received or radiated by the acoustic structure and the impedance of the medium becomes a part of the acoustic structure.

Impedance values for acoustic network elements have been treated by various writers[4] and derivations will not be given here. The values applicable to the most common elements are shown in Fig. 1, which also includes the equivalent electrical representation. Writing the acoustical quantities P and U directly in the equivalent electrical circuit instead of the corresponding electrical quantities E and I serves to eliminate confusion. The physical constants for use with this figure are given in Table II in both the cgs and the mks systems. To illustrate the methodology of network synthesis by means of an ex-

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[4] H.F. Olson, "Elements of Acoustical Engineering," D. Van Nostrand Company, Inc., N.Y., p. 86, etc.; 1947.

TABLE II

PHYSICAL CONSTANTS FOR ACOUSTIC NETWORK ELEMENTS

QUANTITY	SYMBOL	CGS UNITS	MKS UNITS
Atmospheric Pressure (Usual, at sea level)	P_0	10^6 dynes/cm^2 (microbar)	10^5 newtons/m^2
Density of air at 20°C (at sea level)	ρ	1.2×10^{-3} gram/cm^3	1.2 kg/m^3
Coefficient of viscosity for air	μ	1.8×10^{-4} gram/cm-sec (poise)	1.8×10^{-5} kg/m-sec (mks poise)
Ratio of spec. heats c_p/c_v for air	γ	1.41	1.41
Velocity of sound in air at 20°C	C_v	34,400 cm/sec	344 m/sec

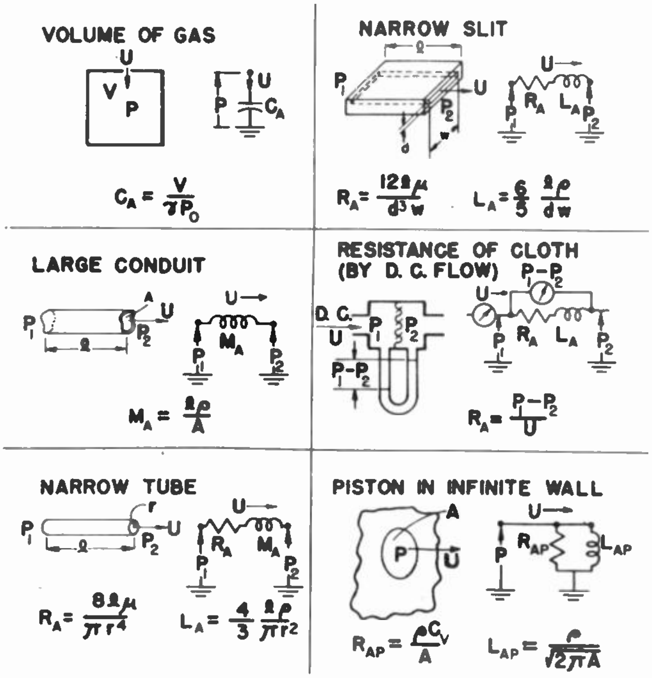

Fig. 1 – Acoustic impedance values of most common elements by the EFP analogy. For values of physical constants, see Table I.

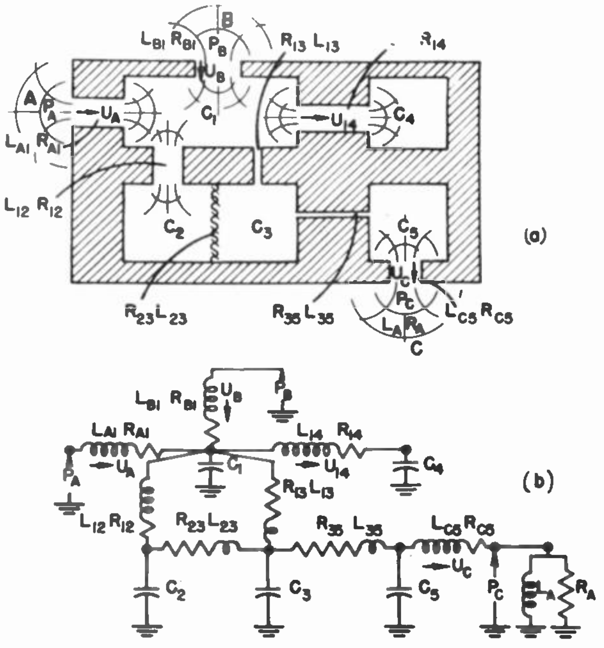

Fig. 2 – Representative acoustic structure (a); Equivalent circuit by the EFP analogy (b).

ample, an acoustic structure is shown in Fig. 2(a) and its equivalent circuit in Fig. 2b. The structure is assumed small compared to the wavelength and therefore representable by lumped impedance elements. This structure contains five volumes of air C_1 to C_5 represented in Fig. 2(b) by corresponding electric capacitors. Since the pressure throughout a volume is constant, a connection made to any part thereof is subjected to the same sound pressure. Constant pressure is tantamount to a constant potential, and hence the whole volume may be considered equivalent to an equipotential "terminal." This is analogous to the case of a capacitor consisting of an isolated sphere in space where the "other" terminal may be thought of as being a "ground."[5] Therefore, one side of each capacitor C_1 to C_5 is shown connected to "ground." One obvious consequence of the grounding of the one side of the acoustic capacitor is the proposition that the equivalent acoustic capacitances of volumes cannot be connected in "series."

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[5] B.B. Bauer, "Transformer analogs of diaphragms," Jour. Acoust. Soc. Amer., vol. 23, no. 6, pp. 680-683; 1951.

At this point it is timely to make a distinction between the "terminals" and the "points of connection." Professor Firestone defines a terminal, in part, as follows: "A terminal of a specified type is the entire portion of an element or structure which is compelled to have the same value of one specified measurable quantity at any instant."[6] Thus the conduits leading into the volumes in Fig. 2(a) have different points of connection, but still are connected to a single pressure terminal.

The volumes are connected by conduits which may have the form of pipes, capillaries, slits, or cloth barriers. As may be seen in Figs. 1 and 2, conduits define acoustic inertance and resistance. Conduits of relatively large cross-section, (i.e. having minimum cross-sectional dimensions of several mm or more) are predominantly "inductive." Conduits of small cross-section, such as capillaries or thin slits, (with minimum cross-sectional dimensions of a few thousandths of an inch or less) are predominantly "resistive." Cloth, suitably mounted to prevent vibration forms an excellent acoustic resistance and it is widely used as damping element in acoustic structures. R_{23} is a cloth resistance. At each point of connection between a conduit and a volume where there is a change in cross-section, there is acceleration of the air from zero velocity to a velocity U within the conduit. The flow of air is shown by means of streamlines at the end of conduits. This acceleration causes an end-effect inertance added to inertance of the conduit. This end effect may be approximated by assuming the existence of a mass-less piston at the ends of the conduit.

From the point of view of methodology the following procedure may be followed: First, the acoustic compliances of all volumes are represented by capacitors connected to ground (or to a common buss). Next, the free terminals of all capacitors are interconnected by the inductive and resistive elements which comprise the conduits. In the equivalent circuit diagram, it is convenient to show the connections as being predominantly inductive or predominantly resistive by the relative length of the inductive and resistive components. Let the sound pressure impinging upon the entries A and B be P_a and P_b respectively. These pressures are shown as potentials to ground.[5] At C, the structure is confronted by the radiation impedance of the medium, Z_a. This impedance is represented approximately by a parallel combination of inductance L_a and resistance R_a. The pressure at the mouth of C can be obtained by multiplying the volume current U_c by Z_a.

IV. MECHANICAL ELEMENTS

The construction of equivalent circuits of mechanical structures by the EFP analogy is somewhat more complicated than that of acoustic structures. Mechanical forces and motions have magnitudes and directions, and hence, are vector quantities, while electrical potentials and currents in a circuit are scalar. To avoid complications resulting from this distinction, we restrict our analysis to mechanisms constrained to move along one axis. The mechanical network elements, or building blocks, are shown in Fig. 3. "Free" mass M can be represented by inductance L-short-circuited upon itself, and the loop current i represents the velocity v. The spring C_m has two ends which are acted upon by equal and opposite forces F. Therefore, the equivalent condenser C has two pairs of terminals acted upon by equal and opposite voltages e. The velocities of spring ends v_1 and v_2 are, in general, unequal. They are represented by currents i_1 and i_2. The compression of the spring occurs at a rate $v_1 - v_2$ which corresponds to the current flow $i_1 - i_2$ through the condenser. Similar considerations apply to the mechanical resistor R_m which is represented by the electrical resistor R_1.

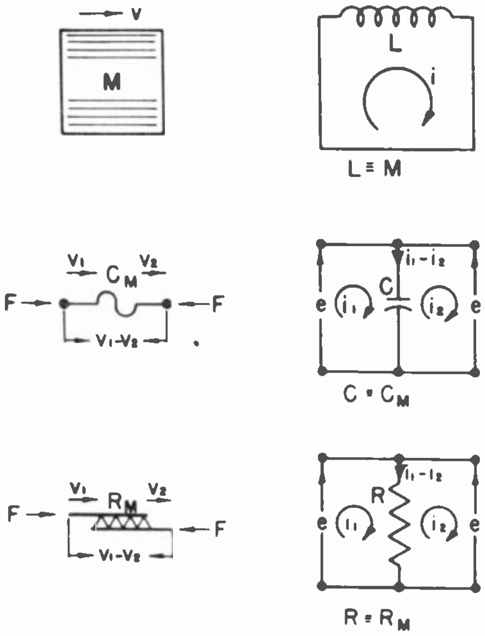

Fig. 3 – Basic mechanical network elements and equivalent electrical circuits by the EFP analogy.

The short circuited inductance is equivalent to a free mass. To represent a mass which is acted upon by a force, an emf generator must be coupled into the loop. If the motion of the mass is impeded by springs or damping elements, then means must be found to couple these impedances into the circuit. One way of achieving this is by breaking the circuit of the loop and connecting the generator or impedance to the two resulting terminals. This practice is not always possible in the equivalent analysis of mechanical structures as may be seen from the following set of examples.

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[6] Firestone, correspondence with the author, 1953.

In Fig. 4(a) we have a relatively simple system consisting of three masses connected by two springs. On the right hand side is the equivalent circuit. To obtain this equivalent circuit, we have broken the loop connecting the two ends of the inductance M_1 at the left hand side, for the purpose of inserting a generator with a voltage E which represents the force F, and again, at the right hand side, for the purpose of connecting one set of terminals of the capacitor C_{12}. Similar connections have been performed elsewhere in the circuit. This procedure is almost self-evident and poses no special difficulty. A more complicated situation is shown in Fig. 4(b) which depicts four masses connected by four coupling springs. This structure is not as simply portrayed as the previous one. However, by a bit of visualization and cut-and-try methods it can be determined that the correct equivalent circuit is shown on the right hand side of the figure. While this electrical circuit has little geometric resemblance to the mechanical structure, its correctness may be checked by noticing that the sum of the voltage drops across the elements in the circuit of the inductances is the same as the sum of the forces acting upon the corresponding masses. This is an acknowledgement of the equivalence between the laws of Kirchhoff and d'Alembert.

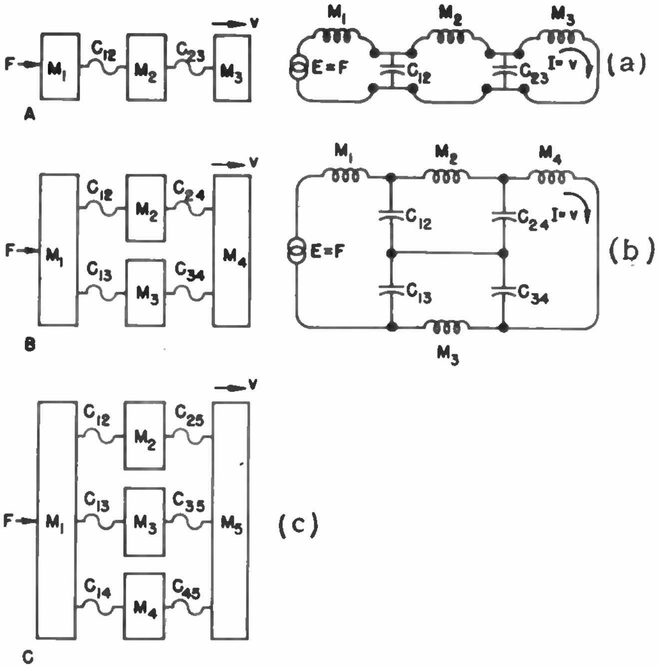

Fig. 4 – Mechanical structures of increasing complexity and equivalent circuits by the EFP analogy.

A still more complicated structure is shown in Fig. 4(c) which shows five masses interconnected by six springs. An equivalent circuit is not given at the right hand side, because none can be found by the means discussed so far.

V. TRANSFORMER COUPLINGS

Thus, it is seen that mechanical systems of progressively increasing complexity present progressively increasing difficulty in the synthesis of the equivalent circuits by the EFP analogy.

One of the reasons is to be found in the fundamental difference between our basic concepts of mechanical elements and the corresponding electrical circuit components. As shown in Fig. 5(a), a mass is usually thought of as a rigid body obeying Newton's laws; its counterpart, i.e., an inductance, comes to mind as a coil with two free terminals. It is obvious that no current can flow through such coil. It helps to clarify our thinking to visualize a free mass as being equivalent to an inductance short-circuited by means of a loop as shown in dotted line. Every point of the circuit carries the same current, the same as every point of the mass travels with equal velocity. The mass constitutes a single velocity terminal, and the loop constitutes a single current terminal. A spring, in 5(b), has two velocity terminals, but the equivalent condenser, at right, has four points of connection. To represent a free-free spring, these points of connection must be closed with loops as shown by dash-lines. Each of these loops becomes a current terminal corresponding to the respective ends of the spring. Similar considerations apply to the mechanical resistor in Fig. 5(c). By this process the terminals and points of connection of mechanical elements become identified with the corresponding entities of electrical circuit elements.

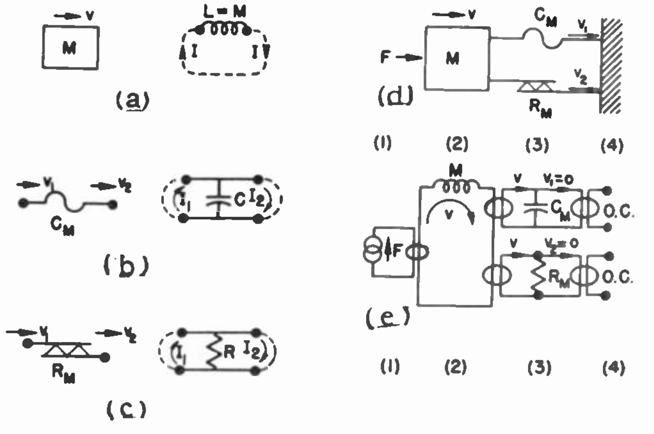

Fig. 5 – "Free" mechanical elements and transformer couplers to denote connections between mechanical elements.

Next, means must be found to couple the loops without breaking the circuit. This can be readily done by bringing the corresponding wires together and surrounding them with an ideal magnetic core of infinite permeability and zero losses, thus forming an ideal transformer of 1:1

turns ratio.[7] As an example of this type of connection, Fig. 5(d) represents a system consisting of a force (1) driving a mass (2) which is coupled by means of a spring and mechanical resistor (3) to the reference frame (4). The equivalent circuit is shown in Fig. 5(e) where constant voltage generator (1) is coupled to the inductance loop (2) which in turn is coupled to the corresponding terminals of a spring and resistance (3). The latter are terminated in the reference frame (4) which appears as an "open circuit" since v_1 and $v_2 = 0$. The ideal cores are represented by the heavy circles. Writing mechanical quantities F, V, etc. directly in the equivalent electrical circuits instead of the corresponding electrical quantites E, I, etc. serves to eliminate confusion.

Figure 5(e) suggests immediately that if a mass is made vanishingly small, the mechanical circuit will reduce to a velocity junction, and the equivalent inductance-less loop becomes an electrical current junction. By the way of example, a velocity junction is shown in Fig. 6(a) and its equivalent circuit in Fig. 6(b). The velocity of all terminals at the junction is v. To facilitate the drawing of the ideal transformers in equivalent circuits the magnetic core can be omitted. Instead we have adopted the convention that two adjoining parallel wires constitute the two windings of the ideal transformer.

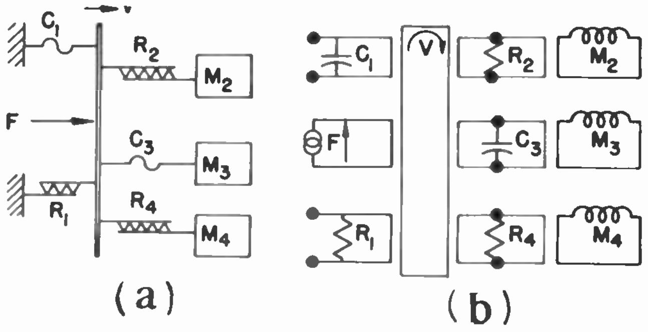

Fig. 6 – Velocity "junction" by the EFP analogy using transformer couplers.

The following section illustrates specific application of transformer couplers to the problems of equivalent circuit analysis.

VI. UTILIZATION AND REMOVAL OF TRANSFORMER COUPLINGS

As we demonstrate the use of transformer couplings, we shall also indicate methods for removing them without altering the voltage and current relationships, therefore arriving at the conventional-type analogy circuits. The use of ideal transformers adds no difficulty in the analytical treatment of circuits. However, for the purposes of experimental circuit work, it is desirable to remove the transformers, wherever possible.

Our first example is shown in Fig. 7(a). The mechanical system consists of three masses interconnected by springs and resistors in tandem. In Fig. 7(b) is the equivalent circuit by EFP analogy with transformer couplings. The methodology for drawing these circuits consists first in drawing the loops constituting velocity junctions and those containing masses, and next adding the condenser and resistor elements and driving generators, with the aid of transformer couplers.

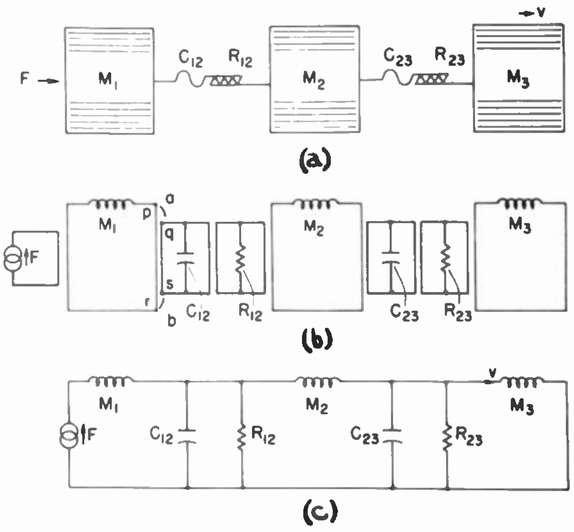

Fig. 7 – (a) Mechanical structure; (b) Equivalent circuit by EFP analogy with transformer couplers; (c) Transformer couplers removed.

The circuit equations of Fig. 7(b) can be written as if the transformers were not present simply by remembering the voltage and current relations in an ideal transformer. In this manner, the usual mesh and junction equations can be written and solved in an ordinary manner.

For experimental circuit work, as in analogy computers, it is desirable to remove the transformers. This must be done without disturbing any voltage and current relations in the circuit. The simplest way of doing this is to select any two transformer-coupled meshes which have no *conductive* connection and connect together two adjacent points, say p and q, of the coupling transformer with a jumper "a." At that instant, points r and s become equipotential, since the primary and secondary voltages in a 1:1 transformer are identical. Therefore, r and s can be connected by jumper "*b*". Now the transformer $pqrs$ has no further purpose and it may be removed from the circuit. Each additional loop in Fig. 7(b) which has no conductive connection to the circuit can be connected in this manner resulting in the circuit of Fig. 7(c), which is the conventional EFP analogy circuit for the array in Fig. 7(a).

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[7] B.B. Bauer, "Transformer couplings for equivalent network synthesis," Jour. Acoust. Soc. Amer., vol. 25, pp. 837-840; 1953.

A somewhat more complicated mechanical array is shown in Fig. 8(a). It consists of four masses interconnected by four sets of springs and mechanical resistors. Fig. 8(b) is the equivalent circuit by impedance analogy with transformer couplings. It is gratifying to note that the geometry of the electrical circuit is very much like the geometry of the mechanical circuit. There are 13 transformers, 12 of which can be removed if desired, as in the previous example. In Fig. 8(b) this is indicated by the jumpers placed at either side of the transformers, and it results in the circuit of Fig. 8(c). The transformer $pqrs$ cannot be removed in this manner since a jumper between points p and q will short out the inductance M_3 and upset voltage and current relations. However, if we can trace an impedance-less conductive connection between the corresponding points of the windings, such as the points p and q, then these points become equipotential and may be connected together. This condition will occur if the inductance M_3 is moved from the branch p-t to the branch r-u, as shown in dotted outline. This can be done with impunity since the sum of voltage drops in the mesh t-p-r-u is not affected by the position of M_3. After M_3 has been moved to its new position, p-q and r-s can be connected as shown by the dotted jumpers a and b, resulting in the removal of the last transformer. The final circuit is given in Fig. 8(d). This is similar to the circuit in Fig. 3(b), except for the advantage of having been synthesized without the need for the use of the cut-and-try approach.

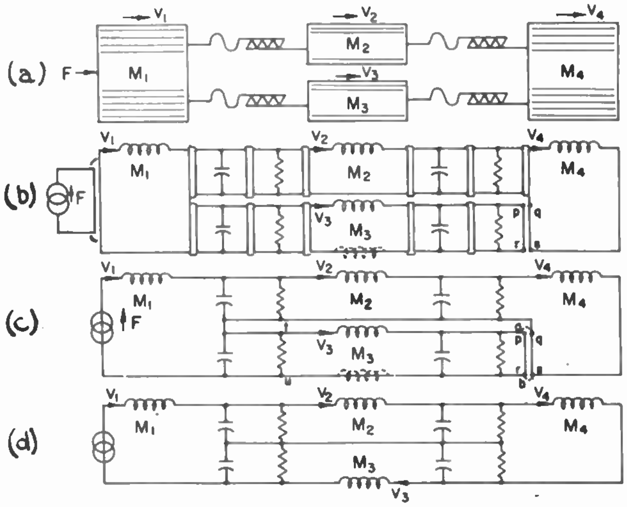

Fig. 8 – (a) Mechanical network; (b) Equivalent circuit with transformer couplers; (c) Removal of transformer couplers; (d) Final equivalent circuit.

In Fig. 9(a) is the mechanical array consisting of five masses M_1 to M_5 interconnected by three independent spring-mass-spring systems, which is the same as that shown previously in Fig. 3.

The equivalent circuit can be readily obtained by the transformer analogy as shown in Fig. 9(b). Again, we notice a geometric resemblance between the circuit and the structure, and this is a great help in drawing these circuits. Let us proceed to remove as many transformer couplers as possible. By removing, first, all the transformers between the loops with no conductive connection we successively remove all the transformers except f and g as shown by the jumpers numbered 1 to 22 inclusive. The resulting circuit appears in Fig. 9(c). The transformers f and g remain. To remove f, the inductance L moved around to the other side of the loop as shown in the previous example. As soon as this is done, the connections 23 and 24 can be made, therefore removing the transformer f. Transformer g remains and cannot be removed. The final equivalent circuit is shown in Fig. 9(d). It is evident that the user would be needlessly taxing his ingenuity if he attempted to draw the equivalent circuit of Fig. 9(a) by the conventional method of impedance analogy.[8],[9]

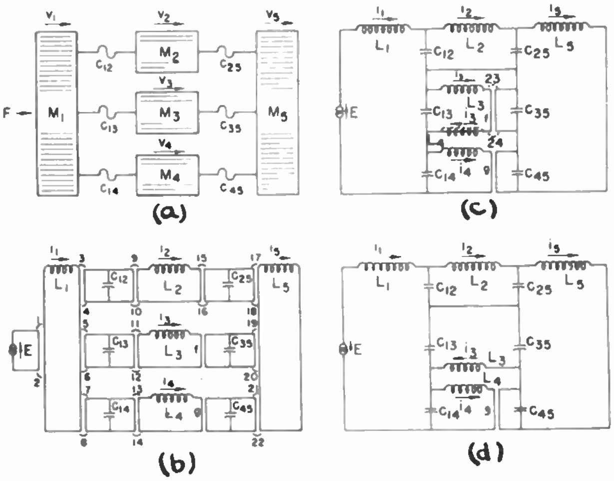

Fig. 9 – (a) Mechanical network; (b) Equivalent circuit with transformer couplers; (c) Removal of transformer couplers; (d) Final equivalent circuit. Transformer "g" cannot be removed.

VII. ANALOG FOR DIAPHRAGMS

The transfer of energy between the acoustic and the mechanical side of a structure requires the use of some sort of diaphragm. Ideal transformer couplers have been found to be of much value in representing the action of diaphragms. Each side of a piston-like diaphragm or a portion thereof of projected area A_n may be thought of as a means for transforming an actuating force F_u into a sound pressure $p_n = F_u/A_n$. At the same time, linear velocity v_n of the surface causes a volume velocity $u_n = A_n v_n$. This mechanical-acoustic transformation is seen to be analogous to the transformation of voltages and currents between the primary and the secondary

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[8] A. Bloch, in: Jour. Inst. Elec. Engrs. (British), vol. 92, p. 157; 1945.

[9] A. Bloch, in: Proc. Phys. Soc. London, vol. 58, p. 677; 1946.

windings of an ideal transformer of turns ratio $1{:}1/A_n$. Furthermore, the impedance connected to the secondary appears reflected at the primary multiplied by the ratio $1{:}1/A_n^2$. This is analogous to the impedance transformation between mechanical and acoustical systems coupled by a diaphragm. The use of transformer analog has the advantages of (1) separating the mechanical and the acoustic portions of the circuit and (2) allowing the mechanical elements to be represented in terms of mechanical impedance units and acoustical elements in terms of acoustical impedance units, and (3) making possible the synthesis of circuits which are not feasible without the use of transformer analog.[5]

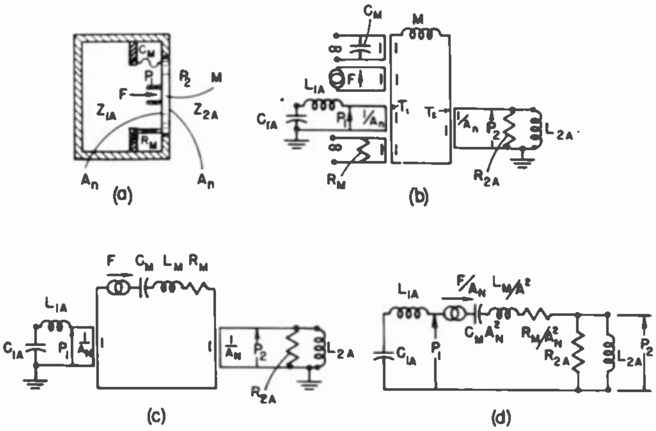

Fig. 10 – (a) Piston diaphragm in an enclosure; (b) Equivalent circuit with transformer couplers; (c) Partial removal of transformer couplers; (d) Total removal of transformer couplers.

VIII. PISTON DIAPHRAGM

A piston diaphragm, together with its equivalent electrical circuit based upon the transformer analogy is shown in Fig. 10. By the way of example, in (a) the piston is mounted in a box so that one of its sides encloses a cavity and the other is allowed to radiate into the medium. This will be recognized as the familiar direct radiator loudspeaker in an enclosure. Let the piston impedance be a mass *M*, connected to the reference frame by a mechanical resistor R_M and a spring C_M which comprise the annulus of the cone. In (b) the mass is shown as an inductance *M* in the circuit of a loop, with the moving coil force generator and the mechanical impedances coupled into the circuit by means of transformer couplers. Both sides of the piston have equal projected areas A_n, which are acted upon by sound pressures P_1 and P_2, respectively. Transformers T_1 and T_2 represent the two active areas of the diaphragm.

The left hand side of the piston is confronted by the impedance of the box. This is known to be an inductance L_{1A} owing to the mass of the air and a compliance C_{1A}, formed by the spring of the air. The right hand side confronts the radiation impedance of the medium Z_{2A}, which is represented by a parallel combination of resistance R_{2A} and inductance L_{2A}.[10] A convenient simplification is achieved by removal of the 1:1 transformers as shown in (c). This is always possible in the case of a diaphragm with two equal sides, and which has no mechanical and acoustical connections to other diaphragms. A further simplification takes place through a removal of the $1{:}1/A_n$ transformers as shown in (d). When this is done the impedance of the mechanical elements must be multiplied by the factor $1/A_n^2$ to be in conformity with the impedance of the acoustic elements. The transformer concept has permitted easy visualization and solution of problems which have not had sufficient attention heretofore.

IX. DIAPHRAGMS WITH SUBDIVIDED SIDES

As an example of the use of transformer analog of diaphragms, we formulate an improved equivalent circuit for a moving coil microphone or receiver, shown in Fig. 11(a). The equivalent circuit is shown in 11(b). For simplicity, the mass of the diaphragm and the voice-coil, together with the compliance and resistance of the suspension are placed directly in the circuit of the loop, as shown in the previous example. Let the effective projected area of the external diaphragm surface be A_1. The inside surface of the diaphragm is divided by the moving coil into two surfaces having effective projected areas A_2 and A_3 where $A_1 = A_2 + A_3$. Each of the latter two surfaces is confronted by cavities forming acoustic compliances C_2 and C_3; these cavities being interconnected by the circumferential slits formed between the moving coil

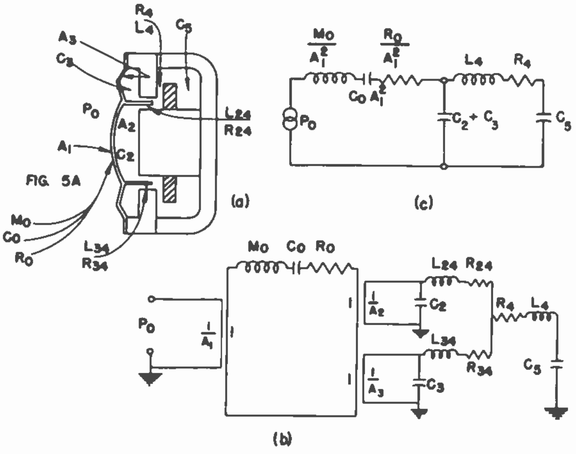

Fig. 11 – (a) Moving coil dynamic microphone; (b) Complete equivalent circuit with transformer couplers; (c) Conventional approximate equivalent circuit.

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[10] B.D.H. Tellegen, "The Gyrator, a new electric network element," Philips Res. Rept. 3, pp. 81-101; 1948.

and the pole pieces, and which define acoustic impedances Z_{24} and Z_{34}. At their point of juncture, they are connected together to another circumferential slit or similar contrivance furnishing an acoustic impedance Z_4. The fluid volume through Z_4 enters the cavity within the body of the microphone which forms an acoustic compliance C_5. This provides an exact equivalent circuit of the microphone. For comparison, the approximate equivalent circuit often published is given in Fig. 11(c). The approximate circuit is correct only in the specific instance when $A_2/A_3 = C_2/C_3 = Z_{34}/Z_{24}$, which condition permits the removal of transformers, and, not so incidentally, avoids cross-resonances between the internal cavities and slits.[5]

X. RECAPITULATION AND PROJECTION

By this time the reader has probably gleaned an understanding of some of the changes taking place in the early concept of electro-mechano-acoustic equivalences of Volta, Ohm, and Rayleigh. Today, the physicist no longer seeks mere conformity between the differential equations governing the variables, but attempts to find other aspects of geometric and physical similarity between the structure and its equivalent circuit. In this manner the equivalent circuit is developed with greater ease and assurance than heretofore and also certain equivalent circuits can be synthesized which are not feasible by the older methods.

Geometric conformance between an acoustic circuit and its equivalent network comes about naturally with the EFP analogy, especially with the realization of the fact that a volume can be represented by a grounded capacitor. The physical terminals of pipes, capillaries, etc. connecting these volumes are in a 1:1 correspondence with the electrical terminals of corresponding electrical components, i.e. inductors and resistors. Therefore, there is no difficulty in synthesizing acoustic structures. Equivalent circuits of mechanical structures have presented difficulty with the EFP analogy in the past because of the failure on the part of the early investigators to provide configurations of the electrical circuit elements with terminals chosen to have correspondence to the terminals in the respective mechanical circuit elements. When this condition was remedied, as by use of transformer couplers, these difficulties largely disappeared.

An alternative solution to the use of transformer couplers in the synthesis of equivalent circuits of mechanical structures is the use of the IFP analogy. IFP analogy is to mechanical structures what EFP analogy is to acoustic structures. However, in adopting the IFP analogy, the user will find that he has traded one set of difficulties for another, since transformer couplers are required in the synthesis of certain acoustic circuits.[7] In many electro-acoustic applications, the mechanical circuit is relatively simple, but the acoustical structure is complicated; hence the advantage of the EFP analogy. In the converse situation, of course, the IFP analogy may be of real benefit.

A still further solution is the use of what B.D.H. Tellegen[10] has called a "Gyrator" which is a "black box" with two sets of terminals, the current and voltage of one set being related to the voltage and current of the other set, respectively, by a real constant. An equivalent circuit for the mechanical structure in accordance with the IFP analogy could then be connected to one set of terminals and an equivalent circuit for the acoustic structure, in accordance with the EFP analogy, would be connected to the other set of terminals. Unfortunately, the "Gyrator" has not been physically realized, and there are sound reasons for asserting that it cannot be realized by purely electrical circuit means. The nearest approach is a pseudo-gyrator called a "Transverter" proposed by this author over a decade ago. This device is shown in Fig. 12. It is trivial to prove that in this type of device $E_P = jI_S$ and $I_P = jE_S$. A similar device can be obtained by substituting terms of opposite reactance. Networks of this type or their inverse will provide a primary voltage and current related to the secondary current and voltage by the constant of proportionality j or $-j$. In a practical Transverter, to maintain the proper relationship between the elements, the reactances must be variable, and suitably coupled to the oscillator to maintain the proper impedance relationships at all frequencies. A device of this type is difficult to build, and because of its 90° phase-shift it does not answer all the problems of coupling between the EFP and the IFP analogy. Therefore, at present the choice of a single analogy and the use of transformer couplers is a more practical answer. Evidently, however, much remains to be done in this field.

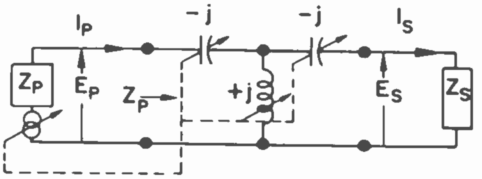

Fig. 12 – "Transverter" – Impedance connected across one set of terminals appears inverted at the other set of terminals.

ACKNOWLEDGEMENT

The very stimulating correspondence and discussions with Dr. Floyd Firestone and Dr. Horace Trent, dealing with the problem of analogs, is acknowledged with gratitude.

FREQUENCY MODULATION PHONOGRAPH PICKUPS*

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HISTORICAL INTRODUCTION

Phonograph pickups have much in common with microphones. In fact, European literature generally refers to them, as well as to other types of such vibration transducers, by the generic name microphones, whether they be used for the translation into electrical vibration, of sound, mechanical vibrations of solid bodies, molecular vibrations in solids, etc.

We in America divide this broad concept into two parts and call sound-in-air transducers "microphones." The mechanical vibration transducers we call "pickups." This is probably a more sensible nomenclature, since the word "microphone" means microsound and connotes generally the idea of a sound-to-electrical vibration transformation. Pickups are considered as pure mechanical vibration transducers, chiefly where there is little or no accompanying sound, and involve in no way the translation of such accompanying sound waves into electrical waves.

CAPACITY MICROPHONES

The DC Polarized Condenser Microphone

The Wente dc polarized condenser microphone (Ref. 1) was first disclosed in 1917, and has, in the intervening years, and particularly since radio broadcasting began in the early nineteen twenties, become widely known and used. It has, however, some serious disadvantages, due to its high audio impedance and low output. These disadvantages manifest themselves as current-leakage produced noises, the requirement of good shielding against electro-statically introduced hum or other electrical disturbances, the need of a very high gain af amplifier, and the placement of the first tube of that amplifier in or immediately adjacent to the microphone. The latter is mandatory due to the very high audio frequency impedance of this microphone. All of this combines to make a bulky and cumbersome design, further complicated by the need for power input and af output lines in the connecting cable. An additional drawback is the ever-present falling-off of the af output at very low audio frequencies unless a prohibitively-high, charge-limiting resistor be used. While enjoying wide use and popularity for some years after it supplanted the older double-button, stretched-diaphragm carbon microphone, it has since fallen into obsolescence, except for certain restricted uses, and has been supplanted by microphones of other types, such as the piezo-electric, ribbon, or coil (electro-dynamic) types.

THE RF CONDENSER MICROPHONE

Because the principle of direct, mechanicoelectric, frequency modulation has had no more than a few superficial, scattered references in American technical literature, outside of patents and because it has many applications in electronics (for example, it has been used in numerous investigations of vibrations of bodies too light or too delicate to admit of contact type pickups, as in microphonics of vacuum tube elements and the vibrations of violins; as a pickup for commercial electronic musical instrument vibrators, such as strings (including non conductors), reeds, rods, tubular chimes, etc.); and more particularly, because it is utilized in many of the phonographic frequency-modulation systems (including the Weathers pickup, the Zenith Cobra Pickup, and a type used by Motorola's Hi-Fi system) it is pertinent to inquire into the origins and background of these systems, which were concerned first with microphones, and later with phonograph pickups.

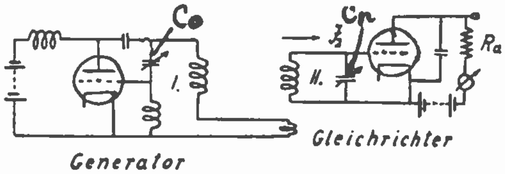

Bild 2. *Die Schaltung der „Halben Resonanzhöhe"*

Fig. 1

This transduction principle solves all of the problems involved in the dc polarized, condenser microphone. Because it is not a velocity-operative arrangement, as are af magnetic, electrodynamic and piezo-electric types, it is flat at any af vibration frequency of its control element. Its af impedance is of the order of a few ohms, so that electrostatic hum induction is absent. Used with a tuned rf transmission line or special bridge-type circuits, the oscillator-detector tube and its circuits may be separated by an ordinary one-conductor shielded cable, with no loss of efficiency.

The first published technical article on the frequency-modulation microphone principle, as applied in vacuum tube circuits, was made in Germany by H. Riegger (Ref. 2). The Riegger microphone circuit is shown in Fig. 1.

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*Manuscript received June 1, 1954

Fig. 2 shows the working point on the resonance curve of the transmitter or the receiver. The condenser microphone may be either C_o in the oscillator, or C_r in the receiver. Here the transmitter oscillator or the tuned receiver is frequency modulated, so that the working point P of the resonance curve of one slides up and down on the resonance curve of the other. This converts frequency modulation into amplitude modulation of the rf carrier in the receiver grid circuit, where it is detected and amplified into the plate load circuit for indication by the meter or other dc device, or for translation into sound by an appropriate electroacoustic transducer, or for further amplification and reproduction by a loudspeaker, or for the actuation of other devices. It may be added that because the sensitivity of such a system is extremely high, especially at the high or ultra-high radio frequencies, a high-gain audio amplifier is not needed, as much of the gain is provided in the rf circuit.

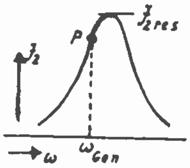


Bild 3. *Der Arbeitspunkt auf der Resonanzkurve bei der Schaltung der „Halben Resonanzhöhe“*

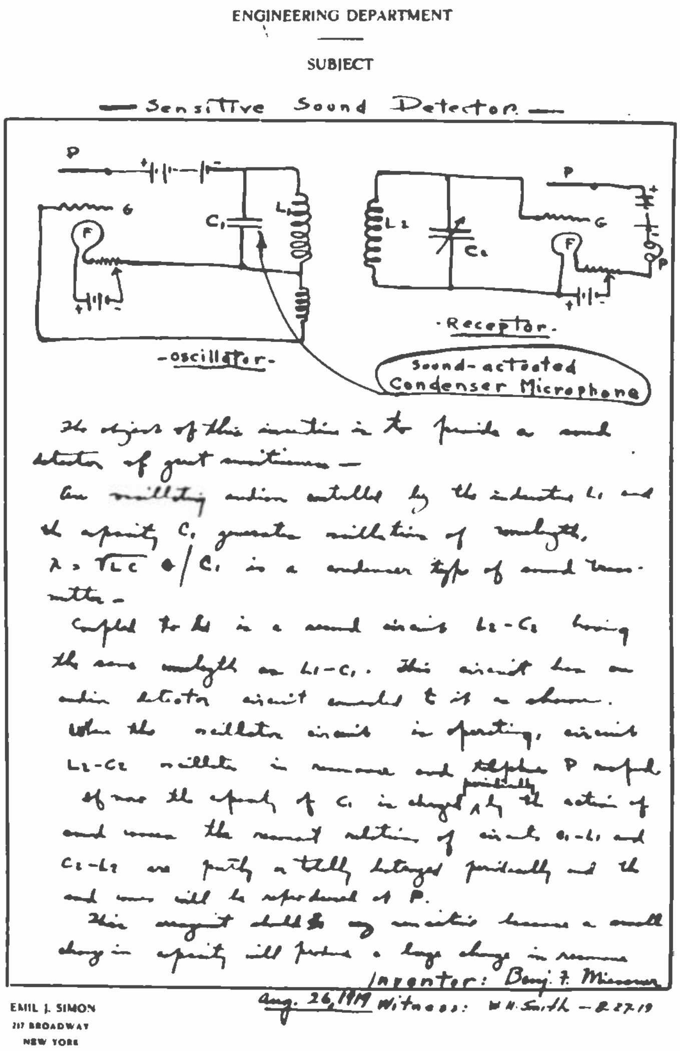
Fig. 2

PRIOR, HITHERTO UNPUBLISHED DISCLOSURES

Some years prior to the Riegger disclosure, however (while never hitherto published), the author conceived, reduced to practice by appropriate test, and disclosed privately to his radio engineering associates of that time, the precise Riegger arrangement, wherein the condenser microphone is placed in the transmitter's oscillator circuit in order to modulate its frequency.

Because of its historical significance, a reproduction of the recorded invention is shown in Fig. 3. No patent application was filed at that time on this invention. Radio broadcasting had not yet been introduced, and because such equipment was not suitable for wire telephony, there appeared to be but little demand for such a microphone system.

However, on June 8, 1927, when radio broadcasting and electric phonographs were in full swing, the writer, (then unaware, as are most radio engineers at this late date, of the Riegger disclosure), filed a patent application upon this principle, and disclosed its use for both microphone and phonograph pickup applications. This showed the condenser as a frequency modulator in both the oscillator and in the slightly off-tune receiver, and capacity types of phonograph reproducer.



ENGINEERING DEPARTMENT

SUBJECT

— Sensitive Sound Detector —

The object of this invention is to provide a sound detector of great sensitiveness —

An ~~oscillating~~ action controlled by the inductance L1 and the capacity C1 generates oscillation of wavelength, $\lambda = \sqrt{LC}$ / C1 is a condenser type of sound transmitter —

Coupled to this is a second circuit L2-C2 having the same wavelength as L1-C1. This circuit has an audion detector circuit connected to it as shown.

When the oscillator circuit is operating, circuit L2-C2 oscillates in resonance and telephone P responds. If now the capacity of C1 is changed periodically by the action of sound waves the resonant relation of circuits C1-L1 and C2-L2 are partly or totally destroyed periodically and the sound waves will be reproduced at P.

This arrangement should be of great sensitiveness because a small change in capacity will produce a large change in resonance

Inventor: Benj. F. Miessner

Aug. 26, 1919 Witness: W. H. Smith — 8.27.19

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Fig. 3

The original group of five drawings is reproduced here as Fig. 4. In this group of drawings, Fig. 1 shows a fixed frequency oscillation source, with a capacity-modulated, tuned receiver of simple type. Fig. 2 shows the receiver resonance curve with operating points *Xa* or *Xb*. In Fig. 3 is shown a vacuum-tube oscillator circuit, which is frequency modulated by the condenser type microphone or phonograph pickup, coupled to a fixed-tuned rf amplifier, with antenna radiator. Fig. 4 shows a fixed-frequency V.T. oscillator with a coupled, grid leak-condenser, am detector, having its tuned input circuit frequency-modulated by the condenser microphonic device, an af amplifier stage, and a loudspeaker. Fig. 5 shows a capacity-type phonograph pickup. Cited as ante-dating references against this patent application were the U.S. Patents to: Little (Ref. 3), Nyman (Refs. 4 and 5), Davis (Ref. 6), Bothe (Ref. 7), Reisz (Ref. 8), and Waltz (Ref. 9).

One other patent was subsequently found, but it was not cited by the Patent Office, nor was the Riegger disclosure cited. This patent is Ehret, #785,804 March 28, 1905 (Ref. 10). The earliest of these patents, namely,

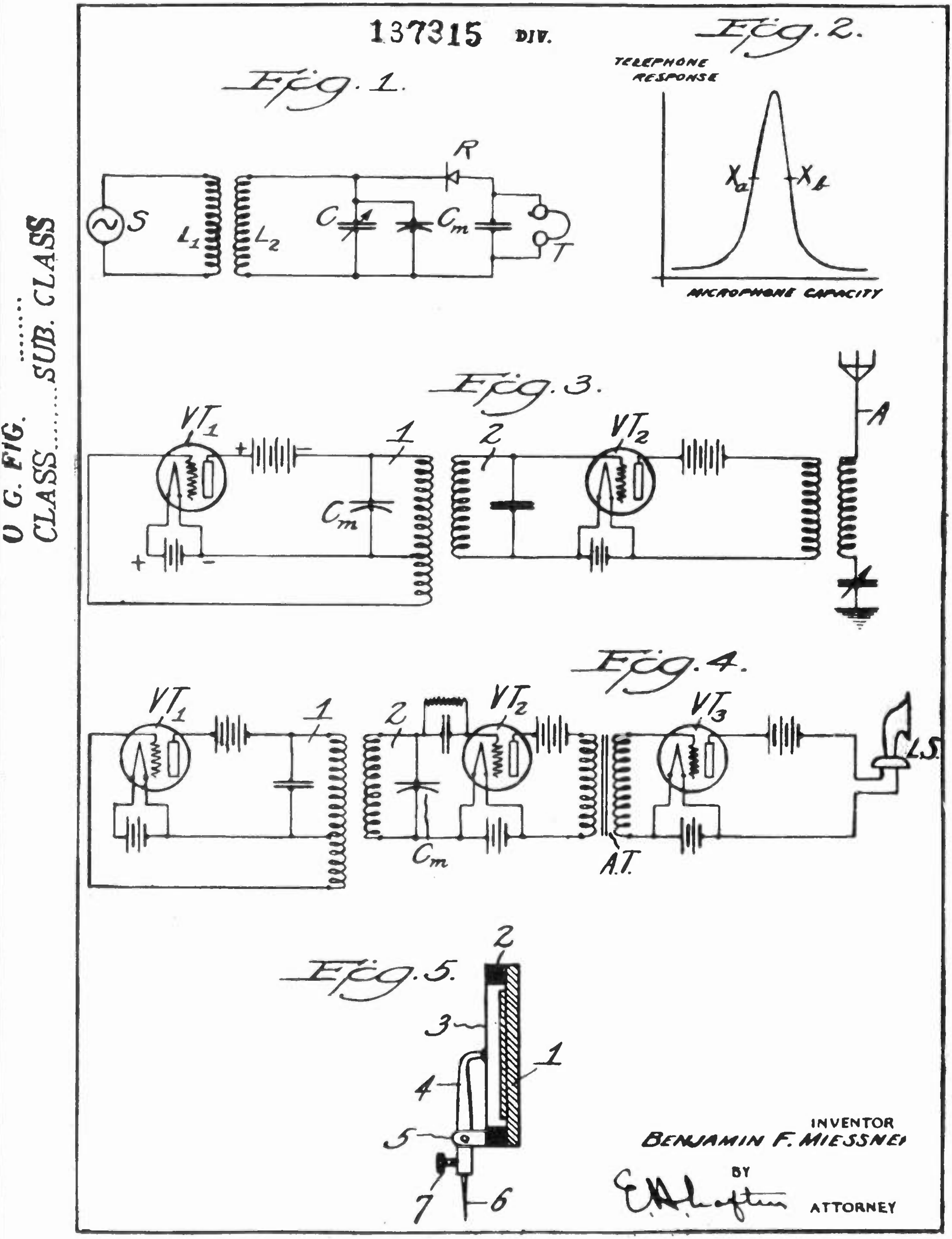
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Fig. 1.
S
L1
L2
R
C
Cm
T
Fig. 2.
TELEPHONE RESPONSE
Xa
Xb
MICROPHONE CAPACITY
Fig. 3.
VT1
1
2
VT2
Cm
A
+
-
Fig. 4.
VT1
1
2
VT2
VT3
Cm
A.T.
L.S.
Fig. 5.
1
2
3
4
5
6
7
INVENTOR
BENJAMIN F. MIESSNER
BY
ATTORNEY
U G. FIG.
CLASS.......... SUB. CLASS

Fig. 4

that to Cornelius D. Ehret, of March 28, 1905 and the later one to A. G. Davis (of the General Electric Co.) of Dec. 26, 1905, both show condenser microphones as frequency modulators for rf circuits. The Davis patent shows the condenser microphone only in the *receiver* circuit, using a fixed, super audible, frequency (ac generator) transmitter. Here it modulates the tuning of the *receiver* at the half resonance point (best is 70%) of the rf resonance curve.

The Ehret patent discloses use of the condenser transmitter, i.e. a spark discharge type of transmitter, with an ultra-audible spark discharge rate. There is also disclosure of transmitter keying circuits utilizing frequency modulation from one to another discrete frequency. This was widely used later in high-power, arc-type transmitters, where make-and-break keying systems for the entire rf power were not feasible.

Naturally the disclosures in these two early patents were applied, not to modern vacuum tube oscillator and receiver apparatus, but to the apparatus available at the time, when these were not known. However, in view of these references, the writer's patent application was abandoned. One of the most interesting technical and mathematical treatments of this subject is to be found in the 77-page Doctors Dissertation of Ladislaus Kozma, (Ref. 11), diploma engineer of the Technical High School of Karlsruhe. This paper includes the disclosure of rf balancing circuits and tuned transmission lines, for practical use (in broadcast studio microphones) of this fm microphone-system, wherein the rf oscillator is at a remote location.

The previous discussion concerns capacitative types of microphone and phonograph pickups.

Inductor or electrodynamic types are also well known in the art. In these a conductive, vibratile element, in the rf magnetic field of a coil, modulates the inductance, and hence the frequency of the coil's resonance circuit; or the coil itself may vibrate to and fro, with respect to a fixed conductor; or the conductor, in either case, may be replaced by a magnetically permeable material, such as powdered iron with low hysteresis losses, and practically no I^2R losses.

As an example of such structures, I refer to one of the earliest patents (Ref. 12), filed Nov. 30, 1938 by the writer. This patent discloses the use of an inductance coil connected as a frequency determining element in an oscillator circuit. A conductive vibrator near the axial end of this fixed coil modulates the inductance of the coil, and hence, the frequency of the rf circuit of which it is a tuning element. Appropriate circuits are provided for discrimination of the frequency modulated oscillation. The disclosed application is for electronic musical instruments, particularly; for this electrodynamic type of modulator, a flat, conductive reed was shown as the vibrator.

Another disclosure of this electrodynamic type of fm modulator, in this case, for an fm phonograph pickup, is contained in an article, "FM Phono Pickup" by N. H. Lessem, (Ref. 13). However, the structural design of the vibratory coil and needle system obviously does not meet modern requirements for a high natural frequency, and for high compliance.

A number of RCA inventors have also addressed their attentions to designs of this electrodynamic type. Among them are W. Van B. Roberts, C. M. Sinnett et al, A. Badmaieff, W.R. Koch, and P. Weathers. Their patents (see References) date from 1942 to 1945. Inventors of the Hazeltine Corporation also account for a number of patents utilizing these principles in apparatus designed particularly for war-time mine detection, surgical metal-location, and so on.

The writer's patent (Ref. 14) on a phonograph pickup is described also in Radio-Craft (Refs. 15-16), and Electronics (Ref. 17). These describe phonograph pickups of the capacity and magnetic types, in which the needle alone, without any attached mass, such as vane, coil, armature, etc., is the vibratory member. Because the top end of such a needle may be fixed, or provided with vertical (only) compliance, and the bottom end is effectively (except for groove skating) locked in the record groove, the needle acts as a mechanical vibrator of the "fixed-fixed" type (for theory see Rayleigh, (Ref. 18), having a natural, lateral, resonance frequency of the order of 10,000 to 20,000 cycles per second. Thus the needle-resonance bugaboo (which has always intruded its distortions into phonograph reproduction) is cured at its source, without any necessity for use of electrical equalization methods, which introduce additional, undesirable, transient effects.

If the pickup electrode (or coil, in the case of an electrodynamic counterpart used with a flat needle) is located as close as possible to the jewel tip of the needle, the translation efficiency is maximum, and any possible effect of needle resonance is minimized.

With a tuned transmission line, such as that which has been developed by my associate, R. K. Beauchamp, (now of the Los Alamos Scientific Laboratory) or like that shown in some of the subsequent patent literature, such as the U.S. patents of C.W. Hansell (Ref. 19), N. M. Rust (Ref. 20), C. M. Sinnett. (Ref. 21), (Ref. 22), or P. Weathers (Ref. 23), it is possible to locate the oscillator-detector apparatus in a radio receiver chassis (instead of in the tone arm). In the case of a broadcast studio microphone it can be situated at the end of a long, rugged, coaxial cable, along with the other conventional broadcasting circuit apparatus in the control room, as manufactured by the Stephens Co. of California.

It seems to the writer that such a phonographic pickup and rf translator circuit provides the ultimate in performance for pressed records. Needle resonance is eliminated; vertical compliance is provided; needle mass with its attendant problems of groove skating and record wear is reduced to the absolute minimum by the allowable very-low vertical needle pressure; an absolutely flat transducer characteristic is obtained; an extremely high order of af output is provided in the rf to af circuit, allowing comparatively low af gain, with a pickup structure of extreme simplicity, ruggedness, and low cost.

In addition to these features, this patent discloses an extremely simple method for securing automatic volume expansion. In this action it operates not only as a volume expander for the volume-compressed frequency range of commercial recordings, but it also furhter reduces the very low surface noise, made possible by the low needle pressure and by the absence of resonant response in the needle. A by-product of the "needle-only" vibrator design, it permits easy replacement of the jewel-tipped-needle, if and when it should become necessary. A more detailed investigation of such a pickup will be described later.

Obviously, this whole art cannot be reviewed here, however interesting and illuminating it may be, but serious students, as well as inventors in this field, can hardly afford to neglect any part of it. The list of prominent, radio-industry, engineering names alone (in the appended list of References) should be sufficient indication of its importance. It is becoming increasingly so, as evidenced by the rapidly growing technical and patent literature, as well as by the practical applications of these principles in many specialized fields. However, one particular commercial phonograph pickup, which utilizes these principles, will be described in a companion paper. A detailed report on an investigation of it will be made, because it is one of only two in this field, and also because the published literature concerning it ascribes its operation to other principles.

RECENT DEVELOPMENTS

One other patent is especially interesting. This is #2,436,946, to F. B. Tatro, of Chicago, and issued March 2, 1948. It has a number of very good features, but chiefly interesting is his disclosure of a very simple method for using the existing circuits of a super-heterodyne receiver with variable, rf reactance pickups. That is, the IF oscillator circuit is provided with a frequency-changing switch, so that this frequency can be altered to a value quite close to that of the IF amplifier system. Switching in a fixed (instead of the variable) condenser, sets the oscillator frequency at a point on one side of the IF amplifier resonance curve, where it is steepest and most linear. Therefore, the IF oscillator, the IF amplifier, the detector, and the whole audio system, already present in a radio receiver or radio phonograph combination, very effectively supply all the additional circuitry for translating the rf reactance modulations of the pickup into sound.

That this subject has been of great interest to audio engineers is very well evidenced by the patent literature. There are at present over one hundred patents on fm phono-pickups alone; RCA accounts for about forty; General Electric, Westinghouse, Bendix, Zenith, and Bell Laboratories have also been rather active. The other patents are distributed among the smaller companies and individual inventors. Practically all of their patents follow, by a year or more, the writer's disclosures and demonstrations.

In addition to the Zenith Cobra phono-pickup, several other manufacturers use the fm principle, for phonographic and other purposes. Among these are Weathers and Motorola. Stephens, in California, uses it for a condenser microphone system. The Bureau of Standards has used it to measure microphonics-producing vibration of vacuum tube elements. It is used in the manufacture of steel sheets for gauging thickness. Hazeltine engineers, as stated before, have used it for so-called "mine detectors." Oil prospectors use it for geophones. In Germany, it has been applied to the study of violin soundboard vibrations, where phase and amplitude relationships are important, and where the loading and/or damping effects of contact type pickups cannot be tolerated. It is used in the record cutting industry for monitoring the operation of the cutter needle. Since 1926, the writer, in addition to his 1919 use for condenser microphones, has used this principle experimentally for phonograph pickups. He has used it, since 1931, for translating the vibrations of musical instrument vibrators, such as strings, reeds, rods, bars, tubes and the like, both for conductive and for dielectric vibrators (for example gut-type bowed strings). His licensee, Ansley Radio Company, produced electronic pianos (the "Dynatone") before war II, using fm capacitative pickups from strings. Brush Development Co. uses this fm principle for gauges. The writer's most recent development, a stringless piano (recently demonstrated by The Rudolph Wurlitzer Company), uses this principle in the form of capacitative pickups, spaced about .005" from the tip ends of hammer-struck, fixed-free reeds, to produce very realistic piano tones, having a full range of precisely, integrally-related partial frequencies, and normal rates of damping throughout the scale. AM-rf types have also been patented and used by the writer.

It is seen, therefore, that the fm-rf translator principle has many uses, aside from phono-pickups, and there is every indication that these uses will expand, not only in those fields mentioned, but in many others yet to be found. It can be made tremendously sensitive, merely by increase in the carrier frequency, as well as by rf and af amplification chains. It is a beautiful principle, ideally suited for many applications involving translation of minute vibrations, or displacements, or even of other things, such as dielectric constants, magnetic permeability, locating flesh-imbedded bullets and the like.

For phono-pickups, this fm principle is ideal, as previously stated, because the mass of the record-vibrated needle can be reduced to the absolute minimum, that is, the needle alone, without attached armatures, coils, crystals, etc. (except the stylus tip). It may be used either as a variable *distance*, or as a variable *area* type of modulated capacitance device (the former yielding an almost linear amplitude characteristic and the latter, one which is absolutely linear).

If the needle be made in the form of a thin-walled tube of magnesium or (preferably) titanium, its mass is reduced almost to the vanishing point, so that its vibrational reactance is extremely low. If the viscous damping material be placed at the pivoted end, where it does not add appreciably to the vibratory mass of the needle, the needle reactance is so low as to require only the smallest tracking pressure; needle and record wear, groove skating etc., are then effectually eliminated.

It would appear therefore that, so far as mechanico-electrical record translators are concerned, such a pickup is as near the ideal as can be expected, and very much nearer to that goal than are the conventional pickups now in common use. As audio engineers become more familiar with fm principles and their applications to phonography, and so long as the present type of record disc is used, they will sooner or later apply these principles, especially where high fidelity reproduction is desired. As in every other industry, new ideas require much too long a time between invention and common practice, because ideas, like physical bodies, have inertia and the bigger they are, the more difficult it is to get them in motion!

The writer has already sensed the still-rising, though future decline, of mechanico-electric recording and reproduction, and gone ahead to the next horizon of sound on discs, namely, photo-phonographs. His patent #2,654,810 of October 6, 1953, discloses such a record and translator, using all of the accumulated knowledge and experience of the variable-density sound-on-film art; but at the rate with which industry adapts itself to new ideas, this may not be used for *another* ten or twenty years!

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