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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TABLE OF CONTENTS

EDITORIALS

FROM CHAPTERS

TECHNICAL PAPERS

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.

Annual Assessment: $2.00

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The TRANSACTIONS of the IRE Professional Group on Audio

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PGA -- 1953-54

Marvin Camras
Armour Research Foundation
Chicago 16, Illinois

This year has seen drastic political changes in major world governments, and also in the PGA. Elected and appointed officers are:

Marvin Camras, Chairman 1953-54 (Armour Research Foundation, Chicago, Illinois)

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A. M. Wiggins, 1953-54 (Electro-Voice, Inc., Buchanan, Michigan)

An informal luncheon meeting was held Wednesday, March 25, to acquaint old and new committee members. As a result of the discussion it was decided that we continue to issue TRANSACTIONS OF THE IRE-PGA on a bi-monthly basis. It was also decided to study income and expenses so that the annual assessment can be revised. However, the assessment of $2.00 will continue until further action by the administrative committee.

PGA has grown so remarkably in the last vear that we ought to take inventory of member's interests and affiliations. 'A survey by postcard is planned. The results will help the officers and editorial staff to serve PGA better, and to make this the best year in our history.

EDITORIAL COMMITTEE REORGANIZATION

Daniel W. Martin
The Baldwin Company
Cincinnati 2, Ohio

For the past two years the IRE-PGA has been very fortunate to have Mr. Benjamin B. Bauer, Shure Brothers, Inc. as editor-in-chief of its TRANSACTIONS. As a matter of fact Mr. Bauer, with only token assistance from the PGA Editorial Committee and more substantial publication assistance from IRE headquarters, has transformed TRANSACTIONS of the IRE-PGA from an irregular, mimeographed newsletter to a regularly scheduled, technical publication with well defined format, policies and procedures. The Editorial Committee wishes to thank Mr. Bauer for his successful efforts and for his willingness to continue as editorial advisor and an active member of the committee, while serving as the new Secretary-Treasurer of IRE-PGA.

The reorganization of the Editorial Committee includes not only new and additional personnel, but also a revised plan of operation. The regional editorship idea is not to be abandoned completely, but will be retained as part of the new plan. We will attempt to distribute some of the editorial functions, and to assign subject-matter classifications within audio to individual committee members, while each member of the committee will serve as a regional editor in the particular region centered about his geographical location. Members of IRE-PGA will know whom to contact on a regional basis by referring to the addresses of the editorial committee members listed on the inside cover.

The rapid growth of IRE-PGA is believed to have resulted in large measure from IRE membership interest in the advancement of audio technology through timely publication of the results of fundamental research, of engineering development and design, and of experience gained in the use of audio systems. It is the pleasant responsibility of individual IRE-PGA members to be active in these matters, as well as interested. When some new principle or device or concept has been discovered, or when something well known has been reexamined to new advantage, the membership of IRE-PGA will certainly appreciate a first chance to hear about it through TRANSACTIONS of IRE-PGA. Policies on republication of material elsewhere, previously explained in these columns, will continue.

CINCINNATI CHAPTER, IRE-PGA, 1952-53

The Cincinnati Chapter of the IRE-PGA has completed its second yearly program of monthly meetings and technical papers, under the leadership of the following officers for 1952-53:

Chairman: Roy E. Kolo, Cincinnati and Suburban Telephone Company
Vice-Chairman: E. M. Jones, The Baldwin Company
Secretary-Treasurer: Albert Meyer, The Baldwin Company

The Audio Chapter sessions were regularly held at the headquarters building of The Technical and Scientific Societies Council, immediately following the Cincinnati Section IRE meetings. This arrangement has proved beneficial to both section and chapter. The chapter has enjoyed the whole-hearted support of the section in all of its activities. The following technical papers were given, generally with demonstrations and aural-visual aids.

"The Technique of A-B Listening Tests", Daniel W. Martin, The Baldwin Company.

"British Audio", H. A. Hartley, London, England

"Quiet, Please", Robert Holden, E. C. Decker Company

"Historical Development of the Loudspeaker", Wm. H. Breunig, The Baldwin Company

"Fifty-Thousand Hands", M. E. Strieby, American Telephone & Telegraph Co. (joint IRE-AIEE)

"Magnetic Structures for Audio and Acoustical Devices", C. A. Maynard, Indiana Steel Products Co.

"Carillonic Bells", George J. Schulmerich, Schulmerich Electronics, Inc.

At the April meeting the following officers were elected for 1953-54.

Chairman: E. M. Jones, The Baldwin Company
Vice-Chairman: W. W. Gulden, Cincinnati and Suburban Telephone Company
Secretary-Treasurer: J. P. Goode, Cincinnati Time Recorder Company

STATUS OF MILITARY RESEARCH AND DEVELOPMENT IN ACOUSTICS AND RADIO*

Paul J. Weber
Bureau of Ships, Department of the Navy
Washington 25, D. C.

Summary

The fields of acoustics and audio engineering are finding many new military applications within the Army, Navy and Air Force. Continued progress is also being made toward improving the performance of existing audio systems and techniques to better meet increasingly stringent operational requirements. Some recent developments and proposed projects in these fields are discussed. Problems which are as yet unsolved are mentioned. The procedure established within the Department of Defense for coordinating all research and development in the broad field of acoustics-in-air is described.

A. Military applications of audio

The allied fields of acoustics and audio are playing a variety of important roles in the military operations of the Army, Navy and Air Force. Typical examples are the following:

1. Voice Communications

The most familiar military application of audio is its use for voice communications.

In the Army, ground units are linked together by field telephones. Figure 1 shows a soldier wearing one of the latest Army sound powered telephone handsets. Special features of this handset (shown in Figure 2), include a hand-operated generator for signalling another station, a buzzer with volume control for receiving an incoming call, and a visual signal for silent calls.

In the Navy, communication between key stations aboard ship is handled almost entirely by sound powered telephones and intercommunicating units (see Figure 3) which provide selective two-way amplified voice communication. A typical control station operator on a Navy submarine is pictured in Figure 4. Note the extent to which he is wired for sound -- a headset, two sound powered telephone handsets, a radio telephone handset for exterior communication, a microphone for one-way broadcast to a special information circuit and an intercom unit.

Small hand-held battery powered public address sets called electric megaphones are used aboard ships to facilitate such operations as fueling at sea and small boat handling.

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*Presented at the Southwestern IRE Conference, February 7, 1953, in San Antonio, Texas. Manuscript received February 12, 1953.

This same device is used by the Army's Military Police. The megaphone may be detached from the amplifier and used like the familiar cheer-leader's hand megaphone, while the amplifier is carried in the other hand or set upon the deck.

Larger portable self-powered public address sets are used on beaches during landing operations for controlling the movements of boats, vehicles and personnel.

2. Sound Ranging

A less familiar application of acoustics by the Army is for locating enemy artillery and other weapons from the sound produced by the firing of such weapons. Although this is an old technique, having been employed during World War I, sound ranging still offers some real advantages over other more modern methods. Sound ranging equipment is relatively simple and does not reveal its existence or location to the enemy.

3. Recording

An application of audio which is growing rapidly in scope and importance throughout all three of the services is the use of recorders and recording techniques for the recording and subsequent reproduction of voice, sound and other signals -- both within and beyond the audio frequency range. In addition to the usual uses of voice recorders, there are many applications of a strictly military nature in which recording techniques serve as a valuable tool for signal analysis.

4. Psychological Warfare

An application of audio, which has received new and expanded emphasis since the outbreak of hostilities in Korea, has been in the field of psychological warfare. High powered public address systems mounted in aircraft, and on tanks and other armored vehicles, have proven particularly effective when used for such purposes as:

(1) Directing surrender proposals to by-passed enemy units and to isolated pockets of resistance;

(2) Broadcasting propaganda designed to lower the morale of the enemy and to encourage desertions and surrender.

B. Recent developments

Some of the more significant developments which have been made recently are the following:

1. New Aircraft Audio System

The most ambitious military postwar development in audio has been the development by the Air Force of a completely new audio system of high intelligibility interphone equipment for military aircraft. The interphone system of a military airplane provides the means by which the individual crew members of a multiplace airplane converse with each other. The system also provides terminal equipment for the various radio receivers and transmitters employed for plane-to-plane and plane-to-ground communications. The high acoustic noise levels in today's planes has seriously reduced the voice communication effectiveness of World War II equipment. A completely new line of audio equipment components had to be developed. This resulted in a dramatic improvement in intelligibility under the most adverse conditions encountered in modern military aircraft. The improvement was brought about by a combination of the following means:

(1) Carbon microphones with their inherent distortion, instability, and limited frequency response were replaced by moving coil dynamic microphones;

(2) The microphone was designed for pressure gradient operation to discriminate against background noise, particularly the lower frequency components of propeller aircraft noise. A rubber mouth shield was added to give additional noise discrimination against high frequency noise components encountered in jet aircraft (Figure 5). Better noise insulation was built into the earphone cushions;

(3) Earphone receivers of the moving diaphragm magnetic type were replaced by moving coil dynamic receivers;

(4) The design of both the microphone, receivers, and the associated amplifier circuitry included means for eliminating the effect of altitude variation on the performance of the system. This is better appreciated when we consider the enormous range over which the acoustic impedance of the air medium itself varies from sea level to an altitude of 40,000 feet;

(5) Speech clipping, signal compression and frequency equalization were all employed in the amplifier circuits to decrease signal strength variations and to improve the overall signal-to-noise ratio in the ears of the listener;

(6) A great deal of attention was paid in designing the earphone cushions to provide maximum comfort for the wearer, permitting the wearing of headphones without fatigue for long periods of time.

2. Flight Deck Announcing

The military are the biggest users of high powered audio systems. The largest known concentration of audio power exists on board a large Navy aircraft carrier. Each carrier of the MIDWAY class has installed seven audio power amplifiers, each capable of delivering 1,000 watts of audio output power. Three of these seven amplifiers are used to provide through-ship sound coverage. Nearly 1,000 loudspeakers are used for this purpose. The other four kilowatts of audio power are fed to a small number of super-power loudspeakers (see Figure 6), usually referred to as "bull horns," which cover the flight deck with sound, permitting speech and alarm signals to be directed to pilots and to plane handlers engaged in flight operations. These loudspeakers are mounted on the island structure, the only structure which projects above the level of the flight deck. The system produces a minimum sound intensity level of 110 decibels over the entire area of the flight deck, which is approximately 1,000 ft. long by 100 ft. wide. This represents a length of two city blocks and an area of 2½ acres.

On the new aircraft carrier which the Navy is building, referred to as the FORRESTAL class, there will be no island structure. The new carriers will truly be flat tops. Sound coverage of the flight deck, which is considerably larger than previous flight decks, is still an operational requirement, in spite of the fact that there is no longer any place to mount the "bull horns." To solve this problem, the Navy has under development a new compact high-powered loudspeaker of compound horn design having an extended frequency range for maximum speech intelligibility in the presence of the higher noise levels which are expected; and having a wide sound dispersion angle to permit uniform coverage of the flight deck when using a large number of such speakers spaced at regular intervals along the edges of the flight deck.

3. Voice Plane

Another development employing high-powered audio equipment in connection with aircraft is the so-called "voice plane" (Figure 7) being used currently in Korea for psychological warfare purposes. It is a medium bomber fitted with four 500 watt amplifiers, each feeding a multiple-driver horn type of loudspeaker (Figure 8) mounted in the bomb bay (Figure 9). These planes are capable of delivering a message on the ground of approximately thirty seconds duration when flying at an altitude out of accurate range of small weapons fire. Other smaller systems are designed for ground use on tanks and armored vehicles (Figure 10). Still smaller systems are carried and set up by hand in front areas for broadcasting tactical propaganda (Figure 11).

4. Low Frequency Recording

Some significant achievements have been made in the development of new recording techniques. The results of one Navy-sponsored development was recently reported.* The electron beam reproducing head for magnetic tape recorders permits the reproduction of extremely low frequency signals and preservation of signal wave form without the complexities of equalization and phase correction, and without the use of frequency modulation usually employed for this purpose.

5. Improvement of Testing Techniques

A minor phase of military research, but one worth mentioning, is the effort that goes into the investigation and development of test techniques and methods of measurement. It must be borne in mind that the military departments are required by law to buy their technical equipment and supplies under open competitive bidding procedures using specifications based upon performance requirements. In the field of audio, the state of the art in some areas has not yet progressed to the point where it is possible to completely define the performance of an item by objective tests alone. Anyone familiar with the efforts of the Institute of Radio Engineers, Radio and Television Manufacturers' Association or of the American Standards Association to establish standard test methods and values for loudspeakers will confirm this fact. At the present time three projects of this type are being pursued by the Navy's Material Laboratory at the New York Naval Shipyard. We buy what we call noise cancelling microphones, and yet we have no satisfactory way of measuring the noise cancelling properties -- except by using actual talkers and listeners in an artificial noise field. One of these projects, then, concerns itself with seeking objective means for evaluating the effectiveness of a microphone in discriminating against background acoustical noise; and of finding a method for predicting its performance in any given noise situation using data obtained from objective tests. A second project is concerned with a basic investigation of non-linear distortion, its causes, its effects, its measurement and acceptable limits for various audio components including loudspeakers. A third project is concerned with a similar investigation of flutter and wow in recording and reproducing systems. We believe the results of these investigations will contribute to and advance the state of the audio art. This type of work is unclassified, and it is planned to report the results obtained at open meetings of technical societies.

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* "Electron Beam Reproducing Head for Magnetic Tape Recording" by Dr. A. M. Skellett and Dr. Lawrence E. Loveridge, National Union Radio Corp., and Mr. J. Warren Gratian, Stomberg-Carlson Co. -- Presented by Dr. Skellett at the Southwestern IRE Conference in San Antonio, Texas, Feb. 7, 1953.

C. Unsolved Problems

And now, a word about some of the problems which still lie ahead of us, and which suggest future research and development work.

1. Sound Propagation in Air

One of the most important unsolved problems is the lack of adequate fundamental data and understanding of the propagation of sound in air under non-homogeneous conditions. What little data is available covers only ground-to-ground (or horizontal) propagation of sound through air. There is a dearth of data covering air-to-ground (or vertical) sound propagation. Much needs to be known about the effects of varying atmospheric conditions and terrain on sound transmission. There are a number of military applications for which this information is needed, one of which is the psychological warfare problem already described. Typical questions which must be answered regarding the operation of loudspeaker systems from aircraft are the following:

(1) What are the audio power requirements and optimum system characteristics (such as frequency response) for successful sound transmission to the ground?

(2) How should loudspeakers be mounted and baffled on the aircraft for optimum performance; and how does the speed of the aircraft affect this problem?

(3) How can we predict the performance on the ground which we will get under a given set of atmospheric conditions?

2. New Techniques of Sound Amplification and Reproduction

The demand for audio power in airborne loudspeaker systems is already in excess of that which can be satisfied with a reasonable size and weight of equipment mounted in the plane -- using the audio techniques which are known today. The solution to this problem requires discovery of radically new techniques of audio amplification and efficient conversion from electrical to acoustical power. One possible new approach to the loudspeaker problem which should be explored is one wherein the audio amplifier can act as a valve to control or modulate the flow of energy drawn from some source other than the amplifier itself. This is intended to apply in a much broader and more general sense than the one example of a "modulated air stream loudspeaker."

3. Wideband Recording

In the field of recording, all three departments are actively investigating methods for distortionless wideband recording and reproduction. Immediate applications exist for recorders capable of recording and playing back signals of frequencies up to five megacycles. The number and scope of such applications will be limited mainly by the complexity, size and weight of the system developed. The simpler, the smaller, and the lighter they can be made, the more uses they can be put to. In some cases research programs in wholly unrelated fields are being retarded awaiting the availability of recording equipment capable of recording signals at least up to 100 kilocycles without phase shift, drift or frequency instability.

D. Army-Navy-Air Force Coordination

Following this discussion, one might well ask, "With so many parallel applications of audio and acoustics within the three departments, is there not a great deal of duplication and overlapping?" With so many different groups and laboratories, so widely separated geographically, each attacking similar problems but from their own local viewpoints, there might be some doubts as to whether this could be otherwise. The following comments will describe the way in which "unification" is working within the Department of Defense in the areas of acoustics and audio.

1. Research and Development Board

The IRE Proceedings recently contained an article* which described the work of the Research and Development Board of the Department of Defense. This board is the agency charged with coordination of the research and development program carried on by the Army, Navy and Air Force. The RDB is made up of committees and panels, staffed by part-time military and civilian experts, each concerned with a specific field of science or a certain type of weapon.

2. Allocation of Responsibility to a Single Service

Certain technical areas exist in which all three services are equally active, and in which the operational requirements for equipment and systems are very similar. Acoustics-in-air is such an area. I use the term acoustics-in-air to differentiate the audio phases of acoustics from the underwater or sonar phases. In a few cases such as this, the RDB has recognized the desirability of providing a mechanism for closer and more continuous coordination and guidance of the research and development program on a day-to-day basis, than could be achieved through the normal workings of committees and panels which meet infrequently. What

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* "Research and Development for National Defense" - by Edwin A. Speakman - Proceedings of the I.R.E., July, 1952, p. 772.

the RDB has done in these cases is to assign primary responsibility to one of the three departments for the coordination, supervision and guidance of the research and development work in all three departments.

Such an allocation of responsibility was made in the field of acoustics-in-air to the Department of the Navy. The Navy's Bureau of Ships is the agency which has been chosen to do this job. Thus in effect, the Bureau of Ships has been deputized by the RDB to coordinate the acoustics and audio research and development for all laboratories and offices and bureaus within the Army, Navy and Air Force.

3. Solving the Problem of Effective Communications

What specific actions are being taken by the Bureau of Ships under the RDB allocation to achieve effective coordination between the three departments in this field?

First we must consider the big problem in any large organization. Coordination is only as good as the internal communication. In the Department of Defense the normal channels for communication or flow of information within and between the services, follow the established organizational and functional lines. This creates a real problem of delivering timely information to the man at the bench and the man with the slide rule, who wants and needs to know. What does finally reach him is often bound together with so much other unrelated information, and carries so high a security classification, as to discourage its use. Principal emphasis has therefore been placed upon establishing well-oiled channels of communication so that all engineers and scientists working in acoustics are kept informed of what the others are doing.

4. Periodic Bulletin

Several steps have been taken to increase and speed up the vital flow of information. One of these has been to publish a periodic "Acoustics-in-Air Bulletin" containing news and notes on new projects, proposals, reports and current status of work within the various fields of military acoustics.

The style of the bulletin is informal in nature, to make easy reading for busy people. The bulletin is mailed directly to all key personnel within the three departments who are concerned with any phase of acoustics research or development.

5. Semi-annual Symposium

Effective as this and other measures have been for transmitting the written word expeditiously, they cannot do the whole job. There is still an appreciable delay before the results of a research and development project find their way into writing -- and some indeed are not written down at all. This problem has been solved in part by conducting a Department of Defense acoustics-in-air symposium twice a year, usually held in conjunction with the meetings of the Acoustical Society of America for the convenience of those who may wish to attend both functions. Here papers are presented and discussed by the engineers and scientists of the Department of Defense. Timely data and information are exchanged. New ideas and fresh approaches to common problems are stimulated by these group discussions and interchanges. The security classification of the meetings is set high enough to permit free discussion of all aspects of the problems, including actual military applications.

6. Appraisal of Results

It may be too early to fully appraise the results of these efforts. It can be said, however, that in our field of acoustics there has been firmly rooted a spirit of teamwork between the three services and an awareness of the other fellow's problems. Those doing business with the military departments today will not find the rivalry or wasteful competition between services which was a frequent complaint about the military in the days before unification.

A recent example will illustrate the degree of inter-service cooperation which has been achieved. This is the case of the airborne loudspeaker system shown in Figure 8. This equipment was procured through the Army's Signal Corps by the Navy's Bureau of Aeronautics under the direction of the Army's Chief of Psychological Warfare. It was installed by the Air Force in a B-26 bomber. It was flown by Air Force pilots in Korea, while being operated by Army psychological warfare personnel to broadcast Chinese and Korean propaganda messages to the enemy. When certain deficiencies were discovered in the performance of this equipment, the Navy's Bureau of Ships set up and directed a project at its Material Laboratory in the New York Naval Shipyard for a thorough test of the equipment and an investigation of the means which would be required to correct these deficiencies.

The intent of the foregoing remarks was to give some insight into the uses of audio in the Department of Defense, some of the advances which have been made, some of the problems we still face, and some of the measures we have adopted to obtain maximum return on our investment of defense dollars and maximum utilization of our technical and scientific manpower.

Fig. 1

Fig. 2

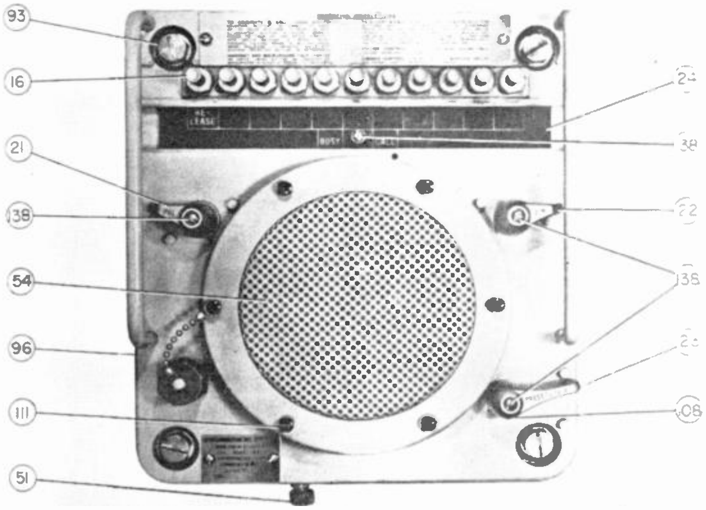

Fig. 3

Fig. 4

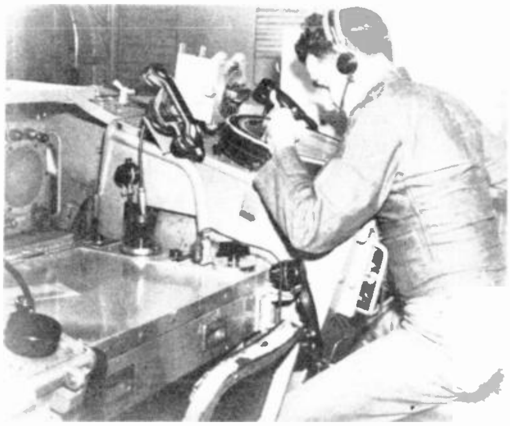

Fig. 5

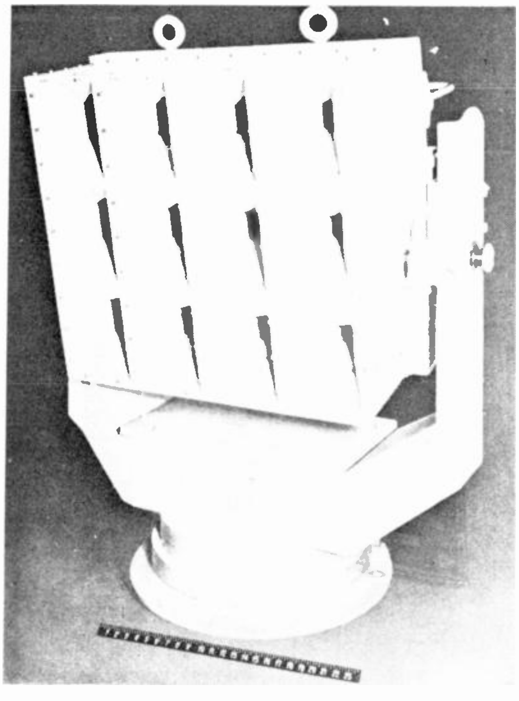

Fig. 6

Fig. 7

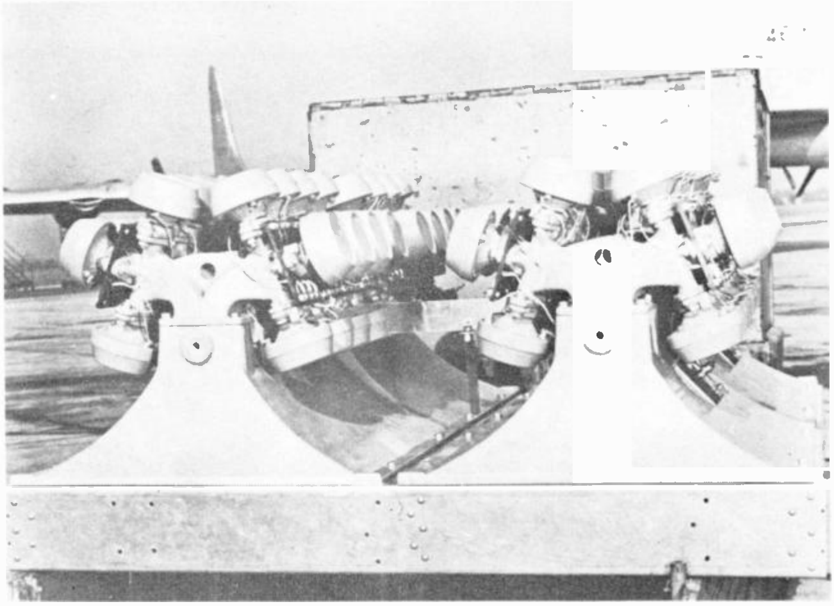

Fig. 8

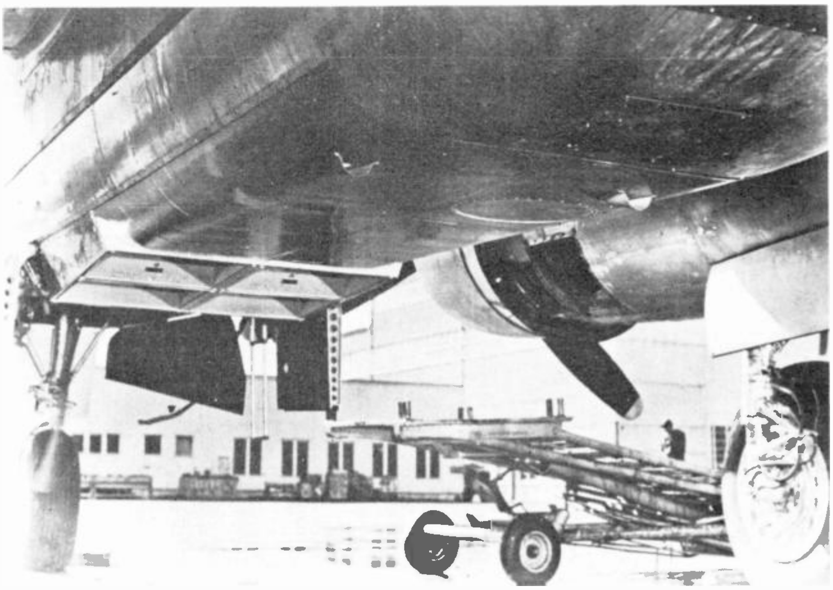

Fig. 9

Fig. 10

Fig. 11

LOUDSPEAKER DEVELOPMENTS*

Paul W. Klipsch
Klipsch and Associates
Hope, Arkansas

If there is ever a culminating design for a loudspeaker it should be a corner type, for this affords the maximum performance for a given bulk of space requirement.

The year 1953 has shown signs of approaching this culmination more closely than any time in the past. One manufacturer's production of corner speakers has run its serial numbers into 5 figures, which is still short of any suggestion of market saturation.

To trace the development of the corner speaker entails listing a short technical bibliography (See appendix). But to trace some of the basic and major developments in loudspeakers entails digging around in material which by current scientific standards is ancient. Every acoustic worker is aware of Rayleigh's Theory of Sound, but may well have overlooked the complete analysis therein of the direct radiator speaker to be invented 46 years later. The principle of images is probably at least 20 centuries old, and as applied to acoustics may be almost as old (surely echoes must have been noticed almost as many centuries ago as optical reflections), but it appears to have been as late as 1929 that the reflections produced by the room walls at a corner were first gropingly sought as a means of improving loudspeaker performance.

The beginnings of the corner speaker would be hard to find; perhaps it would be fair to assume the beginnings involved the use of a single wall, or the idea of a baffle. The first practical use of the baffle appears to have taken place in the late 1920's, but the true origin goes back farther, at least to the aforementioned Rayleigh's mathematical development.

In the present practical form, the corner horn speaker of conservative bulk appears to have originated in 1940 with this writer's patent application and subsequent publications which are included in the bibliography of this paper.

It was in 1877 that Lord Rayleigh published his Theory of Sound. The mathematical treatment of a direct radiator in an infinite baffle was treated under the index item "plate, vibrating circular, effect of air upon." For the reference conscious, the development starts on page 162 of Volume 2, Dover reprint of 1937.

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*Presented at the Southwestern IRE Conference, February 7, 1953, in San Antonio, Texas. Manuscript received February 20, 1953.

Forty-six years after Rayleigh's publication in 1877, the direct radiator loudspeaker was invented by Chester W. Rice and Edward W. Kellogg; this was reported in Proc. IRE in 1923. This dynamic cone speaker development appears to have been first exploited in the Radiola 28, the AC model of which used a fieldcoil dynamic speaker of about an 8-inch diameter, without baffle. The expression, "without baffle," should be especially noted. It is significant that, even in the mid-twenties, science had become so diversified that workers in one field of applied science could not find the pure or applied science writings in other fields. Hence the inventors of the direct radiator, analyzed 46 years before, could be excused if they were unaware of the analysis and significance of Rayleigh's assumptions, which included the baffle or wall with a hole in it within which the piston vibrated.

Actually it was in the late twenties that the workers in the loudspeaker field began to awake to the beneficial effects of a "baffle" (and note again the quotes around "baffle"). Still later, the early thirties, the applications began to appear, and at the present time, in 1953, we still observe the 20-year old influence of the loudspeaker in the hole in the wall.

Olson quotes J. B. (Jim) Lansing as the author of the combined bass cone and coaxial center-fire horn tweeter (Jour. Soc. Mot. Pict. Eng. 46, 3, 1946). This arrangement appears to have been first devised by A. A. Crawford in 1929, when an archive model was made from sketches prepared by Crawford. This speaker type, as a drive system, began to gain popularity after World War II, and is particularly applicable to certain types of corner speakers. Twenty-four years old in 1953, this coaxial speaker idea is only beginning to exert its proper influence in both corner and non-corner applications.

The first speaker system involving a plurality of speakers to reproduce several tonal ranges is variously attributed to a number of workers, depending on the author. Hilliard gives credit to Shearer in 1934; the Crawford patent application of 1928 antedates that by half a decade. The tools for the accomplishment were developed to a state of practicality with the Bostwick tweeter described in the Jour. of Acous. Soc. of America in 1930. But the ground work was laid much earlier. Rice and Kellogg were trying to obviate the expense and bulk of horn speakers in their work leading to the cone speaker, but their IRE paper of 1923 described experiments using 3 horn speakers each working in a portion of the audio spectrum. They observed that this 3-horn speaker sounded better than any design of single horn they had been able to try. The multiple horn speaker reached the highest state of development when applied to corner speaker systems.

As for corner horns, the first patent to describe a potentially wide range performance with conservative bulk was issued to Sandeman in 1934. This was for a trihedral corner horn to be reinvented by Gilson and Andrea in 1951, almost exactly 17 years later as the Sandeman patent was expiring. This discussion is limited to optimum speaker systems, or those wherein maximum performance per unit bulk is approached. This excludes an early horn invention, but since this appears to be the first corner horn it is necessary to mention the Weil patent of 1931.

This writer's contribution began with a corner horn of dihedral symmetry, as contrasted with the Sandeman trihedral structure. Patent application was filed in 1940. Since then improvements in the bass system, and developments in associated treble horns were found necessary to achieve an optimum speaker system.

The year 1952 saw the beginnings of recognition of corner horns. Previously, only this writer and the Electro-Voice Company had exploited the corner horn design. But 1952 saw a number of independent designs, as well as near and remote copies of basic corner-horn structures.

The basic idea of the corner horn speaker depends on the fact that the mirror image formed by a wall doubles the effective radiation area, and enables a relatively small radiating surface to generate a longer wavelength with practical efficiency; the multiple reflections of 3 mutually perpendicular walls in a room corner increase the effective radiating area by a factor of 2 cubed, or 8 times.

The basic horn idea may be applied in two ways: first, as a direct radiator with corner horn back loading, and second, as a series of 2 or more horns at least one of which is an optimized corner type. In the first, the speaker is essentially a direct radiator, but the back of the cone radiator is corner horn loaded to enhance the extreme bass range. In this application it is essential that some special means be provided to hold the bass radiation to a restricted efficiency so it will be a comparable level of loudness with the treble radiation from the front of the cone. This is usually accomplished with some form of acoustic filter having a low-pass characteristic.

In the second form of application of the corner horn, the efficiency is maintained at as high a value as possible, and the middle and extreme treble ranges are radiated with horns exhibiting efficiencies comparable with the bass corner horn. Note that the word "comparable" rather than "equal" is used. It is possible, feasible, and practicable to design bass or woofer horns with efficiencies of the order of 60 to 90 per cent. If we define efficacy as the product of efficiency times the ability to absorb power from a mismatched generator impedance, the woofer efficiency attainable is at least 40 per cent in optimum designs, which means than an acoustic output of 4 watts may be obtained from a 10 watt amplifier. But considering the tweeter, the ultimate efficiency in the absence of deleterious resonant peaking is of the order of 10 per cent at ten thousand cycles and the efficacy will be still lower. In other words, the wide-range multiple-horn system will exhibit a response which is at least 6 decibels down, or perhaps ten or more, at ten kc referred to the woofer range.

The multiple horn, therefore, appears at first glance to be at a disadvantage. However, it is to be noted that the response of a properly designed multiple horn system droops smoothly, and can be readily equalized. This is in contrast to the simpler radiators which exhibit serious peaks and valleys of response which could hardly be equalized to an over-all flat response. It should be hurriedly stated that such equalization should be prior to the final amplifier stage, and not in the form of attenuator pads between amplifier and speaker units.

In the first class of corner horn designs, in which a cone speaker is used as a direct radiator with the back radiation utilized through a corner horn, there are several commercial forms being exploited. The idea is believed to have been first described in this writer's U. S. Patent issued in 1943. The first to be produced was the Electro Voice Regal in 1950, quickly followed by the now popular Aristocrat, the diminutive Baronet and the well-named Royal. Klipsch and Associates introduced the Rebel in the summer of 1950, and a modified improvement in 1951. In late 1952 the Gately "Super-Horn" appeared as a commercial offering which enjoys the novelty of not being a near-copy of earlier widely published corner horn designs.

The corner horn as a back-loading for the direct radiator is the most economical approach to an extended bass range, and the application is apt to be applied to an excess degree. The performance of speaker systems in past years has been deficient in the bass range, and a bass-hungry public has insistantly demanded more bass to the extent that manufacturers have been able to make an easy dollar by feeding an extra dozen decibels in the range below 100 cycles. There is beginning to be recognized a revolt in the ranks of discriminating listeners; the rumbling bass with a lack of transient resolution still finds wide popularity but there is a growing section of the public that demands that percussions have some semblance to realism, and a minority even demands that a drum sound like a drum. The result is that the better designs of corner-horn back loading of direct radiators are being recognized for their controlled response whereby the bass efficiency is limited to a level matching the direct radiator efficiency in the middle frequency range derived from the front of the cone.

In the second class of corner horns, the performance is entirely different; remember the corner-horn back-loaded direct-radiator exhibits the efficiency of a direct radiator, typically of the order of 2 to 5 per cent. The multiple corner horn, on the other hand, is designed to give efficiencies of the order of 50 per cent or more, with the idea that as efficiency is increased the distortion is decreased.

Obviously if the bass horn efficiency is of the order of 50 per cent, it is desirable for other frequency ranges to be reproduced with comparable efficiencies. It has been a major accomplishment to attain decent efficiencies in the middle and upper frequency ranges, while retaining satisfactory pressure response, polar pattern and freedom from extraneous zonal and sectorial diaphragm motions. Electro-Voice has gone so far as to use 4 separate speakers; Klipsch and Associates favors 3 speakers as being less subject to ground-plane reflection interference. The difference is academic technically, though there are economic factors which favor the choice of 3 or 4 speakers, depending on whether one manufactures drivers and buys horns, or manufactures horns and buys drivers.

Tracing the history of the loudspeaker, and particularly the modern types, may appear to be of academic interest only. But a perusal of the subject in depth will reveal an important truth. The corner speaker is fundamentally the most efficient and efficacious. It is the one type which will offer the most performance with least bulk. It is the only means by which the longer wavelengths of music, such as the 16-foot organ pipe tones, can be radiated by structures of size tolerable for use in the living room.

The principle of the corner speaker is so fundamental that it should be the stock in trade of every radio engineer, acoustic specialist, and, for that matter, every one who even merely listens to a record player. If one remembers that the speaker is one of the weak links in the acoustic chain, and that the link is strenghthened by a factor of eight by the wall reflections at a corner, it should be evident that a dollar value increase by a factor approaching 8 is available by taking advantage of the corner. The time should soon arrive when architects will be designing for corner speakers, instead of showing customers house plans with wall speaker installations which were an obsolete fad in the mid 1930's.

APPENDIX

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Klipschorn is the trademark of the Klipsch-designed speaker system built by Klipsch and Associates and protected by the patents listed below:

2,238,023	2,537,141
2,310,243	D 163,700
2,373,692	and pending applications

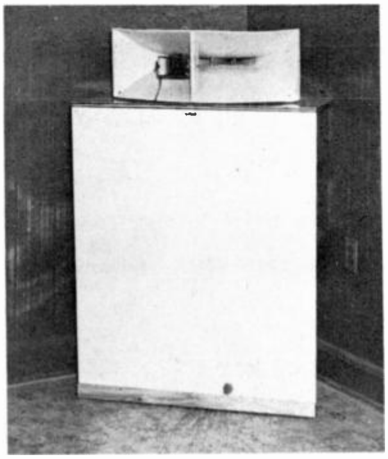


Fig. 1

Modern corner 3-way horn speaker system.
Note "tweeter" nested coaxially with "Squawker,"
both on top of "woofer."

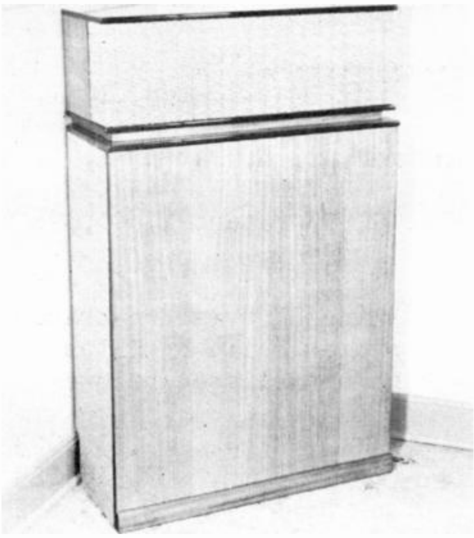
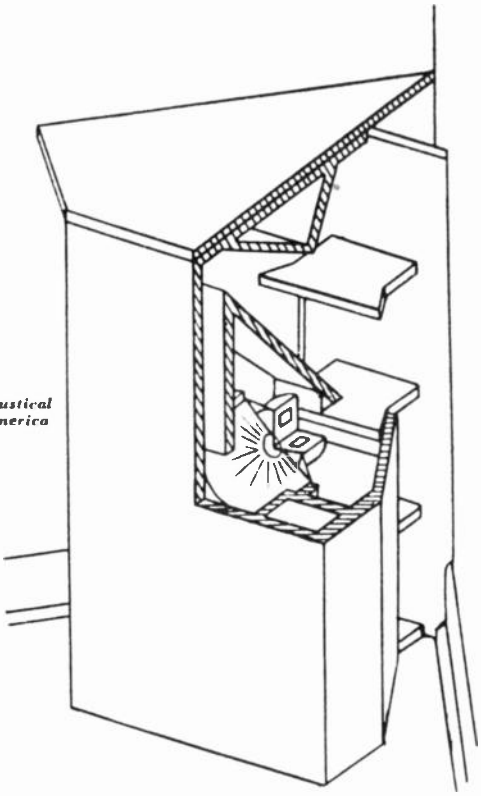


Fig. 2

Mahogany-finished version for home use;
functionally same as system shown in Fig. 1.



Courtesy Acoustical Society of America

Fig. 3 Cut-away view of corner horn woofer.

ACOUSTIC DAMPING FOR LOUDSPEAKERS *

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The fundamental resonance of loudspeakers is recognized by many as a source of annoyance. Usually this resonance can be damped electrically by suitable selection of the amplifier impedance.(1) What is less well-known is that damping can also be achieved by acoustical means incorporated into the loudspeaker or the enclosure. This paper deals with the theory and methods for providing acoustic damping.

Electrical damping requires the use of a low impedance amplifier. When this type of source is not available, and in the absence of other damping means, performance of the system may be seriously impaired. For example, a typical home radio or record player has a pentode output stage without inverse feedback. This type of output stage is known to provide a source of high impedance. A loudspeaker driven from this source will exhibit a resonant condition which may cause poor transient response or "hang-over" and it may be responsible for the acoustic feedback in record players. Acoustic damping may be found helpful in this instance.

Another use for acoustic damping will be found in the design of high-fidelity systems, where frequent attempts are made to improve damping by lowering the amplifier impedance to a value approaching zero. There is a limit to the amount of damping which may be obtained in this manner.(2)(3) Furthermore, electrical damping per se is not very effective in eliminating the resonance in cabinets with reflex ports. Acoustic damping can readily provide such additional damping as may be required.

Much effort and circuitry has been devoted to attempts to obtain damping from the electrical side. By contrast, the use of acoustic damping has been given little attention. In this paper we outline a simplified theory of acoustic damping for loudspeakers and enclosures. To provide a rational basis for the design of acoustic damping the acoustic constants of the loudspeaker and the enclosure must be known. Thence, an equivalent electrical circuit can be set up and the damping resistance may be determined experimentally by adjusting the electrical circuit constants. Keeping this approach in mind, first we derive the resonant frequency equations of a loudspeaker in a flat baffle and in an enclosure. Next, from these two equations we determine the acoustic mass and compliance of the loudspeaker cone. Thirdly, we set up an equivalent electrical circuit and determine the required damping resistance. And finally we build the acoustic damping into the enclosure and test its acoustic performance.

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II. EQUIVALENT CIRCUITS OF LOUDSPEAKERS AND ENCLOSURES

The equivalent circuit of a loudspeaker installed in an "infinite" flat baffle is shown in Fig. 1. In actual practice, of course, the baffle need not be infinite, but only considerably larger than the loudspeaker. The acoustic mass of the moving system (consisting of the voice coil and the piston diaphragm) is represented as an inductance L_{AM}; the acoustic compliance of the elastic suspension is shown as a capacitor C_{AM}. These terms can be calculated from measurements of the resonant frequency, as shown later in this paper. The driving pressure due to the voice-coil force is represented by a constant voltage e_o. We assume that the loudspeaker is driven from a high impedance source. Therefore, the damping factor reflected from the electrical side Z_{AP} equals zero. Either side of the piston is confronted by the acoustic impedance of the medium, Z_{AP}. This impedance is shown grounded because, from the acoustical point of view, it has only one available driving point terminal.(4)

It will suffice our purpose to represent Z_{AP} by a parallel combination of an inductance L_{AP} and a resistance R_{AP}.(5) These elements can be calculated in terms of the properties of the medium and the effective radius of the piston <u>r</u>:

$$L_{AP} = \rho/\sqrt{2}\pi r = 0.00027/r \quad \text{grams-cm}^{-4} \text{ "Acoustic henrys"} \tag{1}$$

$$R_{AP} = \rho c_v/\pi r^2 = 42/\pi r^2 \quad \text{dynes-sec-cm}^{-5} \text{ "Acoustic ohms"} \tag{2}$$

where, r is measured by the perpendicular distance from the axis to the mid-point of the flexible annulus of the cone, cm.

ρ is the density of air, grams per cc
= 0.0012 for normal atmosphere.

c_v is the velocity of sound in air,
= 34,400 cm per sec. in normal atmosphere.

These equations are given for circular pistons; however, they may be used for pistons of other shapes, in terms of circular pistons of equivalent area.

R_{AP} predominates at high frequency; L_{AP} predominates at low frequency. Loudspeaker resonances occur at low frequency, and hence, R_{AP} can be neglected in the resonant frequency equation:

$$(2\pi f_1)^2(L_{AM} + 2L_{AP})C_{AM} = 1 \tag{3}$$

Resonant frequency can be measured by connecting the voice-coil to a variable frequency oscillator through a high series resistance (to approach a constant current condition) and measuring the voice-coil voltage with a high-impedance voltmeter. At the resonant frequency the voice-coil voltage is a maximum.

When a loudspeaker is installed in a shallow cabinet with open back, its resonant frequency is essentially the same as with a flat baffle of similar dimension.

Next, consider the loudspeaker in an enclosure as shown in Fig. 2. The simplest enclosure is a closed box with a hole of an appropriate size to accommodate the loudspeaker. The design of such enclosure has been treated in detail by Beranek(6) and others. Our purpose is limited to providing its equivalent circuit elements.

To minimize reflections at high frequency, the enclosure may be lined with sound absorbing material such as Fiberglas or Ozite. These materials, when mounted against the walls of the enclosure, offer a negligible amount of sound absorption at low frequency and contribute little to the damping. Therefore, the low frequency impedance confronting the piston is predominantly reactive, and it can be represented by an inductance L_{AB} in series with a capacitance (or compliance) C_{AB}. For rectangular boxes, L_{AB} is given by the semi-empirical equation:

$$L_{AB} = \frac{4}{\pi^2} \frac{\rho \ell}{A_B} \left(\frac{A_B}{A_P} \right)^{2/3} \text{ grams-cm}^{-4} \text{ ("acoustic henrys")} \qquad (4)$$

The equation for acoustic compliance is well-known.(7)

$$C_{AB} = \frac{V}{\rho c_v^2} = \frac{V}{1.41} \times 10^{-6} \text{ cm}^5\text{-dyne}^{-1} \text{ ("acoustic farads")} \qquad (5)$$

where ρ is the density of air - 0.0012 grams per cc for normal atmosphere

A_B is the cross-sectional area of the box, sq. cm.

ℓ is the depth of the box, cm.

A_P is the effective area of the piston, sq. cm.

V is the volume of the box, cu. cm.

Equation (4) holds quite well under these conditions:

1. The loudspeaker is about equally spaced from all the points at the inside periphery of the box.

2. The ratio of the box area A_B to the effective piston area A_P is not in excess of about 10:1.

3. The depth ℓ is about $0.7 \sqrt{A_B}$.

The use of the word "about" is intended to signify that the conditions indicated can be violated considerably without undue error.

The air-load impedance at the front of the cone can be assumed to be given approximately by equations (1) and (2). The resistive component may be neglected in the equation for resonant frequency, as before. The resonant frequency f_2 of this system is contained in the equation:

$$(2\pi f_2)^2(L_{AB} + L_{AM} + L_{AP}) \frac{C_{AM}C_{AB}}{C_{AM} + C_{AB}} = 1 \tag{6}$$

The resonant frequencies measured in the baffle (f_1) and in the box (f_2) enable us to calculate the acoustical constants of the loudspeaker. From equations (6) and (3) the following expressions are derived:

$$L_{AM} = \frac{1 - (2\pi f_2)^2 C_{AB}(L_{AB} + L_{AP}) + 2(2\pi f_1)^2 L_{AP} C_{AB}}{4\pi^2(f_2^{\,2} - f_1^{\,2})C_{AB}} \quad \text{gram-cm}^{-4} \text{ ("acoustic henrys")} \tag{7}$$

$$C_{AM} = \frac{1}{(2\pi f_1)^2(L_{AM} + 2L_{AP})} \quad \text{cm}^5\text{-dyne}^{-1} \text{ ("acoustic farads")} \tag{8}$$

Having thus determined all the important circuit elements of the loudspeaker and the simple enclosure, we are ready to set up the equivalent electrical circuit and determine the damping resistance. Before proceeding, however, we must digress briefly to introduce the subject of acoustic resistance.

III. ACOUSTIC RESISTANCE

Acoustic resistance is encountered when sound is made to flow through thin crevices or slits. Consequently, any broad surface member may be converted into an acoustic resistance by perforating it with small holes, slits, etc., which are calculable by well-known equations.(8) Cloth, felt, Ozite, etc. mounted on a suitable supporting member in the path of sound flow constitutes a simple and inexpensive method for providing good acoustic resistance. The acoustic resistance of these materials cannot be calculated, but it can be measured easily by causing air to flow at a known rate through a given area of material and measuring the pressure drop.

An instrument designed to perform this measurement is shown in Fig. 3. The material is held between two disks which provide an aperture having a known area. The rate of air flow is adjusted by means of the lower gauge which indicates the pressure drop across a standard slit. The pressure drop across the material is shown on the upper gauge which is calibrated to read the specific acoustic resistance of the material in acoustic ohms per sq. cm.

Cloth is an especially satisfactory material and it can be selected to provide any desired specific resistance. For example, the open weave fabrics designated "Ninon" and "Georgette" have resistances from 1/4 to 5.0 ohms per sq. cm. Most sateens, broadcloths, etc. have resistances between 5 and 75 ohms per sq. cm.; sailcloths and similar tightly woven fabrics have resistances upward of 75 ohms per sq. cm.

Usually the acoustic resistance element should have an area about equal to the area of the piston, or greater; this is to avoid constriction of the air flow which would have the effect of added acoustic mass. The specific resistance of the cloth to be employed is easily determined by multiplying the required acoustic damping resistance R_{AC} by the chosen area of the element in sq. cm. The cloth is supported by cementing to a heavy wire mesh or perforated grille to avoid motion in a diaphragm-like fashion. When a perforated grille is used, the effective area is, of course, the net area of the openings. The resistance may be adjusted experimentally, as by blocking some of the holes of the supporting member by means of Scotch tape or cement.

IV. ACOUSTIC DAMPING

Acoustic damping may be applied to loudspeakers and enclosures in many ways. Some of these are shown in Fig. 4. In general, the damping resistance must be coupled to the cone by a sufficiently small enclosure. In this manner, a good deal of the air displaced by the diaphragm is forced through the acoustic resistance resulting in a damping action. In the simplest case, A, the small enclosure, is the sole enclosure and the damping is placed at the back or one of the sides of the box. This small enclosure may be attached to a large baffle, as shown in B, to improve low frequency response. At C, a large enclosure is used, the small enclosure being provided within the larger enclosure. D is similar to C, except that a damped port is provided for reflex action. At E, a port has been added to the enclosure of A; and finally, F shows an arrangement similar to D in which both the speaker and the port derive a measure of damping from a single acoustic resistance element. Many other combinations are possible.

When an acoustic resistance element confronts the external medium, as in A or B for example, the air particles moving through the element are confronted with an acoustic impedance. The approximate value of this impedance may be estimated through the use of equations (1) and (2).

Since our purpose is to describe acoustic damping techniques rather than to evaluate the merit of various designs, only the simplest arrangement, namely that shown in 4-A, will be treated in detail. An experimental speaker system utilizing this arrangement is shown in Fig. 5. It consists of a medium-priced 8" loudspeaker installed in an enclosure with inside dimensions 14 x 14 x 9 inches deep. This enclosure may well be typical of those used in a medium-sized radio or P.A. system. The enclosure has interchangeable backs; one of them is solid, and the other is provided with an 11" diameter hole for installation of the acoustical damping resistance. The choice of this resistance by electrical circuit analysis is to be described.

First, the acoustic constants of this system were determined by the steps previously mentioned. The constants are shown in Table III.

Table III

Measured resonant frequency in box, with back removed . . . . $f_1 = 62$ cps

Measured resonant frequency in box with hard back in place . . . . $f_2 = 98$ cps

Measured effective radius of the piston . . $r = 8.5$ cm

Acoustic mass due to air-load, from equation (1) . . . . $L_{AP} = 0.032 \times 10^{-3}$

Acoustic resistance due to air-load, from equation (2) . . . . $R_{AP} = 0.19$

Acoustic mass of the closed box, from equation (4) . . . . $L_{AB} = 0.028 \times 10^{-3}$

Acoustic compliance of the closed box, from equation (5) . . . . $C_{AB} = 20.4 \times 10^3 \mu f$

Acoustic mass of the piston, from equation (7) . . . . $L_{AM} = 0.147 \times 10^{-3}$

Acoustic compliance of the piston, from equation (8) . . . . $C_{AM} = 31 \times 10^3 \mu f$

Acoustic mass due to air-load upon damping screen, from equation (1) . . . . $L_A = 0.019 \times 10^{-3}$ henrys

Acoustic resistance due to air-load upon damping screen, from equation (2) . . . . . $R_A = 0.07$ ohms

The equivalent circuit using these constants is shown in Fig. 6. The acoustic values are shown in parenthesis. Some of the acoustical elements have a much lower impedance than the electrical components available in the laboratory; in the equivalent circuit, therefore, the impedance of all the constants was multiplied by the factor 2000. The switch S_1 at position A portrays the action with the back removed, because the fluid from the back of the cone is able to enter the external medium. The switch in position B (open circuit) portrays the action with the solid back, since the fluid displaced by the cone is unable to enter the external medium. The switch at C causes the insertion of an adjustable resistance R_{AC} which portrays the acoustical damping resistance due to cloth when the damping back of the box is used. A simplifying assumption is made that the interaction between the back and the front radiation has no effect upon damping and that the air-load impedance at the back of the box remains the same with and without the damping resistance.

The optimum damping resistance was chosen by observing the transient response of the system. A steep pulse from a General Radio Strobotac was applied to a small (10 ohm) resistor "e" inserted in the circuit.

The Strobotac was adjusted to fire about 10 pulses per second. The transient potential developed across Z_{AP} was observed on the screen of an oscilloscope. (The circuit was rearranged to permit the single-ended Strobotac and Oscilloscope to be properly grounded.) Varying degrees of damping were obtained by adjusting R_{AC}. Some of the resulting transients are shown in Fig. 7. "A" is obtained with the switch at A to represent the open-box condition; "B" is obtained with the switch at B to represent the solid back condition; "C" is taken with the switch at C to represent the condition resulting from adjusting R_{AC} to 100 ohms. The corresponding acoustic resistance is 100/2000 = 0.05 ohms. If a greater degree of damping were desired, some of the remaining circuit elements would require alteration.

To provide 0.05 ohms acoustic damping in the loudspeaker enclosure, the damping cloth was mounted on a perforated metal screen with a total net area of 200 sq. cm. Cloth having a specific resistance of 10 acoustic ohms was used.

The actual acoustic performance of the system was tested with the aid of the Strobotac generator connected to the loudspeaker (Fig. 8). A high resistance was inserted in the circuit to simulate the action of a pentode output stage (without inverse feedback). The sound pressure generated immediately in front of the loudspeaker cone was detected by means of a Sound Level Meter Microphone. A flat amplifier was used to connect the microphone to the oscilloscope. Transients were observed with the open box (A), with solid back (B), and with damping back (C). The resulting transients are shown in Fig. 9. "A" is the open-box response; "B" is the response with the solid back attached; under these two conditions a hang-over tone is clearly heard together with the pulses. "C" is the response with the damped back attached. The pulses are heard clearly without the hang-over tone. These oscillograms and listening tests confirm the results predicted by the equivalent circuit.

V. ELECTRICAL VS. ACOUSTIC DAMPING

To compare the electrical damping with the acoustic damping, the following experiment was performed. The hard back was installed and the loudspeaker was connected to the pulse generator as before -- except that a small resistor was connected across the loudspeaker terminals to simulate the effect of low amplifier output impedance. The input was readjusted to compensate for the power loss in the resistor. The resulting transient is shown in Fig. 10A. This confirmed the fact that the action of the electrical damping is similar to that of the acoustic damping, although, in this instance, not quite as effective. Next, the solid back was again replaced with the damped back and the acoustic impedance was slightly adjusted. The resultant transient is shown in Fig. 10B. In this instance, combining acoustic damping with electrical damping resulted in a near aperiodic response which is considered by many as ideal for the reproduction of percussion sounds.

With regard to frequency response, acoustic damping generally should have an effect similar to that of electrical damping. Response may be affected, however, by the specific arrangement of acoustic damping. It is interesting, therefore, to compare response curves for the system which we have described under similar conditions of damping -- electrical vs. acoustic. The measuring set-up for this purpose is shown in Fig. 11. The response measurements were made on the axis at three feet from the cone, with a constant generator voltage and suitable series resistance to simulate the source impedance. The resulting curves are shown in Fig. 12. Only the low frequency is affected by damping, and, hence, the curves stop at 1000 cps. The solid curve is for the loudspeaker in the acoustically damped enclosure and high source impedance. The dash-curve is for the loudspeaker in the open back enclosure and a low source impedance. The dotted curve is for the loudspeaker in the enclosure with the solid back and also a low source impedance. It would appear that the damped-back curve might be chosen as the best compromise because it is the smoothest and the easiest to equalize. It must be reiterated that the system under study is not intended to qualify as a "high-fidelity" system, but rather to represent the conditions which might exist in a home radio or a public address system.

Of further interest is the performance of the acoustically damped loudspeaker as a function of the source impedance. The response curves for high and low impedance source are shown in Fig. 13, and they are quite alike. This may be accounted for by the fact that the voice-coil impedance remains fairly constant owing to the acoustic damping. This comparative immunity from source-impedance effects is not to be minimized, since it provides the audio designer with a degree of freedom in the choice of equipment.

VI. CONCLUSION

Transient response of loudspeakers and enclosures can be effectively controlled by acoustic damping. Furthermore, the response-frequency characteristic of the loudspeaker system need not be adversely affected, and it actually may be improved. Loudspeakers with acoustic damping may operate from high-impedance amplifiers without "hang-over". Performance characteristics become largely independent of the amplifier impedance. Acoustic damping may be designed in a straightforward manner by ascertaining the acoustical constants and using standard experimental techniques of equivalent circuit analysis. We conclude, therefore, that acoustic damping for loudspeakers merits far more serious consideration than it has had heretofore.

ACKNOWLEDGMENT

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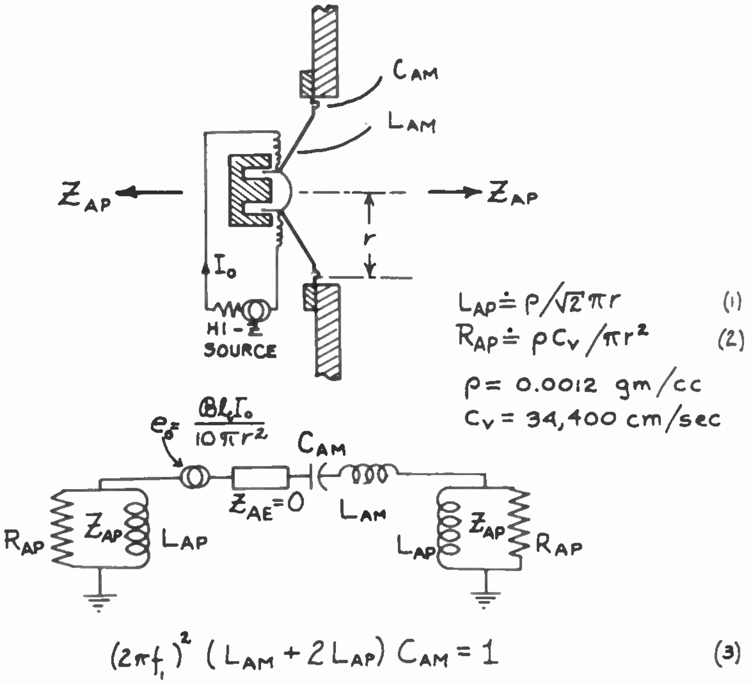
(7)For example, in text of reference (1), p. 89.

(8)For example, in text of reference (1), p. 87.



$$L_{AP} \doteq \rho/\sqrt{2}\,\pi r \qquad (1)$$

$$R_{AP} \doteq \rho c_v/\pi r^2 \qquad (2)$$

$\rho = 0.0012$ gm/cc

$c_v = 34{,}400$ cm/sec

$$(2\pi f_1)^2 (L_{AM} + 2L_{AP})\, C_{AM} = 1 \qquad (3)$$

Fig. 1. Equivalent circuit of a loudspeaker mounted in an infinite baffle

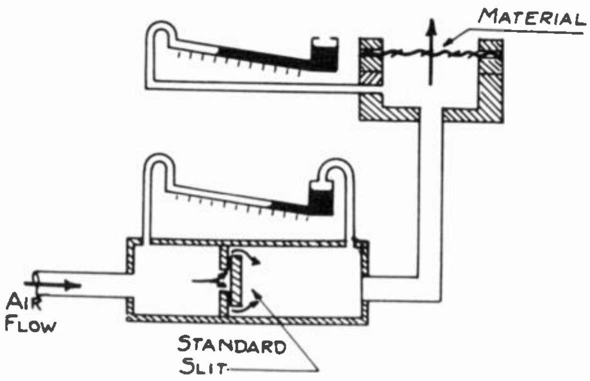
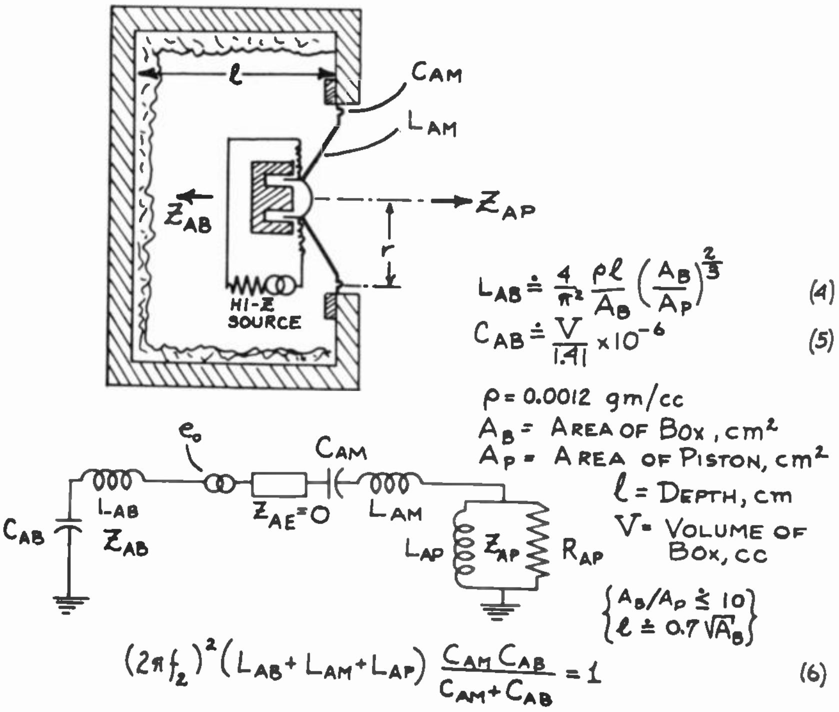


Fig. 3. Schematic arrangement of acoustical resistance meter



$$L_{AB} \doteq \frac{4}{\pi^2}\frac{\rho l}{A_B}\left(\frac{A_B}{A_P}\right)^{\frac{2}{3}} \qquad (4)$$

$$C_{AB} \doteq \frac{V}{1.41}\times 10^{-6} \qquad (5)$$

$\rho = 0.0012$ gm/cc

A_B = Area of Box, cm²

A_P = Area of Piston, cm²

l = Depth, cm

V = Volume of Box, cc

$$\left\{\begin{array}{l} A_B/A_P \leqq 10 \\ l \doteq 0.7\sqrt{A_B} \end{array}\right\}$$

$$(2\pi f_2)^2 (L_{AB} + L_{AM} + L_{AP}) \frac{C_{AM} C_{AB}}{C_{AM} + C_{AB}} = 1 \qquad (6)$$

Fig. 2. Equivalent circuit of a loudspeaker mounted in an enclosure

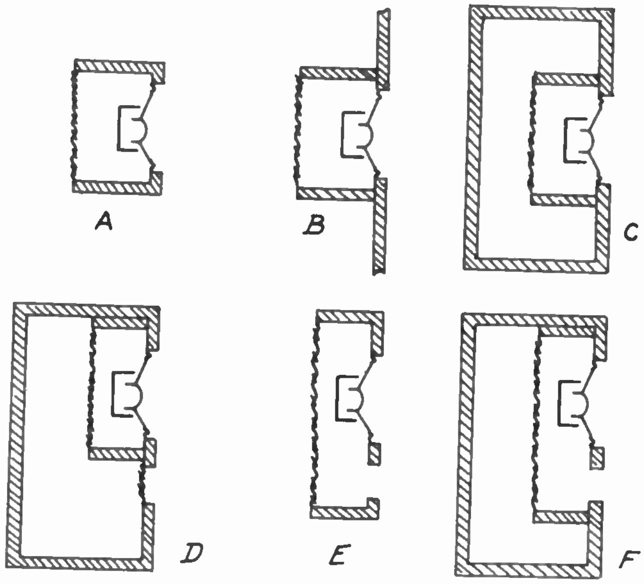


Fig. 4. Some of the means for applying acoustic damping to loudspeakers

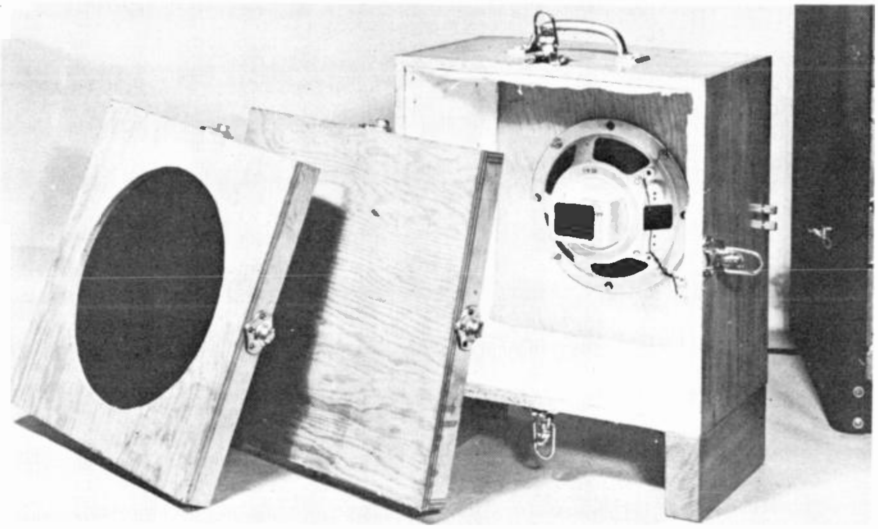


Fig. 5 Experimental loudspeaker system demonstrating acoustic damping

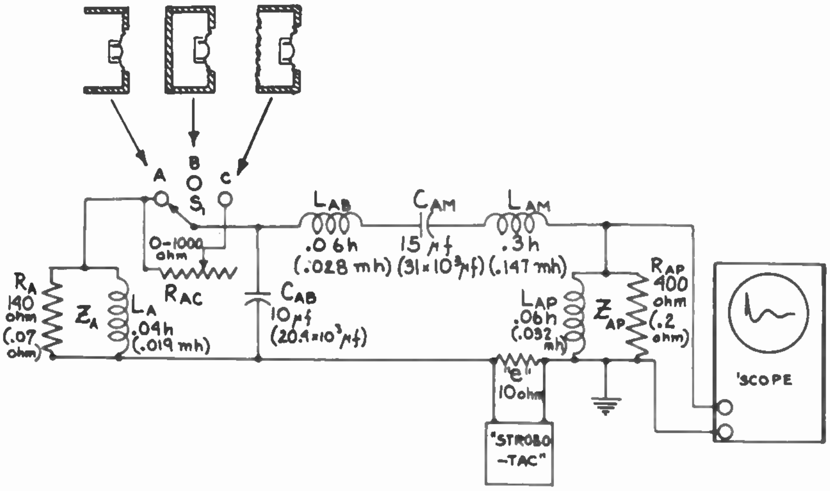


Fig. 6 Equivalent circuit of experimental loudspeaker system

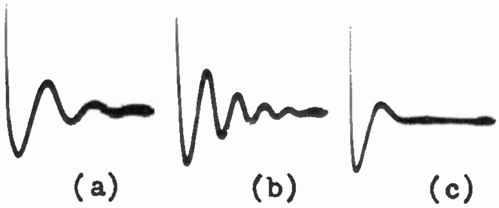


Fig. 7 Transients obtained with equivalent circuit of Fig. 6

(a) simulating open box
(b) simulating closed box
(c) simulating damped box

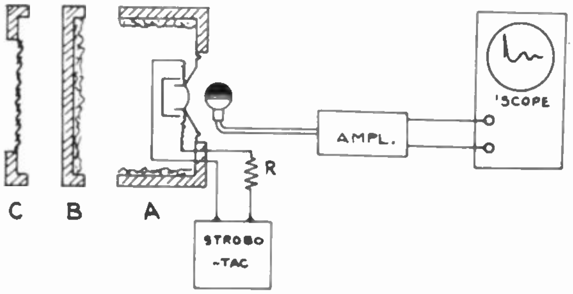


Fig. 8 Schematic arrangement for studying acoustical transients

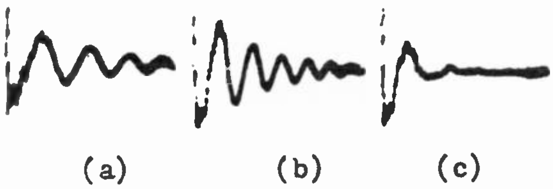


Fig. 9 Transients obtained by
acoustic measurements
(a) open box
(b) closed box
(c) damped box

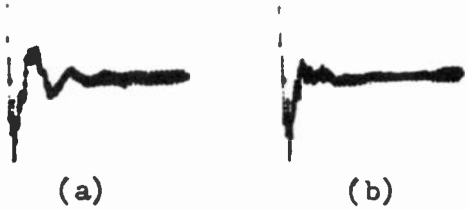


Fig. 10 Transients obtained by
acoustic measurements
(a) closed box with electric damping
(b) acoustically damped box with
electric damping

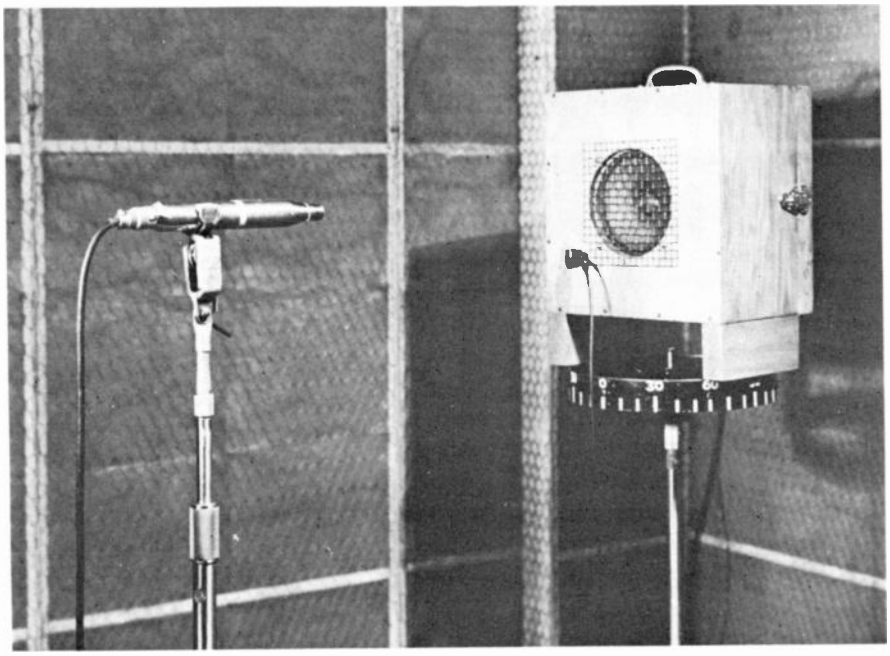


Fig. 11 Setup for frequency response measurements

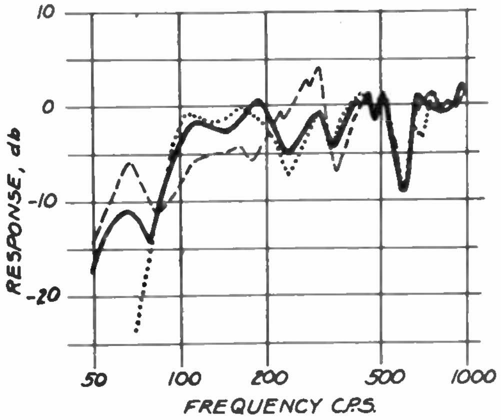


Fig. 12 Frequency response --
Dashed line - open box
Dotted line - closed box
Solid line - damped box

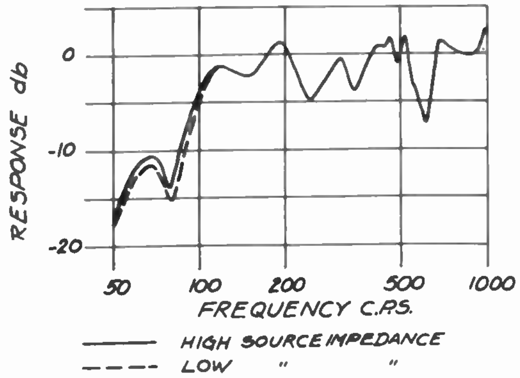


Fig. 13 Response of acoustically
damped loudspeaker as a
function of source impedance

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