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## A LOUDSPEAKER ACCESSORY FOR THE PRODUCTION OF REVERBERANT SOUND\*

Daniel W. Martin and Armand F. Knoblauch\*\*  
The Baldwin Piano Company  
Cincinnati, Ohio

**SUMMARY** — Organ music produced in small rooms having little natural reverberation can be enhanced by the addition of artificial reverberation. A direct method of adding the aftersound to the electro-acoustic transducer itself is described. This is in contrast to the more conventional reverberation systems employing driving transducers, time-delay means, pickup transducers, and mixing and amplifying circuits. Multiply resonant helical mechanical delay lines store the energy and radiate it at a later time. In one model the coupling to the transducer is mechanical, and in the other model acoustical coupling provides a number of practical and acoustical advantages.

### INTRODUCTION

Organs have traditionally been heard in large reverberant rooms. This has affected organ composition and even the technique of playing. Organists prefer to have the organ console far enough away from the organ tone-chamber for listening to the combination of organ and room. In a sense they are playing the room as well as the instrument. This can easily be demonstrated.<sup>1</sup>

Organ music, whether pipe, electronic, or some other type, is enhanced by reverberation. In recent years organs have become economically feasible for use not only in small churches, chapels, and studios having

very short reverberation periods, but in homes where parlor size and furnishings preclude effective reverberation.

The first reverberation means used on organs having electric output,<sup>2</sup> was similar in concept to the reverberation systems employed for recording and broadcasting purposes. Such systems consist of a driving transducer, a multiple time-delay means, one or more pickup transducers, and mixing and amplifying circuits. The devices described in this paper eliminate much of this complication and, consequently, have a decided economic advantage to the domestic user.

One type<sup>3</sup> consists of an otherwise conventional direct-radiator loudspeaker, coupled mechanically to helical coils of wire mounted in front of the cone. Vibrational energy absorbed by the reverberation coils, directly from the motion of the loudspeaker voice-coil, is transmitted back to the loudspeaker cone at a later time, and radiated as reverberant sound.

In a second type,<sup>4</sup> similar reverberation coils are coupled mechanically to a separate cone, which is smaller than the loudspeaker cone and mounted concentrically in front of it. Acoustical coupling provides

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\*\*Now at the Physics Department, University of Cincinnati.

Daniel W. Martin, The Enhancement of Music by Reverberation, *Conv. Rec. IRE*, 1954, part 6, p. 4.

<sup>1</sup>L. Hammond, U.S. Patent 2,230,836; 1941.

<sup>2</sup>Armand F. Knoblauch, U.S. Patent applied for.

<sup>3</sup>Daniel W. Martin, U.S. Patent applied for.

the driving force for the reverberation cone-coil combination, which is an accessory to the conventional loudspeaker.

It is ironic that acoustical physicists and engineers, after years of effort aimed at dispelling the old notion that wires strung through auditoriums would improve the acoustics, would use wire wound compactly into coils in order to produce a simulation of large-room acoustics.

### THEORETICAL CONSIDERATIONS

Helical coils of wire were used twenty-five years ago by Wegel,<sup>5</sup> in mechanical speech-wave transmission lines for time-delay purposes. Resistance termination was used purposely in order to prevent wave reflection and resonance effects. The velocity of the wave transmitted by compressional vibration of the end of the coil is given by the equation

$$V = \frac{d}{\pi D^2} \left( \frac{E_s}{2\rho} \right)^{1/2} \quad (1)$$

in which

$V$  = propagation velocity in turns/second

$d$  = diameter of the wire in cm

$D$  = mean diameter of the helix in cm

$E_s$  = shear modulus of the material, dynes/cm<sup>2</sup>

$\rho$  = density of the material, grams/cm<sup>3</sup>

For infinitely long coils the characteristic impedance in mechanical ohms is given by the equation

$$Z = \frac{\pi d^3}{4D} \left( \frac{E_s \rho}{2} \right)^{1/2} \quad (2)$$

The impedance of a partially damped coil of finite length varies with frequency quite sharply from this value, because of multiple resonances. The frequencies of the normal modes of vibration of the coil are

$$f = \frac{nV}{4N} \quad (3)$$

where

$f$  = frequency in cps

$n$  = an odd integer when the coil end is clamped, and an even integer when the coil end is free

$N$  = number of turns in the helix

The "room" which the reverberation coil simulates is of course one-dimensional, neglecting torsional and transverse modes. Consequently the density of normal frequencies along the frequency axis is uniform, in contrast to the three-dimensional rectangular room, in which the distribution follows the well-known square law<sup>6</sup> function

<sup>5</sup> R. L. Wegel, U.S. Patent 1,852,795; 1932.

<sup>6</sup> Morse, "Vibration and Sound," pp. 291-297, McGraw-Hill Book Co., 1936.

to a first approximation. This is not too serious a disadvantage in the frequency range where a real room becomes replete with normal frequencies, because organ music typically contains complex tones, some harmonics of which will lie near enough to normal frequencies of the coil to cause excitation. Actually some torsional and transverse modes are also excited in practice.

At a high frequency (corresponding to the reciprocal of  $V$ ), where a wavelength approximates a single turn of the helix, the compressional wave starts to disappear from the scene. Although this sets an upper limit on the range of normal operation, some irregular reverberation response is obtained at higher frequencies where, in fact, much of the radiation occurs from the coils itself instead of the cone.

### DIRECT COUPLED MODEL

The main features in the construction of the direct-coupled model are shown in Fig. 1. A perforated metallic driving-dome, cemented to the cone near the voice-coil form, replaces the conventional paper dust-cap of the loudspeaker. A Rivnut expanded within the central hole of the dome provides connection for the machine-screw coupling the dome to the driven end of a group of four reverberation coils. In some models two of the coils are rigidly terminated at a cast bronze support ring, and the other two are terminated in a dynamically free, "hairpin" connection to the ring for static support. This permits both even and odd-numbered modes of vibration to be excited.

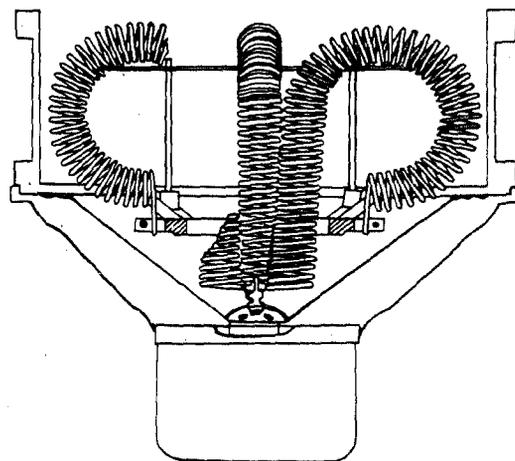


Fig. 1 - Direct-coupled reverberation loudspeaker.

Nylon cords, tied from points along the coils to small metal posts projecting from the support ring, minimize extraneous low-frequency transverse modes and provide some support for the coils under abnormal conditions of shock during local transport. The coils are rigid enough to support themselves and to maintain the preformed shape shown, during normal operation. A cylindrical wooden housing surrounds the coils and connects the

loudspeaker rim to the mounting baffle. By curving the coil axes, the over-all increase in depth is held to less than six inches for a loudspeaker of the fifteen-inch size.

In the design shown the combined mechanical impedance of the group of coils matches approximately the mechanical impedance of the driving loudspeaker between 300 and 400 cps. At the natural frequencies of coil vibration the coil impedance is very high, reducing the steady-state response of the loudspeaker locally at these frequencies. Between these frequencies the normal loudspeaker response-frequency characteristic is retained with a moderate reduction in over-all sensitivity. Because of the reduction in sensitivity the direct-coupled model is always used in combination with another conventional loudspeaker, which dominates the steady-state organ tone.

The lowest frequency of resonance in this design is approximately ten cps for the coils clamped at one end. The lowest corresponding frequency for free-end coils is twenty cps. Thus the frequencies of available compressional modes are multiples of ten cps, giving a rather dense distribution of resonances for musical excitation. If the coil had a much lower first frequency the time delay for the first reflection might be excessive in musical selections involving tones of short duration, giving the effect of a distinct echo.

If the coil had a much higher frequency for the first mode, it would give a sparser distribution of resonances and consequently, would decrease the probability of excitation of each mode. Thus the ten-cycle separation appears to be a good compromise.

The reverberation period measured for this design, using warble-tone excitation, averages approximately four seconds in the frequency range below 1200 cps. Fig. 2 shows a simple comparison of reverberation curves, one of which (A) was recorded at 500 cps in a

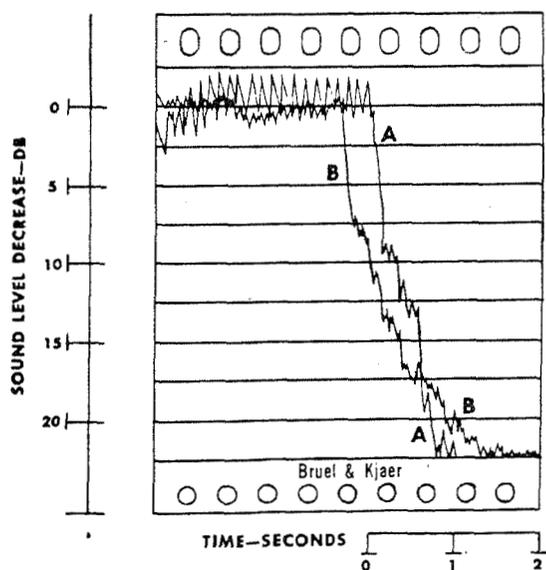


Fig. 2 - Comparison of sound decay curves in (A) large music hall and (B) from reverberation loudspeaker.

large music hall, and the other (B) near the reverberation loudspeaker in a small anechoic room. This is not to imply that the over-all effects were identical, but it does show a degree of similarity.

### ACOUSTICALLY COUPLED MODEL

Fig. 3 shows the general construction of an acoustically coupled model which possesses several acoustical and practical advantages over the direct-coupled model. A separate cone is mounted coaxially in front of the conventional cone, and serves to support and drive the inner end of the reverberation coils. The outer cone also radiates the reverberant sound. At the lower frequencies it is rather transparent acoustically. The driving dome is perforated to transmit the higher frequencies, which normally are radiated chiefly from the central part of the inner cone. Direct sound is also radiated from the annular opening around the edge of the outer cone.

Because the entire reverberation cone-coil structure is supported on the cylindrical shell enclosure, this assembly may be considered an accessory unit which is separable from the conventional loudspeaker which drives it. This is an advantage for shipping, and simplifies the addition of the simulated reverberation feature to existing loudspeaker installations.

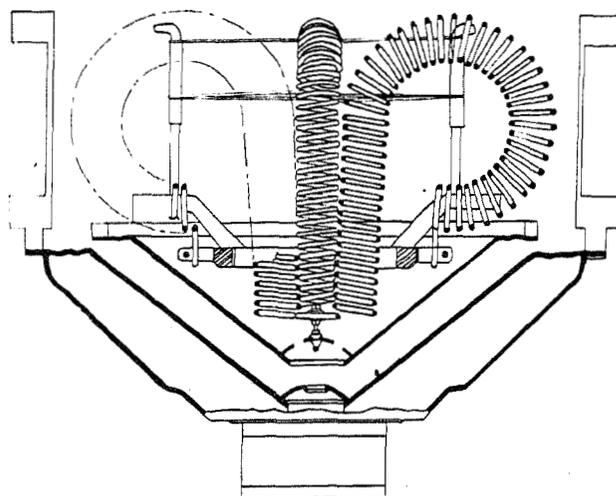


Fig. 3 - Acoustically-coupled reverberation accessory for loudspeakers.

Loudspeaker voice-coil suspensions are designed for high compliance along the axis of motion, and low compliance in the plane normal to this axis. It is the latter factor which permits the direct-drive model to partially support the weight of the driving end of the coil-structure when the axis is horizontal. The direct-drive model has not been used with the axis vertical, because the cone would gradually yield along the axis, displacing the voice-coil from its normal position in the gap. In the acoustically-driven model either vertical or horizontal mounting is possible without reaction upon the voice-coil.

The acoustically-coupled model does not require an additional conventional loudspeaker to supplement its steady-state acoustic output. The economic advantage is obvious. Fig. 4 compares the steady-state response-

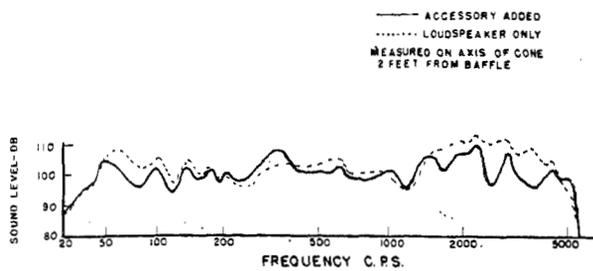


Fig. 4 - Steady-state response-frequency characteristics of a fifteen-inch loudspeaker with and without the reverberation accessory.

frequency characteristic on the axis of a fifteen-inch loudspeaker on a large flat baffle, with and without the reverberation accessory. The response below fifty cps is unaffected. This can be attributed to the annular opening

around the outer cone, which prevents the stiffness of the outer assembly from raising the principal cone-resonance frequency. From fifty to fifteen-hundred cps the response changes are small and variable in sign. Above 1500 cps there is an average loss of approximately five db on the axis, but part of this results from the diffusion of the high-frequency sound waves, a condition considered desirable for organ music.

#### CONCLUSION

A simulated reverberation effect can be provided for organs radiating electroacoustic output in non-reverberant spaces, by the simple addition of a loudspeaker accessory of one of the types described.

#### ACKNOWLEDGMENT

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