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ARTIFICIAL REVERBERATION

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Section Title Page

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ARTIFICIAL REVERBERATION

Summary

Existing systems of artificial reverberation are briefly appraised and their defects discussed. Some possible new systems are described and their potentialities assessed, and it is concluded that these would be free from the defects of existing systems, but that they would probably be costly.

1. Introduction

1.1. History

Artificial reverberation systems were reviewed by Axon et. al[1] in 1955 and Goodfriend and Beaumont[2] in 1959. Since that time, reverberation plates[3] have come into widespread use and other systems have been proposed. Systems employing torsional oscillations of springs have been developed to the point where they are acceptable to broadcasting organisations for some types of programme.[4] Schroeder and Logan proposed an artificial reverberation system[5] claimed to be free of colouration but there are some practical difficulties to its construction and it does not seem to be in use to any significant extent.

A new class of artificial reverberation systems has appeared in which the sound is picked up by a microphone and replayed over loudspeakers in the room in which the sound originates. These include ambiophony,[6] assisted resonance[7] and a system devised by Franssen.[8]

An ambiophonic system requires extensive re-adjustment if the sound source and microphone are moved, so it is inconvenient for broadcasting purposes. Assisted resonance systems which cover the frequency range up to 4 kHz have not yet been demonstrated; existing systems are costly to install and maintain. Franssen claims that his system increases reverberation time without the disadvantage of incipient howlback, but it is not clear to the present authors that this necessarily follows from his theoretical analysis. At any event, verbal reports from those who have seen Dr. Franssen's installation in Holland appear to establish that the system would require a large number of high-quality microphone-amplifier-loudspeaker channels for music. Understanding of this class of systems is far from complete and there is much scope for further research. Such systems will not be discussed further in this report; even if they were improved considerably, they would have very restricted application to broadcasting. Discussion will be confined to those systems in which reverberation is added without requiring access to the studio in which the programme originates.

1.2. Need for new systems

For applications where an accurate simulation of natural reverberation is unnecessary or unwanted, e.g. pop music, existing devices probably give satisfactory quality and they are not unduly expensive. What is lacking is a system which has all the desirable attributes of natural reverberation from a hall having good acoustics. No system has yet been made which provides artificial reverberation which is indistinguishable from the reverberation from a large hall of good acoustical quality. In practice, of course, this ideal is unnecessary since most programme to which artificial reverberation is added already has a considerable content of natural reverberation. However, the nearer this ideal is approached, the more flexible can be the choice of studios and outside halls for broadcasting. If the ideal system were developed it might be possible to broadcast concerts from studios little bigger than is necessary to seat the players.

1.3. Defects of existing systems

The defects of existing reverberation systems are easier to recognise on listening than to describe in words that are meaningful to someone who has not heard such defects. Until it becomes economic to issue sound recordings with reports, this difficulty will remain.

There are two main defects of existing systems:

1. The presence of colourations. A colouration is the subjective impression that sounds of a particular pitch are being unduly accentuated in comparison with the whole spectrum. No precise method has yet been developed whereby it is possible, from objective measurement alone, to predict whether or not a system will produce colourations.
2. The presence of flutter echoes. Flutter echoes are most noticeable with impulsive excitation of the system; they appear as periodic repetitions of the input signal. For more continuous excitation, they appear as periodic amplitude modulation of the

decaying sound after the excitation has ceased. They are associated with periodicities in the system and are too low in frequency to be heard as colourations.

2. Possible new systems

2.1. Development of the reverberation plate

Van Leeuwen has described his attempt to reduce the size of the reverberation plate without impairing quality.[9] The phase velocity of bending waves in a plate is given by

$$c = (2\pi f)^{\frac{1}{2}} \,.\, \left\{Yt^2/12\rho(1-\mu^2)\right\}^{\frac{1}{4}} \qquad (1)$$

where f is the frequency

Y is Young's modulus for the plate material

μ is Poisson's ratio for the plate material

ρ is the density of the plate material

t is the thickness of the plate

If the ratio of wavelength to length and width of the plate is to remain constant, then a reduction in both length and width by a factor r necessitates a reduction in thickness by the factor r^2. Van Leeuwen's plate has the dimensions 170 mm x 130 mm x 5 μm corresponding to r = 1/10, and is made from nickel foil. The effect of air-damping on so thin a foil is great and in order to achieve a mid-band reverberation time of 3 seconds the housing for the plate must be evacuated to a pressure of 133 N/m² (1 mm Hg).

Dr. W. Kuhl of IRT Hamburg, the inventor of the reverberation plate, has for many years been developing an improved version of the device.[10] It is now expected that the new plate will be commercially available in the second half of 1972. A description of the production version of the new plate has been given recently by Rother.[11]

Kuhl's new plate is said to be quite free of colouration and small enough to be carried in a medium-sized saloon car. The area of the plate itself is 0·1 m², about one-twentieth of the area of the standard plate. The thickness is about 0·02 mm, about four times as thick as Van Leeuwen's miniature plate.

Unlike Van Leeuwen's plate, Kuhl's plate does not have to be operated in a vacuum to achieve a long reverberation time and the increased thickness accounts at least partly for this. Kuhl indicates that a plate made of nickel is insufficiently heavy to be resistant to unwanted damping, and implies that only alloys of platinum, silver or gold are satisfactory. He points out that problems are to be expected with the transducers used to excite and to pick up the plate vibration and that the bending-wave impedance of a plate 0·02 mm thick is so small that the moving-coil of an electrodynamic transducer attached to the plate must weigh no more than a few milligrammes.

If the new plate lives up to its claims, and is not too expensive, it may well be the answer to the demand for a high-quality artificial reverberation system which is small enough to be easily transportable.

2.2. Proposed optical method

In 1966 Gouriet suggested an artificial reverberation device involving optical convolution of the sound with the impulse response of a real or artificial room.

If the impulse response of the path (or paths) between a sound source and a microphone in a room is R(t), then the output voltage of the microphone V(t) is related to the sound pressure waveform generated by the source S(t) by the convolution integral

$$V(t) = \int_0^T R(\tau)\,.\,S(t-\tau)d\tau \qquad (2)$$

where $R(\tau) = 0$, when $\begin{cases}\tau<0\\ \tau>T\end{cases}$

In an artificial reverberation machine, R(t) is the impulse response of the machine, S(t) is the input signal and V(t) is the output signal. Gouriet suggested that the convolution could be carried out by making an optical recording of the input signal and passing this over a mask whose optical transmission was a replica of the desired impulse response. The total light transmitted through the mask and recording would be picked up by a photodetector, whose output would be related simply to the required V(t).

The proposal has attractive features. The multiplication in the integrand and the integration itself are fairly easily done optically; the speed with which these operations are carried out clearly presents no difficulties. The mask could represent the impulse response of a known good hall or studio.

However, the method would have serious disadvantages in practice. The expense and delay in producing an optical sound track would be unacceptable operationally. To make the system viable some form of rapidly recordable, erasable and re-usable optical recording medium is required, and no such material is readily available. It could well be a valuable research tool, as an aid to the design parameters of other types of artificial reverberation systems.

2.3. Proposed scale-model method

Scale-modelling of a studio or hall is a useful way of evaluating the performance of a room before it is built. In 1968, Gilford suggested that such a model could be used in an 'on-line' artificial reverberation system.

In model work, a recorded tape is played into a 1/n^th scale model of a room at a speed n times greater than the recording speed, and the sound in the model is re-recorded from a microphone in the model simultaneously. When the new recording is played at the speed of the original tape recording it sounds as if the recording was made in a room similar to the real full-scale room.

As normally operated, such a procedure would be unacceptable for an artificial reverberation machine, because of the delay between the operations of recording and replaying at the different speeds. Gilford's proposed

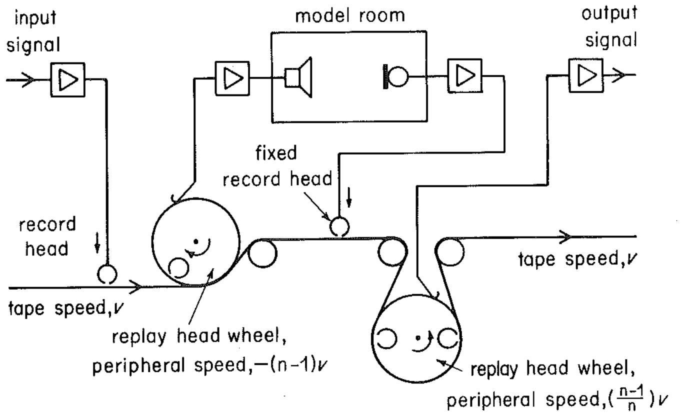

Fig. 1 - Proposed scale-model method

solution was to devise a special tape recorder with two rotating heads. Figure 1 shows the essential features of the idea. The signal to be reverberated would be recorded on tape in the conventional manner. The recorded signal would then be replayed into the model room from a rotating replay head the peripheral speed of which was (n − 1) times the tape speed and in the opposite direction. The speeded-up sections of programme would then be reverberated in the model, picked up by a microphone and recorded by a fixed recording head, on either a new track or the original track after erasure. The new recording is then replayed by a second rotating head-wheel, rotating at (n − 1)/n times the tape speed and in the same direction. Various combinations of number of heads per wheel, head-wheel speed and tape wrap-angle are possible. For the arrangement shown and with n = 8, the wrap-angle of the tape around the first headwheel must be 360/8 = 45° for the head to scan all of the input tape. The tape must wrap around the second head-wheel for at least 180° with the two heads as shown. The room under consideration could be a scale model of a known good room, or it could be a small reverberation room (echo chamber). The advantage would be that the sound would appear to come from a room much larger than it is necessary to build, and the 'small-room' sound associated with reverberation chambers would be absent.

The foreseeable difficulty in the proposal is that of joining up accurately the segments of programme which have been time-compressed and then time-expanded. The problem lacks an economical rather than technical solution, as timing correction systems of adequate performance are available, although they are costly.

A similar proposal, involving a modified transverse-scan videotape recorder, has been suggested by Boutros-Attia.[12] The technological difficulties in this proposal appear to be more formidable than the problems of Gilford's method.

2.4. Proposed digital method

It should be possible, in principle at least, to construct a special-purpose digital computer to carry out the required convolution given in Section 2.2 Equation 2.

A sampled version of the room impulse response $R(\tau)$ would have to be stored in the computer for multiplication with digitised samples of the input signal $S(t)$. Samples of the input signal ranging from the 'present' sample $S(t)$ and all the earlier samples as far back as $S(t - T)$ would need to be stored at any one time; the integration would be merely replaced by addition. For real-time operation, the multiplications and addition would need to be carried out within one sample period of the input signal.

A tentative example will show the scale of the problem:—

Bandwidth 5 kHz, therefore sample rate 12,000 samples/second.

Programme samples coded into 10-bit words.

Simulated reverberation time 2 seconds, therefore $T \approx 2$ seconds.

The number of samples required to simulate $R(\tau)$ adequately is unknown. It would be hoped that 100 would be sufficient. In one sample period the machine would have to carry out the following operations.

1. Read and multiply 100 ten-bit words with another 100 ten-bit words and sum the products.
2. Shift the programme samples one place, discarding the oldest sample and reading in the newest.

Consideration of these requirements indicates that such a machine could be made to work in real time, but that the cost would be high. It is estimated that the cost of the 'hardware' alone for such a machine would not be less than £8000 and would perhaps be as high as £20,000. In any case it would be unwise to embark upon such a device without a clearer idea of the number of samples required adequately to approximate $R(\tau)$. Simulation of a proposed machine by programming a general-purpose digital computer would be a safer (but still expensive) first step.

2.5. Proposed pseudo-random artificial reverberator

A device employing a pseudo-random sequence generator to eliminate the colourations inherent in recirculatory delay systems has recently been proposed by Jones.[13] A schematic drawing to illustrate the principle is shown in Fig. 2.

The signal to be reverberated is converted to digital form as for the method of Section 2.4. Consecutive sections of the signal are then, in effect, convolved with a pseudo-random sequence of numbers, thus producing sections of signal having no colouration. The resultant sections of signal are then weighted progressively so that the envelope of the impulse response of the system approximates the decaying form characteristic of natural reverberation.

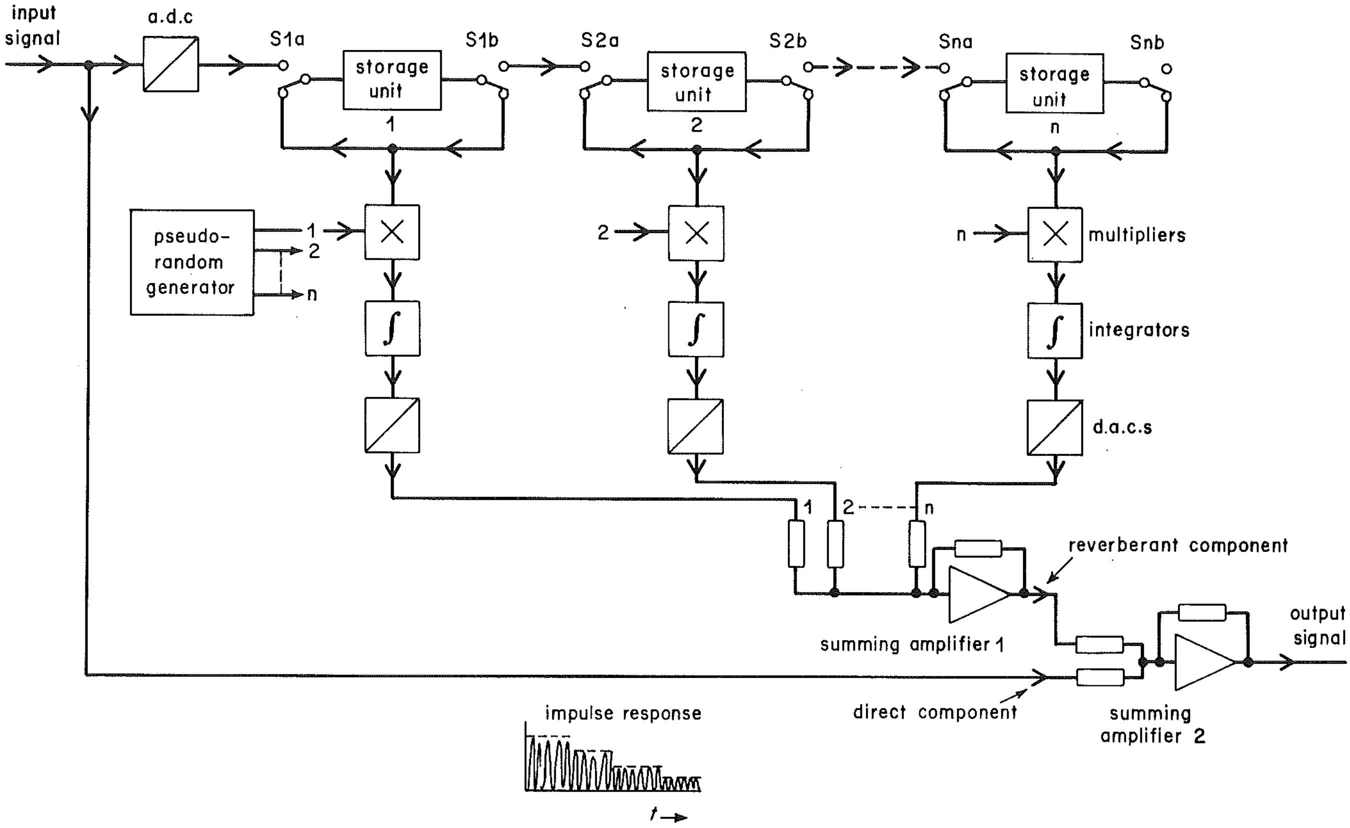

Fig. 2 - Artificial reverberation using pseudo-random sequences

Referring to Fig. 2, the input signal is sampled, digitised and passed to an assembly of N storage units formed from shift registers. Each storage unit has a capacity of n signal samples. At the beginning of a sampling period the switches S1a, S1b, S2a, ... etc., are in their upper positions and one signal sample is moved from the analogue-to-digital converter to the first storage unit, one from the first storage unit to the second, one from the second to the thrid and so on throughout the chain of storage units. The switches are then set to the positions shown and the samples in each storage unit are rapidly circulated once before the signal sampling period is complete. During circulation, each sample is multiplied by a different 'word' (i.e. a number) from the pseudo-random generator and the sum of the resultant products is accumulated in each integrator. The pseudo-random generator has a number of different outputs so that the samples in each storage unit are multiplied by a different set of numbers.

At the end of the summation process, the totals from the integrators are fed to digital-to-analogue converters* and the resulting analogue signals combined in a summing amplifier, after having been attenuated progressively to give the required decaying envelope for the impulse response. At the end of each sampling period, the signal samples are moved one place to the right along the storage unit chain and the pseudo-random generator and integrators are reset in readiness for the next multiplication/summation cycle.

The impulse response of such a reverberator would be a pseudo-random sequence, amplitude-modulated by a staircase function. It seems very unlikely that such a response would give rise to colourations. The likelihood of flutter from the periodicity in the envelope would also appear to be small if there were something of the order of 100 steps in a reverberation time of 2 seconds, i.e. about 1 dB average fall in amplitude per step.

The storage units could be made from currently-available MOSFET integrated circuits. It is estimated that a reverberator having the same basic design standards as those of the non-random device described in Section 2.4 above would cost about £4000 (hardware only).

3. Conclusions

Existing artificial reverberation devices are all unsatisfactory in one respect or another, but apart from projected improvements to the reverberation plate, there seems little prospect of making a high-quality device at an economic price at the present time.

Of the new methods of producing artificial reverberation discussed, the optical method would be an attractive and flexible device if it could be operated in real time with a re-usuable recording medium, the scale-model would be attractive were it not for the expense envisaged in solving the timing-correction problem and the digital method would be prohibitively costly even in its simplest form. The pseudo-random method would appear practic-

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* The function of multiplication, integration and digital-to-analogue conversion may be combined within a single unit.

able, although it would be too expensive for operational use in the precise form described. The construction of a prototype would permit possible simplifications (and cost reductions) to be assessed subjectively.

4. References

1. AXON, P.E., GILFORD, C.L.S. *and* SHORTER, D.E.L. 1955. Artificial reverberation. *Proc. Instn. elect. Engrs.*, 1955, **102B**, 5, pp. 624 – 642.

2. GOODFRIEND, L.S. *and* BEAUMONT, J.H. 1959. The development and application of synthetic reverberation systems. *J. Audio Engng Soc.*, 1959, **7**, 4, pp. 228 – 234.

3. KUHL, W. 1958. The acoustical and technological properties of the reverberation plate. EBU Rev., 1958, **49A**, pp. 8 – 14.

4. MEINEMA, H.E., JOHNSON, H.A. *and* LAUBE, W.C. 1961. A new reverberation device for high fidelity systems. *J. Audio Engng Soc.*, 1961, **9**, 4, pp. 284 – 289, 324 – 326.

5. SCHROEDER, M.R. *and* LOGAN, B.F. 1960. 'Colorless' artificial reverberation. *J. Audio Engng Soc.*, 1961, **9**, 3, pp. 192 – 197.

6. VERMEULEN, R. 1958. Stereo-reverberation. *J. Audio Engng Soc.*, 1958, **6**, 2, pp. 124 – 130.

7. PARKIN, P.H. *and* MORGAN. K. 1970. 'Assisted resonance' in the Royal Festival Hall, London: 1965 – 1969. *J. acoust. Soc. Am.*, 1970, **48**, 5, Pt. 1, pp. 1025 – 1035.

8. FRANSSEN, N.V. 1968. Sur l'amplification des champs acoustiques. Acustica, 1968, **20**, 6, pp. 315 – 323.

9. VAN LEEUWEN, F.J. 1965. 5th International Congress on Acoustics, Liege, 1965, Paper H68.

10. KUHL, W. 1971. Eine kleine Nachhallplatte ohne Klangfarbung. Proc. 7th International Congress on Acoustics, Budapest, 1971, Vol. 1, pp. 461 – 464. Paper 23E14.

11. ROTHER, P. 1971. Nachhallplatte nur noch 800 cm^2 gross. Studioqualität auch für Ü-Wagen. Radio Mentor, 1971, October, pp. 593 – 596.

12. BOUTROS-ATTIA, R. 1962. Instantaneous subjective pre-determination of room acoustics, Paper M42. Fourth International Congress on Acoustics, Copenhagen, August 1962.

13. BBC Patent Application. Simulating reverberation characteristics. Provisional specification No. 38582/71; Filed 17th August 1971.

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