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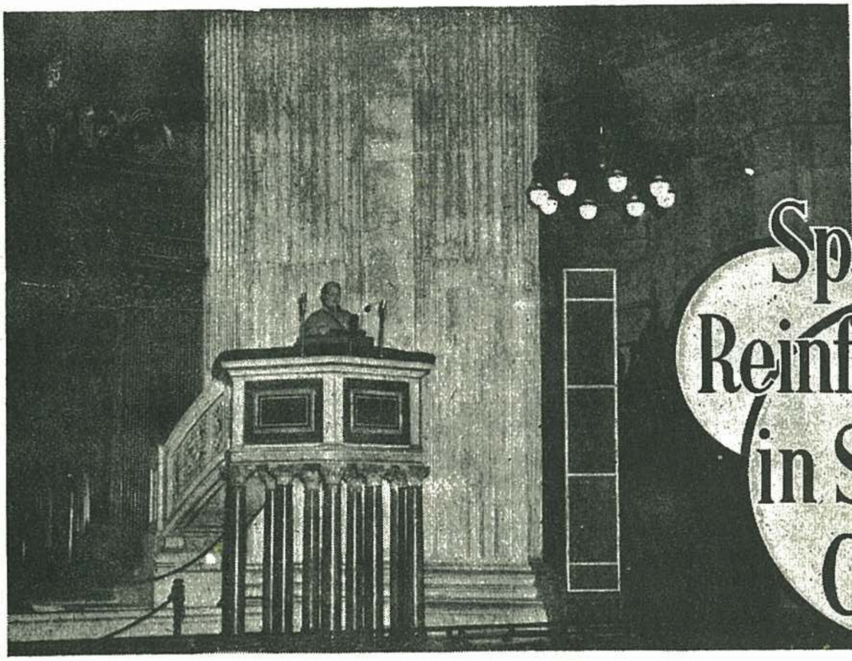

Vertical loudspeaker column for the dome area mounted to the right of the pulpit.

Speech Reinforcement in St. Paul's Cathedral

By P. H. PARKIN,* B.Sc., A.M.I.E.E. and P H. TAYLOR,† A.M.I.E.E.

Experimental System Using Line-source Loudspeakers and Time Delays

THOUGH the 17th-century architect, Sir Christopher Wren, showed some interest in acoustics and sound insulation, St. Paul's Cathedral (Fig. 1) must be one of the most difficult buildings for speech in existence. Its large size (the volume is about five million cubic feet) and the lack of sound absorptive materials result when empty in a reverberation time at mid-frequencies of about 11 seconds (Fig. 2); even when full the reverberation time is still about 6 seconds. In addition there are several concave surfaces which produce strong echoes; the most obvious of these is the dome and its drum which is 111ft in diameter at the base and which rises to 216ft above floor level. The unaided voice cannot be expected to be intelligible over the whole congregation area. Various speech reinforcement systems have been tried, but none with complete success. The system in use before the one to be described here succeeded in making speech intelligible, but only at a considerable sacrifice in quality.

This article describes a system, developed by the Building Research Station in collaboration with Pamphonic Reproducers Limited, which has been recommended to the Dean and Chapter as being the most suitable for the Cathedral. The description is in terms general enough to be of help in the design of systems for other reverberant auditoria.

Frequency Response.—The smaller the frequency range used the simpler are the lesser design problems, but at the same time naturalness must be maintained. Beranek, Radford, Kessler and Wiesner have recently described experiments[1] with speech reinforcement systems in reverberant auditoria in which they found that the naturalness of the reinforced speech was not affected if the frequencies below 400 c/s were attenuated. They also found that, contrary to their original expectations, the intelligibility was not improved by attenuating these lower frequencies. These results are not quite the same as those found by one of the present authors (Parkin, unpublished). In Harringay Arena, when full, the low-level system in use there was switched alternately throughout a performance of a musical comedy from the normal full-frequency range to a restricted range of 300 to 4,000 c/s. Of 40 listeners distributed throughout the arena, 28 said the restricted range was more natural compared with 9 who said the full frequency range was more natural; 24 said that the restricted range was more easily intelligible compared with 12 who voted for the full range. Thus in this auditorium, where the reverberation time (full) at mid-frequencies was about 5 seconds (Fig. 2), there was a definite result in favour of the restricted range.

In the Royal Festival Hall a similar test was made with about 100 listeners, and here, where the reverberation time (empty) at mid-frequencies was about 2.2 seconds (Fig. 2), there was no measurable difference in either naturalness or intelligibility between the full and restricted ranges. In the empty Coliseum Theatre, London, where the reverberation time at mid-frequencies was estimated to be about 1.2 seconds, it was obvious to the four people engaged in the tests

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* Building Research Station, Department of Scientific and Industrial Research.

† Pamphonic Reproducers Ltd.

[1] Beranek, L. L., Radford, W. H., Kessler, J. A. and Wiesner, J. B.; "Speech Reinforcement System Evaluation," *Proc.I.R.E.*, 39, (11) Nov. 1951, pp. 1401-8.

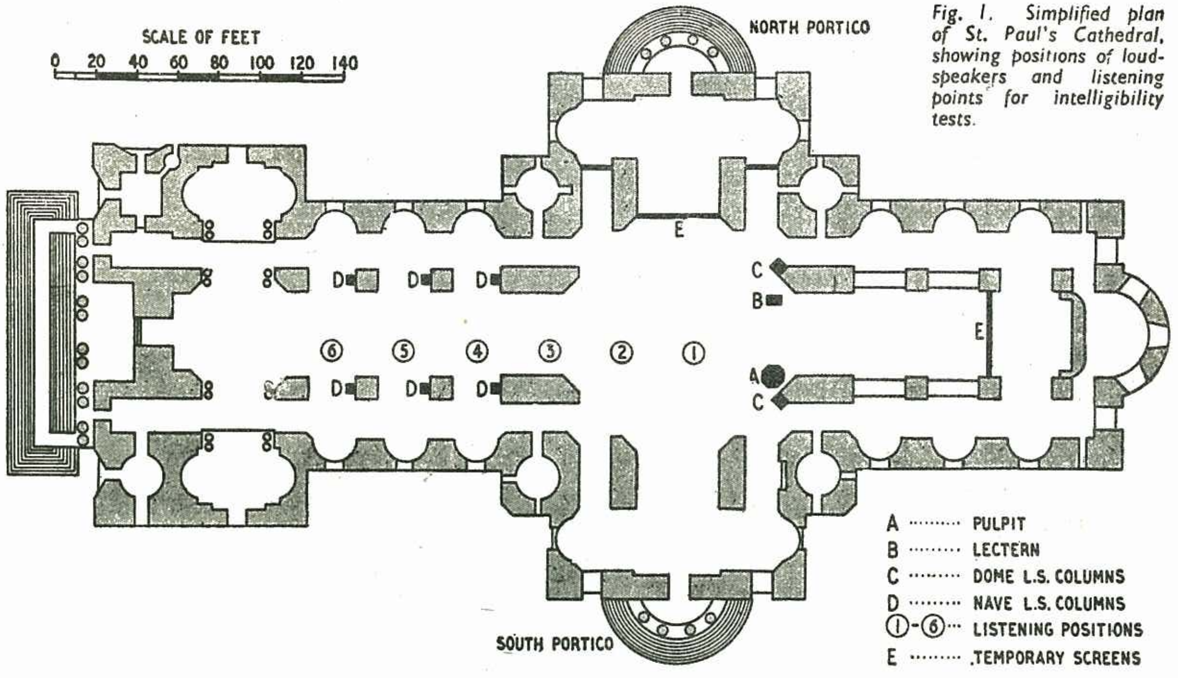

Fig. 1. Simplified plan of St. Paul's Cathedral, showing positions of loud-speakers and listening points for intelligibility tests.

that the restricted frequency range was the less natural.

We see, then, that in the most reverberant auditorium the restricted range was better, in the middle auditorium there was no difference between the ranges and in the least reverberant auditorium the full range was better. For St. Paul's Cathedral it could be assumed that the restricted range would probably be better and would certainly not be worse. The range of 250 to 4,000 c/s was decided on for design purposes ; this was very close to the range used in the above tests in auditoria and was exactly four octaves.

Direct and Reverberant Sound.—The intelligibility of speech under reverberant conditions depends, in general, on the intensity of the direct sound, whether from the voice or the loudspeaker, being at a greater intensity than the reverberant sound. With a point source of sound, the energy density, in ergs per cubic centimetre, of the direct sound at a given point is given by

$$E_D = \frac{P}{4\pi r^2 c} \quad \ldots \quad \ldots \quad (1)$$

where P is the power of the source in ergs per second, r is the distance in centimetres from the source, and c is the velocity of sound in cm/sec. The energy density of the reverberant sound is given by

$$E_R = \frac{4P}{Ac} \quad \ldots \quad \ldots \quad (2)$$

where A is the absorption in the room.

If directional sound source is used directed towards the congregation, the direct sound energy is given by

$$E_D = \frac{\alpha P}{\beta 4\pi r^2 c} \quad \ldots \quad \ldots \quad (3)$$

where α is the fraction of the energy directed towards the congregation and β is the fraction of the solid angle 4π into which the energy αP is concentrated. The reverberant sound energy is given by

$$E_R = \frac{4P}{Ac}(1-\alpha a_c) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

where a_c is the absorption coefficient of the congregation. Thus the greater α is and the smaller β is, the higher will be the intensity of the direct sound in relation to the intensity of the reverberant sound.

If we consider the distance from the source at which the direct and reverberant energy densities become equal, in the case of the point source we get

$$r_1 = \sqrt{\frac{A}{16\pi}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

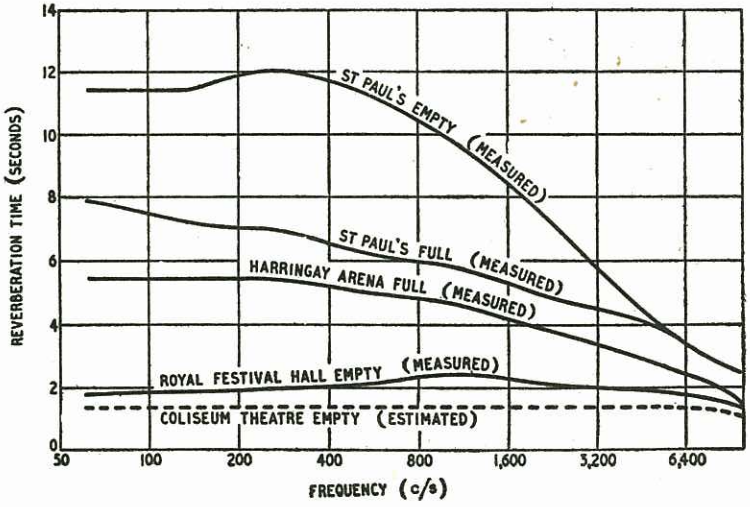

Fig. 2. Reverberation times of some representative large auditoria.

In the case of the directional source we get

$$r_2 = \sqrt{\frac{\alpha A}{\beta 16\pi (1 - \alpha a_c)}} \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

Let us assume that we have a directional source in which $\alpha = 0.9$ and $\beta = 0.03$. Then

$$\frac{r_2}{r_1} = \sqrt{\frac{\alpha}{\beta (1 - \alpha a_c)}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)$$

which, when $a_c = 0.7$, gives $r_2/r_1 = 9$. Thus a directional source with these assumed values of α and β can be expected to cover nine times the distance that a non-directional source would cover before the reverberant sound intensity is as much as the direct sound intensity.

(It should be noted in passing that intelligibility is in practice maintained up to greater distances than those given by the absolute values r_1 or r_2 when $E_D = E_R$. This is because of the ability of the ear to distinguish between wanted and unwanted sound, and because the above calculations are concerned with steady-state conditions, whereas speech is transient. Nevertheless, the *ratio* of r_2 to r_1 does apply to actual conditions.)

Line-source Loudspeakers.—Directional sound sources can be divided into three main types: shaped reflectors, e.g., a parabolic surface with a source at the focus; shaped loudspeakers, e.g., mono-planar horns; and loudspeaker arrays, that is several individual loudspeakers arranged in a pattern to give directionality. Now in St. Paul's Cathedral, and in most cases, we need a beam of sound which is narrow in the vertical plane, so that it can be directed towards the congregation and not towards the reverberant volume above, and which is broad in the horizontal plane so that it will cover the required area. While it would be possible to design sound sources with the required directionality of either of the first two types, the third type—the directional array—is the obvious choice. It is simple to design and can be made from standard loudspeakers with great flexibility. A review of directional arrays is given by Olson[2] and the one that most simply meets the requirements is the straight line source.

The theory of line sources has been known for a long time; Wolff and Malter[3] in 1930 gave a summary of their behaviour, together with the results of measurements, and it is surprising that such sources have not been used more frequently. One of the authors (Taylor) installed two such sources at White City in 1932 which are still in use, but there does not appear to be any reference to their use in this country or in the U.S.A., although they have been developed in Germany recently[4] and are now coming into fairly common use on the Continent.

The directional characteristic of a source consisting of a number, n, of equal point sources radiating in phase, located on a straight line and separated by equal distances, d, is given by

$$R_\theta = \frac{\sin\left(\frac{n\,\pi\,d}{\lambda}\sin\theta\right)}{n\sin\left(\frac{\pi\,d}{\lambda}\sin\theta\right)} \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

where, at a large fixed distance from the source, R_θ is the ratio of the pressure at an angle θ to the pressure for an angle $\theta = 0$ (the direction $\theta = 0$ is at right angles (normal) to the line), and where λ is the wavelength. In the limiting case where n approaches infinity and d approaches zero so that $nd = l =$ the length of the line, we have the ideal straight line source. Equation (8) then becomes

$$R_\theta = \frac{\sin\left(\frac{\pi l}{\lambda}\sin\theta\right)}{\frac{\pi l}{\lambda}\sin\theta} \quad \ldots \quad \ldots \quad \ldots \quad (9)$$

In the practical cases where the source is made up of a number of loudspeakers mounted close together, formula (9) can be used with sufficient accuracy provided that the distance between the loudspeakers is small compared with the wavelength. Thus with a vertical line source we have a directionality in the vertical plane which increases with increasing frequency; in the horizontal plane this arrangement does not cause any directionality. The polar diagram (up to 30 degrees either side of the axis) in the vertical plane of a vertical line source 11ft long at 1,000 c/s is shown in Fig. 3. It is seen that there are secondary lobes which, although the greatest of them is 13 db below the main lobe, might be troublesome in practice. If the line source is "tapered" in strength so that the sound from each element varies linearly from a maximum at the centre to zero at either end, the directionality is given by

$$R_\theta = \frac{\sin^2\left(\frac{\pi l}{2\lambda}\sin\theta\right)}{\left(\frac{\pi l}{2\lambda}\sin\theta\right)^2} \quad \ldots \quad \ldots \quad \ldots \quad (10)$$

Fig 3 shows the directionality at 1,000 c/s of an 11-ft tapered source, and it is seen that the main lobe is slightly broader while the first of the secondary

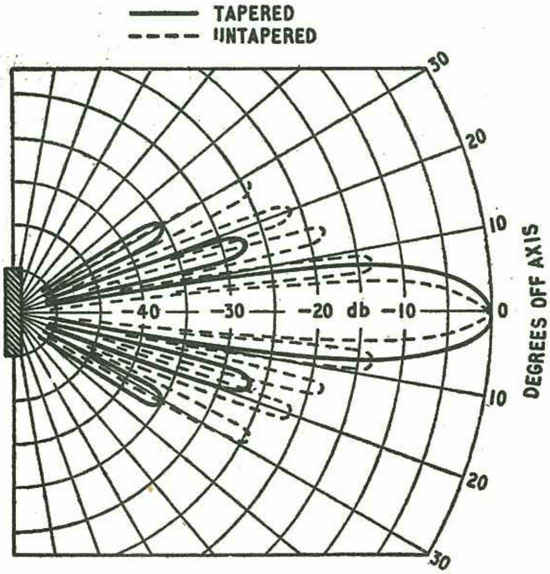

Fig. 3. Directional characteristic at a large fixed distance in the vertical plane of an 11-ft line source at 1,000 c/s.

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[2] Olson, H. F., "Elements of Acoustical Engineering," pp. 26-49 D. Van Nostrand, New York, 1947.

[3] Wolff I. and Malter, L., *Journal of the Acoustical Society of America*, 1930, 2, (2), pp. 201-241.

[4] Meyer, E., Building Research Congress Report, 1951, Division 3. Part 1, pp. 43-48.

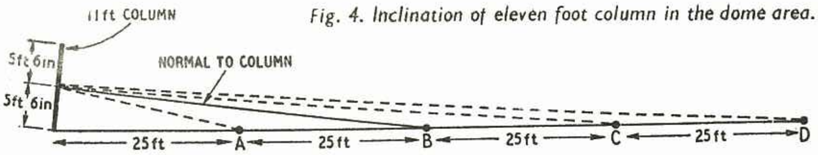

Fig. 4. Inclination of eleven foot column in the dome area.

lobes is reduced to 27 decibels below the main lobe.

We are now in a position to consider the design of loudspeaker line sources (which will be referred to simply as columns) for St. Paul's Cathedral—in the first instance those for the dome area. The two main speech positions were the pulpit and the lectern (Fig. 1) and an obvious decision was to use one column close to each, to be used separately. The horizontal distance to be covered was about 100ft, and the first attempt to cover this area was made using a column mounted about 20ft above ear height and directed down towards the congregation. The expected advantage was that the sound would be nearly all directed into the congregation so that α in equation (3) would be large. It was found, however, that when the dome area was only partly occupied, a condition that the loudspeaker system must contend with, reflections off the stone floor were giving rise to serious echoes. To avoid this, the column was then tried with its bottom at ear height and inclined forward slightly so that the centre of its beam was directed towards the centre of the dome area. The expected disadvantages of this arrangement were that α was smaller and that the sound was at grazing incidence with a corresponding attenuation. In practice, however, these disadvantages were found to be not serious.

This arrangement was, therefore, adopted and it became necessary to determine the length of the column required. It will be remembered that the frequency range to be covered was 250 to 4,000 c/s, and that the directionality of a line source increases with increasing frequency. Without going into detail here, it can be said that in the St. Paul's case a column which was long enough to give sufficient directionality at 250c/s would be too directional at 4,000c/s. Actually, a 6-ft long column for the whole frequency range was tried at one time, but when adjusted so that the listener's ears were at the beam centre when seated, the high frequencies were so sharply beamed that speech became nearly unintelligible when the listener stood up.

It would be possible theoretically to maintain the same directionality over the whole frequency range by cutting off the outer loudspeakers successively with increasing frequency by suitable electrical circuits, but this is rather complicated and has three other disadvantages at high frequencies, at any rate when 10-in loudspeakers are used. The first is that the number of loudspeakers left in circuit is small and cannot then be considered as a continuous line source; the second is that the speakers left in circuit are not tapered properly; the third is that in the horizontal plane the speakers are directional, due to their size being comparable with the wavelength.

In St. Paul's, it was necessary to cover a horizontal angle of about 120 degrees, and Olson[5] shows that, for example, a 16-in loudspeaker at 2,500 c/s is about 10 db down at 60 degrees off the axis. On the whole, the best solution appeared to be to use a cross-over arrangement, and the obvious cross-over frequency to choose was 1,000 c/s which divided the total frequency range into two ranges, each two octaves wide.

Considering the low-frequency part of the column, the highest frequency it had to emit was 1,000 c/s and thus the beam width at this frequency had to be adequate to cover the dome area; it had, however, to be kept as narrow as possible since at lower frequencies the beam would be wider. Any arrangement must be a compromise, since the narrower the beam width the longer the length of the column; the centre of the column is correspondingly higher above the listening plane and thus calls for a wider beam. A consideration of the geometry (Fig. 4) suggested that an 11-ft column would be suitable: this gave a beam width at 1,000c/s of 6 db down at 5 degrees on either side of the axis. In equation (10), R_θ is unchanged if l/λ is kept constant, so that to obtain the same directionality from the high-frequency section of the column at 4,000 c/s, its length had to be one quarter of the low-frequency section, i.e., 2ft 9in.

If we take listener position B (Fig. 4) as our reference point (0 db) then at position A the intensity at all frequencies will be 6 db higher since it is at half the distance from the source; but the intensities at A, C and D, which are off the centre of the beam, will vary with frequency. The actual values will be:

Position	**Relative Intensities (db)**			
	L.F. Section		**H.F. Section**	
	250 c/s	**1,000 c/s**	**1,000 c/s**	**4,000 c/s**
A	+5.5	0	+5.5	0
B	0	0	0	0
C	−3.5	−4	−3.5	−4
D	−6	−7.5	−6	−7.5

Thus at 25ft from the source, the frequency response is slightly irregular, but comparatively few people are as close as this since the column is covering a fan-shaped area. At greater distances the response is practically uniform.

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[5] Olson, H. F., loc. cit. p. 132.

Details of the Equipment and Results of Tests

WE have so far been concerned mainly with the directionality in the vertical plane, but directionality in the horizontal plane may also be desirable. For example, the columns to be used in the dome area of St. Paul's were required to cover a horizontal area in front of them of about 60 degrees on either side of the axis; but radiation to the back was not required and would only have decreased α and increased β in equation (3) of the previous issue.

Kalusche[6] has described two arrangements for obtaining directionality in the horizontal plane, one of which will be briefly described here. Consider a loudspeaker mounted in an "open-backed" baffle of cross-section as shown in Fig. 5(a), employing a certain quantity of packing material. At the front of the loudspeaker there is a pressure p_f, emitted directly, plus a pressure p_b from the back of the loudspeaker which has been diffracted round the baffle. At a given frequency, the vector diagram, Fig. 5(b), illustrates the behaviour; p_b is 180 degrees behind p_f, but is additionally delayed by an angle corresponding to the the path length from back to front, l, and also by an angle corresponding to the time taken, A, to pass through the packing material, the velocity of sound in which is lower than in air. Fig. 5(c) illustrates the behaviour at the back of the loudspeaker; the pressure p_f' from the front is delayed by an angle corresponding to the path difference l and the pressure p_b' from the back, already 180 degrees out of phase with the front, is in addition delayed by an angle corresponding to A. If A is adjusted so that these two angles are the same, then the resultant pressure R is zero providing the intensities of p_f' and p_b' are equal.

If for the packing we use a material in which the velocity of sound is independent of frequency, then the angle corresponding to A can be equal to l at all frequencies. Now at a certain low frequency the attenuation through the packing material can be such that p_b' is attenuated as much as p_f' is attenuated by diffraction. With increasing frequency, p_f' is more attenuated by diffraction and thus the material must have an attenuation which increases with frequency at the same rate; the resultant pressure at the back will then always be zero.

In the front of the loudspeaker at this certain low frequency, p_b will be attenuated by diffraction and by passage through the material; the resultant pressure is given by R in Fig. 5(b). As the frequency increases, the angle corresponding to l plus A increases so that p_b is coming closer in phase to p_f, and R increases; eventually p_b would be more than 360 degrees behind p_f and R would begin to decrease. However, the intensity of p_b is being decreased by diffraction and by attenuation through the material, so that in practice p_b becomes negligible compared with p_f before this stage is reached.

Kalusche describes a design of this type using "packwatte" (which appears to be cotton waste) as the material; at 200 c/s the emission to the back is about 20 db lower than that to the front.

The requirements for the loudspeaker columns for the dome area of St. Paul's have been discussed above in general terms. The length of the low-frequency section was required to be 11 feet; eleven 10-inch (nominal) loudspeakers were mounted as closely together as possible in a cabinet. The high-frequency section (2ft 9in long) was made up of nine 3½-in loudspeakers; the cross-over network was a half-section operating at 1,000 c/s. Each section of the column was tapered in intensity from the centre toward each end by inserting T-attenuators between each loudspeaker and a load resistance equal to the nominal impedance of the speaker; in this way all the speakers in each section could be connected in series, thus providing a convenient impedance for the cross-over network while keeping reasonable damping across each speaker. The back of the cabinet was left open, and cotton waste was used for the attenuation material. Accurate free-field measurements on this column were

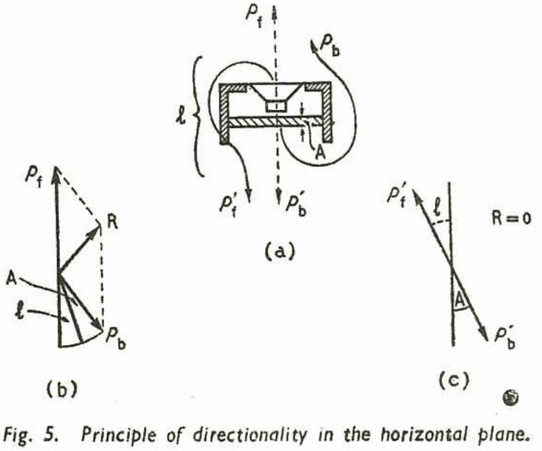

Fig. 5. Principle of directionality in the horizontal plane.

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† Pamphonic Reproducers, Ltd.

[6] Kalusche, H., *Zeitschrift für Angewandte Physik*, 1950, **2**, (10) pp. 411-415. (Available in English from Building Research Station as Library Communication No. 565.)

not possible as it was too big for an echo-free chamber, but some approximate measurements made in the open air, although confused to a certain extent by reflections, did indicate that the directional characteristics in the vertical plane had been realized (Fig. 6).

The frequency response on the axis measured at 30-ft distances showed that the output of the 3½-in loudspeakers was on the average 3 db lower than the 10-in loudspeakers. A 3-db attenuator in the low-frequency section equalized the response. (The gain factor, k, of a line source, defined as the ratio of the sound pressure of the line source on the axis to the sound pressure of a single radiator of the same power,[4] is given by $k=0.73\sqrt{f}\,l$, where f is in kc/s and l is in feet. This formula predicts a frequency response rising 3 db per octave for a given value of l. No such rise was noticed in the measured frequency characteristic, but this may have been because each section of the column covered only two octaves and because the output from the individual loudspeakers may have been falling.)

The speech in the nave area was reinforced using loudspeaker columns mounted on the sides of piers away from the pulpit (Fig. 1). Their design followed the general principles outlined above, but as they each had a much shorter distance to cover (about 35ft) it was not necessary to make them as long as the dome columns. A length of 6ft appeared to be the best compromise between height above ear level and directionality; their low-frequency sections reached the permissible limit of directionality at about 1,400 c/s and the cross-over was therefore designed for this frequency. The length of the high-frequency section was about 2ft. It was thought that the size of the piers they were mounted on provided sufficient directionality in the horizontal plane, so the directional arrangement using cotton waste backing was not employed.

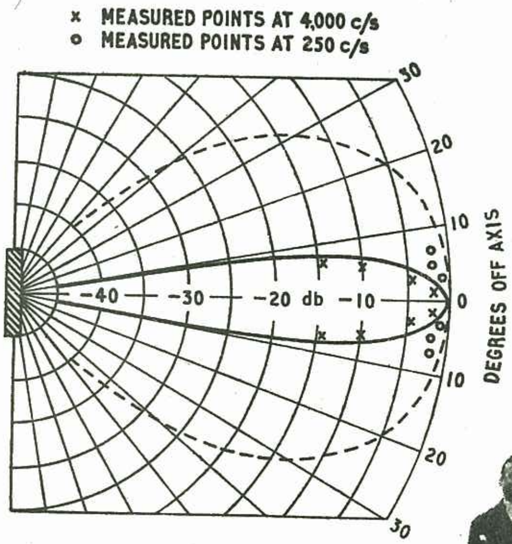
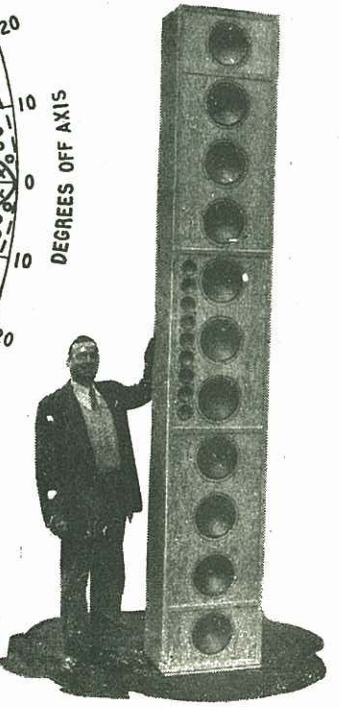
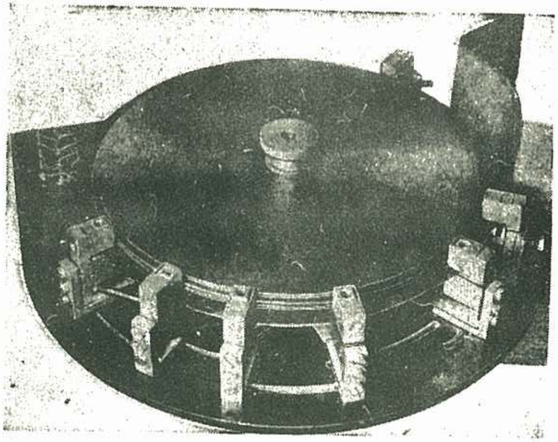


Fig. 6. Directionality in the vertical plane of 11-ft column. The full line is for 1,000 c/s in the l.f. section and 4,000 c/s in the h.f. section; dotted line, 250 c/s in l.f. section and 1,000 c/s in h.f. section.



Loudspeaker column for the dome area of St. Paul's consisting of eleven 10-inch (nominal) units for low frequencies and nine 3½-in high-frequency units. The cross-over filter is centred at 1,000 c/s.



Time delay mechanism for the nave loudspeaker columns, using a disc of magnetic recording material and adjustable playback heads.

Time Delays.—A previous article[7] has described the use of time delays to preserve realism, and this technique was employed in the Cathedral. The first pair of nave loudspeaker columns (Fig. 1) was delayed by a time interval corresponding to the path difference between the pulpit column and the nave columns, plus 5 msec. The second and third pairs were delayed correspondingly, but plus 10 msec and 15 msec respectively. The amplitude of these nave columns was also reduced, and the Haas effect ensured that all the sound appeared to be coming from the pulpit.

The time delay mechanism consisted of a turntable carrying an 11-inch diameter disc of plastic magnetic recording material. This disc extended beyond the periphery of the turntable[8] and provided an annulus supported only at its inner radius. Recording, playback and erase heads were mounted on the deck of the unit in such a way that the underside of the annulus was in contact with the pole pieces of the heads. Small felted weights carried in slides over each head maintained contact between the annulus and the pole pieces.

The recording head was permanently fixed and the playback heads were attached to radius arms which allowed them to be moved and clamped at any position on the circumference of the annulus. A graduated scale, marked off in feet and milliseconds, facilitated the setting-up of the heads to give the required delay times. The maximum overall delay obtainable on this unit corresponded to a distance of 200 yards, the peripheral speed of the annulus being 30in per second. The

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Meyer, E., Building Research Congress Report, 1951, Division 3, Part 1, pp. 43-48.

[7] Parkin, P. H., and Scholes, W. E., "Recent Developments in Speech Reinforcement Systems," *Wireless World*, 1951, 57, (2), pp. 44-50.

[8] Patent Application (Pamphonic Reproducers, Ltd.), No. 22287/1951.

minimum delay between adjacent playback heads corresponded to a distance of 20ft.

Erasure of the recorded sound took place at each revolution of the turntable just in advance of the recording head. In an installation of this sort it is essential to guard against failure of the erasing mechanism; should this happen the recorded sound is continually repeated from the loudspeakers. To cover such an eventuality, the recording was first erased by permanent magnets and then again by a supersonic head. Although the permanent magnets removed the recorded sound the residual noise level was high, and this was removed by the supersonic head.

The recording and playback amplifiers were conventional in design. The main power amplifiers were standard 25-watt public address amplifiers feeding the loudspeaker columns at 100 volts.

Power Requirements.—The tapered columns as designed for St. Paul's are inefficient electrically since nearly all of the acoustic power is radiated from the centre loudspeakers while the electrical power is distributed equally between all the loudspeakers. This could be avoided in a final design, e.g., by use of a tapped transformer, but the loss of power is not important when, as in St. Paul's, the columns are used for speech only and the total acoustic power required is only of the order of milliwatts.

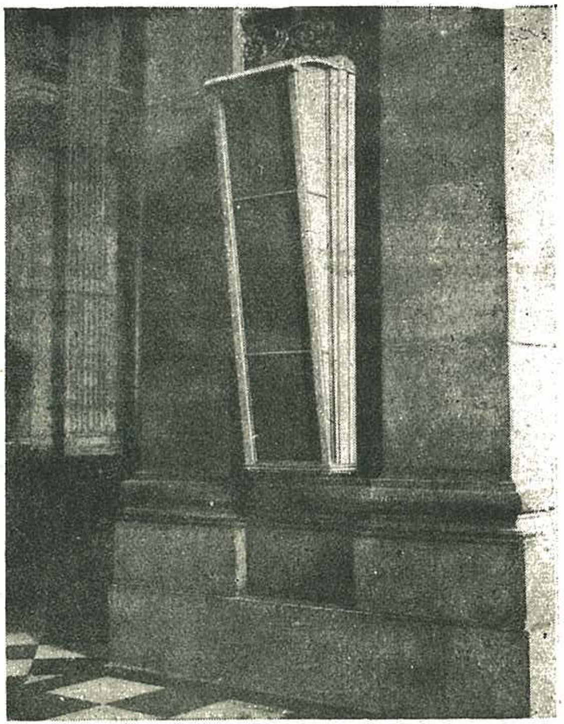
However, another important use of this type of loudspeaker arrangement is to cover large numbers of people, as, for example, at sport stadiums; in these cases the acoustic power required may be considerable, particularly when music has also to be amplified The loss of electrical power must then be avoided, and in any case it is probably better to use a uniform line source; the secondary lobes are still small compared with the main lobe, and the directivity of the line source results in a saving of power. Thus the gain factor, $k=0.73\sqrt{fl}$ for an 11-ft colunm at 1,000 c/s is 8.03, or 18 db. Meyer[4] quotes the example of a 3-metre column with a total electrical power of 75 watts, producing a sound pressure level of +94 db relative to 0.0002-dynes/cm^2 at a distance of 100 metres.

At the time of writing several details of the St. Paul's installation remain to be settled, but they concern this particular installation only and are not of general interest. For example, there is a requirement for speech at the altar to be amplified while maintaining the illusion that the sound is coming from the altar. This will probably be done by installing another column out of sight near the altar and then delaying the dome and lectern columns.

Using the pulpit column plus the six nave columns, the word intelligibility was measured in the empty Cathedral at the six positions indicated in Fig. 1 of the previous instalment, with and without the delays, but otherwise with the system unchanged. It was mentioned in a previous article[7] that time delays would probably improve intelligibility and this is, in fact, the case as is shown by Table I. It is seen that even in the empty Cathedral the intelligibility is high, and from equation (7) we can expect it to be better still when the congregation is present.

TABLE I

Position	Word Intelligibility		Corresponding Sentence Intelligibility	
	Delayed	Undelayed	Delayed	Undelayed
1	99	92	100	97
2	95	93	98	97
3	92	89	97	97
4	93	85	97	96
5	85	61	96	85
6	85	52	96	78



One of the 6-ft loudspeaker columns mounted on the piers in the nave in St. Paul's.

However, the main advantage of the columns plus the time delays is the naturalness of the reinforced speech, a quality which is difficult to measure. With the new system, the illusion that all the sound is coming from the pulpit is maintained over the seating area except, not surprisingly, for the few small areas behind the pillars in which the pulpit is screened acoustically and visually. More important, probably, is the apparent lack of reverberation when the column system is used.

Acknowledgments.—This work is part of the research programme of the Building Research Board of the Department of Scientific and Industrial Research. Thanks are due to the Dean and Chapter and the officials of the Cathedral for help freely given at all times.