Novel Airborne Technique for Aircraft Noise Measurements Above the Flight Path

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Wing-shielding effects for a TriStar airliner in flight have been deduced from a comparison of the engine noise measured simultaneously above and below the flight path; the specialized technique developed for these experiments is described and evaluated. Noise radiated upwards was monitored by flying the aircraft beneath a large instrumented fiberglass sphere suspended from a hovering helicopter; the sphere incorporated a flush mounted pressure microphone and a battery operated telemetry system. Flyover noise at ground level was recorded conventionally. Predicted acoustic diffraction by the sphere is shown to result in good directivity and frequency-response characteristics with pressure-doubling at the microphone surface over a useful wave-number range so that reliable free-field noise data could be readily derived from the flyunder; the sphere also shielded the installed microphone from unwanted helicopter background noise. Experimental checks on this behavior at both model and full scale are reported, including the results of some diffraction studies on a half-scale sphere in an anechoic room.

Introduction

KNOWLEDGE about airframe shielding, reflection, and scattering effects on the far-field noise of complete aircraft is an essential step towards improving the reliability of noise predictions for new projects and in the assessment of possible noise reductions achievable from design or layout modifications. Although progress is being made, clarification of these acoustic interactions, now commonly termed engine-installation effects, is still needed especially under full-scale in-flight conditions. Available experimental data on wing, fuselage, or tailplane shielding effects have been mainly derived from model tests with some inherent compromises in respect of aerodynamic and acoustic similarity, forward-speed simulation, and model noise-source characteristics relative to full-scale conditions. For wind tunnel acoustic experiments in particular, there are also fundamental problems of achieving representative far-field conditions within the tunnel test-section boundaries, and the need to correct the tunnel derived data relating to a stationary model and moving airstream to flyover conditions; these and other constraints on aeroacoustic testing techniques in wind tunnel facilities are discussed in greater detail in Ref. 1. In contrast, full-scale experiments with actual aircraft to measure airframe shielding effects in flight are of course free of these basic difficulties of scale and simulation, but require the application of special noise-measuring techniques and associated flight techniques, since the far-field noise distribution around the whole aircraft is needed, at least in the flyover plane where such effects are likely to be most pronounced.

This paper describes a technique developed at RAE for the study of noise-shielding effects in flight in which a comparison is made of the noise fields measured simultaneously above and below the flight path. The technique has been applied successfully in a recent flight experiment with a Lockheed TriStar airliner to investigate the efficiency of the wings in shielding the engine exhaust noise. For this purpose, the aircraft was flown with power on under wing engines only, the center engine being set at flight idle.

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The wing-shielded engine noise radiated upwards was monitored by flying the aircraft directly below a downward-facing microphone flush-mounted in the surface of a 1.83-m (6-ft)-diam sphere suspended from a hovering helicopter (Fig. 1). The noise field below the aircraft was measured conventionally using an array of microphones at ground level to reduce interference caused by ground reflections. The signal picked up by the sphere microphone was relayed to a remote ground recording station by means of a battery-operated amplifier and FM transmitter system installed in the sphere.

A central feature of the technique is that the pressure response of the sphere microphone to far-field noise originating from the moving aircraft is controlled in a known way through diffraction by the acoustically-rigid sphere. For the distant source conditions of the flight experiment, the diffractive behavior then becomes dependent only on a nondimensional parameter, ka, where k is the wave number and a is the radius of the sphere; as a result the size of sphere needed to obtain any desired directivity and frequency-response characteristics can be determined. At high values of ka, the sphere acts essentially as a reflector, augmenting the received aircraft noise propagating upwards, but acts as a noise shield against the downward-propagating helicopter noise because of the formation of a well-defined acoustic shadow region. The paper examines this behavior in detail, and includes comparisons between predicted performance and experimental data from full-scale tests and measurements on a half-scale sphere in an anechoic room.

Development of the Airborne Technique

Background

Prior to the start of the development program, the possibility of using laterally-positioned microphones on a tall tower or tethered balloon cable was considered as a means of examining the shielded noise field above the flight path of the TriStar, one advantage being that if the microphones are at sufficient height, interference from ground reflections can be made negligible, and free-field noise data acquired directly. However, it was considered that since noise-shielding effects are weaker and more difficult to interpret at lateral positions, measurements should preferably be made as close to the flight path as possible and that the development of an airborne technique as outlined earlier would therefore be necessary.

The planned use of a helicopter, however, raised the problem of the level of background noise produced at the suspended microphone. Early estimates for hover conditions at full weight clear of ground effect indicated that even with a

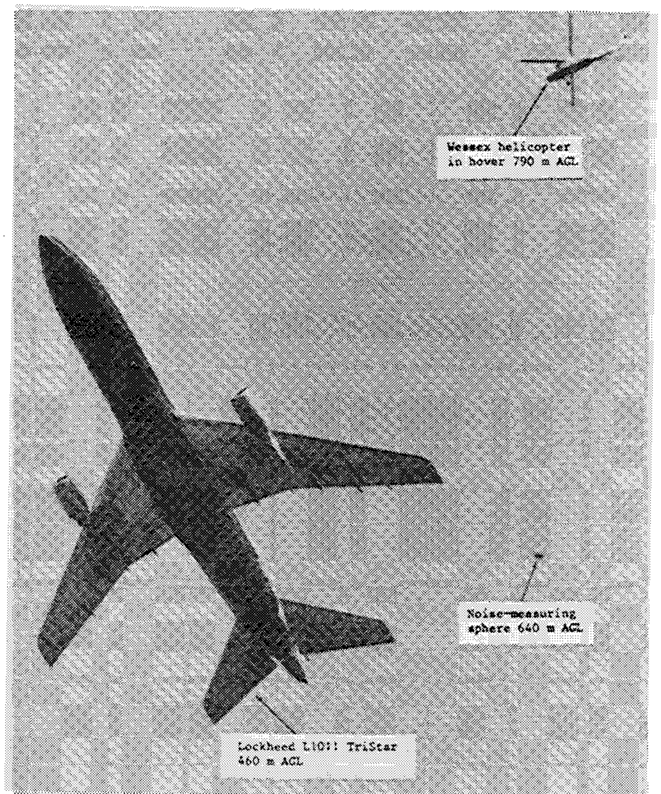

Fig. 1 Application of airborne technique to wing-shielding study on TriStar aircraft.

cable length of 150 m, the background noise levels would be too high to permit reliable measurement of the noise from the TriStar, especially if the wing acted as an efficient shield, and that the microphone itself would require shielding. While the use of a circular or square "baffle-board" surrounding the microphone could have provided a useful amount of screening for reasonable dimensions, its more critical effect on the response of the microphone to the direct noise from the TriStar was less predictable because of surface reflection and edge-diffraction phenomena; similar effects occur with the use of ground-boards for the measurement of aircraft flyover noise,[2,3] and the literature indicated that large and possibly uncertain corrections would be needed to produce free-field data when using a basically two-dimensional screen.[4,5] Operational problems with the use of a suspended baffle-board arrangement in the flight experiment were also foreseen.

Further consideration of the diffraction problem led finally to the concept of embodying the microphone in the surface of a rigid sphere. Preliminary estimates of the scattering effect showed that it should be possible to achieve a 6 dB enhancement of the TriStar noise over a wide range of frequencies, together with a substantial reduction of the helicopter background noise reaching the microphone. The basic features of this behavior in relation to the design and performance of the airborne microphone system are now considered in more detail.

Diffraction by a Sphere

Directional Effects

The principle of reciprocity provides a useful analogy for describing the diffraction effect. In Fig. 2, although the positions of the source S and measuring position M are exchanged, the problems are equivalent. Thus in Fig. 2a, the field measured at M on the surface of the sphere due to source S at distance r is the same as would be measured at M with S on the sphere surface, Fig. 2b, for a similar subtended angle or azimuth angle θ. One practical consequence of this is that alternative but equivalent experimental arrangements can be employed to investigate sphere diffraction.

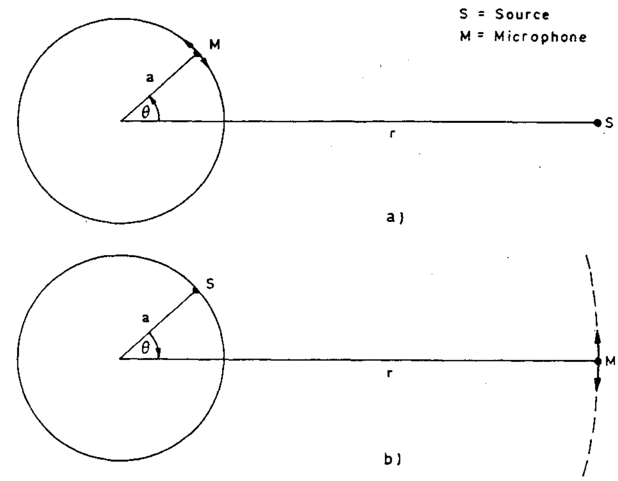

Fig. 2 Reciprocity theorem for sphere diffraction.

Qualitatively, the scattering effect becomes significant when the acoustic wavelength λ becomes comparable with the sphere radius a, so that the nondimensional wave number $ka = 2\pi a/\lambda = (2\pi f/c)a$, where f and c are the frequency and speed of sound, respectively, is both a convenient similarity parameter and descriptor of the process.

An exact analytical solution, valid at all frequencies, for the radiation pattern produced by a point source on the surface of a rigid sphere was first given by Lord Rayleigh.[6] Although his numerical computations were restricted to $ka \leq 2$, effectively to low frequency, he notes that while the field of the source is almost omnidirectional in front, behind the sphere there is a region of raised sound intensity relative to that in the rest of the shadow now commonly referred to as the "bright spot" by analogy with the corresponding optical effect. Experimental confirmation of these features and reasonable agreement with prediction have been reported, for example, by Wiener[7] up to a ka of 10, and more recently by Delany, Burton, and Rennie[8] up to a ka of 32.

These authors give the directivity pattern or polar distribution function for the variation of sound pressure over the surface of the sphere, in terms of azimuth angle θ, as

$$D(\theta,r) = \sum_{0}^{\infty} (m+\tfrac{1}{2}) P_m(\cos\theta) \frac{h_m(kr)}{h'_m(ka)}$$

where $P_m(\cos\theta)$ is the Legendre polynomial of order m, h_m is the spherical Hankel function of order m, $h'_m(z) = (\mathrm{d}/\mathrm{d}z)h_m(z)$, and r is the source distance from the center of the sphere; tabulated values of the relative variation $D(\theta,r) - D(0,r)$ as a function of ka are also given for two source distances, $r = 20a$ (typical of model experiments) and $r = \infty$.

For the distant source conditions of the flight experiment, Fig. 3 shows the predicted directivity at values of ka from 2 to 128. The curves show clearly that omnidirectional behavior to within -1 dB should occur at a ka of 4 and above over a total azimuth angular range of about 120 deg, that is 60-60 deg, which exceeds the angular variation needed for the shielding experiment. It is also apparent that the relative level of the bright spot at 180 deg azimuth, which in the experiment is formed by sound from the distant helicopter, decreases rapidly, and that the spot becomes more sharply "focused" as ka increases from about 4.

Thus $ka = 4$ was taken as the lower experimental limit so that with a selected sphere diameter of 1.83 m the microphone response would be uniform down to a frequency of about 250 Hz, and directional variations would not exceed 2 dB even at 100 Hz, which was considered reasonable; the upper value of ka at 10 kHz is then 170. As shown in Fig. 4, this performance is combined with predicted efficient shielding of the microphone from helicopter noise at frequencies above about

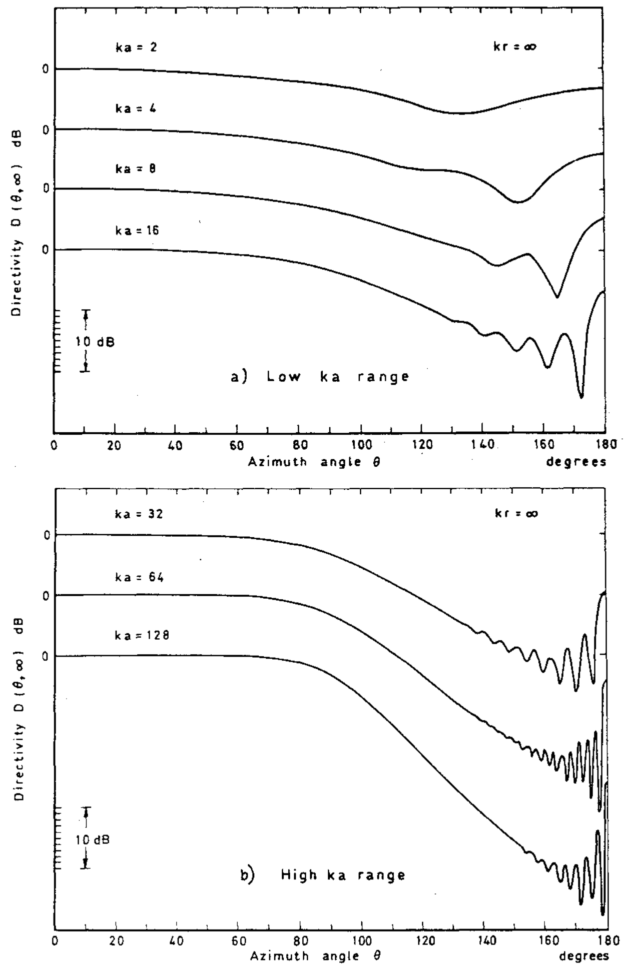

Fig. 3 Wave-number effect on predicted directivity for distant source (data from Ref. 8).

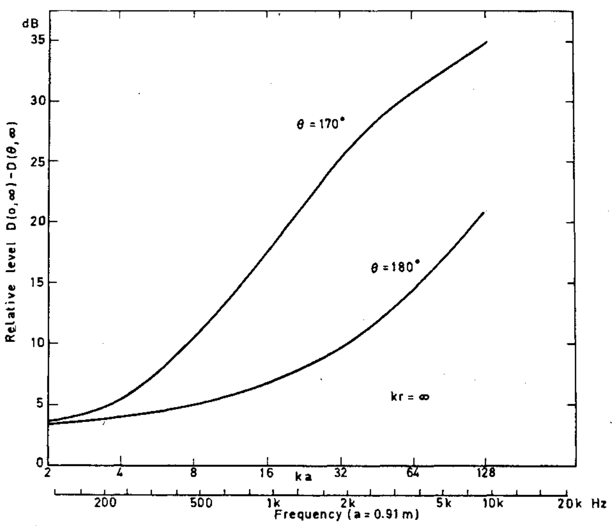

Fig. 4 Wave-number effect on predicted relative level of bright spot region (data from Ref. 8).

250 Hz. Data are given for two azimuth angles, 180 and 170 deg, and it can be seen that the shielding at 170 deg is considerably improved at higher ka as a result of the focus effect already referred to. To take advantage of this, the microphone was positioned at 10 deg azimuth rather than 0 deg, requiring an offset of about 16 cm on the sphere surface, which still left the microphone response to the TriStar noise little affected (see Fig. 3).

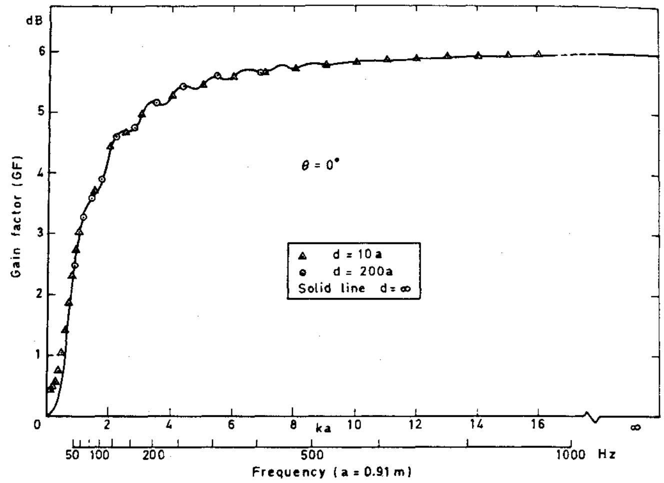

Fig. 5 Predicted variation of gain factor with wave number for normal incidence.

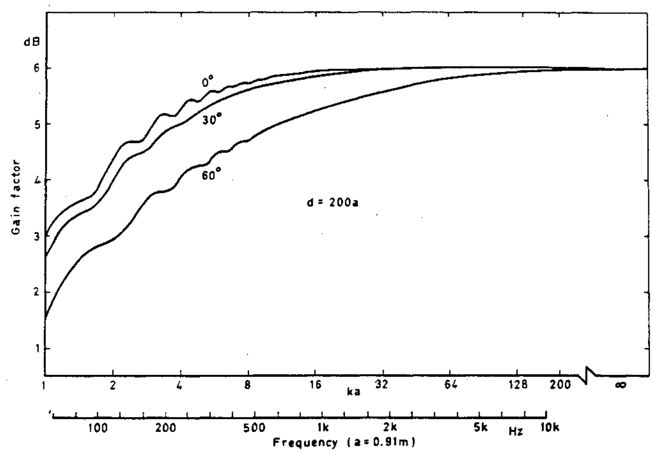

Fig. 6 Effect of sound incidence angle on gain factor.

Variation of Gain Factor

Because of the diffraction process, the sound pressure on the surface of the sphere is increased above the free-field (sphere absent) level by an amount which depends on the frequency, and this is usually referred to as the gain factor (GF). At high frequencies $ka \gg 1$, the sphere acts essentially as a perfect reflector resulting in pressure-doubling or a GF of 6 dB; conversely at low frequencies, $ka \simeq 1$, the sound field does not "see" the sphere and the GF tends to zero.

In Ref. 4, Delany and Rennie quote the theoretical axial gain factor for a point on a sphere as

$$\left|\frac{p}{p_0}\right| = \frac{2}{ka}\left(\frac{d}{a}-1\right)\left|\sum_{m=0}^{\infty}(m+\tfrac{1}{2})\,\frac{h_m(kd)}{h_m'(ka)}\right|$$

where p is the pressure measured by a microphone in the surface of the sphere, radius a, p_0 is the free-field pressure, d is the distance between the source and microphone, and the other terms are as previously defined; the predicted variation of GF with wave number for normal incidence at the microphone and with $d = 10a$ (typical of their experimental scale) is shown in Fig. 5. For convenience, a frequency scale is also shown marked at conventional one-third-octave intervals. The smooth variation of GF with frequency may be noted and this feature allows easy and reliable correction of measured data to free-field conditions by simply subtracting the appropriate value of GF at a given frequency and azimuth angle; in most cases, for the higher values of ka, the overall correction will be simply -6 dB.

Also shown on Fig. 5 is the result of a calculation of GF for $d=200a$ which is typical of the flight experiment. The differences with the $d=10a$ case are quite insignificant and tend to confirm the experimental findings of Delany and Rennie that for $d>a$, the gain factor is substantially independent of d.

For azimuth angles other than zero, the incidence angle is, of course, not normal and the gain factor alters slightly. The effect is illustrated in Fig. 6 for typical angles ranging from 0 up to 60 deg which were expected in the shielding experiment; again, the differences are generally small and only exceed 1 dB at low frequencies and at large angles.

Anechoic Room Experiments

Some basic diffraction tests were carried out on a model sphere in an anechoic room with the main objective of checking the directional behavior and the shielding effect in the bright spot region described earlier. The tests were made with a half-scale sphere (diameter 0.91 m) so that the *ka* values from about 4 to 170 representative of full scale could be achieved without the need for special ultra-high-frequency sound sources. This size, and the space restriction of the anechoic room, resulted in a source distance of about $r=4a$ compared to $r=200a$ at full scale. However, as source distance has only a relatively small effect on the diffractive behavior,[8] the model scale tests were considered reasonably representative. In fact, the effect of the greater source distance full scale is to reduce the directionality so that the model-scale data would be pessimistic in this respect.

The experimental arrangement is shown diagrammatically in Fig. 7. The anechoic room had dimensions of 5.2 m length × 4.6 m width × 4.0 m height and the wall lining of acoustic wedges gave a cutoff frequency of about 200 Hz. The sound sources were conventional high-frequency horn or dome-radiator-type loudspeakers excited with band-limited white noise of 400-Hz bandwidth to provide a constant output level over the test frequency range from about 500 Hz to 20 kHz; in the forward direction the source polars were almost omnidirectional up to about 3 kHz but at the higher test frequencies displayed the usual "beaming" characteristics. The diffracting sphere was made at RAE and consisted of a smooth plastic shell filled with a hard plastic foam to provide rigidity; it was suspended by wire from the roof of the anechoic room its lower surface being attached to a turntable to allow rotation in a horizontal plane. The sound pressure variation around the equator was measured by a 6-mm-diameter condenser microphone flush mounted in the sphere surface. After bandpass filtering to lessen the effect of any background noise, the microphone output was coupled to a level recorder driving the turntable so that direct polar plots of the diffraction pattern were produced. During the tests, care was taken to avoid interference caused by sound reflections off supports, etc.

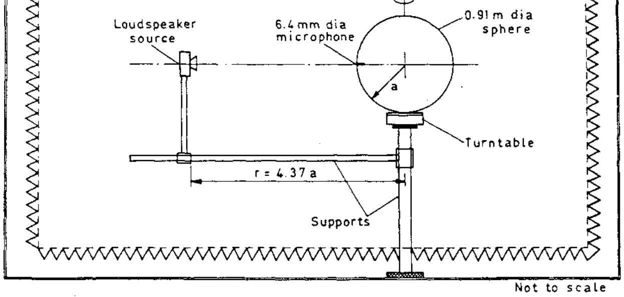

Fig. 7 Experimental arrangement in anechoic room.

Sample patterns obtained at six test frequencies covering the *ka* range from about 5 to 168, and for $r=4.37a$, are shown in Figs. 8a-f. Also plotted are theoretical points at azimuth angular intervals of 5 deg. At the lower range of frequencies, up to a *ka* of about 20, good agreement was found between the measured and predicted directivity (including the bright spot feature), for example, Figs. 8a-c, but at high frequencies discrepancies appeared with the measured sound levels, particularly at high azimuth angle, becoming significantly less than predicted, Figs. 8d-f. At first, it was considered that this effect possibly arose from averaging of the incident sound field across the finite diameter of the microphone diaphragm, but estimates showed that this could not account for the large differences observed. Another possibility is that the sphere was less uniformly "illuminated" at the higher test frequencies because of "beaming" by the sound source already described, leading to an apparently larger shadowing effect at high angles.

Sphere Construction

The full-size diffracting sphere used in the wing-shielding investigations was also designed and constructed at RAE (Fig. 9). The basic structure consisted of two 1.83-m-diam hemispherical shells each made up from a laminate of several layers of resin-bonded glass fiber fabric reinforced with internal struts and bolted together at their circumferences. A small removable panel at the side of the lower hemisphere gave access to the instrumentation pack, and another at the base carried the telemetry aerial and microphone installation. Provision was made for the flush mounting of two 13-mm-diam condenser microphones covered by a hemispherical foam windshield at opposite 10 deg azimuth positions, with the stub aerial between mounted axially and pointing downwards. Both hemispheres were filled with a polyurethane foam compound to provide rigidity. The outer surface of the sphere was sprayed with a conducting coat of zinc, to provide electrical shielding and to facilitate radar tracking, and was then finished in fluorescent orange paint with a black sector so that any spinning motion could be detected. Four supporting wires each about 2 m long were attached by cleats on the upper surface and joined to a ball-bearing swivel at the end of the main 150-m-long suspension cable, so that any twist in the cable was relieved. (This technique was successful in that no spinning of the sphere while airborne was observed.) The total weight of the in-service sphere plus cable was about 200 kg and a wooden cradle was provided to facilitate its ground handling.

Telemetry Installation

A telemetry data link was used to relay the sphere microphone signal to a ground recording station situated some distance away from the airfield area where the flight experiment was conducted. By employing a frequency-modulation technique good frequency response and linearity with low overall background electrical noise could be achieved. The equipment installed in the sphere is shown in Fig. 10. The miniaturized FM transmitter had a carrier frequency in the 400-MHz region and an rf power output of about 4 W into a matched 50-Ω load provided by the stub aerial, the metallized surface of the sphere acting as a "ground plane." The power input was 28-V dc at about 0.9 A supplied via a voltage regulator from a rechargeable NiCd battery. The microphone was of special design to operate on 28 V polarization supplied from long-life batteries in the preamplifier. The ground receiving system consisted of a "local" monopole aerial coupled via a UHF to VHF converter to a commercial tunable FM receiver incorporating afc. The output was recorded conventionally on a FM tape recorder, and also displayed on a level recorder to provide "on-line" monitoring of the noise data as the flight experiment progressed.

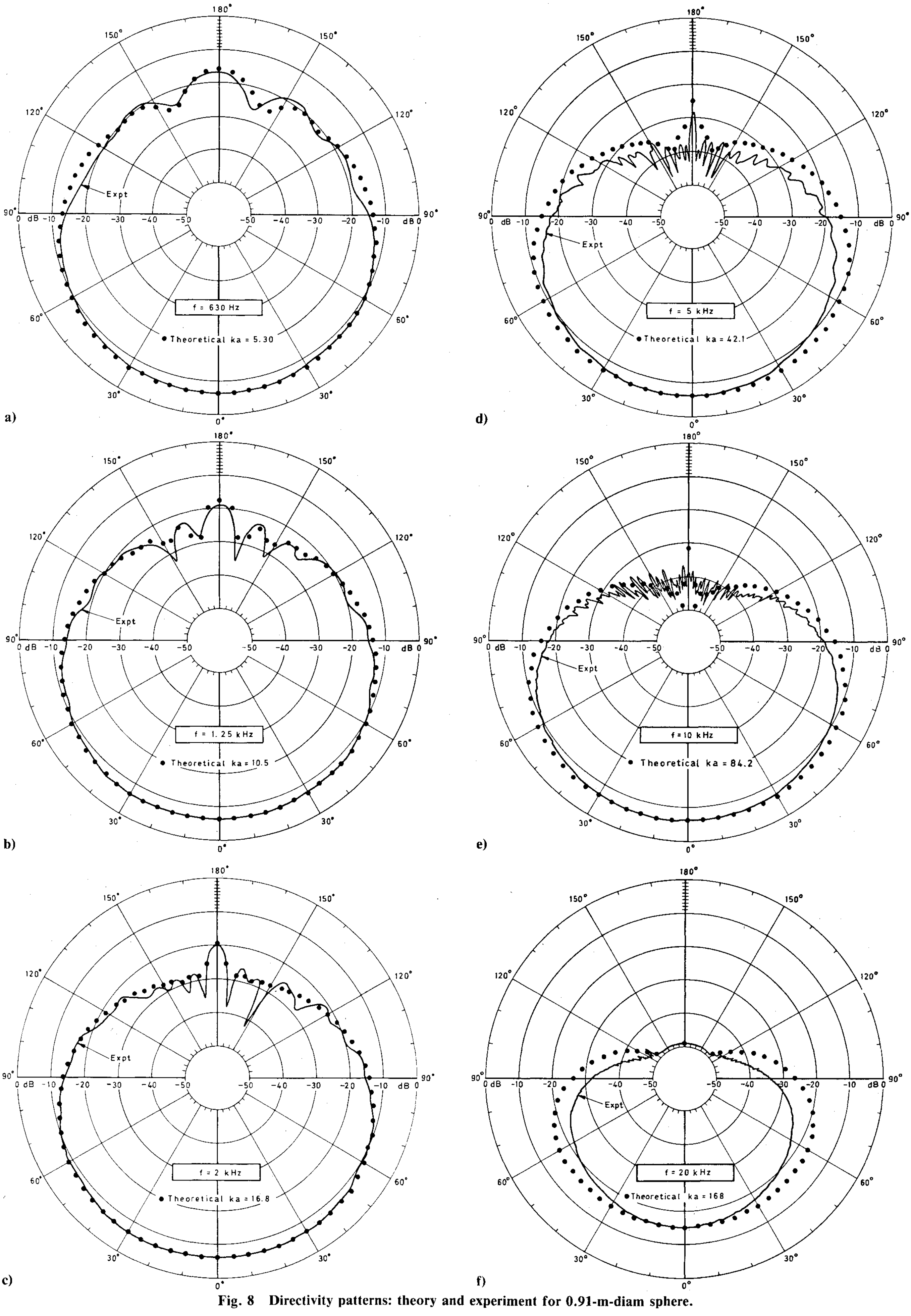

Fig. 8 Directivity patterns: theory and experiment for 0.91-m-diam sphere.

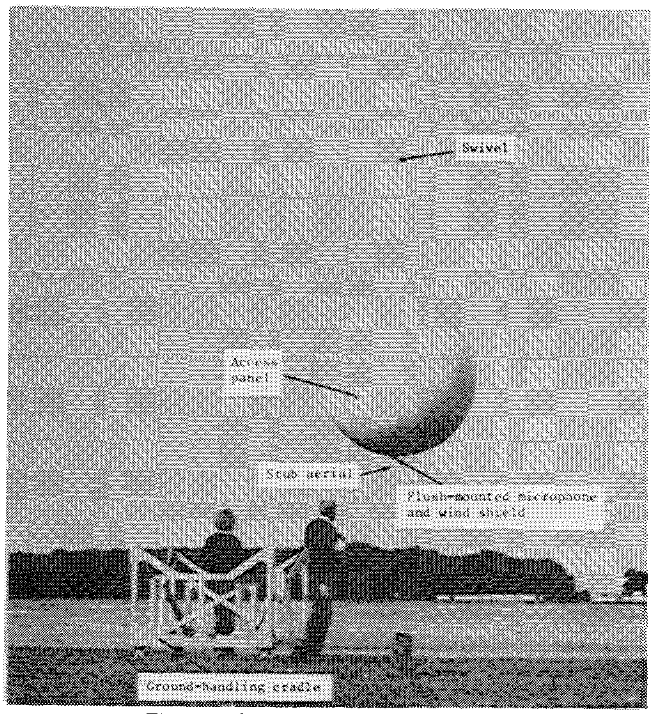

Fig. 9 1.83-m-diam diffracting sphere.

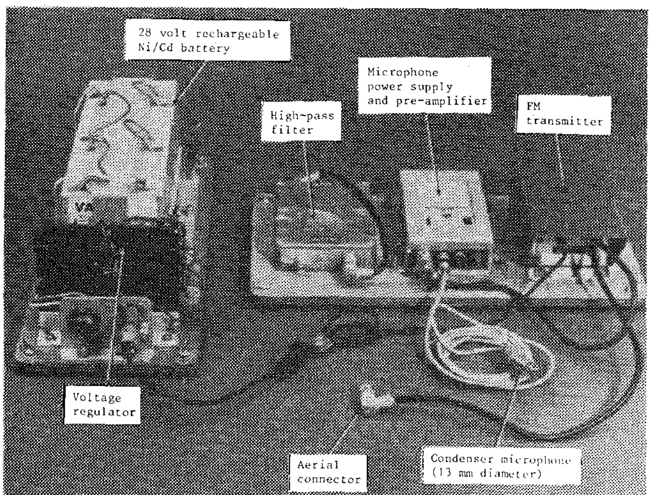

Fig. 10 Microphone telemetry equipment.

Frequency-response calibration of the entire system was effected using an electrostatic microphone actuator over the range 20 Hz-20 kHz. To within -0.5 dB the response was flat from about 60 Hz to 3 kHz and was about -4.5 dB at 10 kHz. Separate tests showed that a roll-off at high frequencies above 3 kHz resulted from the pressure-response characteristic of the microphone (which was of free-field type) and a slight roll-off at low frequencies with the behavior of the FM receiver. These tests confirmed that the frequency response of the telemetry recording system was determined almost entirely by the pressure-response of the microphone.

The linearity of the system was checked directly from the rms transmitter input/receiver output voltage characteristics obtained at various test frequencies from 200 Hz to 10 kHz using a beat-frequency oscillator and a high-resolution af voltmeter. In general, for all frequencies, the linearity was within 1% of the maximum permissible input to the transmitter (1-V rms) or less than 0.1 dB.

The quiescent no-signal electrical noise level of the complete system was less than 2-mV rms, giving a dynamic range of at least 54 dB, which was adequate for the measurement of aircraft noise. The overall signal/noise ratio was limited, in fact, by the performance of the FM tape recorder used to about 50 dB, this being a typical working figure.

As regards setting the sensitivity of the system, in this case by adjustment of the gain of the microphone preamplifier, allowance must be made for the fact that whereas the calibration usually employs a sinusoidal signal (e.g., a piston phone) the aircraft noise signal is of random character and peak clipping will occur if the gain is set too high. For the TriStar experiment a crest factor of 3 was taken, so that the maximum permissible transmitter input was reduced by a factor of $\sqrt{2}/3$.

Full-Scale Performance

Shielding Effect of Sphere

An experimental check on the efficiency of the sphere in reducing the background noise produced by the Wessex helicopter in hover was made under full-scale conditions; the method simply involved a comparison of the shielded noise level at the suspended sphere with a measurement of the direct noise at the same position, namely, 150 m below the helicopter.

With the Wessex in position at 790 m AGL, as for the wing-shielding experiment, the background noise picked up on the sphere microphone at 640 m AGL, was sampled and recorded for about 30 s. This altitude was more than sufficient to ensure negligible interference from ground reflected noise. The noise at ground level of the helicopter alone, in hover at 150 m altitude and at similar weight, was then measured on a separate occasion using 13-mm-diam pressure microphones lying on a flat concrete surface. This technique, described in Ref. 9, results in a pressure-doubled signal 6 dB above free-field over the whole noise spectrum up to a frequency of about 8 kHz, the first cancellation frequency being slightly above 13 kHz. In general, the noise levels recorded for analysis were steady to within ± 2 dB, although it was noticeable that maintaining a free-air hover could occasionally result in large changes of level, of up to 10 dB. Ten 1-s samples of the ground level and sphere noise recordings were analyzed on a one-third-octave frequency analyzer and an averaged spectrum of each signal obtained, corrected to mean atmospheric conditions of 12°C and 50% relative humidity; no correction was needed for the altitude effect on the pressure response of the sphere microphone as the change in sensitivity was negligible at 640 m AGL.

In Fig. 11 the solid lines show spectra of the direct helicopter noise on the sphere (curve A, $\theta = 0$) and the shielded noise (curve B, $\theta = 170$ deg). Curve A was derived from the ground noise spectrum by applying a small correction at low frequencies to represent the fall in gain factor below 6 dB for the equivalent measurement on the sphere; the correction amounts to a level reduction of 3.6 dB maximum at 50 Hz, falling to less than 1 dB at 200 Hz, and effectively to zero at 1 kHz and above when the gain factor reaches a value of 6 dB.

The substantial shielding effect of the sphere, especially at high frequencies is clearly demonstrated. Overall, this amounts to a reduction of 7.1 dB in terms of the OASPL over the full measured frequency range from 50 Hz upwards; over the more restricted frequency range from 250 Hz upwards, of interest in the wing-shielding experiment, the measured sphere shielding increases to about 7.5 dB overall. Curves C and D are predicted spectra for $\theta = 170$ and 180 deg, respectively, obtained by simply adding the appropriate theoretical directivity at a given center frequency to the spectrum levels for $\theta = 0$ deg (curve A). It can be seen that the extra shielding effect obtained by positioning the microphone at $\theta = 170$ deg, rather than at the bright spot, is reasonably well predicted. In overall terms, curve C predicts shielding of about 6.5 and 8.8 dB for the two frequency ranges quoted earlier, in reasonable agreement with the measured values. At the bright spot, the corresponding predicted shielding is only 4.4 and 5.0 dB overall and significantly less than the measured amount.

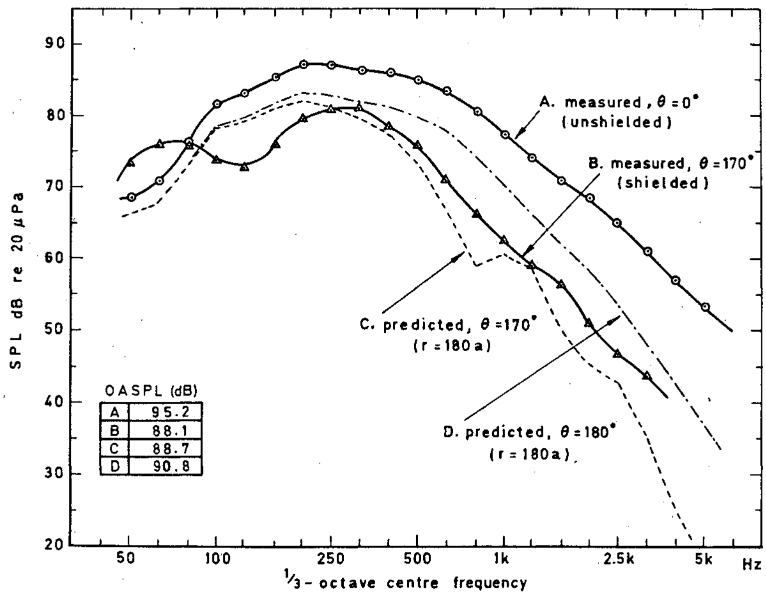

Fig. 11 Measured and predicted shielding of helicopter background noise by 1.83-m-diam sphere.

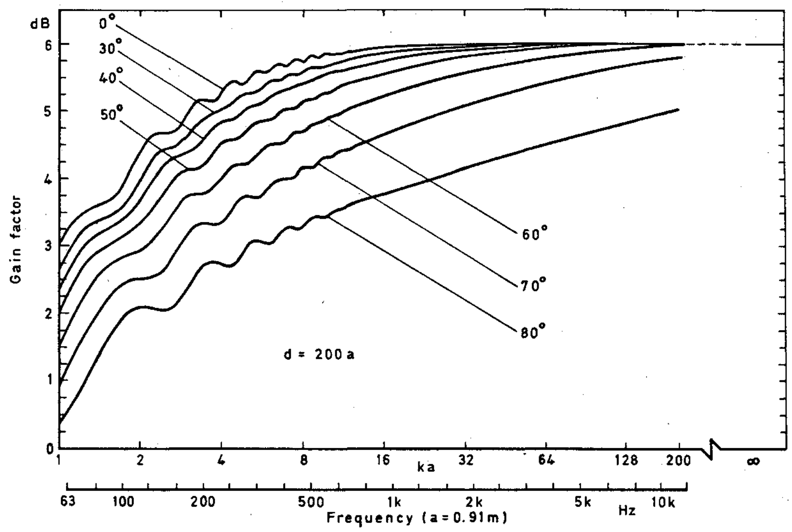

Fig. 12 Variation of gain factor with frequency and sound incidence angle.

Free-Field Corrections

Correction of the measured far-field aircraft noise to free-field conditions requires subtraction of the computed gain factor of the sphere, as described earlier in this paper, together with any appropriate frequency-response corrections in the recording equipment. In the present system, the only significant equipment response correction concerned the microphone; the use of a pressure capsule, rather than a free-field type, had it been available, would have resulted in a virtually flat response to 10 kHz.

The gain factor required can be determined at a given frequency of analysis and angle of incidence of the sound field from Fig. 12, which presents similar, but more detailed, results to those in Fig. 6 for a source distance of 200 sphere radii and angles extending up to a maximum of 80 deg. Although the computed values relate strictly to pure tones, the gain factors on the "illuminated" side of the sphere will be practically the same for filtered random noise at the center frequency of a one-third-octave-band or narrow-band analysis.

The angle of incidence in an actual flight experiment will usually form a primary analytical parameter related to a fundamental variable such as the angle of sound emission to the engine axis. In the present application, incidence angle is defined as the angle between a sound ray from the source to a vertical through the sphere center so that if the microphone were on the vertical, the incidence angle would be equal to the azimuth angle, θ. However, because the microphone is, in fact, at 10 deg azimuth and the sphere may rotate, the azimuth angle may differ from the incidence angle by ± 10 deg at any instant. In practice the effect of this uncertainty will be small since the gain factor at a given frequency can be seen to vary only slowly with azimuth angle up to the maximum value of about 60 deg likely to be encountered in a flight experiment, and an average correction to free field will be sufficiently accurate. If greater precision were needed, the microphone position should be at zero azimuth angle but resulting, as we have seen, in some loss of shielding by the sphere.

Concluding Remarks

The design, development, and performance of a novel airborne technique to enable accurate measurements of the noise field above an aircraft in flight has been described; a central feature of the technique is the use of a rigid spherical diffractor surrounding the sensing microphone so that accurate evaluation of the diffraction effects on the microphone response was possible. It has been shown that a reasonably sized sphere will result in good directivity and frequency-response characteristics with pressure-doubling at the microphone surface over a wide frequency range. The corrections to free-field conditions are therefore straightforward and have been evaluated for a range of typical frequencies and sound incidence angles; in most cases, the corrections are simply −6 dB and are found to be independent of the source distance. It has also been demonstrated that efficient shielding by the sphere will lead to a substantial reduction in the helicopter background noise reaching the microphone, thereby further improving the reliability of the aircraft noise measurements.

The technique should find useful application in studies of airframe shielding, reflection, and scattering effects when basic data representative of full-scale conditions in flight are required.

Acknowledgments

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