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A Differential Microphone for In-Duct Acoustic Measurements

By C. M. E. RILEY
Whittle Laboratory, Cambridge University Engineering Department

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Summary

A brief description is given of a technique using a differential microphone to measure the sound field structure within the duct of a rotor. The advantages and problems of direct in-duct, as opposed to far-field, measurement are discussed, and the present approach presented. The construction and calibration of the differential microphone are briefly described, and results from some of the experiments in which it was assessed are used to demonstrate its application.

* Present address: Shell Research Ltd., Thornton Research Centre, Chester.
† Replaces A.R.C. 36 800.

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1. Introduction

One of the major problems in any engine noise research programme is to find an accurate method of measuring noise. By far the most common method used in the ground testing of engines or rigs is to mount a number of microphones at a large distance (relative to the scale of the engine or rig), and to measure the 'far-field' noise. This method is relatively simple, although corrections may have to be made for sound reflection from the adjacent ground or building surfaces. It was the method used by Tyler & Sofrin[1] in their early experiments to demonstrate their theories of mode generation, and has been used for nearly all the full scale engine testing, and a great deal of the rig testing performed in this country and the United States – the new anechoic facility at NGTE is equipped for far-field measurement. However, there are some advantages in undertaking direct measurements of the sound pressure field within the duct of the fan or compressor before it is radiated to the far-field. In-duct measurement allows the modal patterns to be measured before they are distorted by the duct termination, and avoids the need for any correction to account for reflections from surrounding features. It also enables more detailed measurement of the field structure, which is likely to give a better understanding of its origins, and thus lead to more effective techniques for noise reduction.

Examples of reported in-duct measurements are those made by Mugridge[2], on a 152 mm diameter low speed fan, and by Moore[3], on a 1 m diameter fan, in both cases the modal structure measured by circumferential traverse of a microphone being compared with the patterns determined by far-field measurement. Smith[4] used axial traverses of a single microphone to measure the amplitude of the wave generated by a low speed fan, and its reflection from the duct termination. Harel & Perulli[5] used a combination of axial and circumferential traverses to make detailed measurement of the sound field from a 600 mm diameter fan.

2. In-Duct Measurement

One of the problems in using in-duct measurement is that any measurement will be of the standing wave that is set up by the interaction of the generated wave from the rotor, and its reflection from the duct termination. Thus measurement at a single position in the duct will not give the true amplitude of the generated wave, unless the reflection coefficient of the duct termination is effectively zero. Hence Smith undertook an axial traverse of sufficient length to measure at least a half wavelength of the standing wave, and thus obtain the sound levels at the node and antinode. From these, the amplitudes of the generated and reflected waves are easily calculated. However, a detailed axial traverse has several disadvantages. Firstly, it is obviously impossible to perform in situations where the duct wavelength is less than a half wavelength of the standing wave, and this precludes its use in the important case of inter-blade-row measurement. Secondly, the length of time involved in making the necessary number of measurements is considerable, and this necessitates constant conditions in the rig, especially constant $\sqrt{T}$ corrected rotor speed. Very small variations in rotor speed can make large changes in the sound level measured at a fixed position, due to the accompanying shift in the sound field pattern. In the present investigation, the most dramatic change measured was 19·9 db for a speed change of 1·3 per cent. Thirdly, there is the practical problem of the application of a detailed axial traverse to a real machine. Either considerable modification to fan or compressor casings will have to be made to accommodate a wall mounted microphone, or the microphone will have to be mounted on a suitable stand and introduced through the intake. This latter method may lead to spurious signals from the additional modes excited by the wake from the microphone, and again precludes measurement between blade rows.

The structure of the sound field within a duct can be determined by measurements taken at one plane in the duct if the differential microphone developed in the present investigation is used, provided the wave numbers of the component waves are known. The technique involves the measurement of the sound pressure level at the given position by a conventional microphone, and the phase shift of the signal from some fixed event of the sound field generating mechanism; for example, the passage of the blades of the rotor past a pick-up. The level and phase of the differential are then measured at the same axial position, particular care being exercised that the rig is operating at precisely the same conditions. The differential and absolute signals thus measured may be represented by two vectors $\mathbf{X}$ and $\mathbf{Y}$ respectively, and the two points $\mathbf{Y}+\mathbf{X}/2$ and $\mathbf{Y}-\mathbf{X}/2$ represent the level and phase at two positions on the standing wave separated by the spacing of the differential microphone tappings. The two points lie on the ellipse which can be drawn to determine the level and phase at any point on the standing wave, and provided the wavelengths of the two waves which form the standing wave are known, the amplitudes of the two component waves can be determined.

The amplitudes of the two component waves may be readily determined algebraically. For a given propagating mode, the standing wave may be considered in its two component waves travelling in opposite directions. The pressure amplitude due to each wave may be written:

$$p_{1,2}=A_{1,2}\,e^{i(\omega t+\phi_{1,2}\mp\alpha_{1,2}x)}$$

where

$A_{1,2}$ are the amplitudes in each direction
$\alpha_{1,2}$ are the corresponding wavenumbers
$\phi_{1,2}$ are the corresponding phase angles

Thus at any one position the pressure amplitude p due to the mode may be written

$$p=p_1+p_2=\mathrm{e}^{i\omega t}\{A_1\,\mathrm{e}^{i(\phi_1-\alpha_1 x)}+A_2\,\mathrm{e}^{i(\phi_2+\alpha_2 x)}\}.$$

If the signal level Y and phase ϕ_Y measured by a conventional microphone at this same position are such that

$$p=Y\,\mathrm{e}^{i(\omega t+\phi_Y)}$$

then

$$Y\,\mathrm{e}^{i\phi_Y}=A_1\,\mathrm{e}^{i(\phi_1-\alpha_1 x)}+A_2\,\mathrm{e}^{i(\phi_2+\alpha_2 x)}.$$

Now consider the differential signal between two points at $x+\Delta x/2$ and $x-\Delta x/2$. This may be expressed by

$$\Delta p=p_{x+\Delta x/2}-p_{x-\Delta x/2}$$

$$p_{x+\Delta x/2}=\mathrm{e}^{i\omega t}\{A_1\,\mathrm{e}^{i(\phi_1-\alpha_1[x+\Delta x/2])}+A_2\,\mathrm{e}^{i(\phi_2+\alpha_2[x+\Delta x/2])}\}$$

and

$$p_{x-\Delta x/2}=\mathrm{e}^{i\omega t}\{A_1\,\mathrm{e}^{i(\phi_1-\alpha_1[x-\Delta x/2])}+A_2\,\mathrm{e}^{i(\phi_2+\alpha_2[x-\Delta x/2])}\}.$$

If the signal level X and phase ϕ_X from a differential microphone at this point are such that

$$\Delta p=X\,\mathrm{e}^{i(\omega t+\phi_X)}$$

Then

$$X\,\mathrm{e}^{i\phi X}=A_1\{\mathrm{e}^{i(\phi_1-\alpha_1[x+\Delta x/2])}-\mathrm{e}^{i(\phi_1-\alpha_1[x-\Delta x/2])}\}+A_2\{\mathrm{e}^{i(\phi_2+\alpha_2[x+\Delta x/2])}-\mathrm{e}^{i(\phi_2+\alpha_2[x-\Delta x/2])}\}.$$

The value assigned to x is purely arbitrary, depending on the assumed origin, and thus may be set to zero. By rewritting the expressions in the form

$$Y\,\mathrm{e}^{i\phi_Y}=Y(\cos\phi_Y+i\sin\phi_Y)\quad\text{etc}$$

and comparing the real and imaginary terms:

$$Y\cos\phi_Y=A_1\cos\phi_1+A_2\cos\phi_2 \tag{1}$$

$$Y\sin\phi_Y=A_1\sin\phi_1+A_2\sin\phi_2 \tag{2}$$

$$X\cos\phi_X=A_1\left\{\cos\left(\phi_1-\frac{\alpha_1\Delta x}{2}\right)-\cos\left(\phi_1+\frac{\alpha_1\Delta x}{2}\right)\right\}+A_2\left\{\cos\left(\phi_2+\frac{\alpha_2\Delta x}{2}\right)-\cos\left(\phi_2-\frac{\alpha_2\Delta x}{2}\right)\right\} \tag{3}$$

$$X\sin\phi_X=A_1\left\{\sin\left(\phi_1-\frac{\alpha_1\Delta x}{2}\right)-\sin\left(\phi_1+\frac{\alpha_1\Delta x}{2}\right)\right\}+A_2\left\{\sin\left(\phi_2+\frac{\alpha_2\Delta x}{2}\right)-\sin\left(\phi_2-\frac{\alpha_2\Delta x}{2}\right)\right\}. \tag{4}$$

Using the identities $\cos(A-B)=\cos A\cos B+\sin A\sin B$ etc., equation (3) gives

$$X\cos\phi_X=2A_1\sin\phi_1\sin\frac{\alpha_1\Delta x}{2}-2A_2\sin\phi_2\sin\frac{\alpha_2\Delta x}{2}\,; \tag{5}$$

from (2)

$$\sin\phi_2=\frac{Y\sin\phi_Y-A_1\sin\phi_1}{A_2},$$

so from (5)

$$\sin\phi_1=\frac{X\cos\phi_X+2Y\sin\phi_Y\sin(\alpha_2\Delta x/2)}{2A_1(\sin(\alpha_1\Delta x/2)+\sin(\alpha_2\Delta x/2))}. \tag{6}$$

Similarly from equation (4)

$$X\sin\phi_X=-2A_1\cos\phi_1\sin\frac{\alpha_1\Delta x}{2}+2A_2\cos\phi_2\sin\frac{\alpha_2\Delta x}{2}. \tag{7}$$

From (1)

$$\cos\phi_2=\frac{Y\cos\phi_Y-A_1\cos\phi_1}{A_2},$$

so from (7)

$$\cos\phi_1=\frac{-X\sin\phi_X+2Y\cos\phi_Y\sin(\alpha_2\Delta x/2)}{2A_1(\sin(\alpha_1\Delta x/2)+\sin(\alpha_2\Delta x/2))}. \tag{8}$$

Then from

$$\cos^2\phi_1+\sin^2\phi_1=1$$

$$\left(-X\sin\phi_X+2Y\cos\phi_Y\sin\frac{\alpha_2\Delta x}{2}\right)^2+\left(X\cos\phi_X+2Y\sin\phi_Y\sin\frac{\alpha_2\Delta x}{2}\right)^2=4A_1^2\left(\sin\frac{\alpha_1\Delta x}{2}+\sin\frac{\alpha_2\Delta x}{2}\right)^2:$$

by multiplying out and collecting terms,

$$A_1=\frac{\sqrt{X^2+4Y^2\sin^2(\alpha_2\Delta x/2)-4XY\sin(\alpha_2\Delta x/2)\sin(\phi_X-\phi_Y)}}{2(\sin(\alpha_1\Delta x/2)+\sin(\alpha_2\Delta x/2))}. \tag{9}$$

By using substitution from equations (1) and (2) for $\cos\phi_1$ and $\sin\phi_1$ in equations (5) and (7), a similar expression for A_2 is obtained:

$$A_2=\frac{\sqrt{X^2+4Y^2\sin^2(\alpha_1\Delta x/2)+4XY\sin(\alpha_1\Delta x/2)\sin(\phi_X-\phi_Y)}}{2(\sin(\alpha_1\Delta x/2)+\sin(\alpha_2\Delta x/2))}. \tag{10}$$

There is some simplification of the results of equations (9) and (10) if the assumption is made that $\alpha\Delta x$ is small. Then

$$\sin\frac{\alpha_1\Delta x}{2}\simeq\frac{\alpha_1\Delta x}{2} \tag{11}$$

and

$$\sin\frac{\alpha_2\Delta x}{2}\simeq\frac{\alpha_2\Delta x}{2} \tag{12}$$

which gives

$$A_1=\frac{\sqrt{X^2+(Y\alpha_2\Delta x)^2-2XY\alpha_2\Delta x\sin(\phi_X-\phi_Y)}}{\Delta x(\alpha_1+\alpha_2)} \tag{13}$$

and

$$A_2=\frac{\sqrt{X^2+(Y\alpha_1\Delta x)^2+2XY\alpha_1\Delta x\sin(\phi_X-\phi_Y)}}{\Delta x(\alpha_1+\alpha_2)} \tag{14}$$

This approximate assumption is valid for small $\Delta x/\lambda$ i.e. the differential microphone spacing small compared with the acoustic wavelengths. This is desirable from the need to produce a small transducer to allow inter-blade-row measurement. The results of equations (13) and (14) are also obtained if the alternative approximate assumption is made to establish Δ_p

$$\text{i.e.}\quad \Delta_p=\frac{dp}{dx}\Delta x$$

Note that the analysis only requires the difference of the phase angles from the two signals, so they can be referenced to any convenient event in the system, independent of the axial position of measurement Assuming that the differential microphone is mounted with the two tappings aligned axially, then Δx is the distance between them.

The same information can be derived from two separate measurements of sound pressure level and phase a a known axial spacing. However, unless the spacing is large compared with the wavelength, then there is the inaccuracy inherent in determining a small difference by measuring two large quantities. A second advantage of the differential microphone arises when it is used in flow conditions, where random noise will be generated by bursts of turbulence convected over the microphone. Provided the length scale of these disturbances is large compared to the spacing of the differential microphone tappings, an almost identical noise generating signa will be present at each tapping, and thus will be to a large extent self cancelling, thereby increasing the signal to noise ratio.

3. The Differential Microphone

The differential microphone used in the present investigation is shown schematically in Fig. 1. The assembl is mounted in an aluminium tube 13·0 mm diameter and 100 mm long so that it may be held in the sam mountings used for ½" Bruel and Kjaer microphones. The two 1·7 mm diameter pressure tappings are on 8·78 mm diameter pitch circle of the tube. The 8 mm × 20 mm copper alloy diaphragm is held in resin plasti on the axis of the assembly, the chambers each side being connected to the tappings. These chambers are mad as small as possible to increase their resonant frequency, their volume is approximately 0·4 cc. The diaphragn is mechanically connected to a cantilever, which carries a pair of film type strain gauges, one on each side. Th leads from these gauges are taken by a shielded cable to a separate module in which the resistance change o the strain gauges due to the deflection of the diaphragm is measured and outputted as a voltage via a amplifier. The amplifier has trim resistors for zero and gain. The broad band noise level of the output i approximately 9 mv.

The differential microphone requires an AC calibration to obtain both the output level for an applied pressure difference, and the phase shift between the applied signal and the output, due to both mechanical and electrical influences. It was calibrated against a measured standing wave in a modified Bruel and Kjaer type 4002 apparatus, the standing wave tube of which was replaced by a 2 m perspex tube, approximately 100 mm diameter. A wooden microphone mounting block, positioned on the tube 350 mm from the driving loudspeaker, was fitted with five inserts, drilled to take a ½" Bruel and Kjaer microphone and spaced 10 mm apart. A sixth insert, in the same plane as the centre one of the five, was fitted to take the differentia microphone. At the far end of the tube there was an adjustment piston, mounted on a threaded rod passing through the end cover of the tube, with a travel of approximately 750 mm. The driving loudspeaker was powered via a 15 watt power amplifier from the generator section of an SE Labs (EMI) Ltd type SM 2001 frequency response analyser. The signal from both the ½" Bruel and Kjaer microphone and the output from the differential microphone amplifier module were fed via the filtering and amplifying circuits of a Bruel and Kjaer type 2107 analyser to the correlator section of the type SM 2001 analyser. The correlator section gave the output of the type 2107 analyser referenced to the original generator signal.

The calibration method was as follows. The generator section of the type 2001 analyser was adjusted to the required frequency. The adjustment piston was then moved so that part of the standing wave near to an antinode was positioned at the microphone mounting block, thus avoiding calibration on a part of the wave where rapid amplitude and phase changes occur over a small axial distance. The power supply to the amplifier was adjusted to give the required signal level from the differential microphone, and measurement of this level, and the sound pressure levels at the five microphone positions, were made using the type 2001 analyser. Interpolation of the five microphone signals gave the signals at the positions of the two differential microphone tappings, and the vector difference of these is the applied differential signal. Comparison between this, and the differential microphone output, gives both the amplitude and phase calibration, as all signals are internally referenced within the SM 2001 analyser.

Calibration results for a number of different frequencies are shown in Figs. 2 and 3. The amplitude calibration shows some divergence at the lower frequencies, and this is probably due to drift of the differential microphone amplifier over the period of time between the calibrations. However, during the experiments on the rig, the microphone was check calibrated at the frequency of, and immediately after, its use in the rig. The results for the phase shift, Fig. 3, are rather more consistent, confirming that the amplitude changes are due to amplifier drift. The results indicate that the present design has a resonance at a frequency of approximately 1·2 kHz. The normal maximum frequency of use was 910 Hz, and this might be thought to be too near this resonance for accuracy. However, some confidence in the accuracy of the differential microphone even near this resonance is derived from firstly the fact that, even at 1 kHz, the output signal increased linearly with the applied differential signal, and, secondly, the symmetry of the phase calibration. This symmetry is demonstrated by making two observations of the differential microphone amplifier output signal at each calibration point, the second with the microphone turned 180 degrees in its mounting in relation to the first, so that the two pressure tappings are reversed. In theory, the two output signals should be identical in amplitude, and 180 degrees out of phase. Table 1 shows results typical of such a test. The variation in the output signal between the two calibrations at the same frequency was very small; the amplitude less than 2 per cent and the mean phase shift between the applied signal and the amplifier output less than 0·5 degrees. This gives some confidence in the accuracy of the method of calibration and the symmetry of the differential microphone.

4. Results from Rig Tests using the Differential Microphone

A large number of acoustic experiments have been undertaken for the assessment of the differential microphone, using the rig previously described by Smith, although it has been somewhat modified. The rig consists of a single stage, 305 mm diameter 0·75 hub-tip ratio rotor, mounted in a parallel walled duct. The rotor is powered independently of the upstream air supply system, and there is provision for mounting either a series of gauzes or an IGV row upstream of the rotor so that the wakes are convected thereon. The blade numbers are chosen to excite the first order circumferential mode.

The differential microphone assessment has been done in a series of experiments in which the rotor was run at a number of speeds, and measurements made of the acoustic waves generated by interaction between the upstream generated wakes and the rotor. The measurements made using the differential microphone technique were compared with measurements derived from axial plotting of the standing wave where this was possible, and with the theoretical prediction due to Smith. The results shown in Figs. 4 and 5 are r.m.s. sound pressure levels non-dimensionalised by air density (ρ) and blade relative air speed (W); note that the scale is linear. Fuller details of the experiments are given in reference 6.

Fig. 4 shows a series of results for the acoustic wave which travels upstream from the rotor, measured after it has passed through the gauzes. The figure shows the amplitudes measured using a $\frac{1}{4}''$ Bruel and Kjaer microphone to plot out the standing wave. Also shown are the results obtained using the differential microphone in conjunction with a $\frac{1}{2}''$ Bruel and Kjaer microphone; these results are the mean of three results obtained 20 mm, 35 mm, and 50 mm upstream of the gauzes, in which the variation was typically less than 5 per cent. The 'prediction × measured T' results were obtained from the amplitude of the upstream travelling generated wave given by Smith's prediction, multiplied by the measured transmission coefficient of the gauzes. The value of T was taken as $1-R$, where R was the reflection coefficient of the gauzes obtained from differential microphone measurements of the upstream and downstream travelling waves between the gauzes and the rotor. The low value of T at a blade relative Mach number of 0·105 results from a high value of the measured R. There is strong evidence from other tests that this is due to the reflection from far upstream being particularly strong at this speed, rather than there being a non-linear reflection response of the gauzes. Fig. 4 thus shows wave amplitudes measured by three different methods with a good degree of agreement.

Fig. 5 shows results obtained using the differential microphone for measurement of the upstream travelling wave between the IGV row and the rotor, compared with the theoretical prediction. The experimental results are slightly higher than the predicted results, but this is thought to be due to the strong secondary flows which were found downstream of the IGV row even at the rotor inlet plane—the theoretical prediction uses the upwash on the rotor blades calculated from the measured $2-D$ wakes. However, except very near cut-off, the agreement between the prediction and the measured results is good, especially bearing in mind the difficulties inherent in measuring the acoustic waves in the confined space between blade rows.

5. Conclusion

The differential microphone developed in the present investigation has been shown to be capable of accurate measurement of the sound field within the duct of a rotor. Some modification to the present microphone is necessary for use at higher frequencies, but the feasibility of the technique has been demonstrated.

Acknowledgements

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6	C. M. E. Riley	In-duct measurement of tone noise produced by a low speed rotor. Unpublished dissertation; Whittle Laboratory, Cambridge University Engineering Department.

TABLE 1

Typical Calibration of Differential Microphone—Demonstration of Symmetry

Calibration Frequency = 1000 Hz 5 Jan 1975

Applied signal N/m^2		Differential microphone output signal mV			
		1		2	
level	phase	level	phase	level	phase
3·65	−29·67	57·94	106·01	58·27	−74·58
2·54	−28·61	41·38	106·31	42·16	−73·31
1·88	−28·72	31·40	107·04	31·64	−72·73
1·50	−22·67	22·51	108·05	22·54	−71·72
0·92	−26·37	14·30	108·36	14·06	−71·94
		Mean phase shift = 134·36°		Mean phase shift = −45·65°	

Calibration Frequency = 645 Hz 18 Aug 1975

Applied signal N/m^2		Differential microphone output signal mV			
		1		2	
level	phase	level	phase	level	phase
8·90	−155·73	95·32	−5·89	96·58	174·13
6·89	−157·99	73·01	−5·79	74·23	174·61
4·82	−157·32	52·32	−5·20	52·92	174·53
3·41	−157·28	36·82	−4·53	37·31	175·38
2·39	−155·23	23·65	−3·87	23·96	176·38
		Mean phase shift = 151·65°		Mean phase shift = −28·28°	

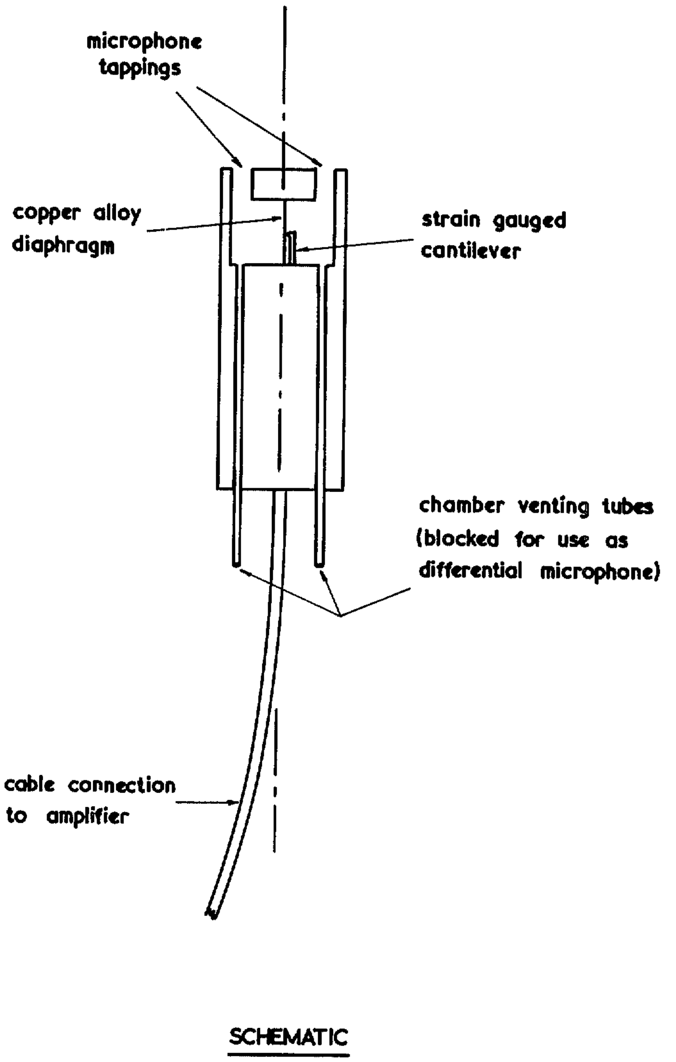

FIG. 1. Schematic diagram of the differential microphone showing the principal components.

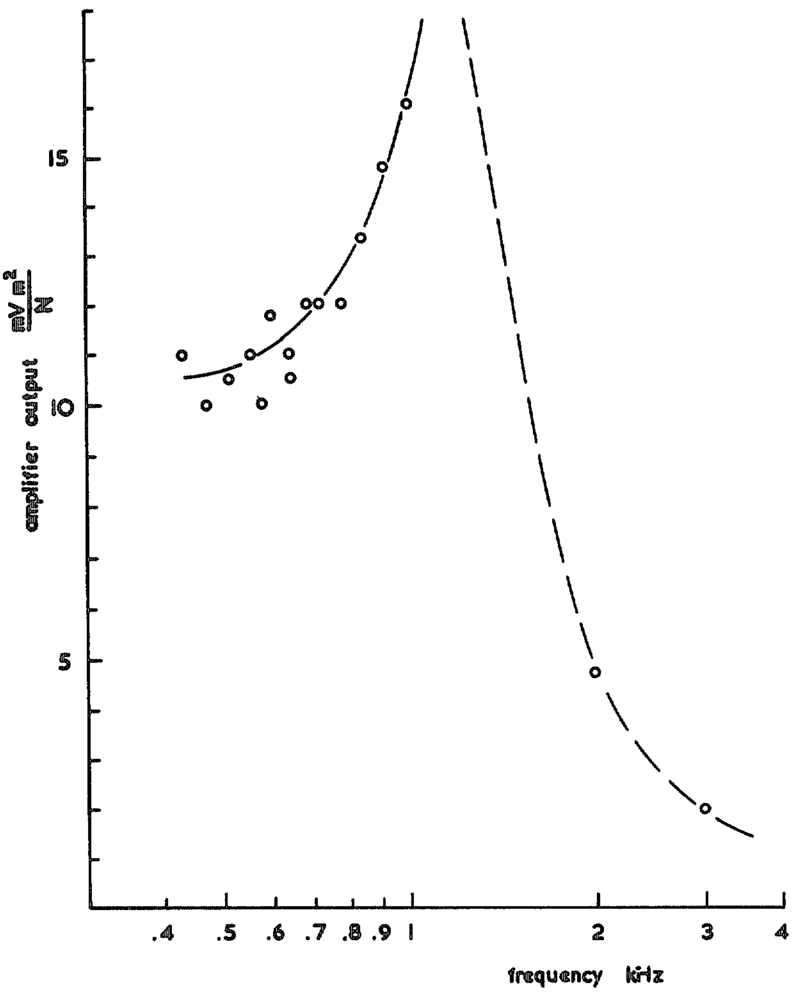

FIG. 2. Differential microphone output signal amplitude calibration.

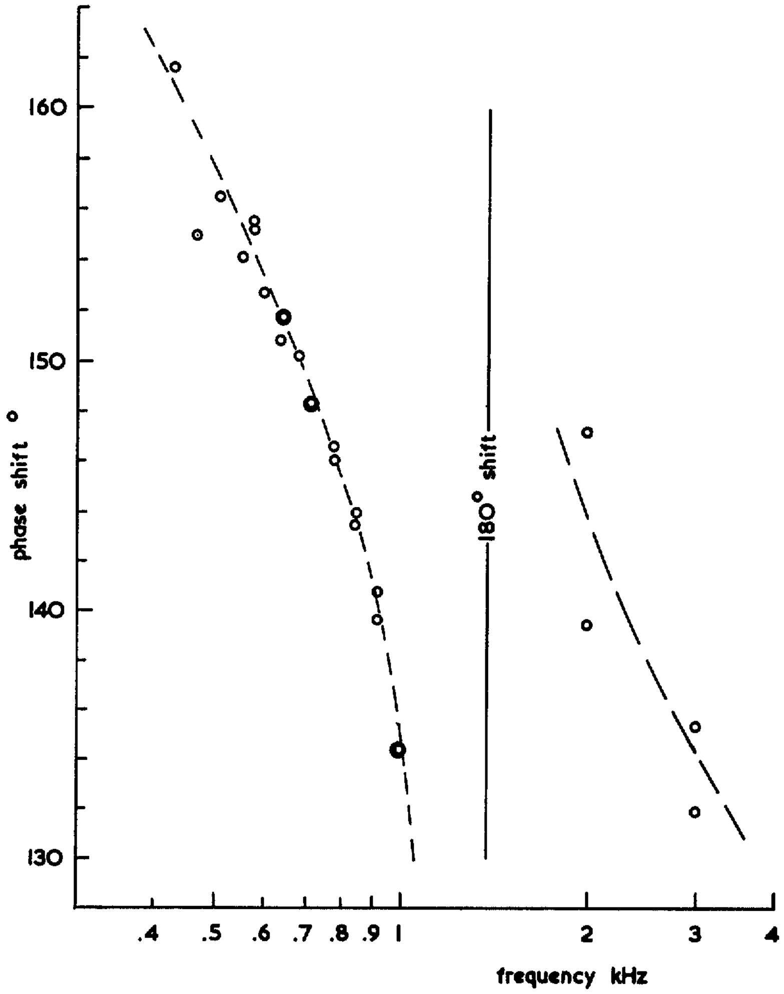

FIG. 3. Differential microphone output signal phase calibration.

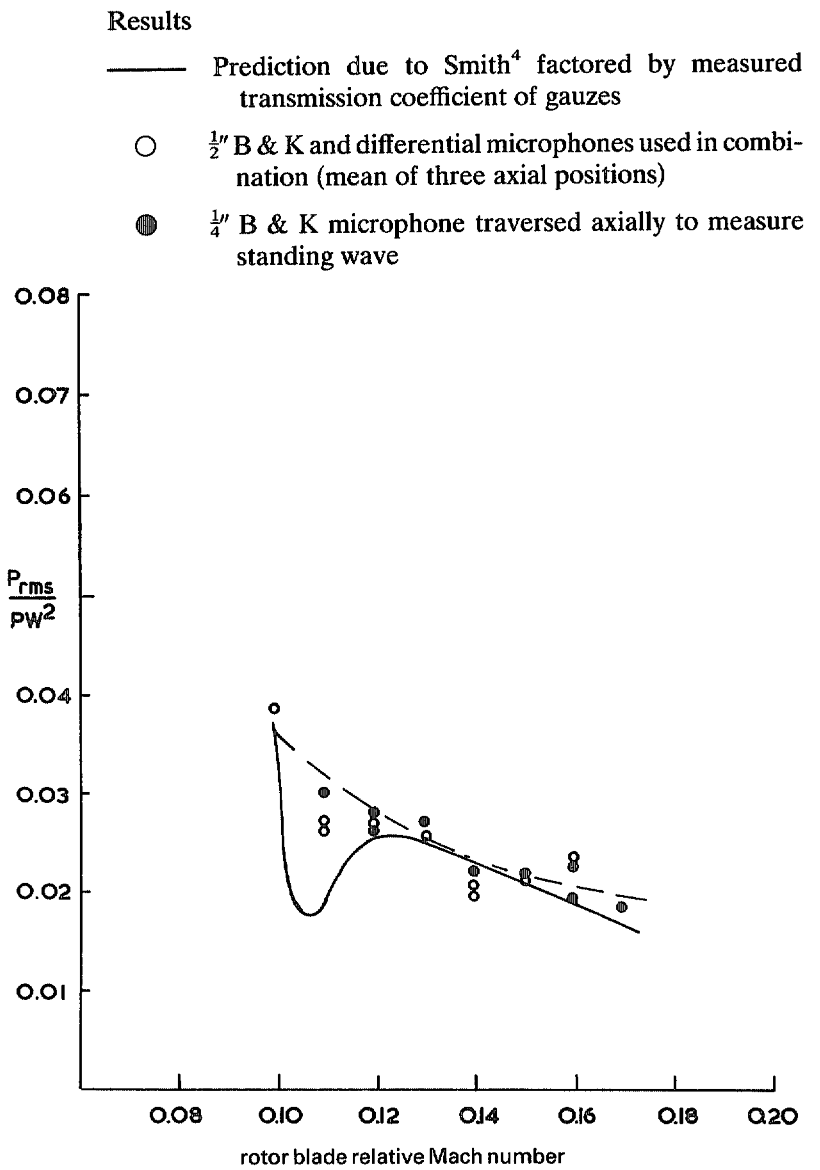

FIG. 4. Upstream propagating acoustic wave excited by convection of gauze wakes on to rotor measured upstream of gauzes.

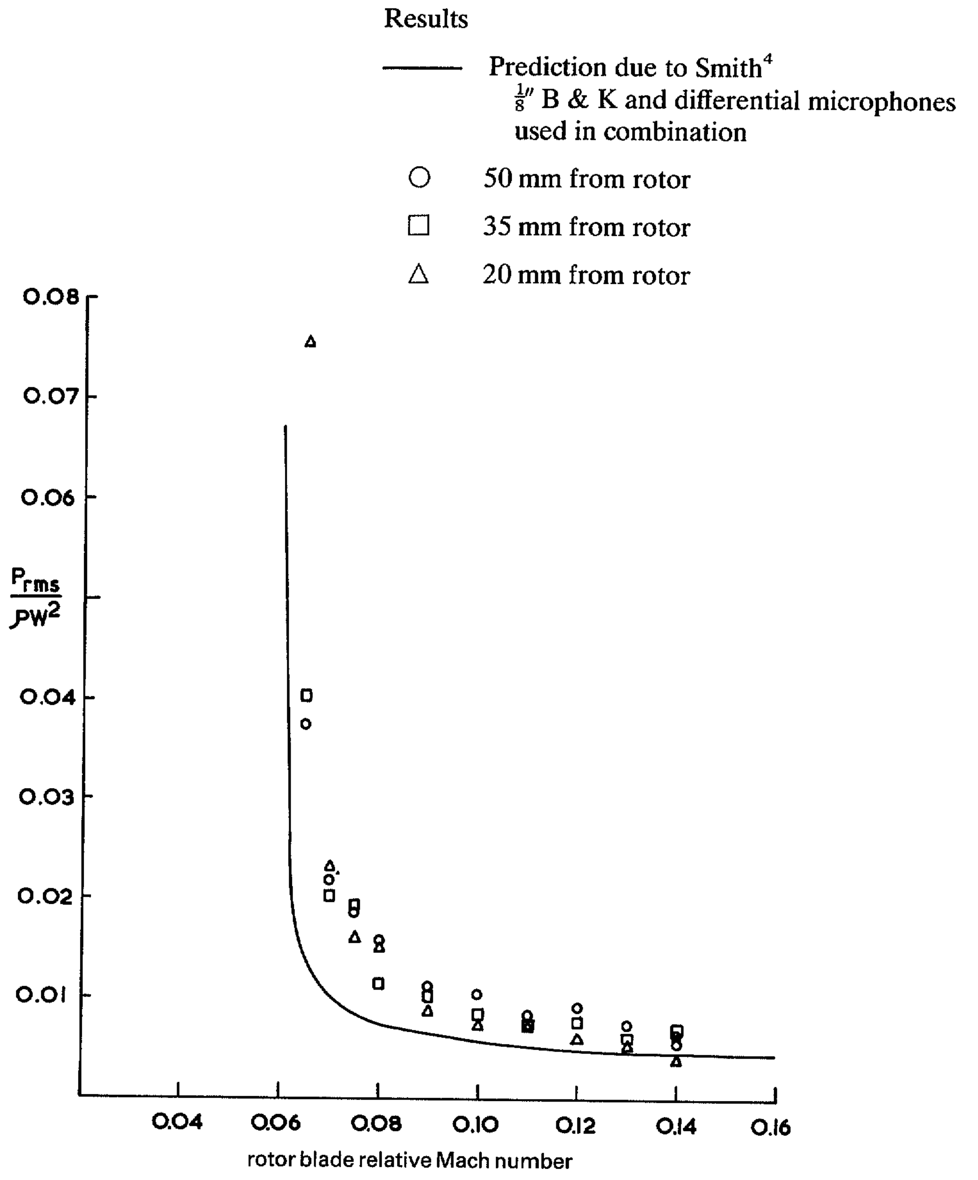

FIG. 5. Upstream propagating acoustic wave excited by convection of IGV wakes on to rotor measured between IGVs and rotor.

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