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AERODYNAMIC NOISE GENERATION BY A STATIONARY BODY IN A TURBULENT AIR STREAM

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When a vortex street formed at the trailing edge of an upstream plate is arranged to impinge upon the leading edge of a small downstream block of similar thickness, a very powerful aerodynamic noise source of tonal quality is formed. Such an arrangement in which the down stream block is suspended on taut wires has been used to investigate Curle's prediction of the relation between the fluctuating lift force exerted by the block on the stream and the radiated sound power in the frequency domain for flow speeds ranging from 70 m/s to 190 m/s.

The possible effect of additional stiff constraint to the motion of the block in the direction of the fluctuating lift force on the radiated noise has also been investigated. The apparent effect of the additional constraint was to increase the magnitude of the fluctuating force on the radiating block but in either the case of constrained or unconstrained block the measured sound power data tends to agree with Curle's prediction at flow speeds above 140 m/s but gradually to diverge upward at lower flow speeds toward a prediction based upon a small vibrating sphere. In all cases the measured sound power levels tend to be bounded by Curle's prediction below and 9·5 dB above by a prediction based upon a small vibrating sphere.

1. INTRODUCTION

As is well known, an obstruction in a turbulent air stream may give rise to aerodynamic noise. Curle [1] has considered the case of an obstruction rigidly fixed in space in a turbulent stream and shown that, provided that the obstruction is small compared to the wavelength of the radiated sound, the source is dipole in nature. Goldstein [2] has interpreted "rigidly fixed in space" to mean infinitely massive, on the assumption that the response is mass controlled, and he has provided analysis for determining when an obstruction may be considered to be rigidly fixed in space. The general case of partial rigidity (finite impedance) seems not to have been considered in the literature.

No obstruction is ever perfectly rigidly fixed in space, and at any structural resonance the response of the object may be quite large, in which case the assumption that it is rigidly fixed is not appropriate. In the latter case, the analysis of Morse [3] for a vibrating sphere, which is small compared to the wavelength of the radiated sound, may be more

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appropriate, but no reference that suggests this possibility and when it might be suitable has been found. However, the question of which model is appropriate in a given circumstance is important since, as will be shown, the same fluctuating force will produce 9·5 dB more sound according to the model of Morse than the model of Curle.

The purpose of this paper is to formulate the problem, to review work which has already been done, and to report a new experimental technique for investigation of Curle's prediction in the frequency domain. The new technique, which is based upon the work of Martin and Bies [4], has allowed investigation of Curle's theory over an extended range of flow speeds.

2. REVIEW OF THE LITERATURE

Curle [1] has considered the influence of solid boundaries upon aerodynamic noise generation and has shown that a rigid surface in a turbulent stream may act as a generator of sound. Curle's considerations lead to the conclusion that a rigid obstruction in a turbulent air stream of low Mach number will radiate as a dipole, where no restriction is put upon the shape of the obstruction other than that all dimensions should be much less than the wavelength of the sound that is radiated.

Curle shows that the sound power of such a source is proportional to the square of the fluctuating lift force exerted by the obstruction on the air stream. In particular, he shows that the pressure distribution over the surface is of no importance; only the integral of the pressure distribution is required to determine the radiated sound power. It will be useful to observe that Curle's theory may be applied to consideration of a small rigidly fixed sphere in a turbulent stream.

Morse [3] has considered the vibration of a small rigid sphere along one axis in an inviscid medium. He has shown that the vibrating sphere radiates as a dipole and he has provided a similar expression to that obtained by Curle relating the force exerted on the medium to the sound which is radiated. As will be shown, for the same radiated sound power the force exerted by a vibrating sphere on a stationary medium is one third of the force exerted by a small stationary sphere on a turbulent medium.

When all dimensions are much less than the wavelength which is radiated, the shape of a vibrating object generally will be unimportant. This consideration suggests that any conclusion drawn from consideration of a small sphere might be thought generally true of objects of any shape but of comparable small dimensions. Consequently, it is proposed that when the dimensions of an object are very small compared to the wavelength of sound which is radiated, consideration of Morse's vibrating sphere may be generalized to include such small vibrating objects.

Ffowcs-Williams and Hawkings [5] extended Curle's theory to include arbitrary convective motion. Starting from the work of the latter authors, Goldstein [2] considered the case of a movable rigid body in turbulent flow and derived a correction to Curle's expression. The latter correction provides means for determining when the ratio of the density of the medium to the density of the obstruction is sufficiently small for the obstruction to be considered rigidly fixed in space.

Clark and Ribner [6] measured the cross-correlation between the lift force and the sound power radiated and the lift force autocorrelation for a small airfoil in an air stream. For an air speed of about 30 m/s they obtained experimental results 2·7 dB below Curle's prediction. They attributed the discrepancy to a resonance of the model which they suggest corrupted the force measurement.

Heller and Widnall [7] investigated, both theoretically and experimentally, the correlation of fluctuating forces on rigid flow spoilers with the resulting sound radiation.

They found sound power radiation from fluctuating lift forces that was lower than that predicted by Curle. They ascribed this discrepancy to the influence of the nearby nozzle, the spoiler being located in a transition region between the confined environment of the pipe and the free field zone.

Amiet [8] used Curle's prediction to develop a theory that predicts the sound pressure radiated by an airfoil of given geometry from the turbulent flow properties. He then applied his theory to the experimental results of Fink [9] and found that his theoretical results showed a discrepancy with the measurements of up to ± 8 dB. Amiet [10] showed that non-compact sources would induce significant variations of phasing of sources on an airfoil interacting with a vortex gust, leading to a strong dependence of the far field sound on the observer position.

In an investigation of circular saw aerodynamic noise, Bies [11] showed the origin of the noise to be the fluctuating lift force acting on the teeth that radiate incoherently as baffled dipoles. He explained the observed fifth power dependence of radiated noise—lower than the expected sixth power dependence—as being due to the location of the sources at the perimeter of the blade.

Subsequently, Martin and Bies [4] investigated the noise generation of a notch in the edge of a rotating disk. They showed that the interaction between the vortex wake shed by the upstream edge of the notch and the downstream edge of the notch was a very powerful generator of noise provided that the notch width was about three times the thickness of the disk. They proposed that the noise was generated when a vortex impinged upon the downstream edge and was deflected out of the notch into the free stream. The latter observation formed the basis for the design of the test apparatus used in the investigations reported here.

Davis and Pan [12] experimentally investigated the noise generated by a turbulent jet interacting with a rigid plate, checking the influence of various parameters (such as flow velocity, nozzle to plate distance and aerofoil chord) on the generated sound. Comparing their results to those predicted from surface acoustic dipoles, edge scattering and unsteady aerofoil lift analyses, they found that plates of small finite chord tend to follow the expected unsteady force dipole behavior.

Bull *et al*. [13] investigated the interaction between a vortex wake and an immersed rectangular plate, and especially the influence of the ratio of the gap width to plate thickness in determining the vortex shedding regime. They found that when the gap between the plates is small, two trapped counter-rotating vortices are formed; but when the gap is large, periodic trailing edge vortex shedding forms a vortex street in the gap. The radiated acoustic power at vortex shedding frequencies was found to be proportional to the 5·7th power of the flow speed, indicating a behavior very close to that of a dipole distribution for which a dependence on the 6th power is predicted.

3. REVIEW OF THEORY OF DIPOLE NOISE GENERATION

3.1. CURLE'S THEORY

Curle [1] begins his considerations of a rigidly fixed object in a turbulent stream using the exact equations of motion of fluid without external forces. After some extensive mathematics and the introduction of some simplifying assumptions, Curle obtains a solution for the density fluctuations in the far field of a source distribution in terms of two integrals, a volume integral describing the contribution due to quadrupole sources and a surface integral describing the contribution due to surface dipole sources. As will be shown, in the flow speed range considered by Curle, the contribution of the volume integral of quadrupole sources is negligible, so that only the contribution of the surface integral of dipole sources is considered.

Curle obtains an approximate solution for a compact dipole source. In writing the expression for a compact source, Curle assumes that X is the position at which the solution is calculated, and Y is a position of integration on the source. He also assumes that there is no normal velocity at the solid boundaries. For example, each surface is fixed or vibrating in its own plane. He introduces a mean distance from the source to the observation point r defined so that $r = |X - Y|$ and he makes the following assumptions: $|X| \gg \lambda$, where λ is a typical wavelength of the generated sound; $|X| \gg L$, where L is a typical dimension of the solid body; and $L \ll c/\omega$, where $\omega = 2\pi f$, f is a typical sound frequency and c is the speed of sound. The second assumption leads to the conclusion that $r \approx X$. The third assumption $L \ll c/\omega \simeq cL/U$ (U being a typical velocity in the flow), leads to $U/c \ll 1$. Since the ratio of the intensity generated by the quadrupoles to the intensity generated by the dipoles is proportional to $(U/c)^2$, the neglect of any quadrupole sources compared with the dipole sources is justified.

Curle finds the following solution for the density, ρ, where ρ_0 is the mean density of the medium, F_i is the resultant force exerted on the fluid by the solid boundaries, x_i is a Cartesian co-ordinate and t is the time co-ordinate:

$$\rho - \rho_0 = \frac{1}{4\pi c^3} \frac{x_i}{r^2} \frac{\partial}{\partial t} F_i(t). \tag{1}$$

Making use of the following relation [14] for sound intensity I,

$$I = \frac{c^3\overline{(\rho - \rho_0)^2}}{\rho_0} \frac{X}{r}, \tag{2}$$

and assuming that the resultant force, F, lies in the direction $\theta = 0$, the following expression for the sound intensity of a dipole is obtained:

$$I_D = \frac{\pi f^2 |F|^2}{8\rho_0 c^3} \frac{\cos^2\theta}{r^2}. \tag{3}$$

Integration over a surface which encloses the solid boundaries gives an expression for the power radiated by the dipole distribution:

$$W_D = \frac{\pi f^2 |F|^2}{6\rho_0 c^3}. \tag{4}$$

3.2. GOLDSTEIN'S CORRECTION

Starting from an extension of Curle's equation for the case of boundaries in arbitrary motion [5], Goldstein [2] considers the case of a body rigidly fixed in turbulent flow. It is to be noted that implicit in the assumption that the source is rigidly fixed is the assumption that the response of the source is mass controlled. Again, neglecting the quadrupole term, Goldstein obtains the following expression for the far field:

$$\rho - \rho_0 \approx \frac{x_i}{4\pi c^3 C_0 r^2} \frac{\partial}{\partial \tau} \left[\frac{F_i(\tau) - V\rho_0 a_i(\tau)}{C_0} \right] \tag{5}$$

where

$$C_0 = 1 - \frac{v(\tau) X}{cr}, \tag{6}$$

$\tau = t - r/c$ is the retarded time, F_i is the net force exerted by the fluid on the surface in the direction x_i, V is the volume enclosed by the rigid boundary and v and a $(=v\omega)$ are, respectively, the velocity and acceleration at the center of the source region.

Assuming that $|v| \ll c$, and that the harmonic force F lies in the direction $\theta = 0$, the source intensity is

$$I_D = \frac{f^2|F|^2 \cos^2\theta}{8\rho_0 c^3 r^2} K \tag{7}$$

where the correction term K, which multiplies Curle's solution, has the following form:

$$K = (1 - \rho_0/\rho_M)^2. \tag{8}$$

The quantity ρ_M is the density of the source. In the experiment reported here, the correction term, K, is essentially equal to one where, as assumed, the response is mass controlled.

3.3. MORSE'S VIBRATING SPHERE

Morse [3] gives the following expression for the sound pressure of an acoustic dipole in spherical co-ordinates:

$$p = A\left[\frac{1}{kr} - \frac{\mathrm{i}}{(kr)^2}\right]\cos\theta, \tag{9}$$

where A is a constant to be determined, $k = \omega/c$ is the wavenumber and i is the square root of -1.

Morse considers a dipole source as being constituted of a small sphere of radius a vibrating along its axis defined by $\theta = 0$. The net force exerted on the surrounding medium by the sphere is the integral of the acoustic pressure over its surface. The total resultant force along the principal axis of the dipole is

$$F = \frac{4\pi a A}{3k}\left[1 - \frac{\mathrm{i}}{ka}\right]\mathrm{e}^{\mathrm{i}(\omega t - ka)}. \tag{10}$$

Writing

$$F = F_0\,\mathrm{e}^{\mathrm{i}(\omega t - ka)}. \tag{11}$$

and assuming that $\omega a \ll c$, the following expression for the constant A is obtained [15]:

$$A \approx \frac{3k}{4\pi c}\left|\frac{\partial}{\partial t}F(t)\right|. \tag{12}$$

Equations (9) and (12) allow the determination of the acoustic pressure and velocity, and lead to the following expression for the radiated power:

$$W_D = \frac{3\pi f^2|F|^2}{2\rho_0 c^3} \tag{13}$$

Comparison of Equations (4) and (13) shows that, for the same radiated sound power,

$$F_c = 3F_m, \tag{14}$$

where the subscripts have been added to indicate, respectively, the force according to Curle, F_c, and the force according to Morse, F_m.

3.4. COMPARISON OF A STATIONARY AND A VIBRATING SPHERE

It may be assumed, referring to equation (1), that the pressure distribution on the surface of a small sphere of radius a in a turbulent air stream is given by equation (9) since Curle puts no restriction upon the pressure distribution. If, following Curle, the acoustic pressure $p = c^2(\rho - \rho_0)$ is introduced, then equation (1) takes the following form:

$$p = -\frac{a^2}{4\pi}\left[\frac{1}{ka} - \frac{\mathrm{i}}{(ka)^2}\right]\frac{\partial}{\partial x_j}\int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi} l_j A \frac{\cos\theta \sin\theta}{r}\,\mathrm{d}\theta, \tag{15}$$

where the direction cosines, l_j, are as follows:

$$l_x = \sin\theta\cos\phi, \qquad l_y = \sin\theta\sin\phi, \qquad l_z = \cos\theta. \tag{16}$$

The introduction of the appropriate direction cosines and the carrying out of the indicated operations of equation (15) gives the following result:

$$p = \frac{A}{3}[1 - \mathrm{i}ka]\left[\frac{1}{kr} - \frac{1}{(kr)^2}\right]\cos\theta. \tag{17}$$

Since the assumption that ka is small is explicit, the latter term may be neglected compared to unity, in which case equation (9) is obtained but reduced by 1/3. Evidently, when the assumed pressure distribution is the same as that of the vibrating sphere but the sphere is rigidly fixed and the pressure fluctuations are produced by a turbulent stream, the amplitude of the radiated sound pressure is reduced by a factor of three, as concluded earlier. This result may be understood when it is remembered that simulation of the surface pressure distribution does not imply simulation of the particle velocity distribution, which is quite different in the two cases.

4. EXPERIMENTAL APPARATUS AND CALIBRATION

A small blade with an elliptical leading edge and rectangular trailing edge placed in an air stream produces a vortex wake at a frequency proportional to the flow speed. When the latter wake is arranged to impinge upon a following small rectangular block of similar thickness at a gap width between upstream plate and down stream block a minimum of three plate thicknesses [16], a very intense sound of tonal quality (essentially single frequency) about 20 dB above the spectral level of the background noise of the jet is produced [17]. As the conditions of Curle's model are satisfied, a simple means for investigating Curle's theory in the frequency domain is provided.

As illustrated in Figure 1, a small metal block of 8 mm thickness suspended on taut wires in the wake of an upstream vortex generating plate of the same thickness in the nozzle of an air flow contraction comprised the measurement apparatus used in the experiment reported here. The gap width between the block and the upstream vortex wake generating plate was 24 mm. The upstream plate was 67 mm wide and 38 mm chord with an elliptical leading edge and a square trailing edge with sharp corners as shown in the figure.

Subsequent tests were also conducted with additional taut wire vertical constraints on the block as indicated in Figure 1. With reference to tests to be discussed and reported, the suspension without the additional constraints will be referred to as unconstrained while the suspension with constraints will be referred to as constrained.

The downstream block was mounted so that the surfaces of the block and the vortex generating plate were coplanar and parallel with the direction of air flow. Alignment was maintained within 0·1 mm across the block which is to be compared with the scale of the turbulence which in turn is of the order of the block thickness indicating an accuracy of the order of 1·25%. The dimensions of the block were chosen so that the radiating surfaces (30 mm × 30 mm) were small enough for the block to behave as a compact source at the frequencies of interest, for which the wavelength would vary between 60 mm and 170 mm.

An accelerometer was mounted in the block to allow calibration of the acceleration response of the block using a shaker, a calibrated force transducer and a Hewlett Packard (HP) 35665A spectrum analyzer under conditions of no flow prior to each test run. A typical calibration using the unconstrained suspension is shown in Figure 2. It is to be noted that while linear response is plotted in the figure the variation in decibels over the frequency range investigated from about 2000 Hz to 5500 Hz is less than 1·5 dB. Calibration using the constrained suspension was similar but was limited to a frequency range below about 4500 Hz. Measurement of the accelerometer output during a test run allowed determination of the force acting on the block and thus calculation of the radiated sound power. Integration of the measured acceleration showed that motion of the block was of the order of one micron.

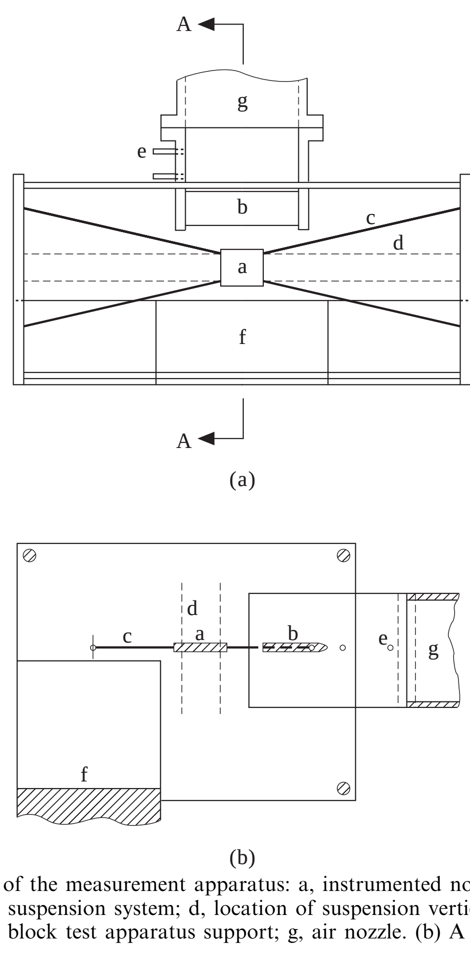

Figure 1. (a) A plan view of the measurement apparatus: a, instrumented noise generating block; b, vortex generating plate; c, taut wire suspension system; d, location of suspension vertical constraining wires; e, static pressure taps; f, heavy metal block test apparatus support; g, air nozzle. (b) A cutaway side view A–A of the measurement apparatus.

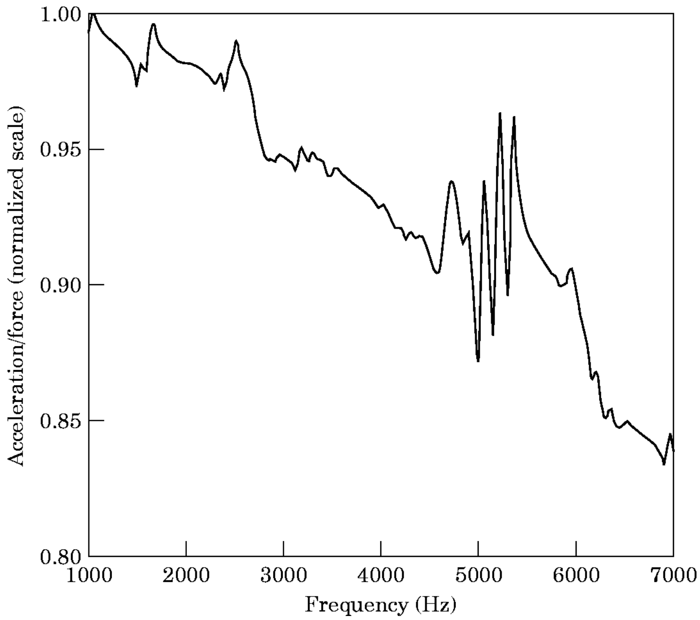

Figure 2. A typical acceleration/force frequency response obtained with the unconstrained block suspension system.

The measurement system was mounted in a 180 m^3 reverberation chamber [17], where previous determination of room reverberation times, T_{60} (s), in one-third octave bands, allowed determination of the radiated sound power using the following equation [18]:

$$L_w = L_p + 10\log_{10} V - 10\log_{10} T_{60} + 10\,\mathrm{Log}_{10}(1 + S\lambda/8V) - 13{\cdot}5 \qquad (18)$$

In the above equation L_w (dB *re* 10^{-12} W) is the sound power level, L_p (dB *re* 20 μPa) is the room mean sound pressure level, V (m^3) is the room volume, S (m^2) is the room total surface area and λ (m) is the wavelength of the sound in the room.

Compressed air for the measurement system was supplied by air storage tanks in a blow-down mode during a run. Static pressure taps in the side wall suspension system for the vortex generating plate (see Figure 1) and previous flow speed calibration using a pitot tube [17] allowed continuous determination of the air flow speed. This arrangement and a fast data acquisition and storage measurement system allowed investigation in the flow range from about 70 to 190 m/s over a Mach number range from about 0·218 to 0·552 at 20°C.

The frequency of vortex wake shedding by the upstream plate was directly proportional to the flow speed and was readily detected and measured in the acceleration response of the block and in the tone radiated into the reverberant room (see Figure 3). The linear relationship between the vortex shedding frequency and the flow speed is shown in Figure 4. For later convenience the data in the figure may be represented by the following empirical equation relating frequency, f (Hz), and flow speed, v (m/s):

$$f = -215{\cdot}8 + 29{\cdot}348v. \qquad (19)$$

The measurement system which has been described allowed quantitative investigation of Curle's Theory by comparing the measured sound power based upon the reverberant room response with the calculated sound power based upon the block acceleration response.

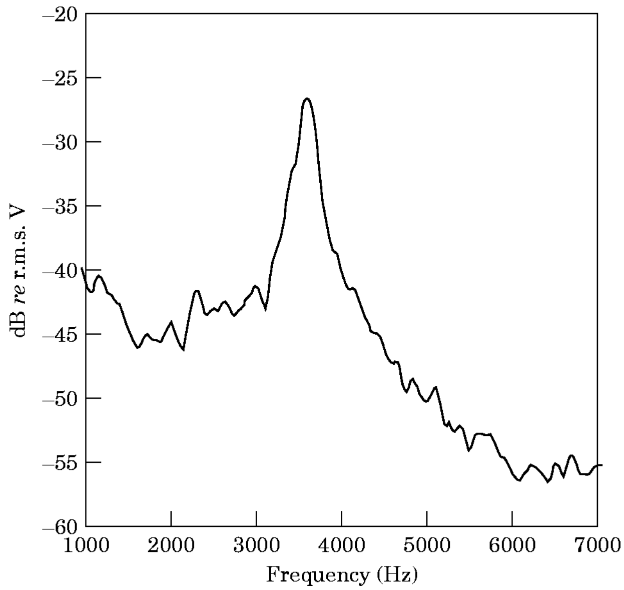

Figure 3. A typical acoustic power density spectrum showing a response at 3·584 kHz.

5. MEASUREMENTS

In the blow down mode of operation used during the tests described here, the flow speed varied from approximately 200 m/s down to approximately 60 m/s as the air reservoir pressure dropped. The flow speed extremes corresponded to peak excitation frequency extremes of 5500 Hz and 1500 Hz for the chosen plate and block thickness of 8 mm. Consequently, measurements were made over nine one-third octave bands, ranging from 900 Hz to 7100 Hz. The geometrical features of the test apparatus (see Figure 1) were kept constant for all measurements.

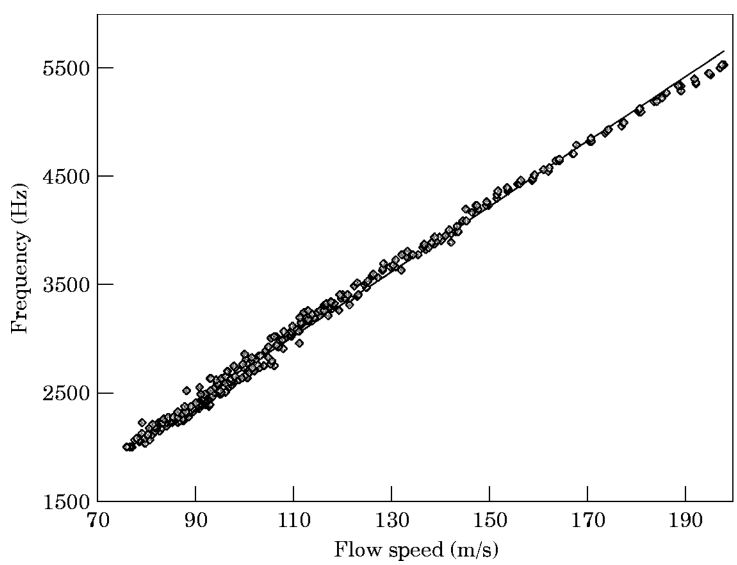

Figure 4. The variation of the vortex shedding frequency with flow speed.

A two-channel HP 35665A analyzer was used for Fast Fourier Transform measurements of acceleration and microphone outputs. Both signals were averaged over 50 measurements, which took about 3 s, during which time the velocity decreased by about 1·4% at 200 m/s (highest speed) and about 0·5% at 90 m/s.

The analyzer was driven by a computer, via a GP-IB card. A Pascal program was written to drive the analyzer for a maximum of 110 averaged measurements that covered the investigated speed range. The procedure for each measurement may be summarized as follows: (1) measure the flow speed; (2) start averaging over 50 measurements; (3) measure the flow speed when averaging is complete; (4) save the two averaged spectra (acceleration and sound pressure); (5) assign measurement numbers to spectra and store in memory; (6) separately assign a run number and save: air speed, frequency and peak level of both acceleration and sound pressure level measurements.

After 110 measurements (acceleration and sound pressure) are performed, the 220 traces are recorded in the analyzer for further processing. The line spectra and the excellent linearity of the frequency with flow speed (see Figure 4) show that the noise is generated by the wake impingement on the down stream block and no other mechanism is powerful enough to affect the measurements. The linearity shown in Figure 4 also shows that there is no feedback between the downstream block and the vortex generation at the upstream plate [17].

6. RESULTS

The results of the measurements are summarized in Figures 5–7. In Figure 5, the r.m.s. force exerted on the block by the impinging wake is shown for both the unconstrained

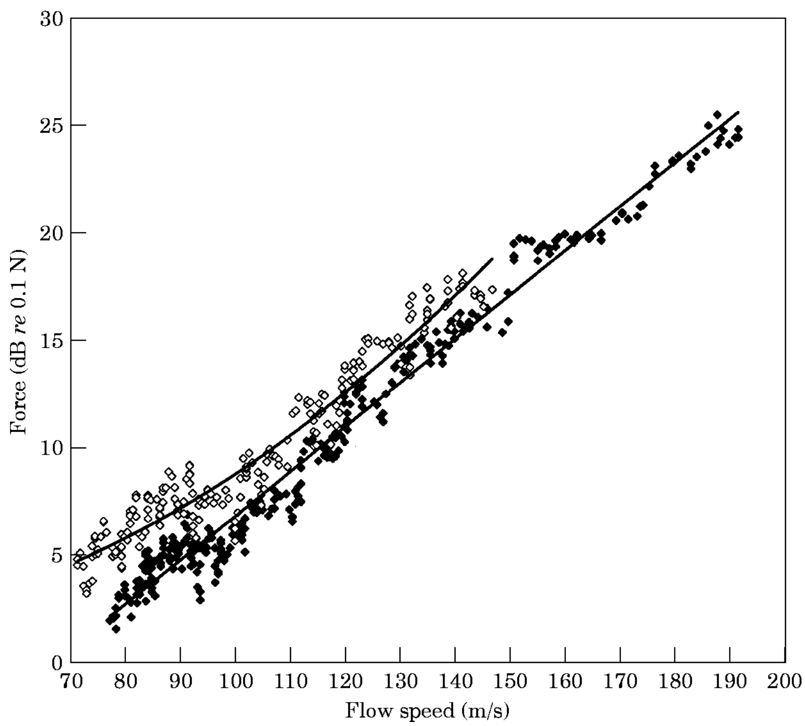

Figure 5. Force measurements plotted versus the flow speed. ◆, Vertically unconstrained; ◇, vertically constrained. Lines indicate estimated means of unconstrained and constrained support data respectively.

and constrained suspension systems as a function of flow speed for flow speeds ranging from 70 m/s to 190 m/s, or effectively as a function of the dynamic pressure, since the dynamic pressure is directly proportional to the flow speed, $P = 0{\cdot}5\rho v^2$. The force, F_N, is shown in decibels defined as $20\log_{10}(F/0{\cdot}1) = 20\log_{10}F + 20$ dB. The data shown in figures in each case is the result of three separate runs for the unconstrained and constrained block suspensions. In the case of the constrained suspension system, difficulties encountered in calibration above a flow speed of about 150 m/s suggested that the data above the latter flow speed was unreliable and thus it has not been reported in the figures.

As shown in Figure 5, the data obtained using the constrained and unconstrained suspension systems differ by 1·5–2 dB, with the former greater than the latter. The implication is that the suspension stiffness has affected the fluctuating force of the impinging vortices. However, as the relation between the fluctuating force and the radiated sound was under investigation, and the fluctuating force and radiated sound were measured essentially simultaneously, the possible effect of the block suspension system is of no importance for the present purpose. Investigation of the interesting possibility that the rigidity of the suspension may affect the fluctuating force (and radiated sound) is deferred to a separate study by the second author.

Quadratic mean lines for the unconstrained and constrained sets of data have been added as shown in Figure 5, and the latter estimates have been used to calculate Curle's prediction shown in Figures 6 and 7. For the unconstrained suspension, the mean line determined empirically is

$$L_w = -9 \times 10^{-6} \times v^2 + 0{\cdot}2062 \times v - 13{\cdot}737, \tag{20}$$

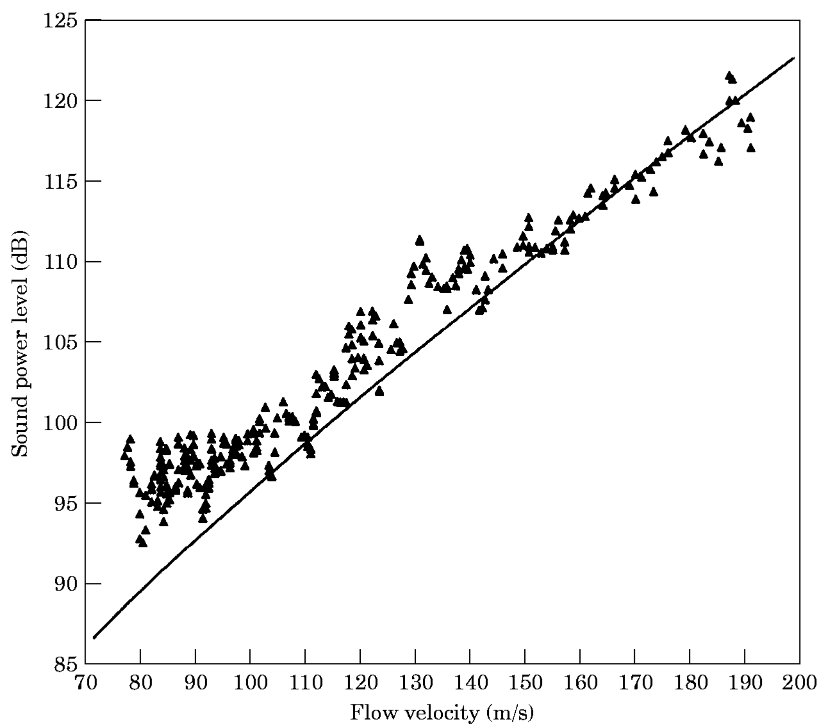

Figure 6. Measured sound power levels in the case of the vertically unconstrained suspension. The line represents the predicted sound power according to Curle.

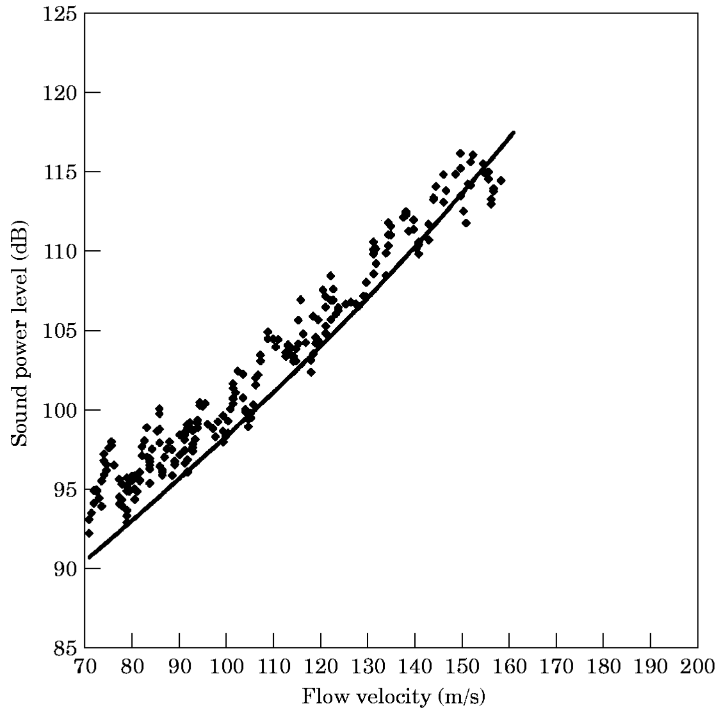

Figure 7. Measured sound power levels in the case of the vertically constrained suspension. The line represents the predicted sound power according to Curle.

while for the constrained suspension the mean line determined empirically is

$$L_w = 0{\cdot}001 \times v^2 - 0{\cdot}0225v + 1{\cdot}4745. \tag{21}$$

Use of the empirical equation (19) and equation (20) for the unconstrained suspension system or equation (21) for the constrained system has allowed calculation of the predicted sound power according to Curle in each case using equation (4) as shown in Figures 6 and 7. Comparison in each figure of the data with Curle's prediction shows general agreement at flow speeds above 140 m/s, but a gradual departure towards levels higher than predicted by Curle at low flow speeds.

Use of equation (13) allows calculation of an upper bound for the predicted sound power based upon analysis of Morse for a vibrating sphere which, as has been shown, is 9·5 dB higher than that of Curle. In either the constrained or unconstrained suspension systems, the data lie below but tend to approach the latter upper bound based upon a vibrating sphere at low flow speeds. The suspension constraint seems to have decreased the rate of divergence toward higer levels than predicted but it is in qualitative agreement with expectations.

7. CONCLUSIONS

A new technique for investigation of Curle's prediction in the frequency domain over an extended range of flow speeds has been demonstrated. Great care taken in calibration and measurement has produced results suggesting the importance of satisfying Curle's assumption of rigid response to obtain Curle's predicted result. Additional constraint on possible motion and sound radiation from a small block suspended on taut wires seems to have had the effect of causing an increase in the fluctuating force exerted on the block by the air stream and an increase in radiated noise. However, in both cases of constrained and unconstrained suspension, agreement between measured sound power and Curle's prediction is good for the case investigated at flow speeds of 140 m/s and greater. At flow speeds below 140 m/s divergence of the measured sound power away from the prediction of Curle towards a prediction 9·5 dB higher based upon analysis of a vibrating sphere due to Morse is observed with the rate of divergence being less in the case of the constrained suspension system.

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