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THE PREDICTION OF SOUND RADIATION FROM BUILDINGS

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INTRODUCTION

There is an important and recognised need to develop methods for accurately predicting noise levels experienced at positions around buildings which house noise sources. These prediction methods are necessary if such buildings are to be appropriately designed and the environment suitably planned.

Three areas for study can be defined in relation to this problem. The first involves work on the prediction of sound fields within factory spaces. The nature of these sound fields will affect the vibration and subsequent re-radiation of noise from the factory shell and this is the second area requiring further study. Some work on the excitation of building elements by internal sound fields has been carried out, but this work has assumed either normally incident plane waves or diffuse sound fields. Research has shown that the sound field within factory spaces conform neither to diffuse field theory nor can it be represented by plane waves. Beyond the factory shell the sound will be influenced by ground and meteorological effects. Although a considerable amount of work has been carried out on outdoor sound propagation it has been related primarily to incoherent point sources. An area of cladding on a building excited by an internal sound field would be an extended source with points on its surface vibrating with constant phase relationships to each other.

The building designer requires to be able to use an expression of the form:

$$L_e = L_i - R + 10 \log s - 20 \log r - 14 + D(f,\Theta,\phi,g) \qquad (1)$$

where L_i is the internal noise level, L_e is the external noise level at a distance of r metres, s is the area of the radiating surface and $D(f,\Theta,\phi,g)$ is a directivity term. In the directivity term f is frequency, Θ is the angle of elevation, ϕ is the horizontal angle and g is a sub-function incorporating the ground effect.

In this paper we seek to briefly review the work carried out to date and to indicate a possible future programme for combining work in all three areas to yield practical predictive methods.

THE RADIATION OF SOUND FROM BUILDING ELEMENTS

Work on sound radiation from building elements has been limited to the study of rectangular isotropic plates of uniform thickness. For this case it is possible to write out the following differential equation which governs the small amplitude transverse vibration

$$D \nabla^4 w(x, y, t) + \rho h \, \partial^2 w(x, y, t)/\partial t^2 = f(x, y, t) \qquad (2)$$

where w(x, y, t) is the displacement function of the plate, f(x, y, t) is the pressure difference function across the plate, $\nabla^4 = (\partial^2/\partial x^2 + \partial^2/\partial y^2)^2$, x and y being co-ordinates in the plane of the plate, $0 < x < a$ and $0 < y < b$, a and b being the lengths of the edges of the plate, t is time, ρ the plate material density, h is the plate thickness and D is the flexural rigidity of the plate.

Shen and Oldham have given details of a solution of this equation using the Galerkin technique [1]. With the plate displacement function known it is possible to calculate the resultant far field sound pressure level using the Rayleigh approximation

$$p(r, \alpha, \beta) = \frac{j\rho_0\, ck}{2\pi r} e^{-jkr} \int_{-a/2}^{a/2} \int_{-b/2}^{b/2} V(x, y)\, e^{jk(x \cos \alpha + y \cos \beta)}\, dx\, dy \quad (3)$$

where p(r, α, β) is the pressure amplitude at point R(r, α, β), k is the sound wave number in air, r is the distance between the origin and the receiving point, R, ρ_0 and c are the density of air and velocity of sound in air respectively, V(x, y) is the velocity amplitude function of the vibrating plate (equal to j ωW(x, y) assuming forced vibration at an angular frequency ω), α and β are the angle between OR and the X axis and Y axis respectively (see Figure 1).

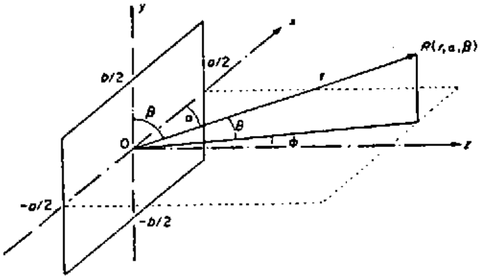

Figure 1 Co-ordinate system

Shen and Oldham, in a study involving theoretical and acoustic modelling, considered two types of exciting acoustic field [1, 2]. For plane wave (or uniform pressure) excitation they found that the plate vibration was such that the fundamental plate mode was most strongly excited other than at frequencies corresponding to a plate resonance. At high frequencies sound radiated from a plate excited in this way tended to be beamed strongly in a direction normal to the plate surface (see Figure 2).

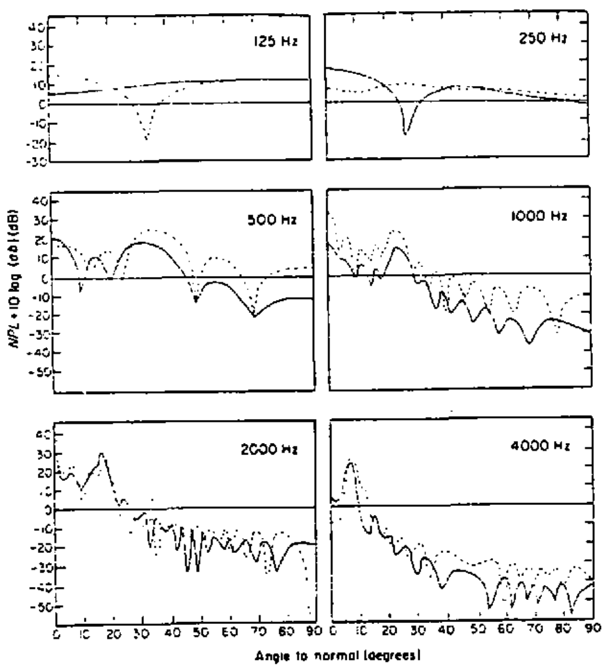

Figure 2   Directivity pattern of uniformly excited concrete panel
——, clamped; ---, simply supported

For a plate excited by a reverberant field no marked directivity effects are observed below the critical frequency. Above the critical frequency lobes are observed in the radiation pattern at an angle given by

$$\phi_m = \sin^{-1}(f_c/f) \qquad (4)$$

where f is the exciting frequency and f_c is the critical frequency (see Figure 3). The sharpness of the lobes also increase as the frequency increases above f_c.

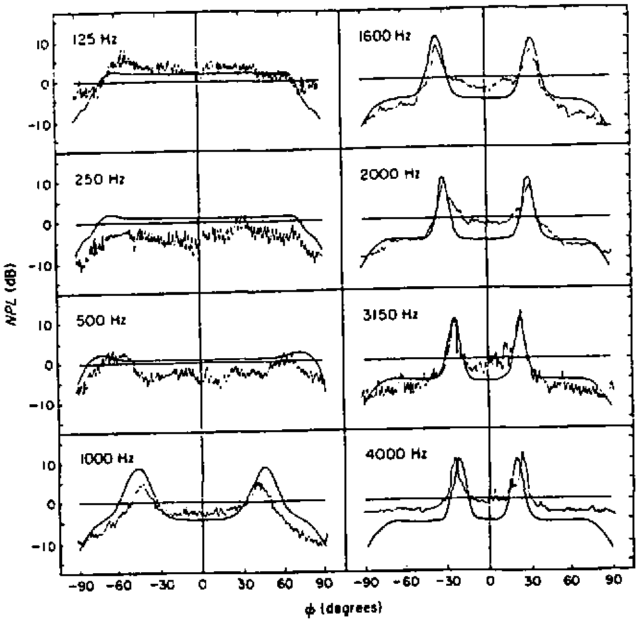

Figure 3 Directivity patterns of asbestos cement panel excited by reverberant field

The directivity of the sound field radiated from a plate for frequencies above the critical frequency is due to a resonance effect. A plate vibrating in a pattern of resonating modes with a high order mode number in one direction is similar to a one dimensional diffraction grating (see Figure 4).

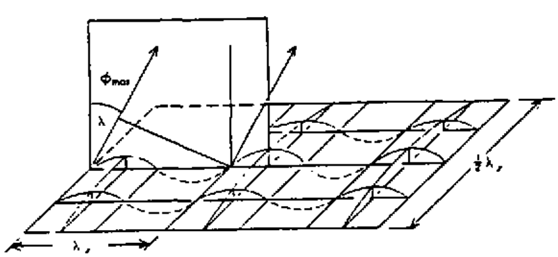

Figure 4 Radiation in the ϕ_{max} direction due to the (5, 1) mode

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In order to develop predictive models for use with industrial buildings it is necessary to extend this work to include building elements more typical of industrial buildings than homogeneous plates, sound fields which are neither truly diffuse nor plane and also the effect of ground cover on the propagation of sound from extended sources.

THE INTERNAL SOUND FIELDS OF FACTORIES

Factories are typically single storey buildings with a large floor area which results in a flat or disproportionate shape. Inside they are usually fitted with a complex arrangement of fittings and machinery. These two factors strongly influence the behaviour of sound in factories which differs considerably from that in more proportionate enclosures, i.e. those in which all three dimensions are similar.

The theory which describes the behaviour of sound in enclosed spaces, namely Sabine's theory, is based on the assumption that sound energy propagates equally in all directions creating a diffuse sound field within a short distance of the source. This condition is closely approached if the enclosure dimensions are similar. However, in disproportionate enclosures, it has been shown that the sound field does not reach a diffuse state so that Sabine's assumptions are not fulfilled and the use of his theory is inappropriate (see Figure 5). The implication for this work is that the sound field acting on the factory enclosure is not reverberant i.e. composed of resonating modes, and hence the Shen and Oldham predictive models may not apply.

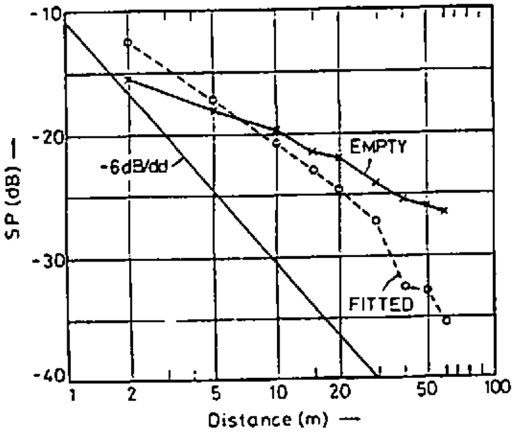

Figure 5 Sound field in factory building. After Hodgson (Ref. 4)

In addition the transmission loss of a partition measured using a conventional transmission suite might not be appropriate to this situation.

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The development of new methods for predicting sound fields in factories has followed three paths, namely, theory; empirical formulations; and scale modelling. Each has had some success, although on the one hand the theoretical work has involved highly sophisticated computer programs and on the other hand empirical methods have tended to be oversimplified. Scale modelling is a feasible alternative, but it can be time consuming and expensive. Recently, Kuttruff [4] and Kurze [5] have developed equations which account for the behaviour of sound in a disproportionate enclosure. They differ from each other in that they consider different mechanisms for the scattering of sound by machinery. In the first case the whole factory floor is considered as an irregular scattering surface whilst in the second case individual scattering objects are assumed. In the paper by Kuttruff a comparison was made between his theory and measurements in a factory; the results showed an encouraging degree of agreement. These new theories have undoubtedly produced a major advance, but they are not yet directly usable. Two main areas of work remain to be tackled.

First it is necessary to determine accurate values for the parameters in the theories - this aspect has had virtually no attention to date. In particular, it is essential to know the absorption characteristics of construction materials used in factories and the scattering effect of the factory fittings.

Secondly, a careful comparison will be required between the results of the prediction methods and measurements in factories in order to assess their accuracy.

A programme of work aimed at providing this information is now in progress at the University of Salford under the direction of Professor P. Lord and Dr. R. Orlowski.

When a satisfactory method of predicting the sound field in a factory building has been developed it can be used to determine the nature of the exciting pressure function over areas of the enclosure.

THE CONSTRUCTION OF FACTORY WALLS AND ROOFS

Factory walls and roofs typically consist of two parallel layers of sheeting. The surface facing the interior comprises flat rectangular panels and the outer surface may be profiled. The effect of the profiling is to alter the bending stiffness so that it differs considerably between that observed in a direction parallel to the corrugations and in a direction perpendicular to the corrugations. This must affect the vibration pattern of the outer panel and hence the sound radiated from it. An added complication is the addition of thermal insulation (usually in the space between the panels) which may have an effect on the loss factor of the radiating panels.

For rectangular orthotropic panels, such as corrugated panels, the bending stiffness along the X axis and the Y axis, D_x and D_y, are different so that there are two different critical frequencies. An increase in the bending stiffness results in a lowering of the critical frequency and hence the directivity effects reported by Shen and Oldham could occur at relatively low frequencies. It is not obvious what vibration pattern (and hence radiation pattern) will be observed for bending wavelengths comparable to the spacing of the corrugations.

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Factory constructions in which thermal insulation is effectively bonded to both the inner and outer sheets could be considered as a three ply laminate. In such a system shearing deformation is usually experienced in the middle layer. The dynamic bending stiffness is variable and dependent on the way in which the panel is forced. The effective bending stiffness for free bending wave propagation is frequency dependent so that the simple concept employed for predicting radiation patterns from single isotropic panels cannot be employed. The situation is so complex that a method for predicting the radiation patterns from theoretical analysis may be impossible to achieve and can probably only be obtained from experimental studies.

It is apparent from an examination of typical factory wall and roof constructions that a considerable amount of experimental work needs to be carried out before a suitable predictive technique can be devised. Such a programme of work is now being embarked upon at the University of Sheffield under the direction of Dr. D.J. Oldham.

THE PROPAGATION OF SOUND FROM BUILDINGS

Sound propagating from a source outdoors is affected by air absorption, by atmospheric turbulence, by wind and temperature gradients, by topography (including natural and artificial barriers) and by ground cover. A comprehensive model for such propagation should be required to incorporate all of these effects. However, the influence that will be most significant in most practical situations is that of the ground surface, known as ground effect. Work in this area has been limited to studies of radiation from point sources. If work in the two areas described above yields a suitable model of a factory wall surface as a vibrating system it should be possible to adapt existing theories to consider radiation from an extended source.

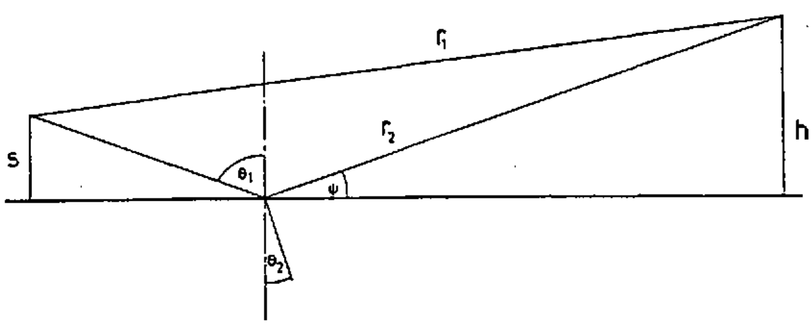

Figure 6 Source receiver geometry

Figure 6 shows the source-receiver geometry normally considered in theoretical treatments of the ground effect. Ground effect is the result of interference between the direct wave and the wave reflected in the ground plane. Most theoretical treatments have assumed an omni-directional point source. It is, however, possible for a building element to be radiating such that the ray reflected in the ground plane differs considerably in intensity from the direct ray. The resultant sound pressure level at the reception point will be a function of the panel directivity and ground surface impedance.

Ground effects are dominant at low frequencies: the longer the range, the more restricted the frequencies for which such effects are dominant. The effect of corrugations on wall panels is, as discussed in the last section, to lower the frequency at which the directivity lobes appear. If the corrugations are vertical then this effect will be observed for radiation in the vertical plane and hence will have an important bearing on the ground effect.

It should be noted that all constructions that differ from simple homogenous panels tend to have a high bending stiffness and hence to lower the range of frequencies at which directivity effects become important.

When satisfactory theoretical models of the radiation characteristics of factory wall and roof construction have been established it is hoped that it will be possible to combine them with ground effect models developed by Dr. K. Attenborough and Dr. N. Heap of the Open University.

CONCLUSIONS

It has been shown that the existing literature on the directional properties of the radiating elements is not necessarily applicable to the typical factory situation. This is because the sound field in factories is not truly reverberant, the panels used to clad factories are not simple and homogenous and the directional nature of the sound radiated is such as to modify ground effect predictions based upon simple point source models.

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EFFECTS OF SOUND ON AEROSOL PARTICLES

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SUMMARY

The work done upto now this project has involved a collection of literature from several areas of current research. A literature survey as such has not been made, instead an attempt has been made to describe systematically the various forces acting on aerosol particles in a sound wave with the aid of the literature collected. It is apparent that the forces acting on a particle in the boundary layer adjacent to a solid surface and its subsequent history are not well understood.

Of major interest in several sonic treatment applications is whether sound can prevent, or at least reduce the probability of, adhesion of particles to solid surfaces. It is conceivable that certain special phenomena may arise, which will not be anticipated by the theory. Therefore it is considered important to study the influence of sound on aerosol particles experimentally as well as theoretically in future work.

BACKGROUND

Although the mechanics of aerosol particles have been extensively researched the effects of sound at audio frequenices on aerosol particles are not well known or understood. Ultrasonic theory and applications have received considerable attention but even here many questions remain unanswered. It is apparently so that applications such as sonic cleaning, particle agglomeration and sonic treatment of combustion processes have largely preceded a deeper understanding of the physical mechanisms responsible for certain effects. A fuller understanding of the mechanisms involved may well lead the way to new applications and also enable present applications to be optimized.

Sound gives rise to various forces, which act on aerosol particles. First there is a primary force, which can be derived from the linear, first order wave equation. This force is relatively large but the time average in an harmonic wave will generally be zero. The second type of force arises from second order effects. These forces are of small magnitude though the time average is usually different from zero and thus the forces will tend to cause drift of the particles in certain directions, c.f. Beissner 1985.

The primary and secondary sonic forces will be modified in regions of close proximity to other particles or surfaces. Moreover other wave motions, in particular a transverse wave causing shear in the fluid, will be excited at surfaces by incident longitudinal waves. Very often there will be forces of several different origins acting on particles especially close to boundaries, e.g. aerodynamic, electrostatic and thermophoretic forces. The net forces and resulting motion of the particle will therefore depend on the interaction of the various forces which will often vary rapidly with distance from the surfaces.

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It is the last category of sonic forces, which is of particular interest in the present case and about which least is known. The present study has been restricted to solid aerosol particles. The mechanics of liquid particles in air is more complicated mainly because of their compressibility and the added complication of evaporation or condensation.

Considering first the primary force, for a simple harmonic wave the following relation between the velocity amplitudes of the particle motion and the sound wave has been developed, Temkin 1981:

$$\frac{u_p}{u} = \frac{1 + y - i\,(2y^{2/3} + y)}{1 + y - i\,(\omega \cdot \tau_d + y)}$$

where it has been assumed that the density ratio $\rho_o/\rho_p \ll 1$ and the substitution $\omega \cdot \tau_d = 4\ y^2\ (9\ \delta_\nu)$ has been made. $y = a/\delta_\nu$ is the ratio of particle radius to boundary layer width. The magnitude of the ratio is seen to decrease monotonically as the frequency is increased, whereas the phase lag of the particle motion with respect to sound velocity has a maximum value at some frequency.

If there is a considerable number of particles, it can be shown that the phase velocity of the sound wave, u, will be slightly reduced as compared with the case that no particles are present, by an amount which increases with decreasing frequncy and increasing mass loading.

The known secondary forces acting on aerosol particles far from any surfaces are the radiation pressure and forces due to wave distorsion, scattering and attenuation. The equations for, and magnitudes of, these forces have been presented in the Swedish National Board for Technical Development, STU, report no. 83-5482.

The secondary forces have magnitudes small compared with that of the primary acoustic force and proportional to the sound velocity or the sound velocity squared i.e. they are strongly dependent on the actual sound pressure levels. They do, in some cases, have magnitudes comparable with the gravitational force. The magnitude of the forces increases with increasing frequency. The direction of secondary forces in a plane wave is always parallel to the wave number in either the plus or minus direction. In the boundary layer this will probably not be true due to velocity and temperature gradients, which will tend to cause rotation. For other wave types excited at a solid boundary the force due to attenuation may be significant tending to push particles away from the surface.

INTERACTIONS BETWEEN PARTICLES AND SURFACES

Of primary interest in many applications is whether or not aerosol particles will adhere to other particles or adjacent surfaces. The possibility of detaching loosely bound particles is also of interest. As regards adhesion of particles there are two facts of the problem; firstly the transport of particles and the probability of collision and secondly the probability of adhesion or agglomeration of particles on collision. The rate of diffusion is

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generally increased due to both the primary and secondary forces exerted on the particles by a sound wave. The forces of sonic origin acting on the particles will increase the length of the path travelled per unit time and therefore in general the probability of collision with other particles. How or to what extent the probability of adhesion on collosion will be affected by sound is largely unknown. It is possible that under certain conditions sound will increase this probability whereas for other values of e.g. acoustic frequency and sound pressure level it may perhaps be reduced.

The main forces responsible for adhesion are van der Waals force, electrostatic force and the surface tension of adsorbed liquid films. Van der waals forces are due to the movement of electrons, which can create momentary charge concentrations in the form of dipoles. Such dipoles will induce complementary dipoles in adjacent material thereby giving rise to an attractive force. The strength of these forces decreases rapidly with separation distance. On a scale only one or two orders of magnitude greater than the size of molecules most surfaces are very irregular and initially particles contact at only a few high points called asperites. Over the whole area of contact the two surfaces are separated on average by a distance, which for "smooth" surfaces is usually assumed to be 0.0004 µm, see figure 1.

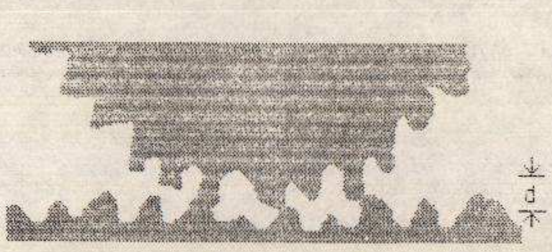

Figure 1. On a microscale "smooth" surfaces exhibit irregularity. Raised portions of the surface are called asperites, contact between surfaces is initially made by the asperites.

After the initial contact has been made the Van der Waals forces and electrostatic forces gradually deform the surface to reduce the average separation distance and increase the contact area. The deformation process may take as long as a few hours. The strength of the forces resisting deformation or hardness of the materials involved controls the size of the ultimate area of contact and therefore the strength of the adhesive forces. Adhesive forces can vary by three orders of magnitude for materials ranging from soft plastic to quartz. At low temperatures particles will tend to become more brittle. Also high acoustic frequencies (ultrasound) will make the particles more brittle and may have considerable effect on the van der Waals forces.

Due to local shearing forces and their own inertia the aerosol particles will not only rotate but also experience lateral forces across the flow. Under certain circumstances these lateral forces will be in the direction away from adjacent surfaces, i.e. constitute lift forces. It is possible that by translation and/or rotation of particles relative to an adjacent surface sound will prevent the build up of van der Waals forces and the probability of adhesion will be reduced.

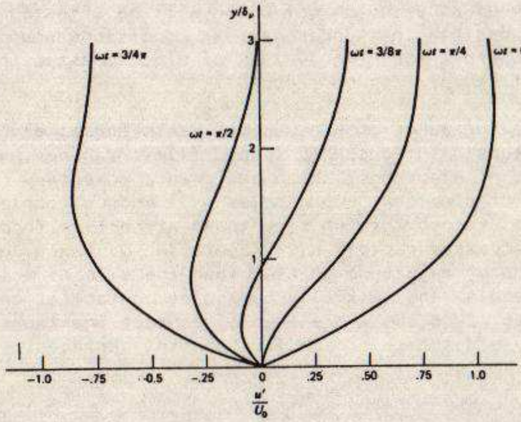

Figure 2. The fluid velocity u'/U_0 in a boundary layer at several instances during a half cycle, where $u' = u_\infty - u$ and the subscript ∞ denotes the free-stream value.

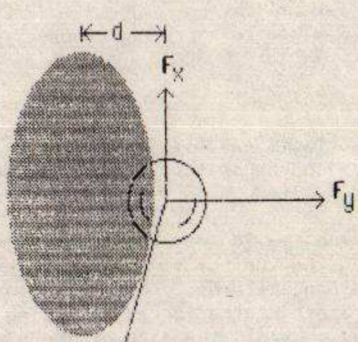

Figure 3. Particle translating and rotating in the viscous boundary layer adjacent to a plane rigid surface.

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Adjacent to a rigid wall in a viscous, flowing fluid there is a sheared velocity profile for which the velocity vanishes at the wall. At low frequencies, the total velocity is due to the superposition of an harmonic oscillation and a transverse wave. In figure 2 from Temkin 1981, the velocity is shown at various instances during one cycle. The question is, what will be the motion of a small particle passing into the boundary layer? Note that the fluid velocity in an intermediate region in the boundary layer is greater on average than the velocity outside the boundary. The boundary layer width, δ_ν, for air at NTP is $2.2 \cdot 10^{-3}/f^{\frac{1}{2}}$ and is thus 220 µm at 100 Hz and 70 µm at 1 kHz, which is considerably greater than the dimensions of the aerosol particles of interest i.e. approx. 1 to 10 µm.

It may be anticipated that the torque of a particle in an acoustically induced shear flow will bear a similar relationship to the local fluid velocity as the rectilinear velocity of a particle in a plane sound wave, i.e. that the rotation of dense particles will be generally smaller than rotation of the displaced fluid and experience a phase lag with respect to it depending on particle size and density and the acoustic frequency.

The presence of the particle will of course distort the local flow. If the inertia of the particle is not negligible, the torque exerted by the shear in the boundary layer will cause a lift force to be exerted on the particle, c.f. figure 3.

It may be assumed that the motion of the particle will increase the shear stress in the fluid in the boundary layer adjacent to a larger surface and consequently the effective viscosity in the fluid film in between. In this sense, sound may be said to act as a lubricant increasing the motion of the particle parallel to the surface. A fuller analysis of the problem requires the solution of the wave equations for suitable boundary conditions at the surface and at the particle, and an analysis of the sonic forces as discussed above.

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