NO. 21625

National Committee for Fluid Mechanics Films

FILM NOTES

for

AERODYNAMIC GENERATION OF SOUND*

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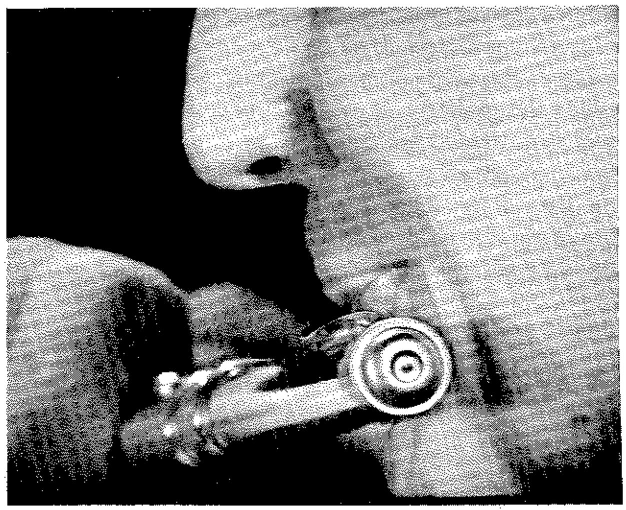
Introduction

A steady stream of air can produce sound (Fig. 1) — sometimes very beautiful sound, sometimes very ugly. Yet sound is a vibration of the air. How can it be produced by a steady air flow? In this film we study why, and how much, a flow, even though produced by a constant pressure difference, can generate the pressure fluctuations that we hear as sound — sound that may be amplified by the presence of obstacles in a stream, and still more powerfully by the action of resonators like the pipes of an organ, or the bubbles whose resonant vibration we shall find causes the "babbling of a brook."



1. A steady stream of air produces sound.

A high-speed jet without resonators can be quite noisy enough. We especially want to study the sound a jet makes so that aircraft and their engines can be designed to keep ground noise levels within prescribed limits when the correct take-off precedures are adopted. Also, in the design of rocket launching sites an important issue is the sound, generated again by a flow designed to be as steady as can be achieved. Admittedly, fluctuations are already present in the rocket combustion chamber or the aircraft jet pipe.

***_AERODYNAMIC GENERATION OF SOUND, a 16-mm B&W sound film, 44 minutes in length, was produced by Educational Development Center under the direction of the National Committee for Fluid Mechanics Films, with the support of the National Science Foundation. Additional copies of the notes and information on purchase and rental of the film may be obtained from the distributor:_**

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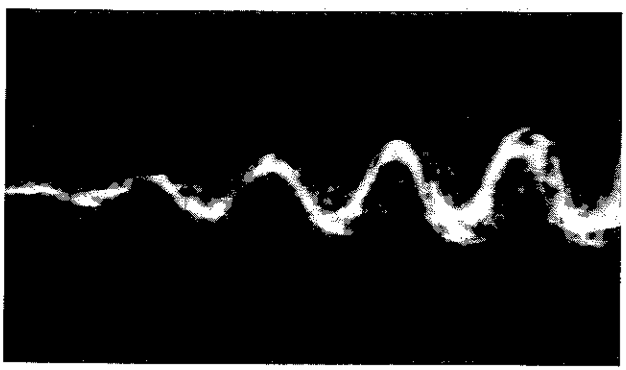
But jet noise that is extremely comparable, if frequencies and intensity are properly scaled on jet diameter, can be produced in the laboratory with an air jet practically devoid of fluctuations in the emerging flow. This raises two questions. First, how do new and quite intense fluctuations arise as the flow emerges into the atmosphere? Secondly, what fraction of the energy radiates away as sound?

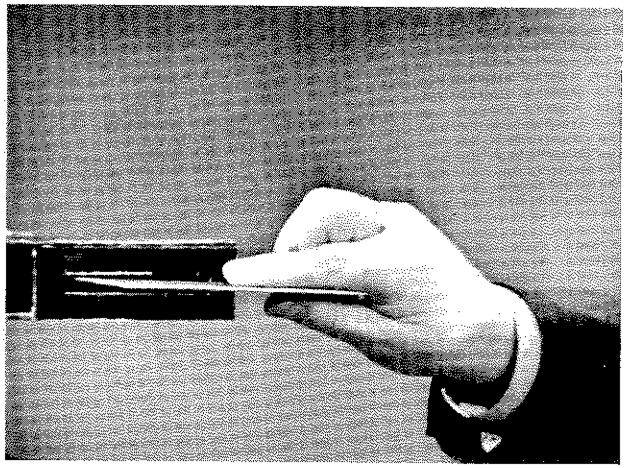
The answer to the first question lies in the words "flow instability." A vortex layer is formed between the jet and the outside atmosphere, and free vortex layers like this can be exceedingly unstable. There is a fast exponential growth of disturbances of a certain type as they travel downstream, so that any small fluctuations present at the orifice, if their frequency is less than a certain value, may have a large positive growth rate and quickly become very big. Now that is an effect of inertia, and it is counteracted by the viscosity of the fluid. The ratio of inertial to viscous effects is the important quantity known as Reynolds number. At high Reynolds numbers disturbances in a wide range of frequencies grow very fast and interact with one another, and we call the result "turbulence." At lower Reynolds numbers the effect of viscosity is to reduce the growth rate of small perturbations so that most disturbances do not grow at all. Then it is only disturbances in quite a modest range of frequencies that have a significant growth rate. So, under those circumstances the disturbance that appears tends to be relatively regular (Fig. 2).



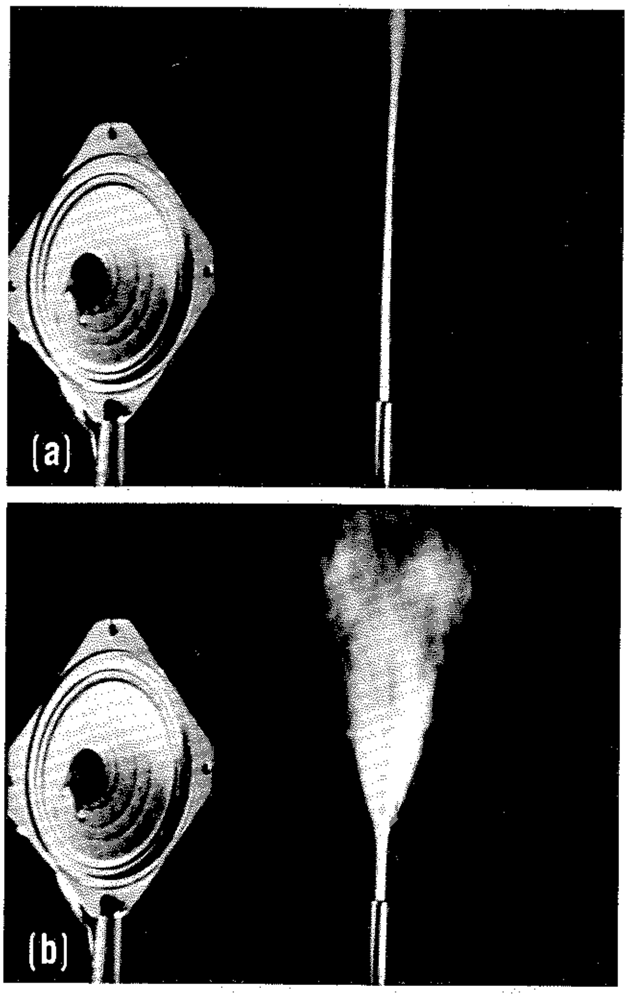
2. Disturbances in the wake of a wire or thin plate can grow to form a "vortex street."

We can make them quite regular by an interesting feedback mechanism using an edge and a jet (Fig. 3). The edge casts off an eddy each time the local angle of attack changes sign. The eddy reacts on the nozzle to create a disturbance at the right moment in the cycle, which in turn is amplified by the jet shear. An extremely regular cycle results from this jet-edge interaction. A similar experiment performed with a cylindrical jet is seen in Fig. 4. At low Reynolds number disturbances grow too slowly to be visible close to the jet. But if a loudspeaker artificially introduces disturbances of the right frequency, they quickly grow to something very substantial.

But it is only at these low Reynolds numbers that jets are in this way acoustically sensitive. At higher



3. An edge placed near the exit of a jet produces an audible whistle.



4. (a) With the loudspeaker off, a low-Reynolds-number jet of smoke remains laminar for an appreciable distance. (b) The loudspeaker is emitting sound at a critical frequency. Disturbances in the jet grow quickly.

Reynolds numbers external sound has no influence on the jet, which quickly assumes a turbulence condition because disturbances in a wide range of frequencies grow fast. At the very high Reynolds numbers that arise in engineering applications, the sound of a jet is just a minor by-product of the turbulence. The turbulence itself is unaffected by its presence.

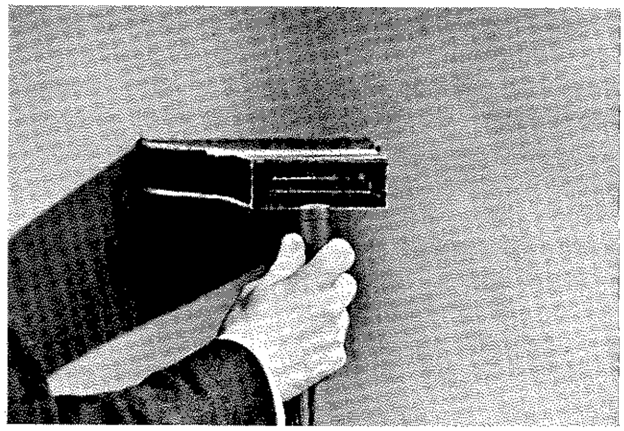
The wake of a wire in the wind is another free vortex layer which, like a jet, is extremely unstable. At low Reynolds numbers (around 100 based on wire diameter) the flow is extremely regular, taking the form of Karman's vortex street, which reacts back on the wire causing it to shed just the right amount of vorticity in each cycle to maintain the street. At higher Reynolds numbers more and more frequencies are important and the flow soon looks quite chaotic.

We have seen, then, that air flowing steadily out of an orifice, or blowing steadily past a wire, may develop fluctuations; at low Reynolds numbers regular ones, at high Reynolds numbers turbulent ones. From this, sound may result in two ways. First, resonators if present may be excited by the pressure fluctuations in the flow and may radiate sound rather efficiently. A beer bottle is a so-called Helmholtz resonator, where the inertia of air flowing in and out of the nozzle and the stiffness due to air in the bottle resisting compression define a frequency, and sound radiation is the main loss term. Also, pipes of variable lengths are used as resonators in musical wind instruments based on the jet-edge method of excitation.

Sound Radiation

We shall now concentrate on how flow fluctuations, like the turbulence in a jet, generate sound without the action of resonators. How much of the energy of the fluctuations succeeds in escaping a sound? The key word here is "escaping." Radiated sound means pressure fluctuations whose energy propagates away from the source with the sound speed: 350 meters per second. Of course, within the flow there are other pressure variations balancing the local fluid accelerations; these do not propagate at all.

Actually the ear, or a microphone, can register these latter pressure fluctuations exactly as if they were sound, but they are called "pseudo-sound,"— only "pseudo" because they do not propagate like sound. For example, the microphone placed very near the jet (Fig. 5) registers pressure fluctations, with a minimum each time one of the mixing-region eddies passes the microphone and maxima in between. But those are pseudo-sound because the minima and maxima travel at the speed of the eddies, and not at the much larger sound speed. These fluctuations are substantial only very close to the jet. If the microphone is moved up and down near the jet, there are enormous changes in the sound heard. Farther out the sound of the fluctuations disappears altogether, but in that region we can with the same microphone find the real sound if we increase the speed of the jet. But the real sound shows much less variation of amplitude with distance. There is some falling off with distance, actually like the inverse square of distance from the nozzle, as the energy is radiated outward all the time.

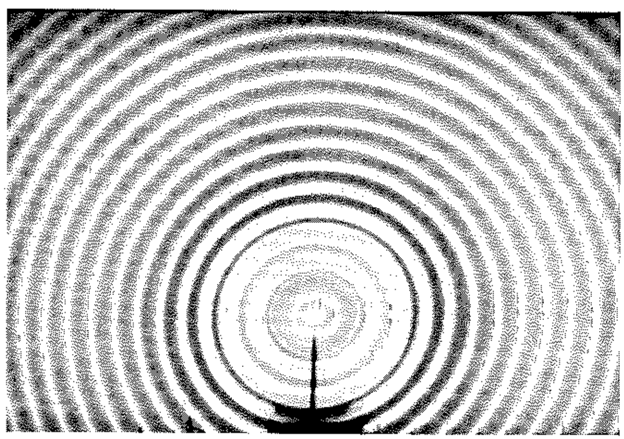


5. A microphone near a jet hears "pseudo-sound."

To summarize, then: at small distances from the orifice there is an intense level of pressure fluctuations known as "pseudo-sound." Here the real sound is at a very much reduced level from the pseudo-sound. Farther out, the pressure intensity decays like the inverse-square law. The reason why radiated sound is so much less than pseudo-sound emerges after we have looked at mechanisms of sound generation.

Mechanisms of Sound Generation

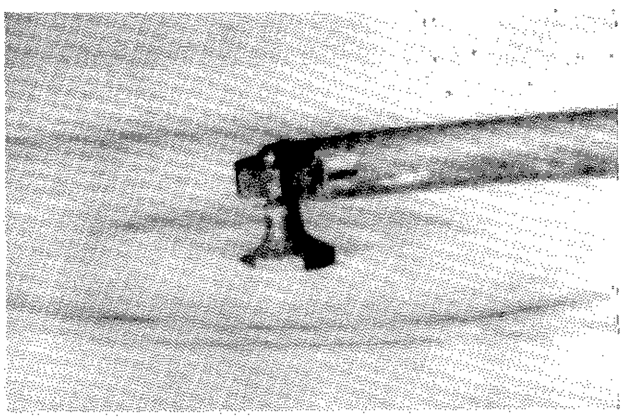
The mechanism that generates a simple inverse-square law of intensity at all distances is a simple source. In Fig. 6 a simple source is observed in a water tank by viewing the shadows of the waves produced on a screen. The depth of the water was chosen to represent sound as well as is possible in the sense that waves in the ripple tank travel at an effec-



6. Shallow-water ripples from a simple source.

tively constant speed. This speed is 20-odd centimeters a second, and propagation from a source is clearly visible. Sound waves travel at speeds over a thousand times faster.

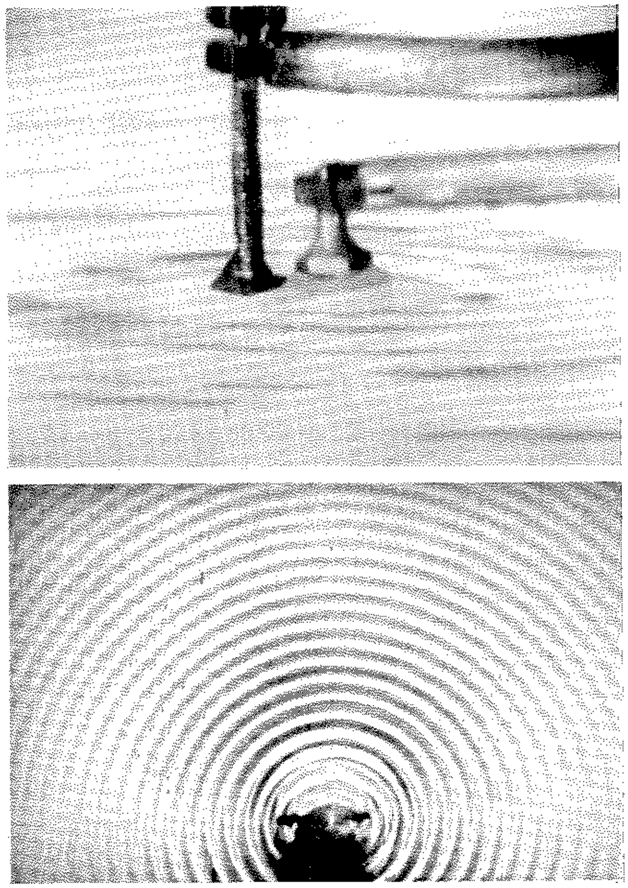
Air pressure fluctuations at a distance r from a sound source are given by: $\Delta p = \dot{q}(t - r/c)/4\pi r$. The variation in inverse proportion to r means that the intensity or energy flow (which varies with the square of Δp) obeys an inverse-square law. The pressure fluctuations faithfully follow those of the source itself except for a time lag r/c which represents the time taken for waves to travel a distance r at the sound speed c. From a source, as its name implies, there is a rate of mass outflow $q(t)$ in grams per second. But it is only rate of change of mass outflow that produces waves, and it is this rate of change $\dot{q}$, often called the source strength, which is mimicked by the pressure fluctuations at a time r/c later. Any foreign body in a fluid, whose volume V pulsates as a function of time, acts like a source, and the mass outflow from the body is equal to the density of the fluid times the rate of change of volume of the body, $\dot{V}$. So the source strength in that case would be proportional to $\ddot{V}$. In fact, the waves in our ripple tank are produced by a foreign body that is pushed in and out of the water (Fig. 7).



7. Oscillating plunger acting as source.

A quite different method of sound generation occurs when two equal and opposite sources are close together (Fig. 8). At any one moment the sum of their strengths is zero. This contrasts with the field of a single plunger (Fig. 6). Although the amplitude of motion near the source is somewhat increased, far less wave energy is propagating away from the source. (Compare the near field with the far field.) In fact, in particular directions (east and west) contributions from the positive and the negative sources almost cancel.

Those contributions do not cancel exactly in most directions, however, because the distance r from the positive source is not exactly equal to the corresponding distance from the negative source. For example, in a direction that makes an angle θ with the line of length l joining the sources, the difference between those distances is approximately $l \cos \theta$. Now, from that difference in the value of r, we can deduce, by differentiating the expression for the simple source field with respect to r, that the field of the pair of sources is:



8. (a) Two plungers close together oscillating 180 degrees out of phase produce the directional wave field of (b).

$$\Delta p \approx \frac{\dot{q}(t - r/c)}{4\pi r \cdot r}\, l \cos\theta + \frac{\ddot{q}(t - r/c)}{4\pi r c}\, l \cos\theta.$$

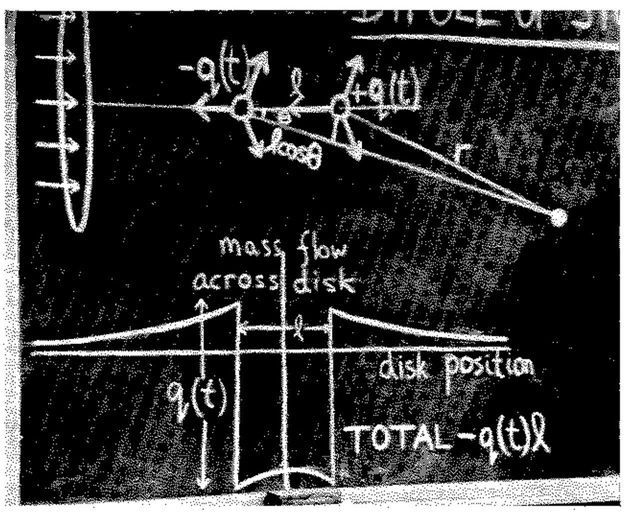
Actually, it is the differences in the amplitude factor r^{-1} that produce the near field term, and the differences in the time lag r/c that produce the radiation, or far field, term. At distances r which are large compared with the distance l between the sources, the pressure fluctuations, in both near and far fields, depend not separately on the strength $\dot{q}$ of the sources and on l, but only on their product $(\dot{q}l)$. The fluctuations would be the same if we had sources that were twice as strong but twice as close together. We call them a dipole sound field, of strength $\dot{q}$ times l.

Now we can see that when l is small enough the dipole field is going to be very much smaller than the simple source field. The near field term is smaller than the simple source field by a factor of at least

(l/r). The far field term depends on the frequency, the ratio of $\ddot{q}$ to $\dot{q}$. The speed of sound divided by the frequency is the quantity λ, the radiated wavelength. The far field term then is smaller than the simple source term by the ratio $(2\pi l/\lambda)$. When this ratio is small, we say that the source region is compact. The source field is compact relative to the wavelength. Now, aerodynamic sound sources are often compact, and we have our first glimpse here into the dual structure of the pressure field. At distances greater than a wavelength or so, the pressure falls off like $1/r$, like a simple source. Closer to the source region than a wavelength or so, the near field term is dominant. The field is then relatively intense, being induced predominantly by the nearest simple source.

Force Associated with Dipole Radiation

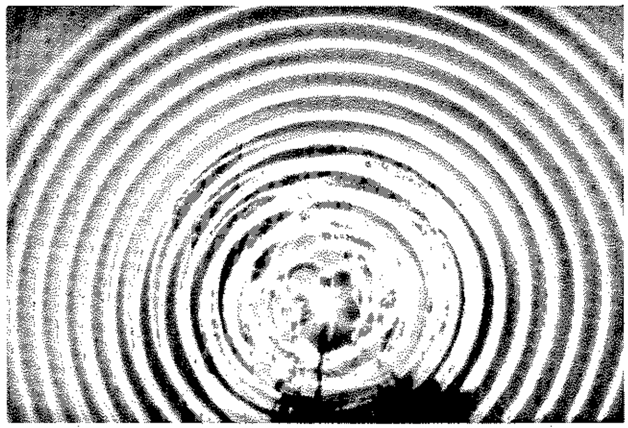
In our ripple tank there is a local back-and-forth movement in the neighborhood of the sources, and locked in this local movement there is a fluctuating momentum. Now, no net momentum can be produced by simple sources, so it follows that in the external dipole field there must be an equal and opposite momentum. We can find out how much by considering the mass flow across different discs strung on the axis joining the two sources. We do not know how much that is, but it is obvious that it must drop suddenly by an amount $q(t)$ at the source where the mass outflow is $-q(t)$, and rise suddenly by $q(t)$ at the source where the mass outflow is $+q(t)$ (Fig. 9). It follows from



9. Mass flux as a function of position for a dipole source.

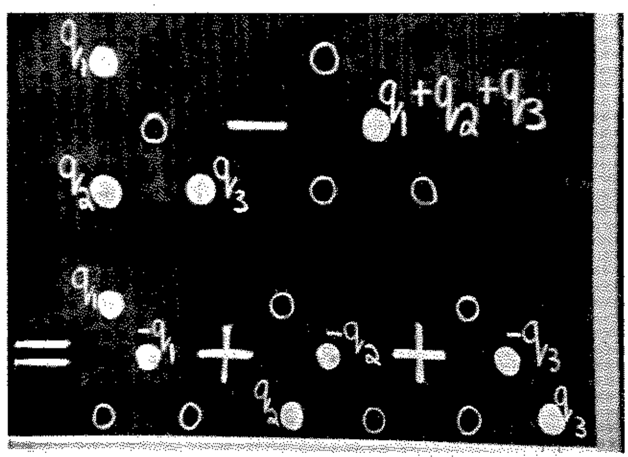
this that when the two sources come closer to make a dipole the total momentum in the region between the sources would be equal to the area under the curve of mass flux versus position (the mass flux being equal to momentum per unit length). That is, the momentum would be $-q(t)$ times the source separation distance, l. There must on the other hand be an equal and opposite momentum in the external dipole field, and this therefore must be $+q(t)$ times l. Now rate of change of momentum equals force, and it follows that the strength of the dipole, $\dot{q}(t)\ l$, is exactly the force with which the dipole is acting on the external fluid, producing a rate of change of its momentum. Actually it would be the same not only in magnitude but also in direction if we take the direction of the dipole as pointing from the negative toward the positive source.

So we can say that a dipole whose strength in magnitude and direction is **F** is equivalent to the action on the external fluid of a force of exactly the same strength.



10. Wave field from a group of three out-of-phase sources whose strengths do not add up to zero.

In Fig. 10 we see the field from a group of sources whose strengths do not add up to zero, and they are not in phase. Yet they generate a rather symmetrical wave field. This illustrates the important principle that any group of compact sources radiates like a simple source at some central point if the sum of their strengths is not practically zero. That is because the difference between the two sets of source arrangements is simply three dipoles, each composed of a negative source at the center and a positive source at one of the peripheral points (Fig. 11). These dipoles are negligi-



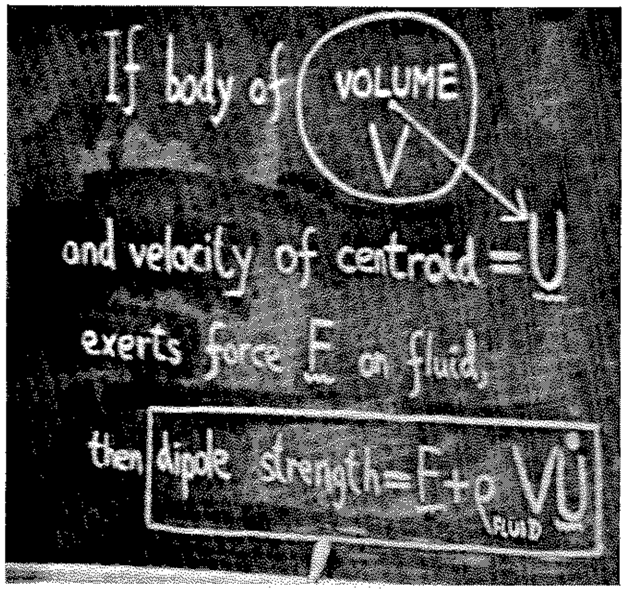
11. The difference between a compact arrangement of three sources and a simple source having the strengths of the sum of the individual sources is three dipole sources.

ble when the source is compact. The same conclusion would be reached if in addition to the sources there was an externally induced dipole resulting from the action of a force.

So, in sound-generation problems we always ask first whether the sum of all the source strengths is significantly different from zero; when that is so, then the total source strength is what dominates the external sound field. For example, when a body is changing in shape as well as in volume, we can represent that fact acoustically by sources distributed round its outside which correspond to displacements of the surface, and by dipoles corresponding to forces. All those would be important in the near field, but in the far field it is only the total source strength that matters, and that would depend on the total rate of change of volume of the body, since only that can affect mass outflow.

Thus, in the ripple tank an irregularly shaped plunger generates a far field similar to that of a simple source, essentially because the difference is the sum of dipole far fields that is reduced in magnitude by the factor ($2\pi l/\lambda$). Similarly, if a bubble in water is vibrating, only its volume change is important in producing sound. Vibrating bubbles have a characteristic frequency depending on the compressibility of the gas. For air bubbles, these regular vibrations of bubble volume have a frequency of about 600 cycles per second divided by the diameter in centimeters, and make quite a musical note. Flows with bubbles produce sound mainly because the bubbles are resonators of various frequencies whose volumes fluctuate in response to pressure fluctuations. So, here again, pseudo-sound makes itself heard by exciting resonators. A simple-source sound field is not so amplified. When bubbles are introduced the radiated sound changes little, because a simple source has a far field comparable in intensity to that of its near field, which is exciting the bubble. But a dipole of the same frequency whose natural far field is weak in relation to its near field has its radiation greatly amplified when the same lot of bubbles respond to its near field.

But in many important cases of aerodynamic sound generation the total source strength is zero, because foreign bodies in the fluid are not changing their volume and the rate of introduction of new fluid is zero or, as with an air jet, practically constant. When the total source strength is zero, the equality between the source arrangements pictured in Fig. 11 remains true, but the second term on the left amounts to nothing. The equality states therefore that the whole sound field is equivalent to a sum of dipole wave fields . . . each corresponding to the action of a force on the fluid. Now, all those effective forces plus any real forces that may be present combine together to form a resultant force, and to a good approximation the far field is that



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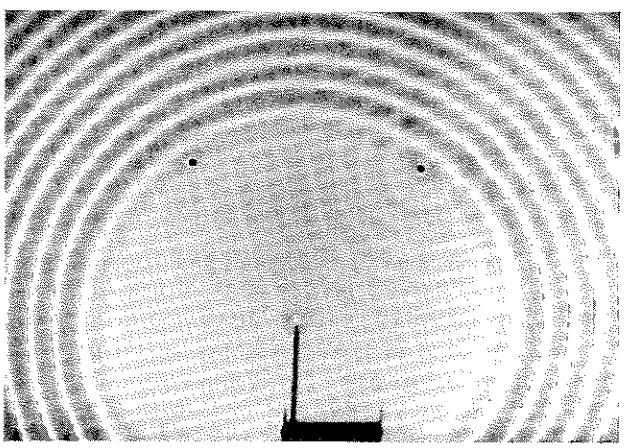
of a single corresponding dipole. Actually, its strength is equal to the total force exerted on the fluid, plus a correction if any bodies are moving through the fluid (Fig. 12). This correction is equal to the rate of change of momentum of the fluid supposed to have been displaced by the body. Actually this correction is often unimportant for air with its low density, but it is used in propeller-noise theory. Each little element of a propeller blade can be represented by a dipole consisting of the force with which it is acting on the fluid, plus the displaced mass of air times its centrifugal acceleration.

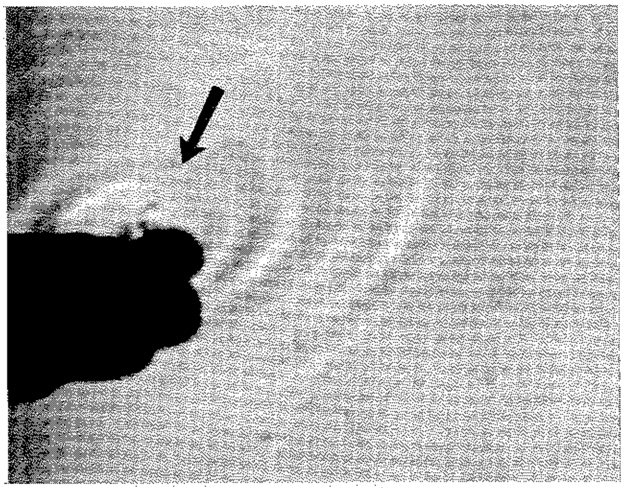
We can illustrate this displaced inertia term in the ripple tank. If we allow a solid body to vibrate just at the amplitude with which the water moves, it makes no waves since the force between it and the fluid exactly balances the rate of change of displaced momentum. But if we hold an identical body at rest,



13. The last waves of a packet of simple source waves pass two objects in the field. At the upper left a freely floating body does not generate waves. A similar object at the upper right is held at rest and produces a scattered wave field.

which needs a different fluctuating force, we observe the dipole field associated with that force, which is what would usually be described as a scattered wave field. We illustrate the case when both bodies are seen together — one scattering and the other not (Fig. 13).

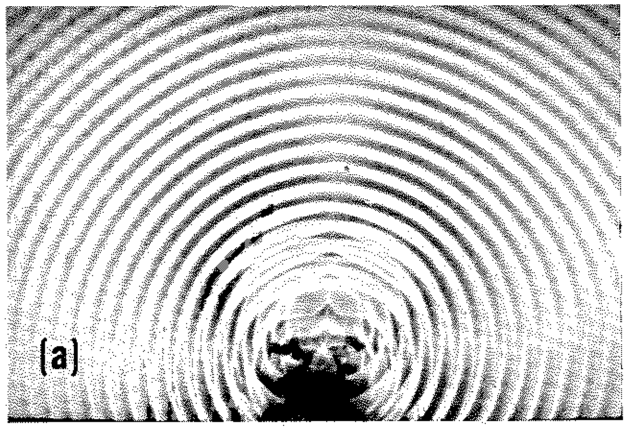
The dipole strength for a rod moved rapidly through the air is simply the force with which the rod acts upon the fluid. The correction term due to acceleration is unimportant. We can illustrate this motion and the waves it generates in the ripple tank. The dipole axis is seen in Fig. 14 to be normal to the direction of motion. The waves are induced by fluctuations of lift force. At higher Reynolds numbers, as we have already seen, lift fluctuations occur over a broad frequency range — they generate acoustic noise. This is an important part of the sound field of aero-engine compressors. Finally, we will leave the subject of dipoles by noting that the wind roars mainly owing to the forces with which solid obstacles resist it. Their geometry is very various and so a broad spectrum usually results.

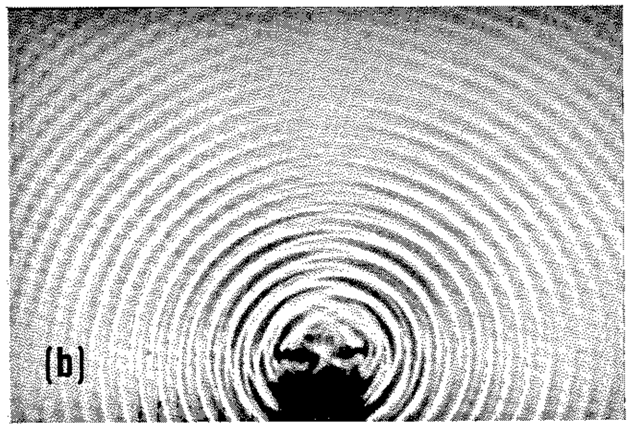


14. A body moving along the direction indicated generates a dipole wave field whose axis is normal to the direction of motion.

Quadrupole Radiation

We introduce our next main subject with an experiment; two rods placed in the ripple tank are vibrated horizontally. They act on the fluid with identical fluctuating forces, in phase, and you can see the single dipole field associated with their resultant (Fig. 15a). Note the strength of the wave shadows in the top left-hand corner of Fig. 15a. In Fig. 15b the two rods are being moved in exact anti-phase so that the total dipole strength is zero; the strength of the wave shadows in the top left-hand corner is considerably reduced. This experiment is particularly important because it shows how much smaller the far field is when the resultant total external force on the system is zero. So when we have air turbulence that is separated from foreign bodies that can act on the air with forces, we shall get radiation of this type with a reduced far field. This wave pattern has a name derived from the fact that two equal and opposite dipoles can be thought of as altogether four sources; the combination is called a *quadrupole*. Notice in Fig. 15b that there are four directions in which the far field is strongest.

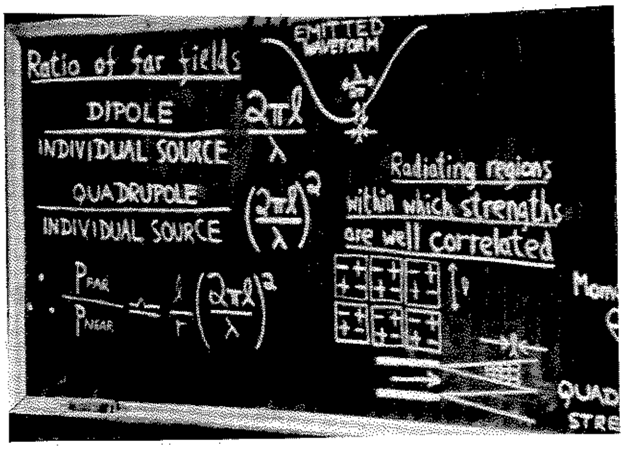




15. (a) Two oscillating rods moving in phase (north-south direction) produce a dipole wave field with intensity minima along an east-west axis. (b) When the rods move 180 degrees out of phase, a quadrupole wave field is produced. The intensity minima are in directions east, north, west, south with maxima in between.

We have seen earlier that the field of a dipole is smaller than that of an individual source by the factor $(2\pi l/\lambda)$, because two sources opposing each other, separated by a length l which is small compared to $(\lambda/2\pi)$, almost cancel. Now a quadrupole has two dipoles opposing each other, so again we repeat this cancelled factor and we get $\left(\frac{2\pi l}{\lambda}\right)^2$ for the efficiency of the quadrupole versus the individual source (Fig. 16). A common example of the quadrupole is a tuning fork, where the two tines vibrate in anti-phase, inducing equal and opposite forces. Much less energy is heard than when one of the tines is baffled so that the field of one of the elementary sources is heard.

These ideas explain why in a turbulent jet the



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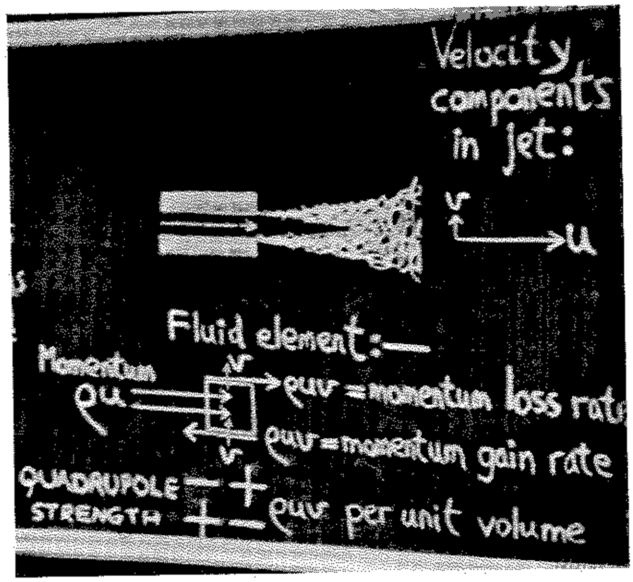

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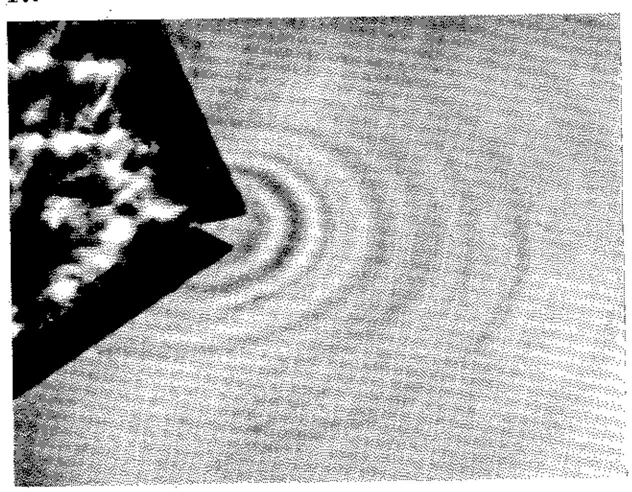


18. Well-ordered waves emanate from a slit in a barrier separating a turbulent flow from tranquil water.

pseudo-sounds, or near-field pressure fluctuations, are so large in relation to the radiated sound or far-field pressure fluctuations. There is no variable rate of introduction of new fluid, so the total source strength is zero. There is no force exerted on the fluid by any foreign body, so the total dipole strength is zero. Therefore we can say that the radiation is of quadrupole type, and far-field pressures to near-field pressures are not simply in the ratio l/r as for a source, but carry the additional factor $\left(\frac{2\pi l}{\lambda}\right)^2$.

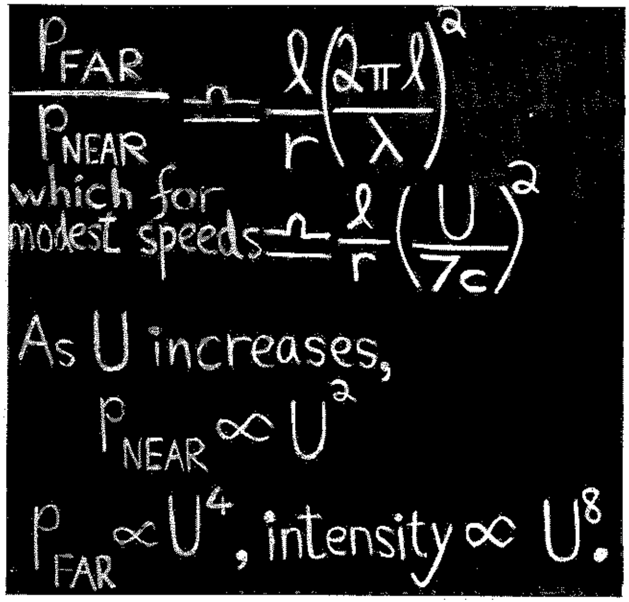
We see already why it is so difficult to reduce the sound of a jet. Any idea that the turbulence in the jet may be modified by inserting solid obstacles will fail. This is because a solid obstacle will induce a dipole field, which is a much more efficient radiator than the quadrupoles which are in the jet alone.

Quadrupole Strength

To find the strength of the quadrupoles we use the fact that the main difference between laws governing how velocity components fluctuate in a turbulent jet and in a simple acoustic medium is that momentum transfer (in and out of a fluid element) is not accomplished simply by pressure. There is additional transport of, for example, the component of fluid momentum ρu by motions at right angles to the velocity v. The resulting momentum transport ρuv can be thought of as a force with which the fluid element acts on the external medium (Fig. 17). It consists of two equal and opposing forces, so it is effectively a quadrupole. Actually the quadrupole strength per unit volume, for quadrupoles of this orientation, may be proved to be ρuv. But what volume does a single quadrupole occupy? The answer lies in the statistical nature of turbulent fluctuations. There is a tremendous interference between waves generated from uncorrelated regions. But from any small region in which the fluctuations are well correlated the waves are relatively well-ordered (Fig. 18). This suggests viewing the turbulence as made up of distinct elements of scale l within which fluctuations are well correlated. Contributions from different regions are uncorrelated. Pressure amplitudes from regions in which correlation is high add linearly, but the mean square pressures add linearly from uncorrelated regions. Measurements in jets have indicated the shape and size of correlated regions or eddies. Measurements also show that the ratio $(2\pi l/\lambda)$ is of the order of the fluctuating velocity in the turbulence divided by the speed of sound. In low-speed jets this ratio is very small.

Sound Output from a Jet

The general formula for quadrupole radiation can be used to estimate the total sound output from a jet of speed U. For modest speeds, $(2\pi l/\lambda)$ is about $(1/7)$ (U/c), because the fluctuation velocities just referred to are about 1/7 of the jet speed. So $(2\pi l/\lambda)^2$ is approximately the square of the speed measured on a



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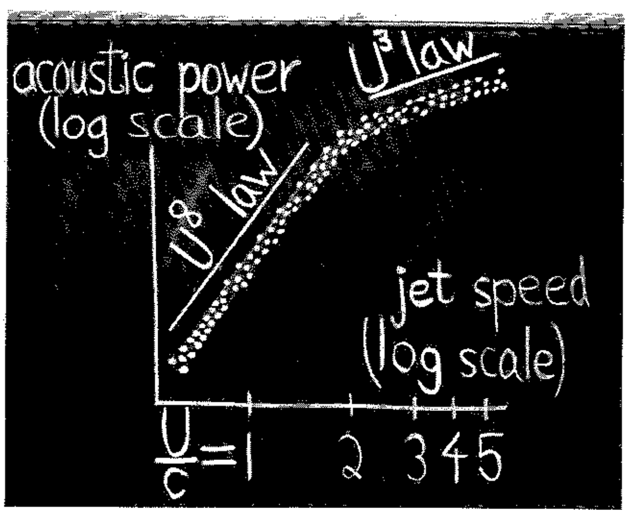
scale of 7 times the atmospheric sound speed. But the near-field pressures themselves vary like U^2, so the far-field pressures go like U^4, and the intensity of sound radiation therefore like U^8 (Fig. 19). This rather crude argument gives a result in surprisingly good agreement with measurements of total acoustic power output for the more moderate values of the jet speed. But there are two corrections that we need to make to it in order to understand noise at the higher jet speeds. First, net turbulence production tends to be somewhat reduced at the higher Mach numbers. That would make power output increase somewhat more slowly at the speeds around $U/c = 1$, more like a U^6 law. But the second correction works the other way and restores the U^8 dependence up to a value of jet speed around 1.5 times the atmospheric sound speed (Fig. 20).

This second correction is due to the fact that turbulent eddies are moving at about half the jet speed relative to the atmosphere into which they radiate. Now, the best-known property of moving sound sources is the Doppler effect, whereby sound coming toward us seems to have a higher pitch than the same sound going away from us. This is illustrated in the ripple tank in Fig. 21. The wavelength ahead of the source is reduced, and the wavelength behind the source increased.



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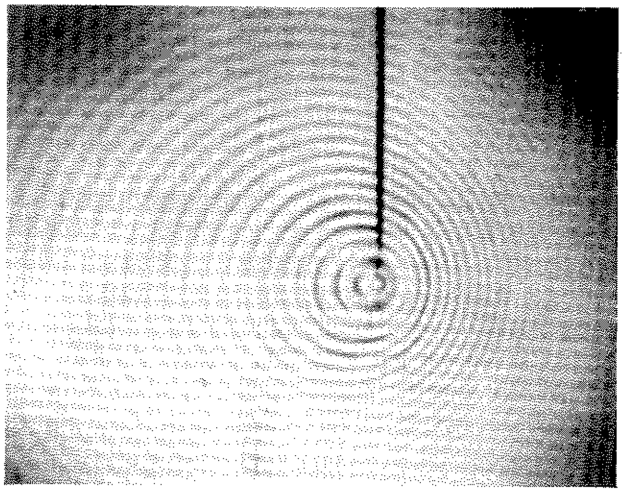
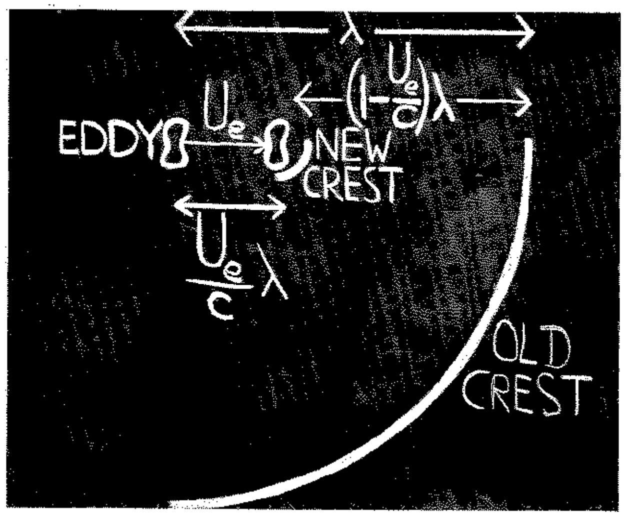


21. A source moving to the right produces shorter wavelengths ahead and longer wavelengths behind.

If an eddy is moving with speed U_e, the wavelength of sound emitted forward is reduced by a factor $(1 - U_e/c)$, essentially because during the time between emission of crests the sound has traveled a distance λ while the eddy has moved on a distance $(U_e/c)\lambda$ (Fig. 22). For emission in other directions making an angle θ with the direction of motion of the eddy, the same argument applies with U_e replaced by the component in that direction, $U_e \cos\theta$. So the wavelength in that case is $(1 - \frac{U_e}{c}\cos\theta)\,\lambda$ (Fig. 23).



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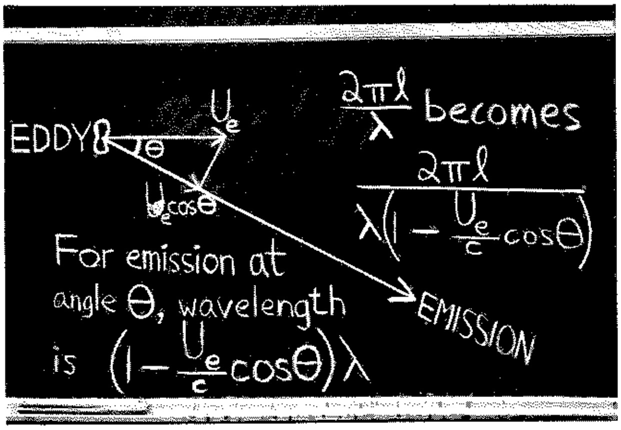
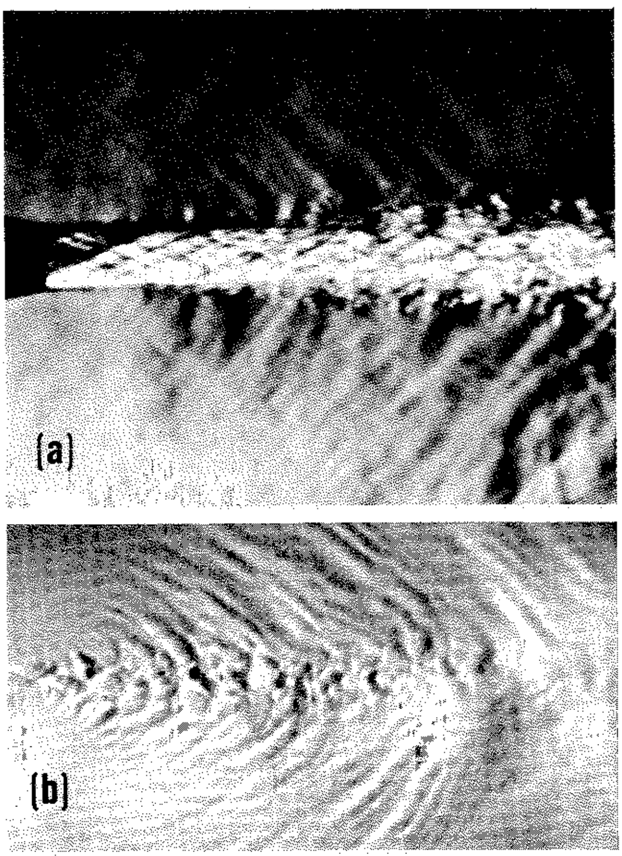


23.

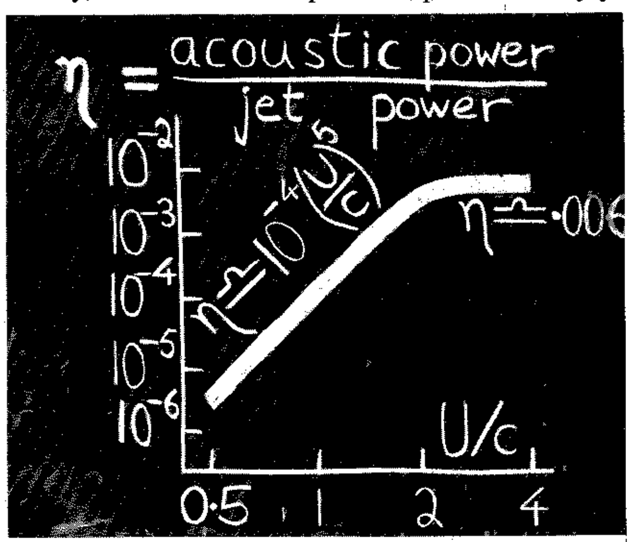
This eddy Doppler factor changes the compactness ratio, $2\pi l/\lambda$, which now becomes $(2\pi l/\lambda)$ divided by the Doppler factor. This now is not so small in the forward directions. So we see here a tendency for preferential forward emission, such as is particularly clearly heard for jets with U/c around 1 to 2. For higher values of U/c preferential emission is at its extreme in the so-called Mach wave direction of supersonically moving eddies. Then $\frac{U_e}{c} \cos\theta$ is equal to 1 and the wavelength evidently reduces without limit. Then there can be no quadrupole cancellation and the sound is just simple source. It's as if the eddy were generating its own supersonic bang. A shadowgraph picture shows that the sound field of a properly expanded supersonic jet is simply a collection of Mach waves (Fig. 24a). A supercritical jet in a ripple tank produces similar waves (Fig. 24b).



24. (a) Shadowgraph visualization of a supersonic jet shows Mach waves emanating at about 45 degrees from the jet axis. (b) Ripple-tank visualization of waves radiating from a supercritical jet.

At high speed, then, we have important consequences stemming from the breakdown of the compactness condition. The sound is then directional and of simple-source type — the pressure falling off like l/r all the way from the turbulence where it varies like U^2. The mean square pressure then varies like U^4.

Detailed arguments on these lines show that the high-speed form of the radiation curve follows a U^3 law and the transition occurs at about $U/c = 2$, where the eddies first become supersonic (Fig. 20). This agrees rather well with the observations. Another way of plotting the results is in terms of the acoustic efficiency, which is acoustic power output divided by jet power (Fig. 25). At modest values of the jet speed this takes quite low values, around 10^{-5}, but at higher speeds when the supersonic-bang mode takes over, the curve levels off to just under 10^{-2}, essentially because the inefficient quadrupole radiation has been replaced by efficient simple-source radiation. More detailed study of data in various frequency bands confirms the view of a turbulent jet as exciting the external acoustic medium in the same way as would clusters of eddy-sized quadrupoles that are traveling in the direction of the jet and whose strengths reflect turbulent fluctuations in the momentum transport.



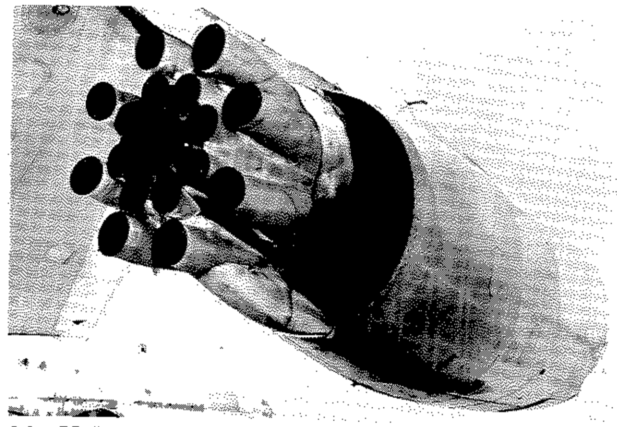
25.

Jet Noise Reduction

Of course, jet-engine powers have consistently increased while at the same time there has been an incentive to get the acoustic power down as far as possible. This has attracted engineers to come ever further down the curve of Fig. 25, with turbo-fan engines at low jet velocities achieving their increased power with large jet diameters. The turbo-fan is attractive for many reasons, of course, but the noise argument was one of the most compelling. This could at best be a long-term solution, however, so other means of jet noise reduction were vigorously sought. This was difficult, but nonetheless important improvements have been achieved using devices which for given jet speed reduce the ratio ($2\pi l/\lambda$) by reducing the turbulent intensity.

The idea is to get the external atmospheric air moving in the same direction as the jet gases so as to reduce the total shear that is producing turbulent fluctuations. The multi-tube design of jet exits (Fig. 26) does this, and has a second important advantage in that the annoyingly intense directional peak from any one of those small jets gets flattened because its sound gets scattered by the presence of all the other jets.

More recent research on aircraft noise reduction has concentrated on compressor noise, which has become relatively more important for the big turbo-fan engines. But that is only one of several fascinating contemporary applications of the basic knowledge outlined on aerodynamic sound generation.



26. Multi-tube jet exit device.

Special scenes in the film were provided by the Pratt & Whitney Aircraft Division of United Aircraft Corporation, the National Aeronautics and Space Administration, and R. W. Webster, Imperial College of Science & Technology, London.

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