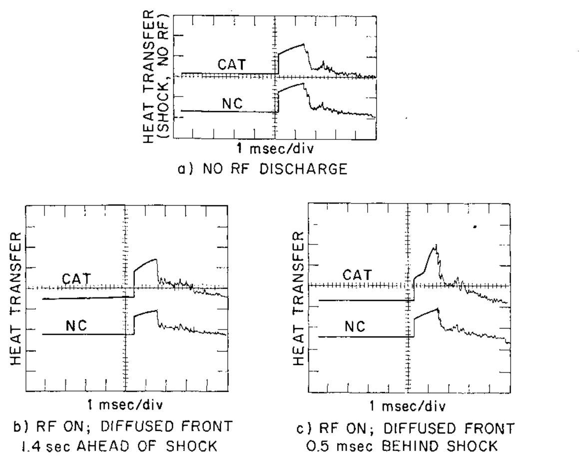

Fig. 2 Heat transfer to catalytic and noncatalytic heat gages with and without rf discharge; $M_s = 2$, $p_1 = 600$ μHg.

established the gas flow and shocked it, but did not turn the rf discharge on. The resultant heat-transfer records to the catalytic and noncatalytic gages are shown in Fig. 2a. Since no atoms were formed, we expect identical records, which is what happened. The slight difference between the two records is due to somewhat different gage sensitivities. The rise with time of the heat transfer during the useful test time is due to attenuation of the shock. This attenuation is of no direct consequence to our experiment. In the second experiment, we turned the discharge on and permitted the front of atoms to pass our probe position before firing the shock. In this way, many of the available sites of the silver oxide catalytic surface could be occupied prior to being exposed to the rapid increase in flux of atoms behind the shock wave. If the surface kinetics follows the change in atom concentration instantaneously on the time scale of this experiment, the heat transfer to the catalytic surface should rise immediately to a higher value than indicated in Fig. 2a (when no rf was applied). This is exactly what happened. The catalytic gage heat-transfer jump across the shock with rf is 50% higher than the no rf case (Fig. 2b), whereas the noncatalytic gage gives a record identical to that of Fig. 2a. The differential heat transfer implies an atom mass fraction of about 3%, which is very close to that which we determine by titration with NO_2.[5]

Finally, the third experiment timed events such that the shock wave arrived at the probe well in advance of the discharged step function gas. In this way we would establish that the rapid response of the surface kinetics was not due to the intentional filling of active sites. For this case, immediately behind the shock, undissociated gas follows so that the initial heat-transfer rises should correspond to those indicated in Fig. 2a. When the front of atoms is convected across the probe, the catalytic heat transfer should rise rapidly. This is precisely what happened, as indicated in Fig. 2c. Again, the noncatalytic gage in this run remained identical to that in the case with no rf discharge.

As a result of these experiments, we conclude that the surface reactions are rapid enough to follow the sudden changes in atom flux, so that the time dependence of differential catalytic heat transfer observed in our shock-tube experiments is not due to slow surface kinetics. With this fact established, and because of the similarity of the atom flux to which the probe has been exposed in these GDST experiments and those to be found in the shock tunnel, we can state that the catalytic probe should behave well as an atom concentration detector in hypersonic shock tunnels. Space does not permit discussion of our method for independently following the atom concentration in these experiments through the use of NO addition[5] (which reacts with the O atoms to produce a glow) and the use of photomultipliers to measure the time history of the glow intensity during the run. It should be stated, however, that the atom concentration histories so determined corroborate the sharpening of the front, as well as the detailed histories of catalytic heat-transfer measurements. Finally, many of the uses for the principle of the glow-discharge shock tube, including the important prospect of measuring gas phase recombination rate temperature dependences are described in Ref. 4.

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Noise of Highly Turbulent Jets at Low Exhaust Speeds

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THAT the noise of jets increases with the eighth power of the exhaust velocity is not only one of the fundamental results of aerodynamic noise theory, it is also an observed property of jet flows throughout the operational speed range of modern engines. At the higher exhaust velocities characteristic of rocket motors, the eighth-power law gives way to a dependence of the radiated energy on the third power of the exhaust velocity or on the mechanical power of the rocket motor. These eighth- and third-power laws are, perhaps, the only fundamental results one can elicit from the theory of aerodynamic noise relating turbulent flow to the distant sound field it induces. They have become widely used and are verified by experimental study.

Efforts to reduce the noise of engines have therefore concentrated, quite naturally, on the reduction of the jet exhaust speed. The advent of the bypass engine brought along a considerable reduction in the noise level, and these have been developed into the modern fan engines with their high bypass air ratio. These systems develop thrust by exhausting an increased mass of air at a reduced velocity and thereby benefit from a reduction in radiated sound. Engines of higher power must go to still lower exhaust speeds to maintain the same noise levels, and it would appear at first sight that this development could be continued indefinitely, until the discrete frequency sound, generated by the fan that propels the bypass air, becomes the dominant noise of large engines. However, a closer study reveals that this trend cannot be continued until the exhaust noise is reduced to an arbitrarily low level. A fundamentally different source of noise becomes evident, a source that is additional to that of the fan. The way in which this usually concealed source of noise enters the problem is

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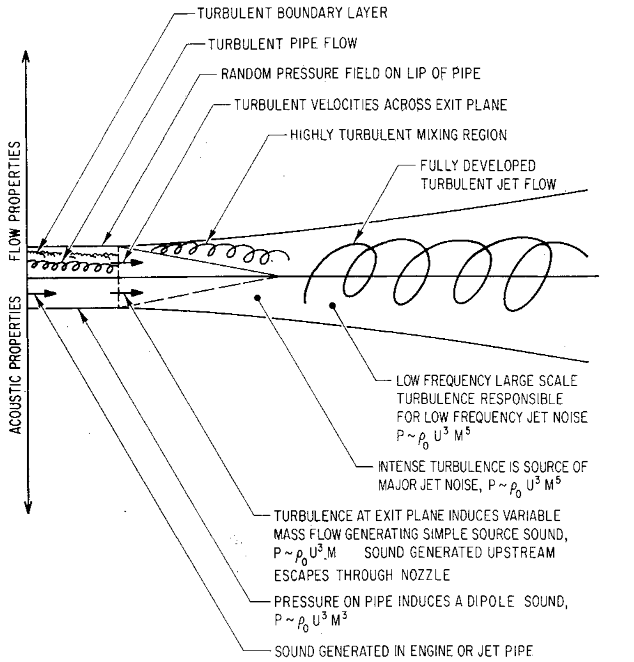

Fig. 1 Schematic illustration of the noise produced by jet turbulence; *P* is the radiated power, ρ_0 the air density, *U* the jet exit velocity, and *M* the Mach number formed by normalizing that velocity with respect to the speed of sound in the uniform atmosphere.

best understood if one recalls the fundamental mechanisms available in a jet engine for creating noise of aerodynamic origin. These mechanisms are illustrated diagrammatically in Fig. 1.

The intense turbulence of the exhaust flow is generated by the shearing action between the high- and low-velocity air streams. That turbulence exists without any close association with solid surfaces on which to react. Lighthill[4] has shown how such free turbulence is acoustically equivalent to a distribution of aerodynamic quadrupoles. Quadrupole sound increases in strength with the square of the turbulence level and the square of a typical frequency. Frequencies increase with velocity, accounting for a proportionality of the radiated sound pressure on the fourth power of the jet speed. The eighth-power law relating sound power to the jet velocity then follows directly. That the noise of a jet engine increases in accordance with this law is confirmation that the turbulence created in the mixing region, and not that already present in the exhaust stream that passes through the nozzle, is responsible for the major sound of jet engines. However, the jet pipe turbulence is also a source of noise, and, at low speeds,

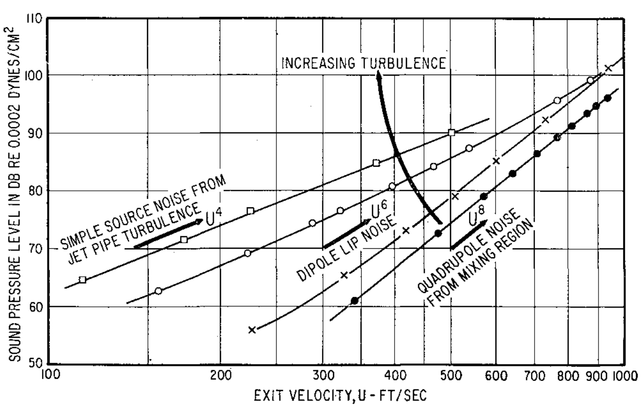

Fig. 2 Effect of jet turbulence upon radiated noise.

a source of inherently higher radiation efficiency than the free turbulence of the mixing flow. To understand the way in which it enters the problem, we must turn to Curle's[1] extension of Lighthill's arguments that show how, whenever turbulence exists near solid or other control surfaces, Lighthill's volume quadrupoles should be supplemented by surface terms.

Sources of the type Curle has described are induced by the reaction of the turbulent pipe flow on solid jet pipe surfaces. Curle has argued that such a sound would be of dipole character and would increase in intensity with the sixth power of a typical velocity. At low enough speed it must overwhelm quadrupole sound with its eighth-power velocity dependence. Since the lip of the jet pipe is likely to be the most important source of this sound, it has been termed "lip noise" and is in fact observed in current low-speed jet experiments.[2] The "lip noise," in turn, will be overwhelmed by an even more efficient source of sound as the exhaust speed is reduced still further. The exhaust nozzle itself is an effective control surface separating turbulent flow generated within the engine and jet pipe from the air into which the jet exhausts. On that control surface exist important sources of sound associated with the unsteady mass flow induced by nozzle exit turbulence. Curle's equations can easily be shown to predict that the sound they radiate will increase in intensity with the fourth power of jet speed. This dependence arises, in part, from the fact that the sound increases in direct proportion to the turbulence level of the nozzle exit flow, and in part from a linear proportionality on typical frequency. Details of the analysis are straight-forward and are easily derived from any standard reference on the subject, e.g., Lyamshev,[5] and Laufer, Ffowcs Williams, and Childress.[3] The fundamentally different way in which this sound alters with changes in the exhaust speed makes it inevitable that, when the exhaust velocity is sufficiently low, the sound generated at the nozzle exit, by quite a different part of the turbulent flow, becomes the dominant source of jet noise.

The important question is then, does this new source of sound become a significant fraction of the total jet noise within a possible operational speed range of a high-bypass-ratio engine? Crude calculations indicate that, for highly correlated turbulence with a level of 10% of the mean velocity, the sound from the nozzle plane would exceed that of the more conventional type at a velocity of the order of 700 fps, clearly close to the operational speed range of a high-bypass-ratio engine. We have conducted experiments that bear out this possibility. It seems from the results that we present in Fig. 2, that a "clean" nozzle produces sound increasing with the eighth power of velocity, whereas the same nozzle, when supplemented by turbulence generators in the upstream region of the flow, produces sound of a much higher level, increasing with the fourth power of nozzle exit speed. At an intermediate level of turbulence, the "lip noise" is apparent, increasing with the sixth power of exhaust speed. At higher speeds, in excess of approximately 700 fps, the familiar velocity-to-the-eighth law is recovered. In the laboratory, then, the new mechanism is clearly important; but our experiment, deliberately crude (aimed only at an illustration of the phenomenon) gives no real quantitative measure of the parameters involved.

In practical systems, too, it would seem to have relevance. The effect was first brought to the authors' attention by J. Large of The Boeing Company who has made a study of jet noise at exit speeds of close to 600 fps. His aim was to study the benefit to be gained by operating engines at that exhaust speed. He observed that the benefit is not as great as that which a velocity to the eighth law would indicate. He found that the dependence of radiated power on exit speed seems closer to a sixth-power than to the familiar eighth-power law. Also, if we search back through the earlier literature on turbojet noise, we find that, in 1952, Mawardi and Dyer[6] observed that the noise of jet engines varied in proportion to the fourth power of velocity at low speed but with the eighth power of velocity at high speed. At that time those results were attributed to rough burning and other engine noise, but it would seem quite possible that the turbojet engine with which they were dealing possessed a turbulence level, at the exit of the turbine, sufficiently high to make the noise source we are now considering more pronounced than that of the conventional type with its dependence on the eighth power of exhaust velocity.

At the present time, this question would seem to have a particular relevance, since the turbulence levels at the nozzle exit are bound to be increased by the current trend to engines of high bypass ratio. When turbine capacities are made large enough to drive the powerful compressors that propel bypass flows, there will be a corresponding increase in the turbulence level. We see then, that there could be an important change-over in the mechanism of jet-noise production at low exhaust speeds, speeds that might be well within the range currently considered for operational aircraft. The change-over and its possible control have not been studied at all. Its significance poses an exciting new field of study that promises to be relevant to the modern jet-noise problem.

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A Miniature Strain-Gage Balance for Hypersonic Force Measurements

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1. Introduction

A MINIATURE strain-gage balance capable of measuring forces as small as 0.001 lb has been constructed at the U. S. Naval Ordnance Laboratory. A balance of this sensitivity is needed to measure the model forces in the Naval Ordnance Laboratory (NOL) Hypersonic Tunnel 4, which operates at Mach 17.5 with a supply pressure of about 100 atm. The useful testing diameter is 6 in.

The balance is an internal, three-component, water-cooled device that measures the aerodynamic force and the center of pressure of models to be tested under hypersonic flow conditions. Because of its small size, the balance is a measuring device particularly attractive in test facilities where space is at a premium. This note presents a brief description of the balance and some of the experimental results obtained with it.

2. Description of Balance

The strain-gage balance measures the axial component of the aerodynamic force and the pitching moments about two points on the model axis, the latter giving the normal component of the aerodynamic force and its location.

A schematic view of the balance and a typical cone model is shown in Fig. 1. The sting, balance, and water jacket are an integral unit. The balance is approximately 2.3 in. long and 0.6 in. in diameter at the base. The cooling water flows through the sting to and from the balance via four metal

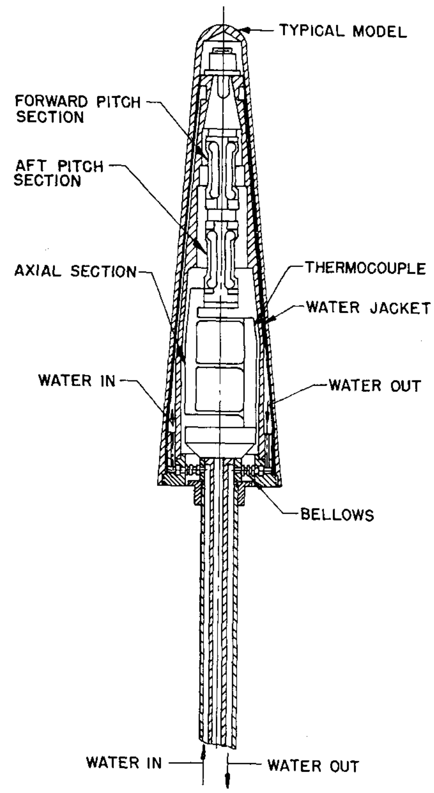

Fig. 1 Schematic view of balance and cone model.

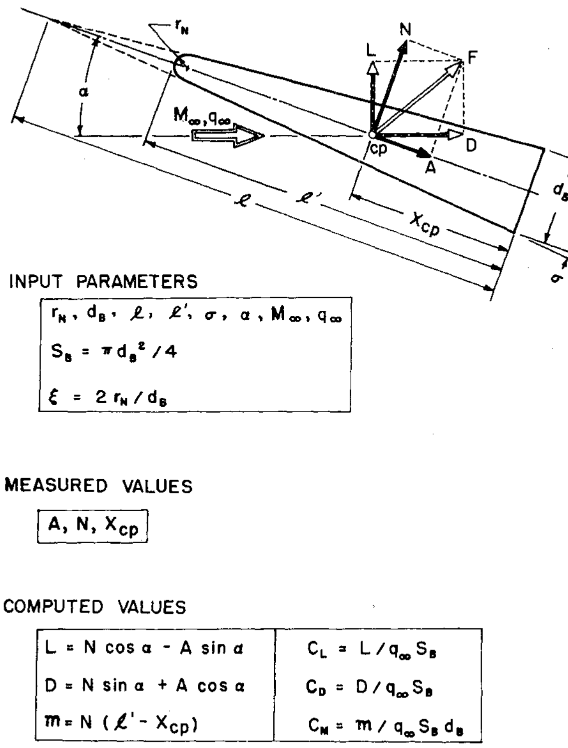

Fig. 2 Cone model geometry and nomenclature.

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