THE FLUCTUATING SURFACE PRESSURE CREATED BY TURBULENT BOUNDARY LAYERS ON HYPERSONIC VEHICLES

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There are a great number of specialized problems which result from flight at extremely high speeds. Some of these problems are new, others are merely magnified by the higher speeds. The fluctuating surface pressures generated by subsonic turbulent boundary layers has received considerable attention in recent years. These fluctuating surface pressures are transmitted through the vehicle skin and result in high internal noise levels. The current crop of jet transports has required considerable insulation to minimize this effect and achieve reasonable passenger comfort. The question arises then as to what levels might be expected by flight at hypersonic speeds. It is the purpose of this paper to make some estimates of the order of magnitude of the levels which might be expected for several cases of current interest.

The fluctuating surface pressures created by a turbulent boundary layer are, of course, dependent upon the physical characteristics of the boundary layer. A considerable body of data now exists, which relates these surface pressures to the local flow conditions for the case of subsonic turbulent flow over a flat plate. In general, these results show that the root mean square of the fluctuating pressures on the surface are directly proportional to the local dynamic pressure of the flow and are largely independent of both Reynolds and Mach numbers. This general result stems from the fact that turbulent boundary characteristics over flat plates change only slowly with both Reynolds and Mach numbers. If, for example, we take the skin friction coefficient as a measure of boundary-layer characteristics we can see that only small changes occur over wide ranges of Reynolds and Mach numbers. Indeed, if we look at dimensionless velocity profiles, either mean or turbulent, we see that such relationships are quite general in nature. Hence, the fact that the dimensionless ratio of root-mean-square fluctuating surface pressure to stream dynamic pressure is essentially constant for the case of subsonic turbulent boundary layers on flat plates or slightly curved surfaces is not surprising and, in fact, provides a clue that subsonic results may be extrapolated to hypersonic speeds for cases where the boundary-layer characteristics are not greatly altered by effects of cooling, pressure gradient, or gas dissociation.

The data to date are summarized in Table 1. The agreement is excellent even though the tests were made in widely varying environments. The data of Willmarth was obtained in a small 4-inch-diameter pipe. The data of Serafini was obtained in a specially designed rectangular acoustic channel, 8 × 18 inches. In these tests the pressure gradient was controllable. The flight data of Mull was obtained on the wing and fuselage of a jet aircraft.

Table 1

Ratio of Root-Mean-Square Fluctuating Surface Pressure $\bar{p}$ to Stream Dynamic Pressure q from Various Sources

$\frac{\bar{p}}{q}$	Mach number	Reynolds number	Pressure Gradient	Type of Test	Author
3.5×10^{-3}	0.3 to 0.8	1 to 20 $\times 10^6$	Favorable	Channel	Willmarth - NACA TN 4139
5.0×10^{-3}	0.65	10 to 100 $\times 10^6$	None	Channel	Serafini - NACA unpublished
5.0×10^{-3}	0.3 to 0.8	2 to 20 $\times 10^6$	Favorable or none	Flight	Mull - NACA unpublished
6.0×10^{-3}	0.3 to 0.7	2 to 20 $\times 10^6$	Favorable	Channel	Willmarth - NACA unpublished

It would appear that a mean value of about 4.5×10^{-3} could be chosen to represent all these data; especially when it is remembered that all these data were measured using microphones and the results measured in decibels.

If we choose the ratio of $\bar{p}/q = 4.5 \times 10^{-3}$ and assume that this ratio holds even at hypersonic speeds, then it is obvious that the highest values of $\bar{p}$ will be obtained when q is a maximum. With this in mind, let us consider what cases might currently be of most interest. Two immediately come to mind; the high-speed nose-cone reentry and the take-off of a powered rocket. At the present time we can probably ignore the problems which might arise from sustained flights at hypersonic speeds. In this instance a great number of other problems must be solved before continuous flight at Mach numbers greater than 5 will be achieved.

We will, therefore, limit the discussion to the reentry of manned or unmanned vehicles and to the take-off and climb-out phase in powered flight. First let us consider the unmanned vehicle, i.e., the ballistic missile, since this represents a somewhat different problem than the manned vehicle. The principal difference is in the deceleration rates which are permissible. This aspect is not too important for the unmanned vehicle; but it is extremely important in the case of a manned vehicle, particularly if we expect the occupant to perform a useful function. Even if the occupant is a passenger only, he would probably object strenuously to being both squashed and fried.

Let us therefore look at the nose-cone reentry problem and see what is involved and whether it appears likely that we can make such a calculation with some hope that the results are correct. Considerations other than noise have determined nose-cone shape, that is, heat transfer. In order to keep the heat transfer rates to the vehicle surfaces to acceptable values, current considerations dictate a blunt-nosed, high-drag body such as shown in Fig. 1. Such a shape has a very strong shock wave ahead of it and even though the stream Mach number is of the order of 20, the flow field between the body and the shock wave is subsonic or slightly supersonic. As a result, it should be possible to use the results presented in Table 1 with an excellent expectation of obtaining the correct result. Furthermore, the pressure gradient around the body is favorable and it would be expected that the boundary-layer characteristics would not be greatly different from subsonic results. Considering then the case of such a body reentering the earth's atmosphere, we will use the following notation to describe the quantities of interest.

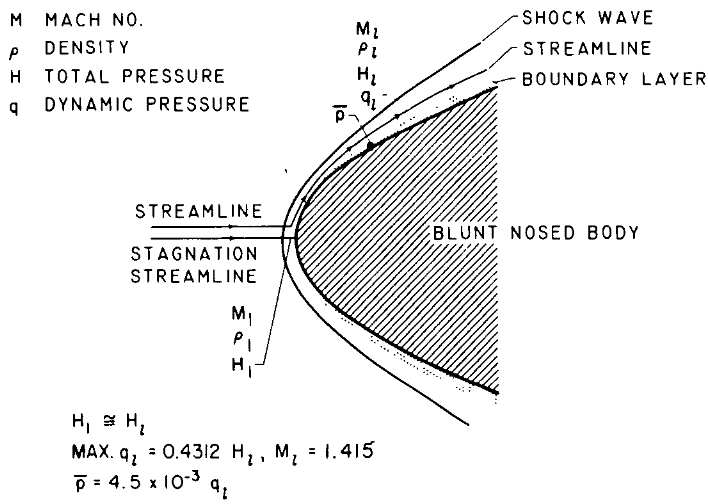

Fig. 1 - Blunt-nosed body at hypersonic speeds

The subscript 1 refers to conditions immediately behind the shock at the nose. The subscript ℓ relates to local conditions between the shock wave and the boundary layer, aft of the nose. Since the root-mean-square pressure $\bar{p}$ is linearly related to q, the point on the body of most interest is where the value q_ℓ is a maximum.

At high Mach numbers an extremely strong bow wave precedes the body and the value of M_1 is about 0.4 for a range of stream Mach numbers from 4 to 20.

If we follow the path of a streamline through the shock and around the body, we get the following picture: Streamlines which go through the shockwave near the nose are bent and flow around the body between the shock wave and the boundary layer. As a streamline moves around the body, the flow speeds up but the total pressure along the streamline is essentially constant. If we take a streamline which lies close to the boundary layer, we see that such a streamline crosses the shock wave very near the stagnation streamline and hence we can assume that the total pressure H_ℓ along this streamline behind the shock is essentially equal to the total pressure of the stagnation streamline behind the shock H_1. With this assumption, the total pressure of this streamline behind the shock can be calculated quite simply from the normal shock relations. The compressible flow relations tell us that the maximum value of q_ℓ for a given total pressure H_ℓ or H_1 in this case, occurs at a Mach number of 1.415. This then determines our point of interest and is independent of the geometry, i.e., we don't need to know the exact shape of the nose; we will pick the particular point where maximum q_ℓ is obtained. This value is uniquely related to H_ℓ at a value of M_ℓ = 1.415 and the ratio q_ℓ/H_ℓ = 0.4312. It should be noted that the calculation procedures used here do not account for any effects associated with extremely high temperatures, such as dissociation or variable ratio of specific heats. It is felt that all such effects would be small in terms of the final answer, which is required only to perhaps the nearest ±3 db.

If we concern ourselves only with the maximum value of q_ℓ and, hence, the maximum root-mean-square pressure at the surface $\bar{p}$ it is possible to calculate $\bar{p}$ during reentry using the normal shock relationships and the reentry calculation procedure described by Allen and Eggers in NACA TN 4047.

Allen and Eggers derived an equation which yields the velocity at any point along the trajectory from reentry into the atmosphere until impact. The velocity at any point was found to be dependent on the initial velocity at reentrance V_E and a parameter herein designated as φ. The parameter φ describes the characteristics of the vehicle, i.e., its drag coefficient C_D, its mass m, its area A, and its reentrance angle into the atmosphere θ_E. It can be assumed that over the trajectory range of interest, i.e., where the Mach numbers and q_ℓ values are high, that φ is essentially constant. That is, φ for a given missile does not vary along the trajectory. Knowing the relationship between vehicle velocity and altitude, an equation relating local dynamic pressure and altitude can be derived in terms of parameter φ and reentrance velocity V_E.

Figure 2 shows the variation of q_ℓ with altitude for a reentrance velocity of 20,000 feet per second and for several values of parameter φ. The vehicle reenters the atmosphere at approximately 200,000 feet and plummets toward the earth. The values of q_ℓ increase to a maximum and then decrease. The peak or maximum value of q_ℓ along the trajectory is dependent on φ. High φ values give low maximum values which occur at relatively high altitudes, whereas low φ values give large maximum values of q_ℓ which occur at relatively low altitudes. High φ values give rapid vehicle decelerations at high altitudes where heat can be radiated rapidly away from the body, which is desirable from heat transfer considerations. The high vehicle deceleration at high altitude results in low velocities at low altitude, which may not be desirable.

In any case, the maximum values of q_ℓ shown here are much higher than anything heretofore experienced. Even with a φ value of 7000, the peak of q_ℓ is over 4000 pounds per square foot, which is five to ten times the values to which we are normally accustomed. The sound pressure levels associated with values of q_ℓ using $\bar{p} = 4.5 \times 10^{-3}\, q_\ell$ are shown on Fig. 3 where sound pressure level is plotted as a function of altitude. The reentrant velocity for these curves is 20,000 feet per second. Curves are shown for φ values of 7000, 4000, and 1000.

It can be seen from this figure that one result of achieving low φ values will be increasing values of surface sound pressure level. For example, if a φ value of 1000

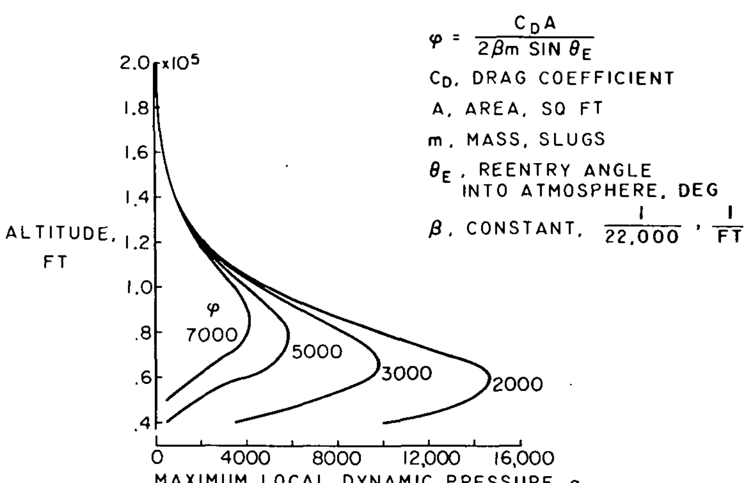

Fig. 2 - Variation of maximum local dynamic pressure during reentry

is achieved, the maximum sound pressure level will be 170 db. This is extremely high and might well result in structural deterioration of the vehicle. This is particularly true since other forces and temperatures are also at near maximum values at this same stage.

One important factor which must be considered is the exposure time. For a value of φ of 7000 the time for the vehicle to fall from say 140,000 feet to 50,000 feet is perhaps 30 seconds. For a value of 1000, the time for the vehicle to travel from 140,000 to 40,000 feet is of the order of 15 seconds.

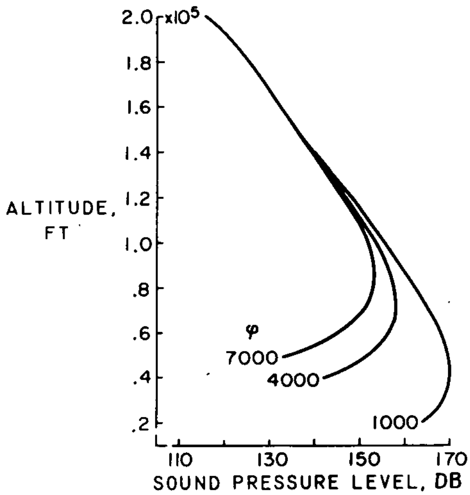

Fig. 3 - Maximum local sound pressure level during reentry

Figure 4 shows the variation of the maximum sound pressure level encountered during reentry; i.e., this corresponds to the peak or maximum of the curves shown on Fig. 3. The sound pressure levels corresponding to this condition have been plotted as a function of the parameter φ for various reentrance velocities. It is evident from this figure that quite high values of sound pressure level will be encountered for nearly all unmanned missiles under current consideration.

It is obvious that the high external levels may well create a structures problem or result in high internal levels which could affect the operation of the vehicle.

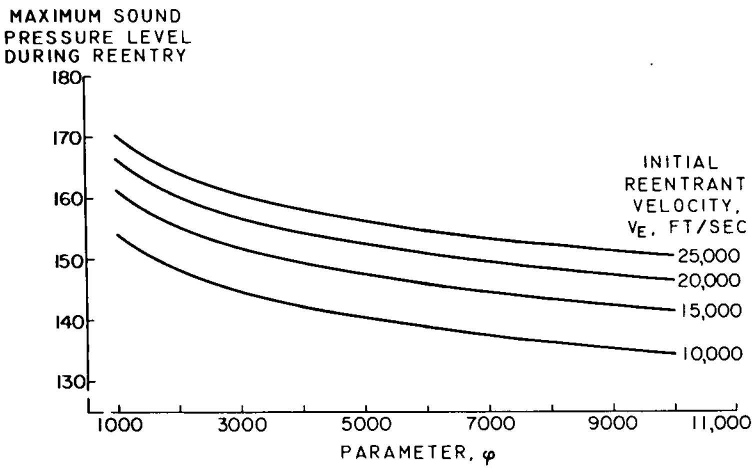

Fig. 4 - Maximum sound pressure level as a function of parameter

Let us now consider briefly the flight of a manned space vehicle. First let us look at the powered or take-off phase and then the reentry phase. Again, as in the previous example, we will consider only what is happening on the nose cone, which in this case contains the occupant and related equipment. Figure 5a gives the velocity, acceleration, and altitude as a function of time from take-off to first-stage burnout. The weight of the payload chosen is 3000 pounds and the orbital altitude approximately 200 miles. As can be seen from the figure, the maximum acceleration is about 130 ft/sec ^{2} or 4 g's. The velocity at the end of burnout is 8600 ft/sec and the altitude, about 164,000 feet. The sound pressure levels which would be expected on the nose-cone region using these results are shown in Fig. 5b. The shape of the nose cone has been assumed to be similar to that for the unmanned vehicle except that it will probably be even more blunt in shape. The results shown represent the maximum value achieved at a single point on the nose-cone surface. The solid curve is the noise which results from boundary-layer turbulence. The dotted curve shows the levels

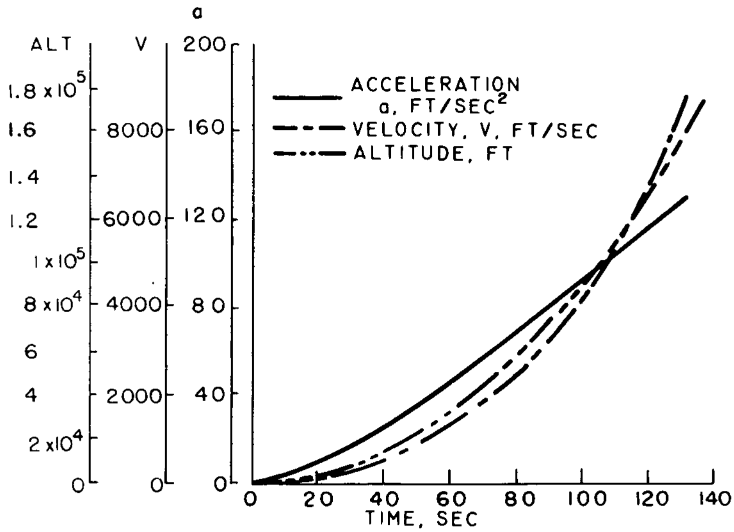

Fig. 5a - Powered phase manned vehicle

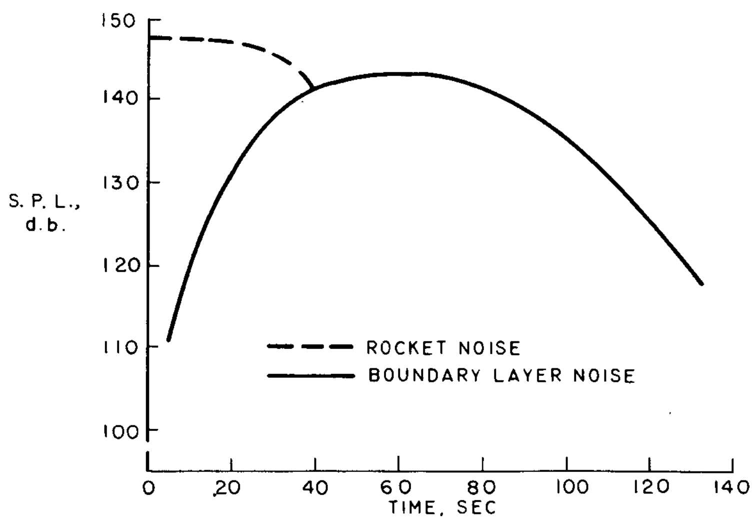

Fig. 5b - Powered phase manned vehicle

which might be expected from the rocket itself. Rocket noise predominates for the first 40 seconds and then the boundary-layer noise takes over. The principal reason for the decrease in rocket noise is that after a flight Mach number of 1 is achieved, the rocket noise is directed predominantly rearward and only a very small amount can be propagated forward. It is apparent from the figure that the levels are low and in fact no higher than we currently experience subsonically. This results from the fact that high dynamic pressures are never achieved since the high velocities only occur at high altitudes.

It would appear that no serious noise problem should occur around the nose region of such a rocket during the initial powered phase of the flight.

Let us now look at the reentry portion of the flight. The velocities, deceleration, and altitudes as a function of time for the assumed vehicle are shown in Fig. 6a. The deceleration is a maximum of approximately 200 feet/second^2 or a little over 6 g's. Notice that high deceleration rates, over 5 g's, exist for about 20 seconds. It might be possible that higher deceleration rates (10 g's) can be used but it would seriously impair the occupant's ability to perform useful functions. If it is noted that the velocity decreases from 26,500 feet/second to 4000 feet/second between 200,000- and

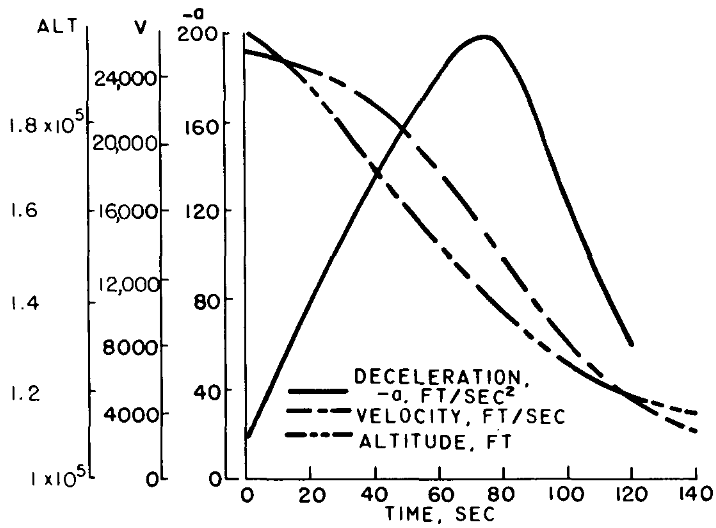

Fig. 6a - Reentry phase manned vehicle

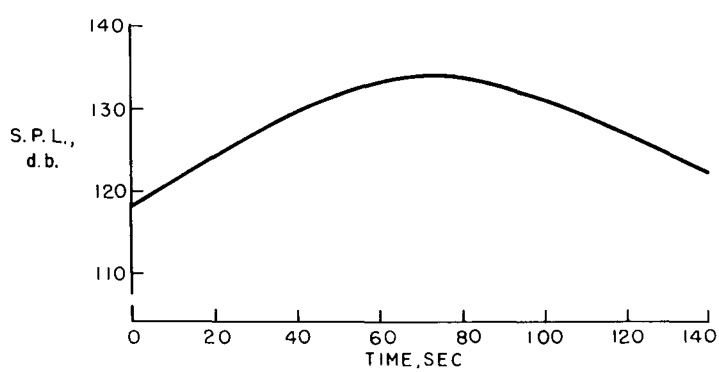

Fig. 6b - Reentry phase manned vehicle

about 120,000-foot altitude, then the low values of sound pressure level experienced during reentry (Fig. 6b) are not surprising. Figure 6b shows a maximum value of sound pressure level of about 135 db, which is quite low and should not create any serious problems.

In conclusion it can be said that the noise levels in the nose-cone region for manned vehicles will probably be low, largely as a result of human limitations to g forces.

The unmanned vehicle, i.e., the ballistic missile, may well have extremely severe noise problems which could result in structural failures or instrument malfunctions. The absolute levels are quite high, perhaps 155 db, for cases of current interest and will probably increase as heat transfer problems are solved.

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DISCUSSION

L. S. G. Kovasznay (Johns Hopkins University)

All the data which shows this rather spectacular constancy of sound pressure level compared to dynamic pressure is based solely on data available up to Mach number 0.8, yet we know that the general nature of supersonic boundary layers is somewhat different. This disturbs me, because Mr. Callaghan has shown that the maximum dynamic pressure "q" will be experienced at a Mach number of 1.415, and we do not yet have boundary-layer noise data for this Mach number.

Now, when looking at, say, shadow pictures of shells, one sees another kind of interesting sound wave pattern and we know from the little information we have obtained, mostly by hot-wire measurements in supersonic tunnels just outside the boundary layer, that the boundary layers don't seem to emit anything spectacular as long as the wall is smooth, uninterrupted and there is only a little sound. But if there is any edge of roughness, then the amount of sound increases tremendously. This may be especially true for ablation cooling, or any kind of pitting on the nose cone, and I expect strong effects of this nature.

There is another question, and it might be possible to treat it theoretically. If one has a hypersonic, blunt body, where the shock wave is hugging the contour, there is an interesting space of subsonic flow between the shock wave and the boundary layer; any disturbance present there will affect the location of the shock wave causing the shock wave to move or "jiggle." There will be an interactive zone which might give reinforcement of fluctuations.

My only caution is that even these aspects of the problem have to be considered in great detail before we accept this type of treatment as even approximate.

I. Dyer (Bolt, Beranek, and Newman, Massachusetts)

Here is a short list of the sources of pressure fluctuations that may also be of importance in missile flights.

We can certainly have rocket engine noise, as Mr. Callaghan has mentioned; rocket engine vibration, which is directly transmitted from the rocket engine to the missile itself; boundary-layer pressure fluctuations, as Mr. Callaghan has also mentioned; and another phenomenon that hasn't been mentioned which we call wake noise. Wake noise is associated with the field downstream of the missile or re-entering body. Also, we have what we might call base-pressure fluctuations for supersonic conditions, and these fluctuations are going to be particularly important for re-entry; oscillating shocks, mentioned by Mollo-Christensen, which depend on the particular design of the missile or re-entry body; the possibility of transmission or convection of vorticity through shocks, a problem which was discussed by Ribner not too long ago. Finally we have the convection of a missile through a turbulent atmosphere.

While many of these sources of pressure fluctuations are probably not too important, I think in re-entry we are probably going to have to worry about base-pressure fluctuations probably to the same extent that we might worry about the boundary-layer pressure fluctuations. This is what preliminary measurements and calculations seem to indicate.

One final comment is this: that the base-pressure fluctuations would likely maximize at the maximum dynamic pressure of the missile, just as in the case of boundary-layer fluctuations.

It may be difficult, on an experimental basis, to look at pressure fluctuations as a function of time and decide whether it is one or another mechanism. An important feature is the scale of the pressure fluctuations. The base-pressure fluctuations are apt to be of a much larger scale and hence more important in exciting vibrations of the missile, even though they may only be the same order of magnitude in pressure as the boundary-layer field.

G. M. Corcos (University of California, Berkeley)

There is very little reason to expect that the pressure fluctuation level at the wall of the boundary layer ought to be independent of pressure gradient. This is a general comment, not restricted to this paper, since other participants have pointed out possibly more serious other sources of noise. Since shear force at the wall and turbulence level depend on the pressure gradient, I think it's a fairly safe guess that the pressure fluctuation would also depend on the pressure gradient and generally increase in positive pressure gradients.

H. S. Ribner (University of Toronto)

Mr. Callaghan makes frequent reference to the fluctuating pressures in terms of "sound pressure levels": these "hydrodynamic" or incompressibly generated pressures are not sound in the strict sense, and I would prefer Blokhintsev's term "pseudo-sound."

E. E. Callaghan

In reply to Professor Kovasznay, the effect of Mach number on the rates of root-mean-square surface pressure to dynamics pressure, $\overline{P}/q$, would appear to be small in extrapolating subsonic results to low supersonic speeds. A recently declassified paper* shows no Mach number effect on $\bar{P}/q$ for a range of flight Mach numbers from 0.8 to 1.4.

It is certainly agreed that the type of calculations performed in this paper can merely predict order of magnitude. It would be expected that strong favorable pressure gradients would lower the ratio of $\bar{P}/q$ whereas adverse gradients would raise it.

In regard to jiggling the bow wave, it would be expected that as long as the stream Mach numbers are 3 or larger the bow wave is exceedingly stable. It would only be at the lower Mach numbers, say 2 or less, that shock wave instability would give rise to large surface pressure fluctuations.

It is impossible to assess what effect ablation type nose cones will have on internal noise. Undoubtedly, the rough surface resulting from ablation will greatly increase the surface pressure fluctuations. On the other hand, the ablating material would be expected to have a very high transmission loss, so that one effect may balance the other.

I agree completely with Dr. Corcos. The case discussed here assumes that the pressure gradient is favorable but not strong. Strong gradients should greatly alter the results. We do have some unpublished flight data which show that strong favorable gradients reduce the ratio of $\bar{P}/q$ considerably. We also have data in the presence of a strong adverse gradient, and for such a case the levels are very high. In one case, separated flow on a wing resulted in a sudden increase of 25 decibels.

For the most part, I must agree with the comments by Dr. Dyer. We have looked at the possibility of noise generation of the type discussed by Ribner† and even if we assume very severe atmospheric turbulence the noise levels generated are very low. Mostly because severe atmospheric turbulence is not really very turbulent at all in comparison to boundary layers or jet mixing, etc.

The question of fluctuating base pressures may well be a very severe problem. It looks very much like the kind of a problem which must be studied in either wind tunnels or rocket-powered models.

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*Norman J. McLeod and Gareth Jordan, "Preliminary Flight Survey of Fuselage and Boundary Layer Sound Pressure Levels," NACA RM H58B11, 1958.

†H. S. Ribner, "Shock-Turbulence Interaction and the Generation of Noise," NACA TR 1223, 1955.

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