EXTERNAL NOISE ENVIRONMENTS OF FLIGHT VEHICLES*

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I. INTRODUCTION

The noise environment of a flight vehicle may be a potential challenge to the success of the flight. Noise environment information thus is an important part of the information required for flight vehicle design and testing. Present day flight vehicles of interest include subsonic and supersonic aircraft and both single and multiple flight extra-atmospheric vehicles. Such vehicles undergo complex and varied aerothermodynamic flight conditions, with correspondingly complex and varied noise environments. This paper discusses some of these external noise environments that might be of importance.

In addition to the fairly well understood environments associated with propulsive systems and boundary layer pressure fluctuations, there may occur important environments associated with other aerothermodynamic phenomena. Unfortunately, it is not possible at this time to present an adequately grounded review of the entire problem area, largely because there are many unknown factors still to be investigated. However, we do present some qualitative and order-of-magnitude information about many of the possible environments in an attempt at an assessment of their significance.

The outlook of the present paper is largely speculative. It is hoped that the speculations will serve to orient some of the research now concerned with flight vehicle environments, and to highlight areas that appear to be of importance and areas that require additional work. No attempt has been made to provide a comprehensive review of the pertinent literature where established results are discussed; the cited references in such cases are intended to be typical rather than exhaustive.

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Calculations of the responses of flight vehicle structures to noise environments are important, for it is only by considering these responses that we can adequately assess the significance of the various environments discussed. Because of the large variability in types and details of structures of potential interest, however, structural response calculations are not given in this paper. Thus, we concentrate on the noise environments per se. Where possible, both pressure magnitudes and space-time correlations of the noise environments are discussed, for these are the quantities that are required to determine the structural responses.

II. ESTIMATES OF NOISE ENVIRONMENTS

Propulsion System Noise

Noise associated with the propulsion system is of major importance in a flight vehicle. Gas reaction motors (rockets and jets) are the principal propulsion systems now considered for advanced flight vehicles; therefore, we shall restrict our discussion to these systems.

Although a considerable amount of noise is generated by the mechanical elements or by the combustion process in a reaction motor, the noise of the turbulent exhaust stream is almost always predominant. References (1-4) review descriptions of turbojet and rocket exhaust noise. Since these two types of propulsion systems generate similar noise fields, and because of the growing importance of rockets in contemporary problems, we shall concentrate on rocket noise in what follows.

The usual rocket powered flight vehicle has a geometry such as shown in Figure 1. The noise sources associated with the rocket are located behind the vehicle. The noise is radiated most strongly at about 40° from the direction of the exhaust flow and has a broad "haystack-shaped" frequency spectrum without any noticeable pure tones. The frequency at which the spectrum minimizes depends on the ratio of the exhaust velocity to the nozzle diameter. The total power radiated by a large rocket is of the order of 1% of the mechanical power in the exhaust stream.

Figure 2 shows typical octave band sound pressure levels on the surface of a stationary large missile powered by a rocket engine. The solid line represents the levels at the nose cone, and the broken line represents the levels at the end of the missile near the exhaust nozzle. The differences in these two spectra arise from the fact that the noise sources are distributed along the exhaust stream, with the higher frequency sources closer to the nozzle and the lower frequency sources further downstream (5). The overall sound power level of the rocket of Figure 2 is 203 db,* corresponding to 20 megawatts of acoustic power.

In addition to the rms amplitude data typified by Figure 2, we must consider the statistics of the pressure fluctuations. Levels that significantly exceed the rms values are important in determining malfunctions of equipment and structural fatigue. Present information indicates that turbojet noise does not quite follow a Gaussian amplitude distribution (6), but there is a need to gain more data, especially concerning the very high amplitudes that occur relatively infrequently. In the case of rocket noise, preliminary indications are that the Gaussian distribution applies in spite of the higher mean levels and the expected non-linearity of the air, but additional data are required in this case also.

Many space vehicles have a high degree of axial symmetry. For such vehicles, the phase properties of the rocket noise field are conveniently given in terms of the longitudinal correlation along the vehicle axis and the angular correlation in a plane perpendicular to the vehicle axis. Because the noise sources are behind the vehicle, the longitudinal correlation is governed approximately by the usual sound propagation relations. Figure 3 shows a longitudinal correlation measured over the surface of a stationary large missile (4). Also shown are the correlations expected from noise emanating from a single point located behind the missile. The measured correlations are in rough accord with the theoretically calculated values. The deviations between measured and predicted values are most likely associated with the fact that the size of the sound source (at a given frequency) is not infinitesimal compared with the measurement distance. Clearly, additional data both on and far from a missile, and in narrower frequency bands, would be helpful in clarifying the problem further.

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*Reference 10^{-13} watt.

An angular correlation measured (4) on a stationary large missile is given in Figure 4. The general behavior of this correlation is explained as follows: At low frequencies the noise sources are sufficiently far from the measurement locations that the noise appears to be coming from one source, and the pressures in a plane are well correlated. At high frequencies the noise sources are sufficiently close to the measurement locations that the noise reaching different angular positions comes from different uncorrelated parts of the noise source.

Up to this point our discussion has been concerned with the noise field of stationary vehicles. Presently available data from moving vehicles indicate that the noise field on the vehicle surface decreases with increasing forward velocity. This behavior could be explained by the assumption that the vehicle motion increases the apparent distance between the vehicle surface and the noise sources in the jet stream. The change in source pressure level ΔSPL due to motion of rocket vehicles at Mach number M is approximately (7):

$$\Delta SPL \cong 20 \log (1-M), \quad \text{db} \qquad\qquad \text{Equation (1)}$$

More data on vehicles in flight are needed to check this relation. Of course, for $M \geq 1$ rocket noise does not reach the vehicle.

The noise field of a rocket is greatly altered when the rocket is within a confining structure, such as a hole in the ground. Such a structure may force the exhaust flow to pass along the vehicle surface, reducing the distance between the noise sources and the surface and increasing the noise levels at the surface. Also, aerodynamic pressure fluctuations in the exhaust flow may be felt more strongly at the vehicle surface. Preliminary data show that within confining structures the noise is on the order of 10 to 20 db greater than that under free field conditions. These increases are strongly dependent on measurement position and on geometrical details. More information on this problem is needed, particularly on the space-time correlations in the combined acoustic-aerodynamic field surrounding the vehicle.

Boundary Layer Pressure Fluctuations

A turbulent boundary layer exists over a considerable portion of the surfaces of a vehicle in flight. Pressure fluctuations are associated with the turbulent field and will cause the adjacent surfaces to vibrate.

The problem of boundary layer pressure fluctuations has been greatly clarified in recent years, although many uncertainties still remain. References (8,9, and 10) give theoretical and experimental data on pressure fluctuations in turbulent boundary layers. The results can be summarized as follows: The overall root-mean-square pressure is about 0.7% of the free stream dynamic pressure. The noise within the boundary layer has a pressure spectrum which, in octave bands, maximizes at a frequency governed by the ratio of the free stream speed to the boundary layer thickness. For low frequencies (below the frequency of the maximum), the octave band spectrum increases at about 3 db/octave; for high frequencies, the spectrum falls off very sharply.

The space-time correlation of the pressure field in the boundary layer can be described broadly in terms of a convecting and decaying field, rather than in terms of a propagating field as is the case for sound. The pressure field convects at a speed of about 80% of the free-stream speed. In addition, it decays, falling to 10% of its initial value in a distance of about 7 boundary layer thicknesses (9,10).

All the foregoing information has been obtained with subsonic boundary layers. Since many vehicles will be supersonic during a large part of the time in flight, it is appropriate to inquire about possible changes that might exist under supersonic conditions. References (3,12, and 13) give some calculations and measurements relevant to this question. The indications are that the results for the subsonic regime will extend into the supersonic regime provided that the free stream conditions are interpreted to be those just outside the boundary layer.

Recent measurements of velocity fluctuations in equilibrium supersonic boundary layers (14) also lend support to the belief that the supersonic case is not too grossly different from the subsonic case. From Reference (14) we may estimate the pressure fluctuations Δp in the supersonic case to be

$$\frac{\Delta p}{\frac{1}{2}\rho_\infty v_\infty^2} \sim \left(\frac{\Delta v}{v_\infty}\right)^2 \qquad \text{Equation (2)}$$

in which it is assumed that the velocity fluctuations Δv travel at the local mean velocity. The quantity v_∞ is the free-stream velocity, and $\rho_\infty v_\infty^2/2$ is the free-stream dynamic pressure. Figure 5 shows measurements of $\Delta v/v_\infty$ obtained from Reference (14), from which we may conclude that the fluctuating pressure is of the order of 0.3% of the dynamic pressure. This value is in rough accord with the subsonic value, although somewhat less. Based on the aforementioned considerations, typical octave band pressure levels associated with boundary layer turbulence are shown in Figure 6. These levels might be expected on the surface of a large missile in powered flight traveling at supersonic speeds, at a condition corresponding to the maximum dynamic pressure just outside the boundary layer. It is to be noted that the levels are quite high and occur at relatively high frequencies.

Some additional uncertainties that have not been adequately explored to date deserve mention. At supersonic and hypersonic speeds, aerodynamic heating will cause heat transfer through the boundary layer. Also, the surfaces may be rough or pitted due to ablation (15). These factors may very well influence the characteristics of the pressure field and need to be investigated.

Wake Noise

The turbulent flow in the wake of a vehicle may give rise to noise radiation. Since no direct data are available on this noise source, we must appeal to qualitative arguments for its estimation. We restrict attention here to vehicle Mach numbers less than unity; for $M \geqslant 1$, sound radiated by the wake cannot reach the vehicle.

Qualitatively, the wake of a subsonically moving vehicle is composed of a region of high shear, flow separation, and concomitant turbulence. This is much the same situation that exists in the jet stream of a gas reaction motor, and we may speculate that the noise radiation characteristics of the two are similar. Figure 7 depicts in qualitative terms the situation in a jet stream and in a wake. In the case of jet radiation, the velocity profile is directed away from the jet engine and the most intense radiation is in the general downstream direction. In case of wake turbulence, the velocity profile is directed toward the moving vehicle and by analogy we might expect the most intense radiation to be in the general upstream direction.

The implications of the qualitative picture described above are essentially borne out by measurements on turbojet aircraft in flight (2,16). Figure 8 shows one of these measurements, from which we can see that the power radiated in the general upstream direction increases with increasing Mach number. However, we must emphasize that additional data are required to more fully establish the mechanism of noise radiation in turbulent wakes.

We proceed to estimate the order-of-magnitude of wake noise based on the proposed mechanism. The total mechanical power associated with the wake may be estimated to be the product of the wake drag and the forward speed of the vehicle. Consequently, we may write the acoustic power, P_W, radiated from the wake as a fraction of the mechanical power:

$$P_W = \eta D v = \eta c_D \frac{1}{2} \rho A v^3 \qquad \text{Equation (3)}$$

where D is the wake drag

c_D is the drag coefficient associated with the wake

ρ is the undisturbed air density

A is the projected area in the flight direction

v is the vehicle speed.

The quantity η is the order of $10^{-4} M^5$, based on the analogy with subsonic jet noise radiation (1). The drag coefficient c_D is of the order of unity or less, depending upon the shape of the vehicle trailing surface. We note that Equation (3) implies an eighth power dependence of power on velocity, in good agreement with the measurements shown in Figure 8.

We may compare the wake radiation with the radiation of noise by rocket engines and turbojet engines. The corresponding acoustic powers for these cases are given by

$$P_r = \eta_r \frac{1}{2}\rho_r A_r (v_r - v)^3 \ , \ \eta_r \sim 10^{-2} \qquad \text{Equation (4)}$$

$$P_t = \eta_t \frac{1}{2}\rho_t A_t (v_t - v)^3 \ , \ \eta_t \sim 10^{-4}(M_t - M)^5 \qquad \text{Equation (5)}$$

where the subscripts r and t refer to rockets and turbojets, respectively. The terms ρ, A, v_r, and v_t refer to the exhaust stream, and the Mach numbers are based on the speed of sound in the undisturbed medium.

With the use of order-of-magnitude values for the ρ and A terms of Equations (3) and (5), and with the use of typical values of the Mach numbers ($M \leq 1$, $M_r \sim 7$, and $M_t \sim 2$), we find that the acoustic power of a wake is much less than that of a rocket engine, and comparable to that of a turbojet engine.

From the estimated power, we may determine the sound pressure on the vehicle due to wake noise. To do this we must take account of the radiation directivity, the spectrum, and the effect of forward motion. As discussed previously, wake noise has a directional characteristic that is reversed from that of jet noise. Also, the spectrum is expected to shift in accordance with the different speed-to-dimension ratios. Finally, the forward speed effect as given in Equation (1) is expected to apply. With these factors in mind, we would conclude: In the case of a missile in powered flight, wake noise is less important than rocket noise. On the other hand, in free subsonic flight of a re-entry vehicle, wake noise may be important. In the case of an aircraft at high subsonic speeds, wake noise may be quite important relative to turbojet noise.

No measurements are available on the correlation of wake noise over vehicle surfaces. However, we may reasonably expect the correlations to be qualitatively similar to those of jet noise.

Sound radiation from the wake of cylinders placed transverse to flow has been calculated and measured recently (17, 18), and displays the general behavior assumed here for noise of vehicle wakes. With transverse cylinders, however, there are additional strong components of radiation associated with fluctuating lift and draft forces. These components are related to the nearly periodic shedding of large scale vortices from the cylinder, rather than to the turbulent portion of the wake. With the very much higher Reynolds numbers and grossly different geometries associated with flight vehicles, vortex shedding does not appear to be of importance in flight vehicle noise environments. However, this general question needs to be clarified further.

Base Pressure Fluctuations

Noise radiated by the wake of a flight vehicle was discussed in the foregoing section. Here we consider the pressure fluctuations associated with wake turbulence that may be felt directly by the base of the vehicle without intermediate sound radiation. These pressure fluctuations may be expected to contribute to the noise environment of the vehicle for both subsonic and supersonic flight speeds, inasmuch as sound propagation is not a factor. There are no direct data available relevant to this noise environment, and we are forced to speculate about its magnitude.

The situation in the wake of a subsonic vehicle was discussed qualitatively in the last section. The supersonic case is more complex because of the existence of shock waves. In Figure 9 we give a qualitative picture of the flow expected at the base of a supersonic flight vehicle (19). As in the subsonic case, there is a region of relatively dead air in a small volume immediately behind the base. The boundary layer over the vehicle surface thickens past the base and forms a turbulent wake a short distance downstream. The qualitative form of the shear profile at the base is expected to be similar to that at the boundary of a supersonic jet issuing into still air (19).

Because of the similarity between the flow at the base and the flow issuing from a jet, we might speculate that the order-of-magnitude of the base pressure fluctuations can be estimated from jet pressure fluctuations. Of interest here are pressure fluctuations measured very close to a jet where the aerodynamic rather than the acoustic field predominates. The pressure fluctuations, Δp, close to the turbulent jet (i.e., in the near field) may be written as (20)

$$\Delta p = \frac{K}{2} \rho v^2 \left(\frac{r_o}{r}\right)^3 \qquad \text{Equation (6)}$$

where ρ is the density and v is the velocity in the jet. The quantity r_o is a characteristic dimension of the jet, and r is the distance from the jet. The proportionality constant K is of the order of 10^{-2}. We may rewrite Equation (6) in a somewhat more convenient form for estimating, by analogy, the base pressure fluctuations:

$$\Delta p = \frac{K\gamma}{2} p_b M^2 \left(\frac{r_o}{r}\right)^3 \qquad \text{Equation (7)}$$

Here p_b is the static base pressure and γ the ratio of specific heats. For subsonic flight p_b is approximately equal to the free-stream static pressure, p_∞. For supersonic flight p_b is about 40% of p_∞ over a wide range of Reynolds numbers and Mach numbers of interest (19,21).

With the use of the foregoing, we may estimate the magnitude of the base pressure fluctuations. We see most directly from Equation (6) that the base pressure fluctuations are expected to maximize at a condition equivalent to the maximum free-stream dynamic pressure of the vehicle, a condition that generally occurs in supersonic flight. A typical set of conditions for maximum free-stream dynamic pressure of a large missile is p_∞ = 150 lbs/ft^2 (60,000 ft) and M = 3. For a conservative estimate, let us take r to be the same order as r_o. Then the base pressure fluctuations in this case will be of the order of or less than 4 lbs/ft^2, corresponding to a pressure level of 140 db. We see that the base pressure fluctuations may be of considerable magnitude and may be comparable to the magnitude of some of the other environments discussed previously.

The wake diameter in the turbulent region is about 50% of the base diameter, over a wide range of flow conditions (19). Thus, the characteristic dimensions and velocities of wakes are not much different from those of usual jet systems. Pressing the analogy with jet pressure fluctuations further, we may therefore expect the spectrum of the base pressure fluctuations to maximize in the audio frequency range.

Not much can be said about the space-time correlation of the pressure fluctuations, except that its scale may be a sizable fraction of the base area. Consequently, this pressure field may couple quite well to the vehicle structure.

It must be emphasized that the foregoing estimates must be regarded as pure speculation. Because of the possible importance of this environment, it is evident that measurements and additional studies of base pressure fluctuations would be extremely helpful.

Oscillating and Moving Shocks

In supersonic flight, abrupt changes in static pressure may occur at some points on the vehicle surface. Motions of these pressure discontinuities constitute a noise environment.

A distribution of static pressures likely to be encountered on the surface of a typical rocket vehicle traveling at supersonic speeds is sketched in Figure 10. Abrupt increases in pressure occur at locations where the surface is sharply concave, and sudden pressure decreases occur where the surface is sharply convex. The static pressure increases outside of the boundary layer occur over extremely short distances -- in fact, over distances of the order of the mean free path of the molecular motions of the fluid (22) (about 10^{-5} in.). The pressure decreases are considerably less abrupt than the increases; they occur over distances of the order of several inches. The sudden pressure increases are called (compression) shocks; the pressure decreases are often called expansion shocks, even though they are not abrupt enough to be considered shocks in the strictest sense of the word.

The values of the pressures indicated in Figure 10 are of the correct order of magnitude for Mach numbers in the range of 5 to 10. (The pressure difference across a shock is not, in general, strongly affected by Mach number for Mach numbers in this range.) Thus, pressure increases across a shock may easily be of the order of the atmospheric pressure at altitude.

The interaction between an attached shock and a boundary layer usually thickens this layer locally and makes the pressure increase felt by the vehicle surface less abrupt. Because of the boundary layer, the surface pressure rise occurs over distances of the order of an inch or two, instead of over the 10^{-5} in. in absence of the boundary layer (22,23). The magnitudes of the pressure differences, however, are virtually unaffected by the boundary layer (23).

When attached shocks are observed in wind tunnels by use of any of the several well known optical devices, they are often found to oscillate. Thus, pressure fluctuations of the order of the atmospheric pressure at altitude will be felt in the vicinity of the shocks. For example, at 60,000 ft, the atmospheric pressure is about 150 lb/ft^2, so that the level of the pressure fluctuations will be about 175 db. Since it is clear that such motions of pressure discontinuities are likely to induce important vibrations in the skin structures of high speed flight vehicles, it is unfortunate that very little is known about the characteristics of these shock oscillations, such as their lineal extent and spectral composition. It is evident that this environment warrants further study.

Shock oscillations of a somewhat different sort have been observed in the presence of flow separation spikes which are often mounted at the front of supersonic vehicles in order to reduce drag. The drag reduction in this case is obtained by essentially replacing the drag associated with a blunt bow shock by the lesser drag associated with a conical shock attached to the spike, although in general both shocks are observed. The bow shock has a tendency to detach and spread the spike shock; under some conditions (depending mostly on Mach number and relative spike length), this spreading continues to the point where the bow shock is weakened so much that the spread spike shock can no longer be maintained. The spike shock then collapses, and the cycle is repeated, resulting in periodic flow fluctuations (24,25).

The effects of spike length and Mach number on the frequency of this type of shock pulsation (24) may be visualized from Figure 11. At Mach 2, a one-diameter long spike is found to produce shock oscillations at a frequency of about 3,000 cps, if the ambient air temperature is 70 ± 30°F. The surface pressure fluctuations associated with these shock pulsations may be quite significant. For example, at Mach 4.3, and with a spike-to-diameter ratio of 4/3, a maximum octave-band pressure level of 163 db was measured (25) at the front of a blunt body like that shown in Figure 11, near the base of the spike. This maximum occurred in the 600-1200 cps range; a nearly uniform decrease of 5 db/octave was observed on both sides of the maximum.

The spike shock pulsations are strongly influenced by the shape of the nose cone. It appears that less blunt configurations have less tendency to set up such oscillations; in fact, hemispherical noses are known to give rise to no shock pulsations at all. More information is needed about the shock-induced fluctuations of pressure on the lateral surfaces of the vehicles, especially for curved nose configurations, so that the responses of the structures can be evaluated more realistically. Also, the effects of Reynolds number and geometric scaling need further investigation before the presently available results, obtained from small wind-tunnel models, can be applied with confidence to full scale craft.

Shocks sweeping across vehicle surfaces may also cause these to vibrate. Such relative motions of shock and vehicle may occur due to explosions, or when one vehicle passes through a shock wave generated by another. The intensities of explosions and of the attendant shocks cover such a wide range that no meaningful order of magnitude can be assigned to the shock strengths. However, the pressure increase experienced by one vehicle passing through the bow shock wave created by another vehicle is given by (2)

$$\frac{\Delta p}{p_\infty} \doteq 0.53\,\delta\,\frac{(M^2-1)^{1/8}}{(y/L)^{3/4}} \qquad \text{Equation (8)}$$

where

p_∞ is static pressure in undisturbed atmosphere

Δp is observed pressure increase

$$\left.\begin{array}{ll} y & \text{is distance between two vehicles} \\ & \text{measured normal to flight path} \\ \delta = D/L & \text{is fineness ratio} \\ D & \text{is maximum diameter} \\ L & \text{is length} \\ M & \text{is Mach number.} \end{array}\right\} \begin{array}{l} \text{of vehicle} \\ \text{producing} \\ \text{shock} \end{array}$$

The foregoing relation applies strictly only for relatively large distances between the two vehicles, i.e., $\frac{Y}{L} > 100$, but may be used to give reasonably reliable estimates for Y/L as low as 5 in some cases. It shows that for high Mach numbers the pressure rise varies nearly as $M^{1/4}$ and thus is not strongly dependent on Mach number, and that the pressure rise varies inversely as only the 3/4 power of distance. As an example of the pressure jumps one may encounter, a vehicle with fineness ratio 0.15, length 100 ft, traveling at Mach 3 at 60,000 ft causes a Δp of about 3 lb/ft^2 to be observed on another vehicle 1000 ft away. The pressure jump is a transient which sweeps over the receiving vehicle at a speed determined by their relative motions.

Flight Through a Turbulent Atmosphere

1. Subsonic flight speeds

When a flight vehicle moves through a turbulent atmosphere at subsonic speeds, the random pressure fluctuations in the turbulence are felt directly by the surfaces of the vehicle. Because the mean scale D of the turbulence is much larger than overall vehicle dimensions, it is often assumed in aerodynamic gust loading problems that the vehicle moves as a rigid body in response to the turbulence. However, there is a wide range of turbulent "eddy" sizes having values larger and smaller than the mean scale D. Eddies whose sizes are comparable to or smaller than the vehicle length L give rise to a random pressure field that will excite vibrations of individual panels on the vehicle surface, rather than excite motion of the entire vehicle.

In order to characterize this random pressure field, we require a value of the rms pressure fluctuation Δp and the temporal scale τ. The static pressure p at the surface of a body is related to the ambient pressure p_o and to the free stream density ρ and velocity v by

$$p = p_o + c\,\frac{1}{2}\,\rho v^2 \qquad \textbf{Equation (9)}$$

where the coefficient c is a function of vehicle geometry, flow conditions, and measurement position (see for example, Ref. (27). Then the pressure fluctuation will be approximately

$$\Delta p \sim c \rho v (\Delta v) \qquad \textbf{Equation (10)}$$

Δv is an "effective" component of the turbulent velocity associated with eddies comparable to or smaller than L. Based on the data in Ref. (26), the maximum value of Δv is an order of magnitude less than the rms turbulent velocity, or about 1/2 ft/sec in the lower atmosphere. The maximum magnitude of c is the order of unity, and it may take on positive, negative, and zero values.

Equation (10) may now be used to obtain an estimate of the upper limit of Δp. For a density of 2×10^{-4} slugs/cu ft, corresponding to an altitude of 60,000 ft, and a forward velocity of 1000 ft/sec, $\Delta p \lesssim 0.1$ lbs/sq ft or a maximum pressure level of 108 db. This is clearly an upper limit, because the value of Δv will decrease with increasing altitude. Also, much lower values of Δp will occur at observation positions where steady flow results show a vanishing value for c. Thus, Δp may vary by orders of magnitude over the vehicle.

The predominant pressure fluctuations experienced by a vehicle moving through atmospheric turbulence result from vehicle motion through the turbulent velocity fluctuations. Therefore, the temporal scale τ of the pressure field associated with the smaller eddies will be

$$\tau = \frac{L}{V}$$

Using a value of L of 100 ft and a forward speed of 1000 ft/sec, we obtain τ equal to 0.1 sec. We may speculate that the corresponding octave band spectrum will be similar in shape to the spectrum of boundary layer noise discussed earlier in the part on boundary layer pressure fluctuations: increasing 3 db per octave at very low frequencies, peaking around $f_{max} = (2\pi\tau)^{-1}$ cps, and decreasing very rapidly above this peak. For the example just considered, the frequency of the maximum is about 2 cps. Frequencies in the audible range, therefore, are well down on the spectrum "tail", and levels in this range will be well below the overall value of 108 db obtained previously. More detailed information on the spectrum shape above f_{max} is required to make quantitative estimates of the pressure levels at audible frequencies.

Some of the pressure fluctuations in atmospheric turbulence are independent of the vehicle motion. These pressure fluctuations are of the order of $1/2\ \rho\ (\Delta v)^2$, and are generally negligible compared with those given by Equation (10).

2. Supersonic flight speeds

When a flight vehicle moves supersonically, it is surrounded by a set of pressure discontinuities or shocks. (This situation has been discussed in the section on oscillating and moving shocks above and is illustrated in Fig. 10). When atmospheric turbulence is convected through one of these shocks, it produces sound pressures downstream of the shock, and these pressures may excite the vehicle structure.

The analysis of Ribner (28) can be used to estimate the overall level of shock-turbulence sound. For the case of a supersonic vehicle, we may assume that the ambient pressure p_o downstream of the shock is constant, independent of the convection speed of the turbulence. Ribner's results for the sound pressure p downstream of the shock then take on the form

$$\frac{p}{p_o} = b(M_u)\,\frac{\Delta v}{v} \qquad \text{Equation (11)}$$

where M_u is the Mach number upstream of the shock and $b(M_u)$ is a proportionality factor. The value of $b(M_u)$ varies very slowly with Mach number, and is approximately 0.6. In an intense turbulent field, such as exists at a jet interface, the ratio $\Delta v/v$ may be of the order of 10^{-1}. For turbulence in the atmosphere, we estimate that this ratio may be the order of 10^{-3}. Using this latter figure, we obtain 108 db for the sound pressure level downstream of a shock at 60,000 ft (p_o = 150 lb/sq ft).

The pressure estimated with the use of Equation (11) is acoustic in that it propagates in the flow as well as convects with the flow. (In contrast, the pressure fluctuations estimated by Equation (10) for the subsonic case are not acoustic.) In the supersonic case there are also non-acoustic pressure fluctuations. These pressure fluctuations are an order-of-magnitude (20 db) greater than those estimated by Equation (11) (28)

The space-time correlation of the shock-turbulence sound may be estimated from the sound propagation speed and the convection speed. The spectrum is not known, but noise measurements in wind tunnels suggest that the spectrum will maximize in the audio frequency range, in contrast to the situation expected in the subsonic case.

3. Retro-rocket turbulence

One proposed method of decelerating a space vehicle consists of firing a rocket in the direction of the forward flight path. As the vehicle decelerates, it may move through a portion of the rocket exhaust stream. The turbulent velocity fluctuations in the exhaust stream can move over and excite the vehicle surfaces, and thereby act as noise sources.

This method of "retro-firing" deceleration would probably be used in a very low density atmosphere. Therefore, a description of the rocket exhaust turbulence requires some understanding of jet behavior in such atmospheres. Unfortunately, little information of this kind is available. We may speculate that the exhaust stream will expand right at the rocket exit nozzle, so that the pressure inside the stream is equal to the (very low) pressure of the surrounding atmosphere. Also, the interface between the expanded jet and the atmosphere may become hot, because of the high relative velocity between the two media. However, we must have a more quantitative picture of the exhaust flow in order to estimate the importance of retro-firing operation as a noise source. Thus, there is a need for experiments to determine the steady and the fluctuating quantities of a rocket exhaust in a low density atmosphere.

Pressure due to Micro-meteorite Impacts

Although the existence of cosmic debris or meteoritic dust outside the earth's atmosphere has been indirectly deduced many years ago, it has been only since the advent of high-altitude rockets and satellites that this dust has been sampled and made the subject of more direct study. With orbital and space flights a reality, the possible noise induced by the continued encounter of vehicles with micro-meteorites naturally becomes one of the many matters of concern.

Relative abundances, masses, radii, and velocities, of micro-meteorites at the edge of the earth's atmosphere are given in Table I, based on one of the most widely accepted estimates (29). This estimate is based on extrapolation of visual, photographic (30), and radio meteor data, but some of the measurements obtained from satellites and sounding rockets seem to agree with it (30,31,32). More data concerning the abundance of the smaller particles may soon become available as a result of studies currently in progress. It is of interest to note that meteorites in general have sponge-like structures, with densities of the order of 0.05 gm/cm^3.

In Table I, no account is made of possible shielding by the earth; a factor of one half should be applied to the number of impacts for vehicles near the earth's surface. Other corrections for distance from the earth cannot be made in absence of precise data on particle and vehicle orbits, but it is likely that the number of meteorites striking a vehicle will decrease with increasing distance from the earth, even if shielding by the earth is taken into account (29). In view of the limits of present knowledge, Table I can be applied with reasonable confidence only for distances up to about 10^4 km from the earth.

From the values given in Table I, one may compute that the average total momentum flux (i.e., pressure) due to particles of all sizes amounts at most to about 2×10^{-9} dynes/cm^2 if shielding by the earth is neglected. This value of pressure corresponds to a pressure level of -100 db, which is negligible compared to that due to other sources. The aforementioned pressure, however, is an average over a long time, and it is quite possible that significantly higher pressures are reached for short periods, particularly if there exist orbital positions where concentrations of particles occur. Also, the instantaneous response of the vehicle structure might be quite high for a single impact, although the long-time average would be expected to be quite low.

III. CONCLUSIONS

We have presented a review of some of the noise environments likely to be important for flight vehicles. Although this review is by no means exhaustive in subject matter or complete in detail of information, it does indicate that the noise environments of a flight vehicle are indeed complex and that much is yet to be learned about these environments.

Of the noise sources we have discussed, rocket and turbojet engines, oscillating shocks, boundary layer pressure fluctuations, base pressure fluctuations, and wake noise seem to be more significant for most cases of practical interest. On the other hand, atmospheric turbulence and micro-meteorites appear to be of less importance.

The need for further measurements to clarify and widen our knowledge of environmental noise is obvious. Such measurements may be carried out most directly on vehicles in flight, but such experimentation is relatively difficult and costly. It is anticipated that laboratory investigations, e.g., of base pressure fluctuations on wind tunnel models, may be extremely useful.

Some phases of the experimental investigations are likely to prove extremely difficult because the noise observed may be due to more than one significant source. For example, the boundary layer and the base pressure fluctuations are both functions of dynamic pressure; measurement of noise on a flight vehicle is apt to show a maximum when the dynamic pressure is at its maximum. However, the contribution of the two aforementioned sources will be undistinguishable unless extreme ingenuity and care are exercised in devising and executing the experiment.

Some sources of structural excitation that we have not discussed in this paper may be quite important. These include: combustion instability and other internal engine oscillations that may be transmitted directly to the structure, transients associated with changes in propulsion, transients associated with separation of vehicle sections (e.g. stages), unsteady thermal stresses in structures due to unsteady motions of the vehicle. A careful assignment of the environmental problem of a flight vehicle should include these and possible other sources, as well as those discussed in the present paper.

METEOROID DATA

Meteor Visual Mag.	Mass (gm)	Radius (microns)	Velocity (km/sec)	Impacts on 3m diameter sphere per day+
5	0.25^{0}	10,600	28	$2.22 \cdot 10^{-5}$
6	$9.95 \cdot 10^{-2}$	7,800	28	$6.48 \cdot 10^{-5}$
7	$3.96 \cdot 10^{-2}$	5,740	28	$1.63 \cdot 10^{-4}$
8	$1.58 \cdot 10^{-3}$	4,220	27	$4.09 \cdot 10^{-4}$
9	$6.28 \cdot 10^{-3}$	3,110	26	$1.03 \cdot 10^{-3}$
10	$2.50 \cdot 10^{-3}$	2,290	25	$2.58 \cdot 10^{-3}$
11	$9.95 \cdot 10^{-4}$	1,680	24	$6.48 \cdot 10^{-3}$
12	$3.96 \cdot 10^{-4}$	1,240	23	$1.63 \cdot 10^{-2}$
13	$1.58 \cdot 10^{-4}$	910.	22	$4.09 \cdot 10^{-2}$
14	$6.28 \cdot 10^{-5}$	669.	21	$1.03 \cdot 10^{-1}$
15	$2.50 \cdot 10^{-5}$	492.	20	$2.58 \cdot 10^{-1}$
16	$9.95 \cdot 10^{-6}$	362.	19	$6.48 \cdot 10^{-1}$
17	$3.96 \cdot 10^{-6}$	266.	18	1.63
18	$1.58 \cdot 10^{-6}$	196.	17	4.09
19	$6.28 \cdot 10^{-7}$	144.	16	$1.03 \cdot 10$
20	$2.50 \cdot 10^{-7}$	106.	15	$2.58 \cdot 10$
21	$9.95 \cdot 10^{-8}$	78.0	15	$6.48 \cdot 10$
22	$3.96 \cdot 10^{-8}$	57.4	15	$1.63 \cdot 10^{2}$
23	$1.58 \cdot 10^{-8}$	39.8*	15	$4.09 \cdot 10^{2}$
24	$6.28 \cdot 10^{-9}$	25.1*	15	$1.03 \cdot 10^{3}$
25	$2.50 \cdot 10^{-9}$	15.8*	15	$2.58 \cdot 10^{3}$
26	$9.95 \cdot 10^{-10}$	10.0*	15	$6.48 \cdot 10^{3}$
27	$3.96 \cdot 10^{-10}$	6.30*	15	$1.63 \cdot 10^{4}$
28	$1.58 \cdot 10^{-10}$	3.98*	15	$4.09 \cdot 10^{4}$
29	$6.28 \cdot 10^{-11}$	2.51*	15	$1.03 \cdot 10^{5}$
30	$2.50 \cdot 10^{-11}$	1.58*	15	$2.58 \cdot 10^{5}$
31	$9.95 \cdot 10^{-12}$	1.00*	15	$6.48 \cdot 10^{5}$

*Maximum radius permitted by solar light pressure.

+Includes all meteorites of mass greater than that indicated in "mass" column.

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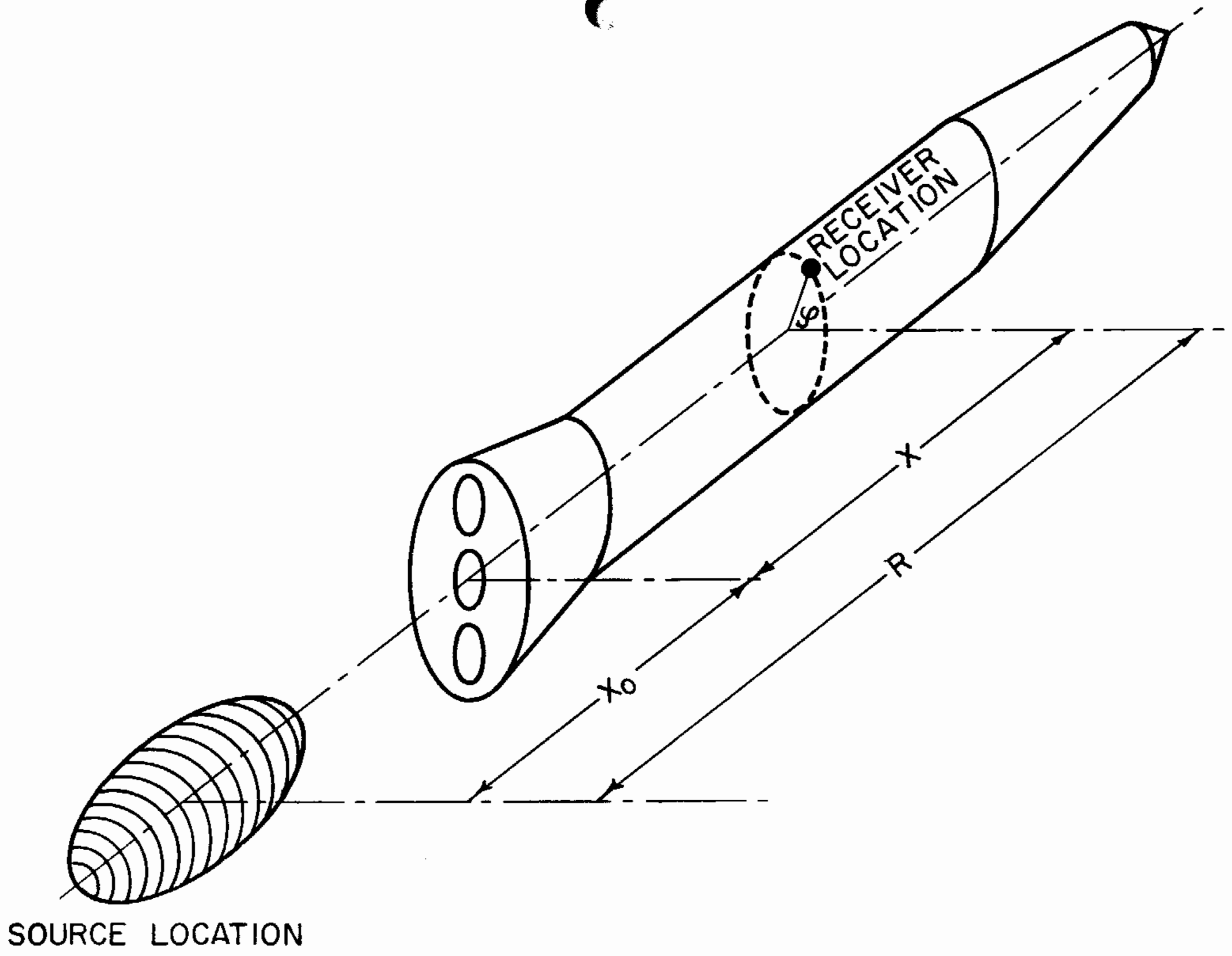

Fig. 1 - Coordinate system for missile and jet noise source. At a given frequency, the source may be considered to be localized within some volume the center of which is at x_o, both of which are functions of frequency.

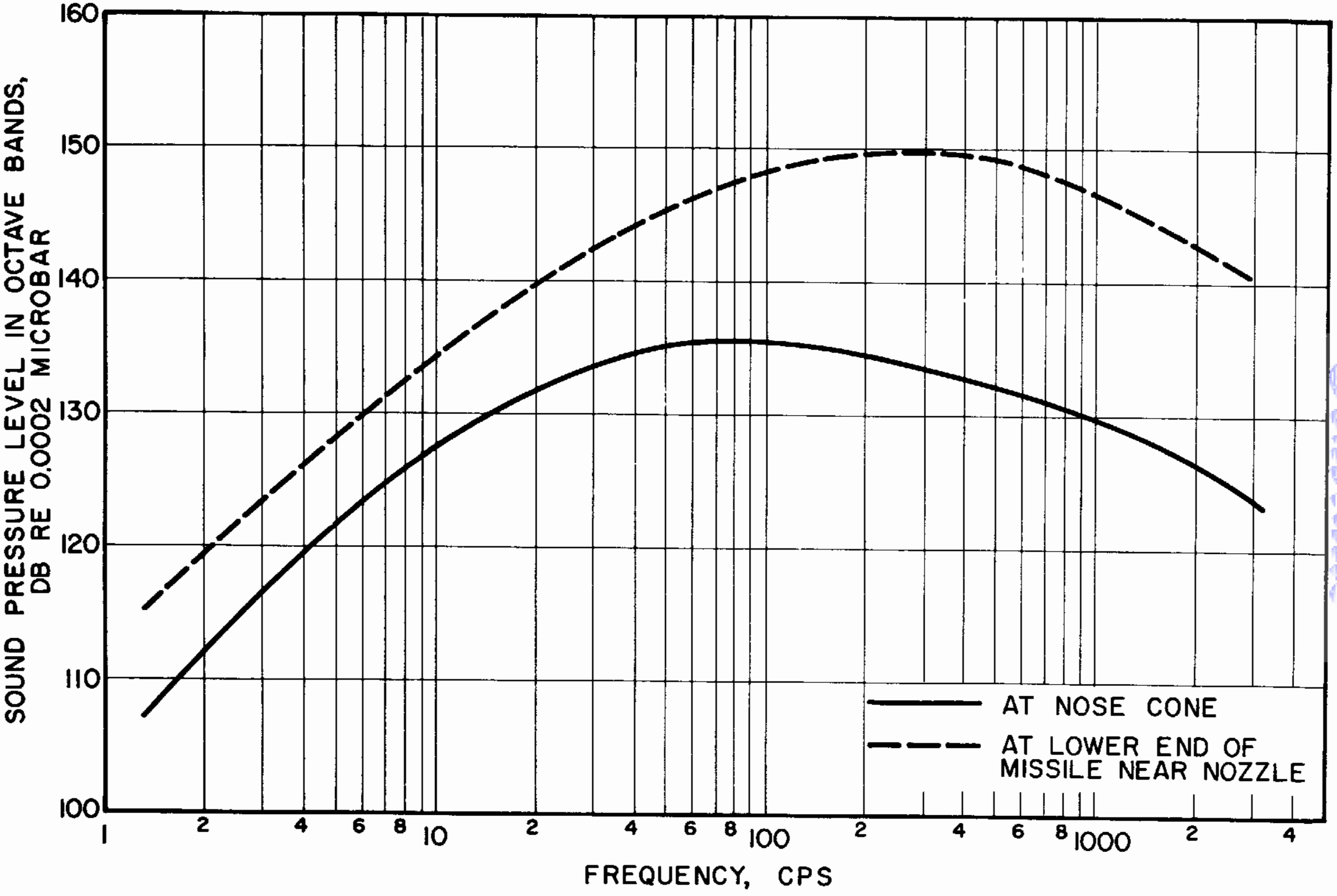

Fig 2 Typical rocket sound levels over a missile surface under stationary conditions

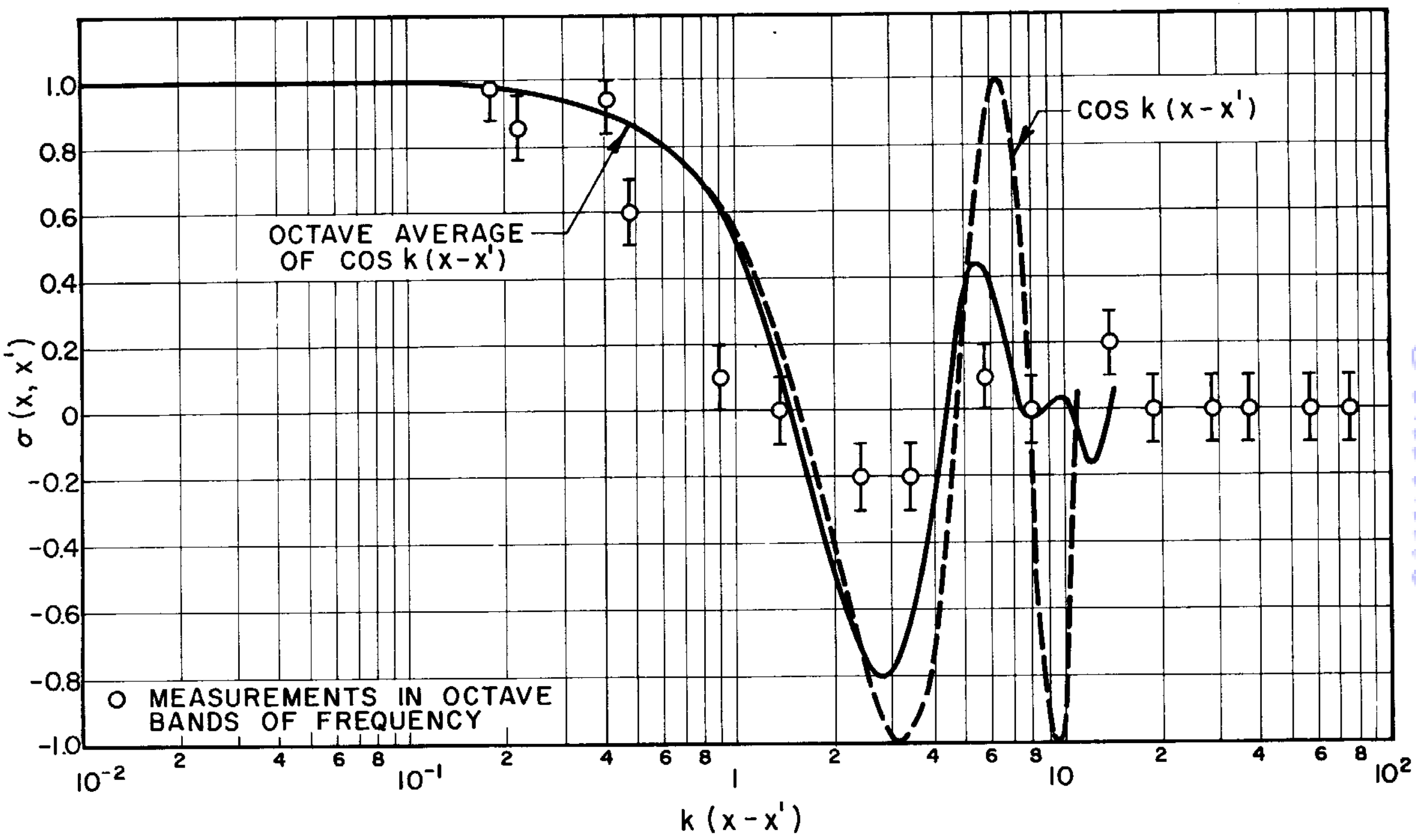

Fig 3 Longitudinal correlation of rocket noise measured over the surface of a large missile. The wave number is k and the longitudinal separation is x-x'.

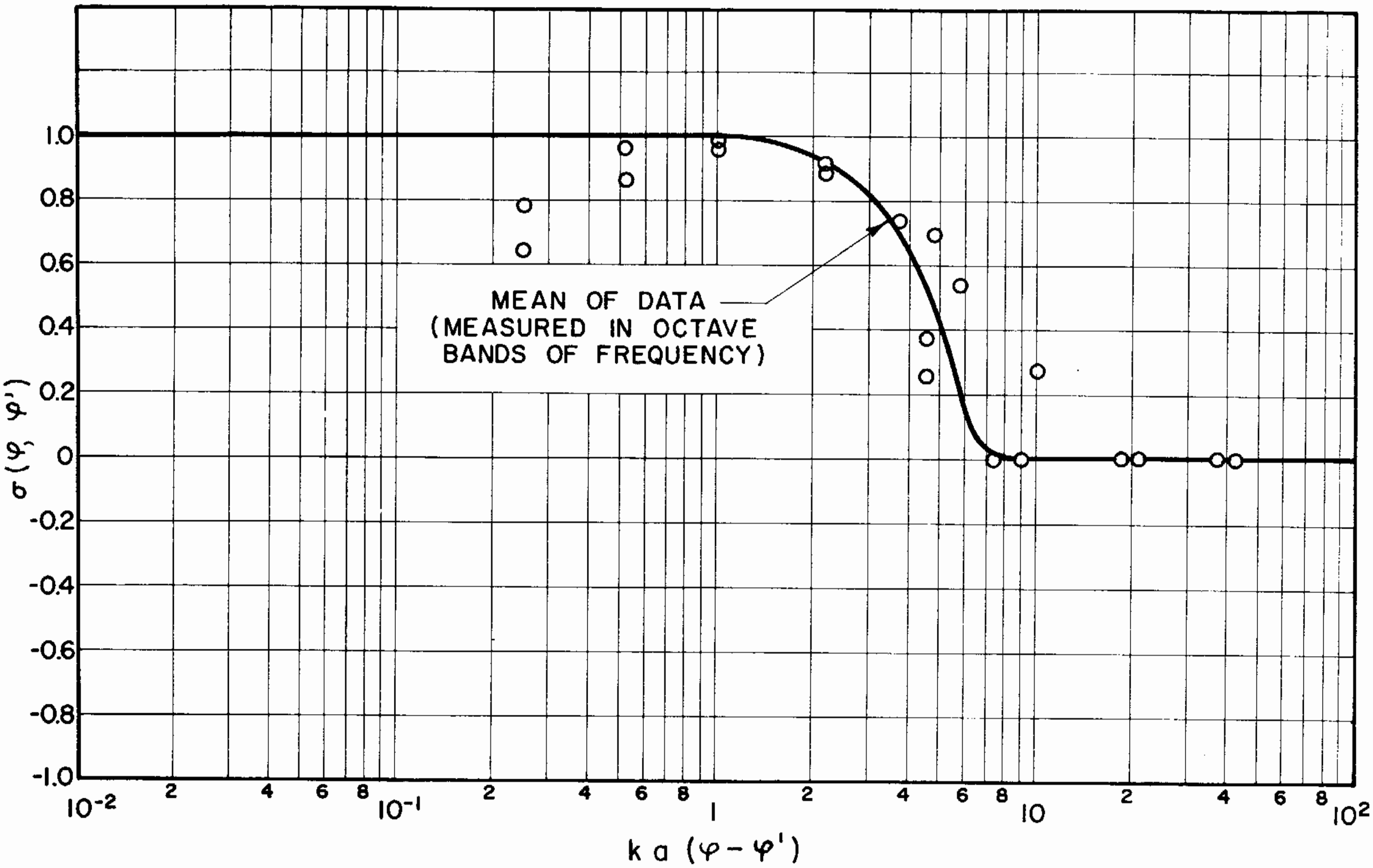

Fig 4 Angular correlation of rocket noise measured over the surface of a large missile of radius a. The angular separation is $\phi - \phi'$.

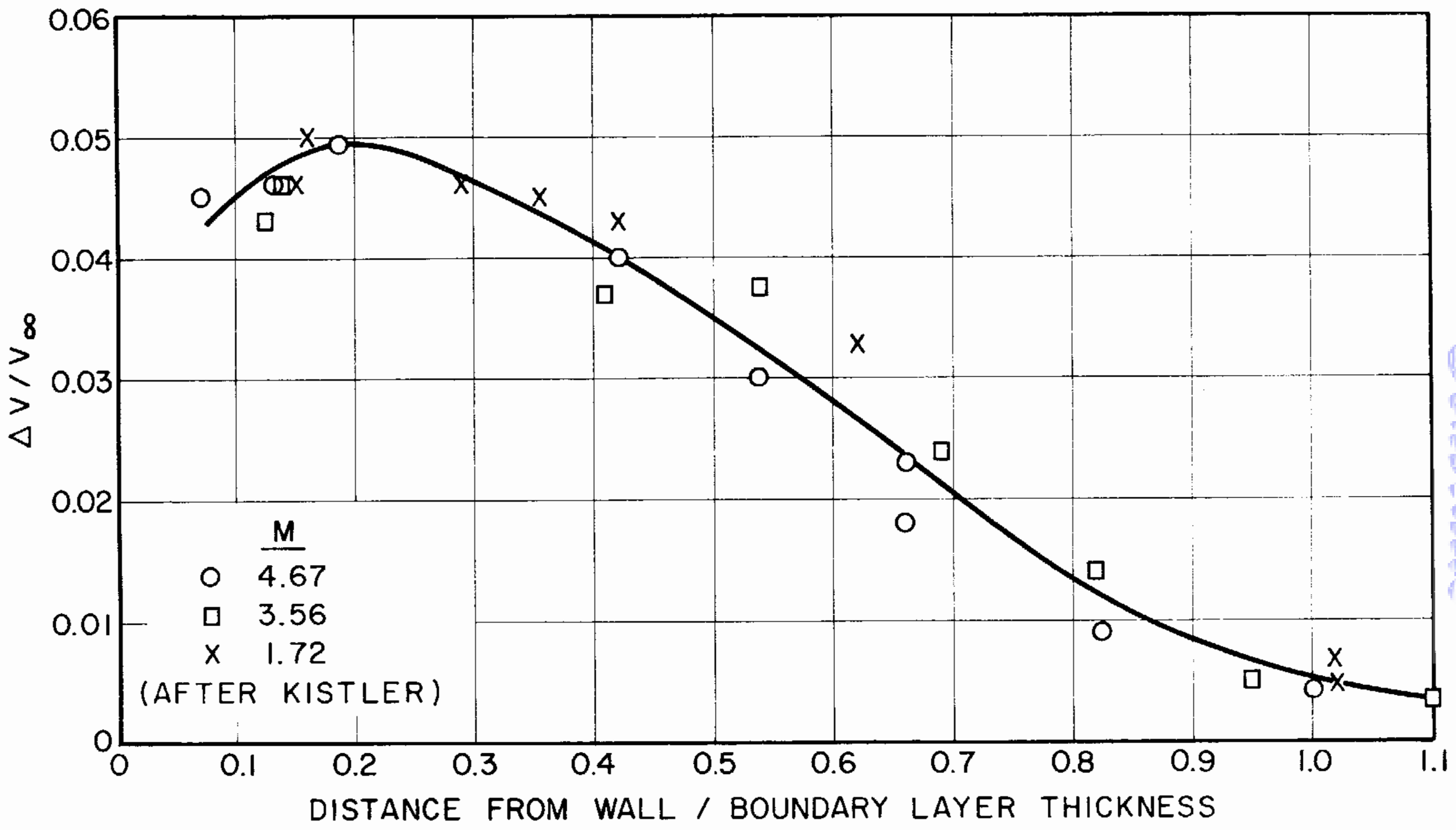

Fig. 5 - Velocity fluctuations (rms) in equilibrium supersonic boundary layers[14]

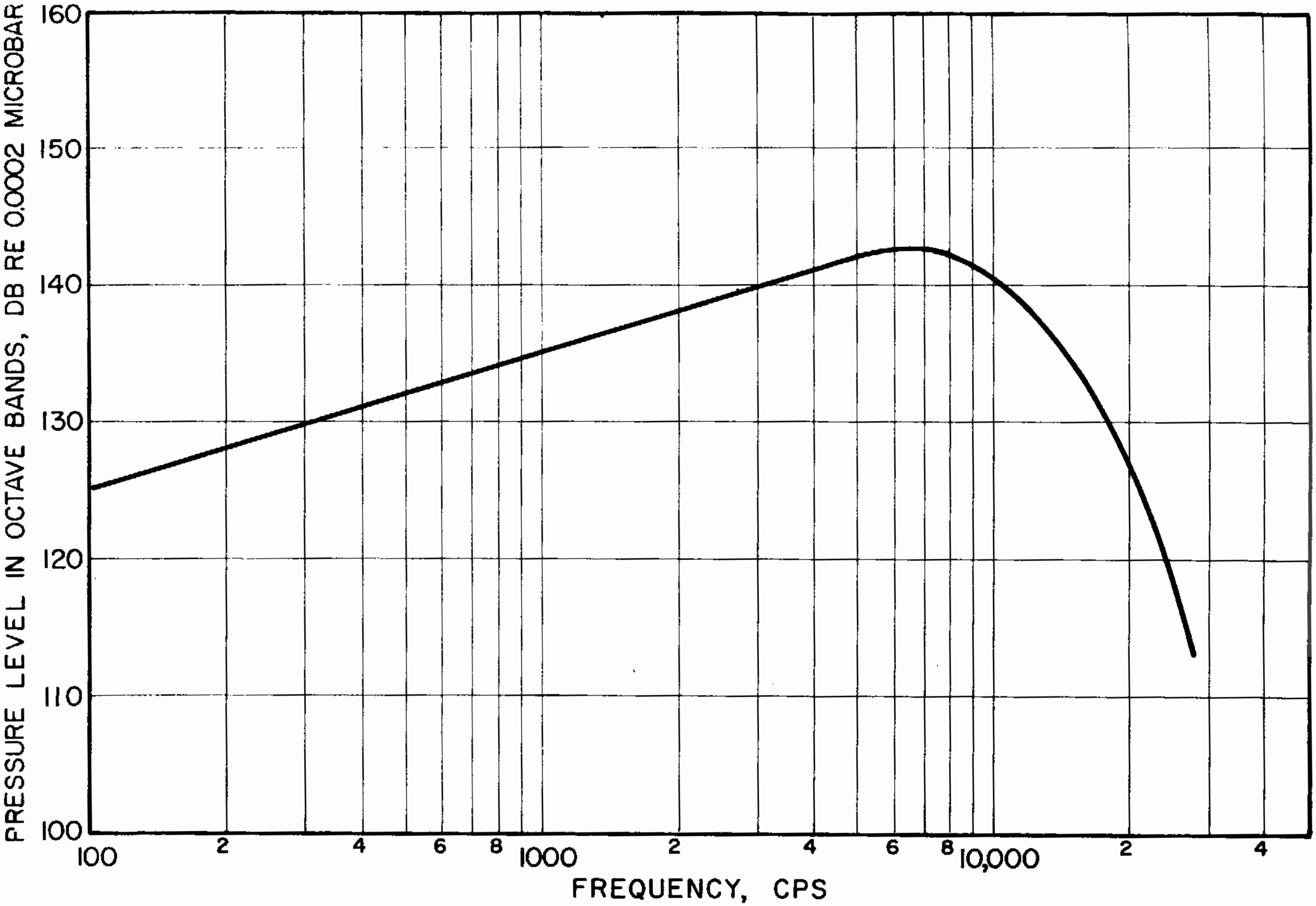

Fig. 6 - Typical estimated boundary layer noise on a missile surface at maximum dynamic pressure (supersonic flight)

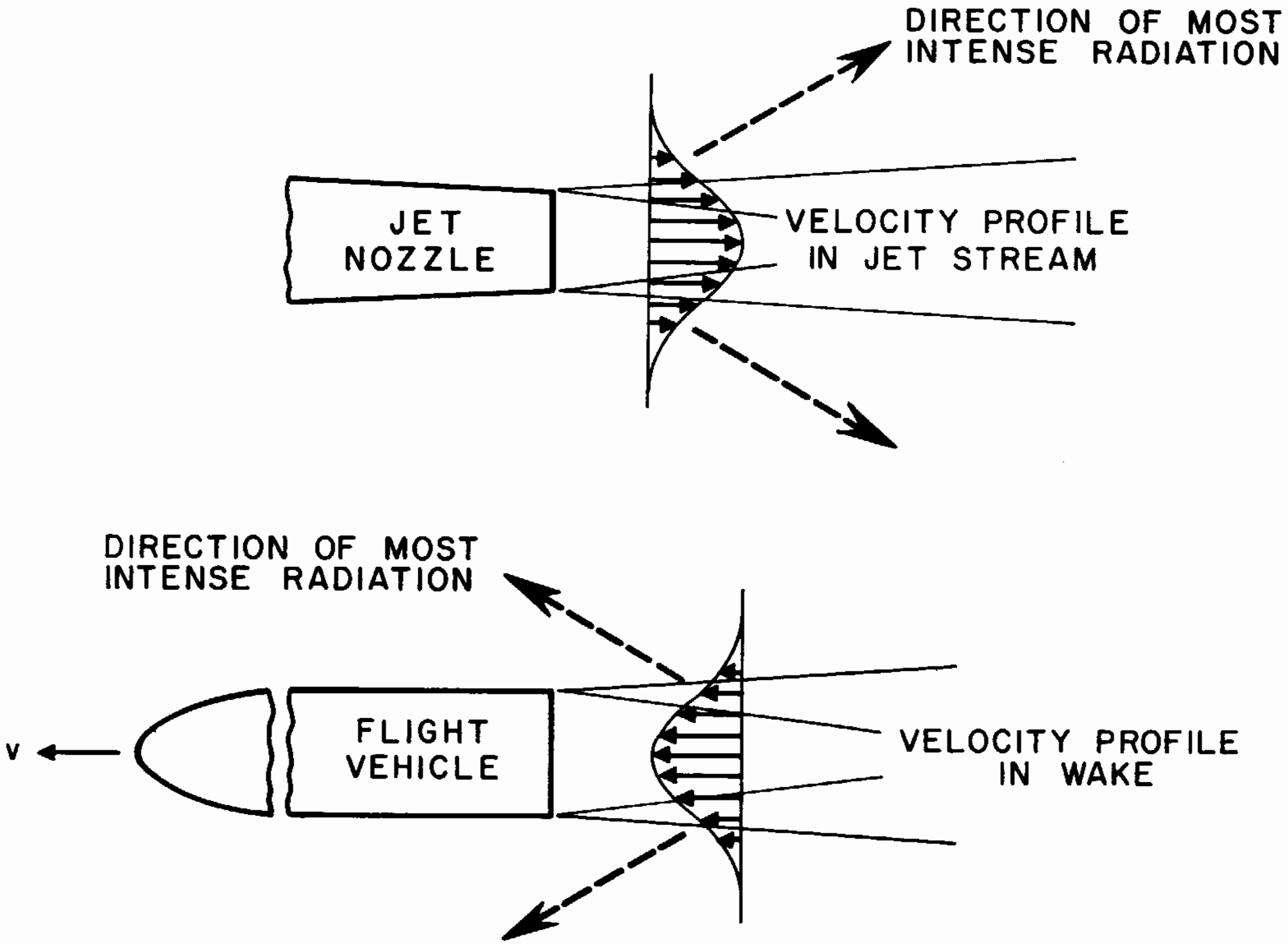

Fig 7 Qualitative analogy between jet noise radiation and wake noise radiation (subsonic flight).

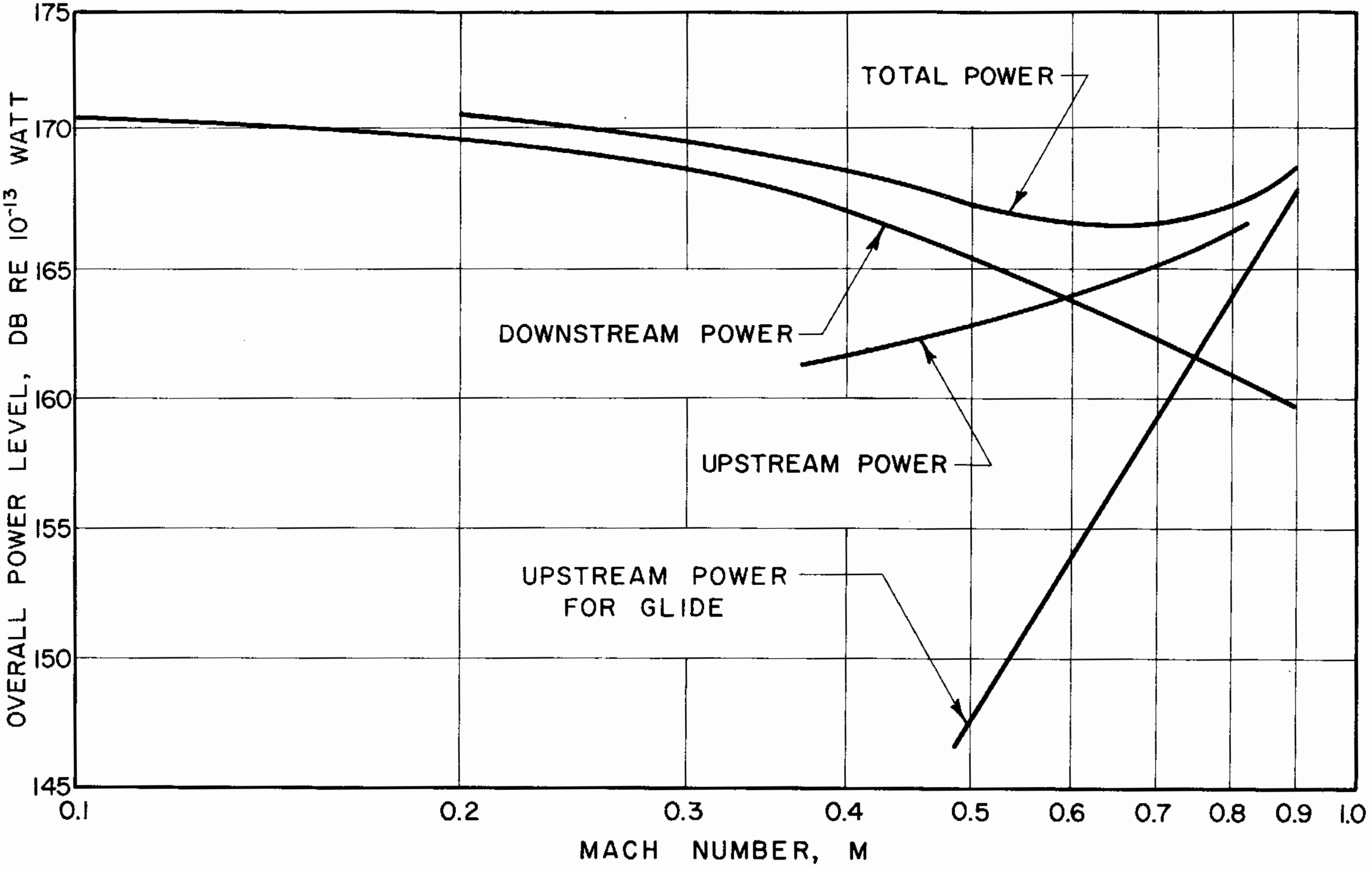

Fig 8 Measured acoustic power of an F-100 aircraft in flight[16/].

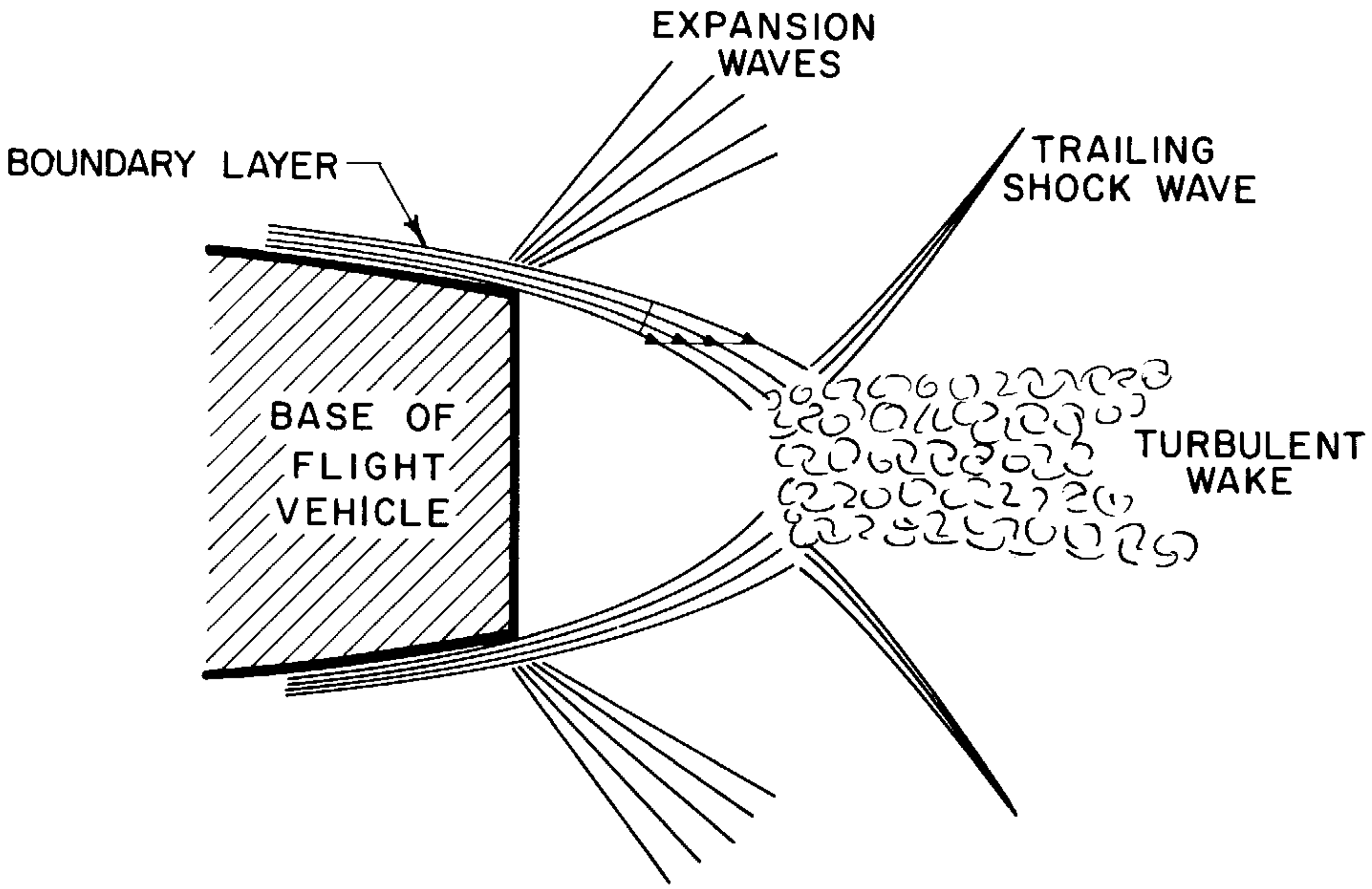

Fig. 9 - Qualitative flow characteristics in the region of the base of a supersonic vehicle19/

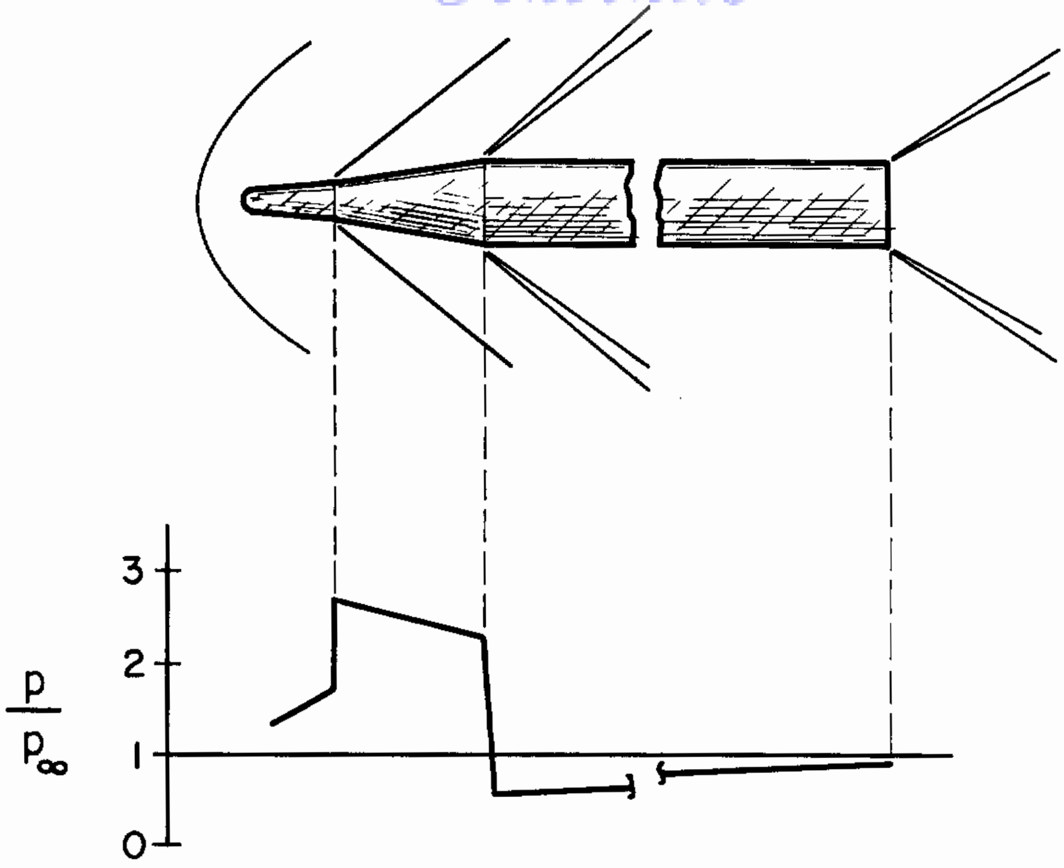

Fig. 10 - Distribution of static pressure over a typical missile. (p= local static pressure at surface, p_∞= static pressure in undisturbed medium).

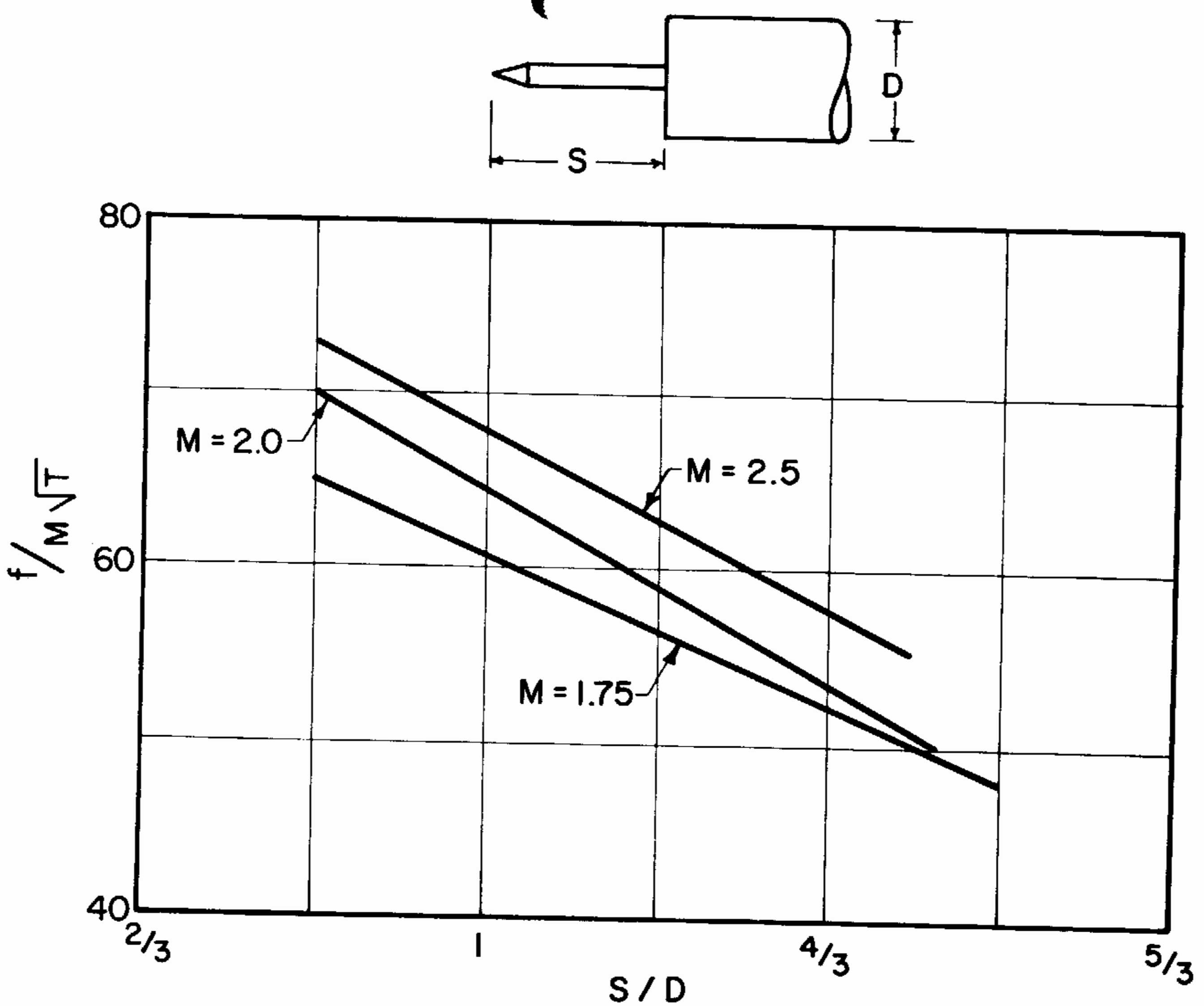

Fig 11 Frequency of shock pulsations vs spike length. Reynolds Number ≈ 4×10^6/ft, D = 1.5", f = frequency (cps), M = Mach Number, T = Free stream temperature ($^{\circ}$Rankine).