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REPORT WR 64-5

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THE AERODYNAMICALLY INDUCED PRESSURE FLUCTUATIONS ON SPACE VEHICLES

by

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SUMMARY 19534

The major pressure fluctuations on a space vehicle will occur in the regions of separated flow and oscillating shocks. The phenomena are conveniently divided into the transonic ($0.8 < M < 1.4$) and supersonic ($1.4 < M < 2.5$) regimes. The transonic regime is best investigated by experiment, and the balance of the evidence is that the phenomena will be essentially random and governed by the geometry of the shoulders. In contrast, the supersonic regime may have discrete shock oscillation frequencies, and the separation regimes will be confined to the flare compression corners. The separation in the supersonic regime may be further divided into two classes characterized by the reattachment region being associated with a shock or an expansion fan. In the first class the separation length depends significantly on Reynolds No. , and will therefore require some care in experimental studies. The separation in this case acts as a 17° fillet between flare and cylinder. In the second class attachment occurs at the top, expansion, corner and the position of this point dominates the flow pattern. The separation forms a region of approximately 12° in front of this point. This angle is dependent mainly on the ratio of step height to undisturbed boundary layer thickness. At low step heights it tends to about 10° and for high steps the value approaches 17° as in the first case discussed.

It would be desirable to produce a theory showing these effects, but more detailed experimental results will be required before a successful theory can be compounded.

The mechanisms causing discrete frequencies may be divided into two classes, one depending on local conditions at the separation point and one depending on the whole flow. Critical experiments distinguishing these types have been suggested. However, it is difficult to understand why the magnitude of the pressure fluctuations in the separated region is so large, and further work will be required on this problem.

Author

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1. Introduction

As the design of space vehicles becomes more and more dominated by non-aerodynamic requirements, it is hardly surprising that unusual, and sometimes unfavorable, regions of external flow occur. One of the important effects of these unfavorable flows is due to the aerodynamically induced pressure fluctuations which appear. These may cause excessive structural responses, and are the suspected cause of several catastrophic failures of space vehicles accelerating through the high q range.

In order to establish proper design criteria on the pressure fluctuation phenomena the designer will require information on four major parameters.

i) Position and Extent
ii) Magnitude
iii) Frequency Spectrum
iv) Correlation Patterns

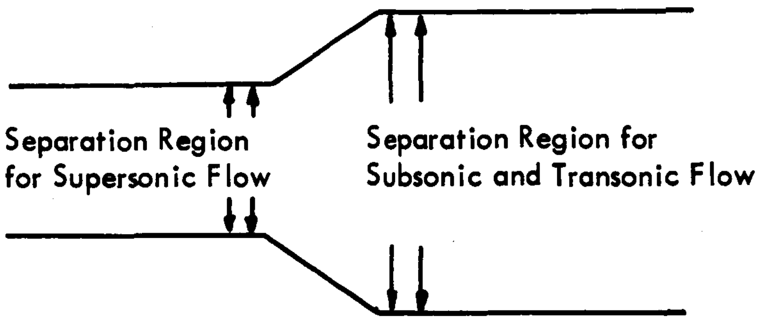
There is not sufficient information available at present to give definite values for any of the above parameters. Although the problem of the prediction of position and extent is somewhat simplified by the fact that mean flow parameters are often the only ones that need to be considered, even a prediction of mean flow will still represent a considerable problem in many cases. The magnitude of the fluctuations is usually found to be a direct function of the total head q and this dependence can be used in making predictions of the probable magnitudes of the pressure fluctuations. The various sources of pressure fluctuations that may occur are listed in Table 1 with their probable levels as a function of q.

Table 1 Sources of Pressure Fluctuations on Space Vehicles

Source	Ratio r.m.s. pressure to dynamic head	From reference
Oscillating Shock Waves	0.1	1
Separated Turbulent Flow	0.1	1
Cavity Resonances	0.03 - 0.06	2
Wakes from Protuberances	0.015 - 0.07	2
Base Pressure Fluctuations	0.015	3
Attached Boundary Layer Turbulence	0.005	2

A plot of total head over the Saturn vehicle during a typical flight is shown in Figure 1, taken from a report by Krause [4]. The free stream total head rises to a maximum near Mach 1.4. From this figure, it is clear that the total range of interest lies from M 0.8 to M 2.5 and includes both the transonic ($0.8 < M < 1.4$) and supersonic ($1.4 < M < 2.5$) regions. The frequency and correlation pattern of the flow represent very difficult prediction problems and a full determination will require an intimate knowledge of the mechanisms at work in the various flows. Consideration of these last two parameters will be deferred until a later place in the report.

As shown in Table 1, the most important sources of pressure fluctuations are separated turbulent flows and oscillating shocks, and attention will be focussed on these phenomena during this report. These two flow features usually occur together and it is not often possible to separate their effects. Boundary layer separation occurs when a surface flow encounters a sufficiently severe pressure rise. Such adverse pressure gradients will occur on a subsonic expansion or supersonic contraction of a flow.



Thus, Saturn type vehicles will tend to experience separations near the shoulders at subsonic speeds and in the compression corners of the flares at supersonic speeds. The transonic regime will be marked by a change from one flow pattern to the other. Experiments suggest that the separations are governed by the geometry of the shoulders up to about Mach 1.4. The values for magnitude of fluctuation for separated flow and oscillating shocks in Table 1 refer essentially to the supersonic compression corner cases. For the transonic cases Chevalier and Robertson report pressure fluctuations which reach peak to peak amplitudes of 0.43 q (Ref 5) and even 0.65 q (Ref 6) at Mach numbers of about 0.9. These values are borne out by the transonic experiments of Jones and Foughner [(7)]. Although the total head is higher in the higher Mach number range, the values of p_{rms}/q expected in the transonic case imply that both regimes will give significant magnitudes of pressure fluctuation. Therefore, it is convenient to consider the supersonic ($1.4 < M < 2.5$) and transonic ($0.8 < M < 1.4$) regimes of separated flow as separate cases, and consideration of the transonic regimes will be deferred until later in this report.

The supersonic pressure fluctuations are essentially associated with the flare compression corner as discussed above. Figure 2, also taken from Ref 4 shows the fluctuating pressure levels actually recorded during a Saturn flight by three transducers near the flare corner. There is an initial peak due to the rocket noise near the ground, but the maximum value is reached near M 2.0. Large amplitudes of fluctuation continue up to M 2.5, and may be partially explained by Figure 1 which shows a plot of the calculated local total head for the flare. The maximum local q is reached at about M 2.2. The high levels recorded by gauge D 159-20 are interpreted as the result of an oscillating shock at that location. The associated value of p_{rms}/q was calculated as 0.16 in Ref 4. The supersonic separated flows between Mach 1.4 and 2.5 are clearly a region of interest from the point of view of aerodynamic pressure fluctuations. The designers' immediate question will be as to the extent of this region of separated flow. This question is best answered by a consideration of the mean flow, and both theoretical and experimental studies of the mean 'steady' state will be required.

2. The Steady Separated Flow in a Compression Corner

In a supersonic flow there is a maximum angle, related to flow Mach number, through which the flow may be turned via a shock. The supersonic flows over a body, or over a part of a body, may be divided into two types corresponding to the surface flow being deflected more or less than this critical angle. This phenomenon is predicted by theoretical analyses which ignore the effect of viscosity, and the critical angle given by the inviscid theory for two-dimensional and for conical flow is shown in Fig 3. Experiment supports the theoretical predictions, and the two types of flow correspond to the well-known cases of the attached and detached bow shock as shown in Figs 4a and 4b. It is reasonable to extend these ideas to the case of flow in a compression corner as shown in Figs 4c and 4d. The flow in Fig 4d is separated, and since it is a result of the inviscid critical angle effect this type of flow may be termed an inviscid separation. Unfortunately, it is not apparent whether the conical or two-dimensional separation criteria give the best reduction for a cylinder/flare junction. The two-dimensional value applies infinitely near the corner, and the conical value infinitely far away. Some intermediate case will give the real criterion.

In any practical case, the flow, particularly that in the neighborhood of the wall, will be modified under the action of viscosity. In fact, even the cases corresponding to 4b are considerably affected by viscosity and the flow patterns in the 'inviscid separation' region of 4d will be governed by viscosity even though the primary agency may be found in the inviscid flow equations. Fig 3 shows that for any given flare angle there will be some minimum Mach number below which inviscid separation will occur, i.e. all flares on space vehicles will be in the inviscid separation regime at some period of the flight. There has been little published experimental work on this type of flow, but there are reasons, to be discussed later, why this flow may be unfavourable from the pressure fluctuations point of view. It is pertinent to note that the bodies in Fig 4a and 4c may be extended to infinity without effect on the flow field, whereas the flow field in Figs 4b and 4d will depend critically on the dimensions of the body or step normal to the direction of the free stream.

Turning now to the case shown in Fig 4c and considering the additional effects of viscosity, it is clear that unusual effects may be expected in the real flow at a compression corner. The approaching boundary layer will have a Mach number distribution from the free stream value down to zero at the surface. Clearly, at some point in the boundary layer the Mach number will fall below the critical value (Fig 3) required to negotiate the corner via a shock. From this point viscous reactions must assist the redirection of the flow. If the local viscous energy transfer processes are not sufficient then no attached traverse of the corner is possible and the flow will separate. Even if the flow does succeed in negotiating the corner without separation, the large pressure gradients normal to the surface caused by the shock-velocity profile interaction may still cause a substantial increase in turbulence level of the flow.

An alternative way of approaching the problem is to consider the pressure increase at the corner caused by the shock. It is well known, from both theory and experiment, that boundary layers are able to negotiate only small adverse pressure gradients. If the pressure jump caused by a shock is larger than that which can be taken by the boundary layer then the boundary layer must be expected to separate.

An extensive investigation of the separated flows over flares on cylinders has been reported by Kuehn (9). In his tests the flare height was large compared with the undisturbed boundary layer thickness, and the flare may be regarded as effectively infinite in these experiments. The flow patterns when the flare heights are of the same order or less than the boundary layer thickness will be discussed later. The basic structure of these 'infinite corner' separations may be ascertained from the photographs in Kuehn's report. The structure is essentially the same in axisymmetric (9) or two-dimensional (10) separations.

The basic flow pattern is a two shock structure as shown in Fig 5a. A main shock is centered on the intersection of the flare and cylinder and will be called the flare shock. A second shock extends forward and encloses a region of separated highly turbulent flow. This second shock will be called the separation shock. It seems reasonable to suppose that the separation shock corresponds to an increase of boundary layer displacement thickness which acts as a fillet between the cylinder and flare. In all the cases investigated by Kuehn both these shocks were substantially straight lines. The mean pressure pattern is shown in Fig 5b. A pressure rise starts near the projection of the line of the separation shock onto the surface of the cylinder, and this leads into a region of constant pressure often referred to as the plateau. The constant pressure region extends to near the corner where a second rise in pressure occurs leading to a peak located somewhere up the flare surface. The second shock, and the second pressure rise, can be associated with the re-attachment region.

Although the exact shape of the separation region is unknown, the concept of a 'separation stream-line' (8) is useful in a consideration of the basic separation processes.

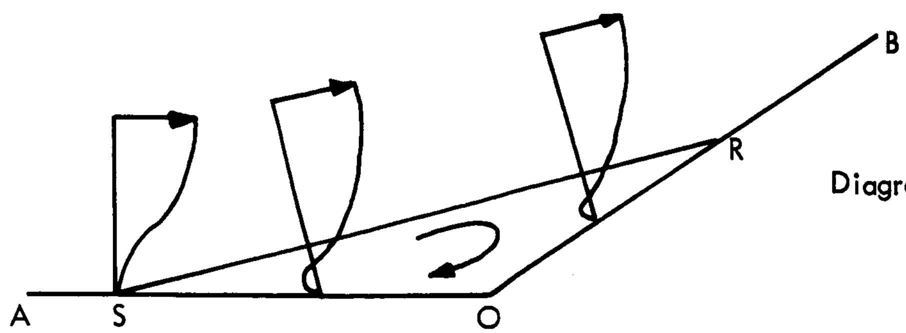


Diagram of the Separated Region

Typical velocity profiles for the separation region are sketched above with separation occurring at S and reattachment at R. A feature of the process is the reverse flow near the surface. A separation streamline SR can be defined as a line through which there is no net mass transport, and within the region SOR there will be a low velocity circulating flow. The external flow sees the surface as ASRB plus any displacement thickness effects of the velocity profile outside SR.

It is of interest to ask how this region SOR will vary for different separated flows, and in order to provide a partial answer to this question the data of Kuehn[9] have been re-analyzed. The results of the analysis are shown in Table 2.

Table 2 Analysis of Kuehn [9]

Kuehn's Fig No.	Flare Angle°	Mach No.	Reynolds No.	Flare Shock Angle°	Separation Shock Angle°	Peak Pressure Ratio	Plateau Pressure Ratio	δ	$\frac{h}{\delta_o}$	$\frac{l_s}{\delta_o}$
5a	20	2.18	8.4×10^4	39	--	2.6	--	0.149	7.64	--
5b	25	2.18	8.4×10^4	43.5	36	2.72	1.82	0.145	10.03	2.5
5c	30	2.18	8.4×10^4	48	37	3.25	1.93	0.140	12.87	5
5d	35	2.18	8.4×10^4	56	37	3.83	1.93	0.130	13.86	8.5
6b	35	2.5	1.1×10^5	--	31	4.83	2.12	0.138	?	8
7a	35	2.56	9.7×10^4	52	31	4.95	2.12	0.141	?	7
7b	30	2.95	9.7×10^4	43	26	4.98	2.2	0.164	?	2.5
7c	25	3.52	9.7×10^4	36	--	4.99	--	0.176	?	--
8a	30	1.79	8.3×10^4	--	44	2.7	1.75	0.124	14.5	9
8b	30	2.49	8.3×10^4	45	33	3.64	1.9	0.151	11.93	3
8c	30	3.31	8.3×10^4	43	29	5.92	2.4	0.169	10.66	1.5
8d	30	4.07	8.3×10^4	39	--	8.0	--	0.188	9.57	--
10a	35	2.92	3.4×10^4	49	--	6.0	2.7	0.159	13.75	2
10b	35	2.92	5.0×10^4	49	30	6.0	2.7	0.151	14.47	4
10c	35	2.92	8.3×10^4	50	29	6.3	2.3	0.148	14.78	7
10d	35	2.92	11.1×10^4	49	29	6.2	2.3	0.146	14.97	7
15d	30	3.3	7.9×10^4	43	28	5.82	2.4	0.169	10.66	2
15d	30	3.3	5.6×10^4	42	29	5.48	2.25	0.205	--	3
17b	30	4.1	8.0×10^4	39	--	8	--	0.188	9.58	--
17b	30	4.1	8.0×10^4	39	≈22	7.8	2.75	0.183	9.84	2

The leading parameters of the flow considered were the angles of the shocks associated with flare and separation, and the peak and plateau pressures recorded. The shock angles were measured directly from the photographs in Kuehn's report and will be subject to errors from the distortion of the schlieren system and printing processes, hence accuracy of more than a degree or so cannot be claimed.

The data are plotted in Fig 6 and an interesting result is immediately apparent. The flare shock angles fall into three families corresponding to the three flare angles, whereas the separation shocks show no consistent effect of flare angle on the results. Results [11] of an inviscid analysis for the shock angles in flow around cones of various semi-angles are also plotted in Fig 6. Since the observed flow has already been affected by the entropy rise of the bow shock, the cylinder/flare model is not exactly conical, and the flare boundary layer displacement effects are unknown, it is not surprising that the experimental and theoretical results are not in complete agreement. However, from Fig 6 an approximate law seems to be that the real flow over the flare is following a curve corresponding to about 3° extra flare angle. Using this we see that the separation region corresponds to an effective flare angle of about 17°, unaffected by Mach number or model flare geometry. This gives a very valuable simplification in the analysis of the mean flow. As a first approximation the turbulent separated flow field may be regarded as producing a 17° fillet between cylinder and flare.

The same analysis has also been applied to the measured pressure ratios. The separation pressure can only be properly defined for the larger separations, but for the smaller separations, e.g. Kuehn's Fig 7b, the value of pressure at the point of inflection of the pressure pattern near the second pressure rise has been taken. The pressure pattern on the flare is typically a rise to a peak followed by a slow falling away. This peak pressure has been taken as the characteristic flare pressure for no better reason than the fact that it can be defined accurately. The results are shown in Fig 7. Also shown are theoretical values for the surface pressure coefficient resulting from conical shock waves at various cone semi-angles [11].

It is arguable whether conical or two-dimensional results would provide a better comparison, particularly in the separated region near the cylinder. However, we can see that the conical results do correlate reasonably for the peak pressures. In any case, the important result of the plot is that again the peak flare pressures fall into three distinct families dependent on flare angle, while the plateau pressures show no dependence on flare angle. There is some scatter of the plateau pressure results, but no evidence of any one parameter in action, although Ref 8 finds that the plateau pressure reduces with Reynolds number. The 17° angle criterion is moderately successful, but there is a trend towards lesser pressures at high Mach number and high pressures at low supersonic Mach numbers.

The results do show conclusively that the larger separations recorded in Kuehn's work are 'free interactions', defined [8] as separations which are independent of downstream geometry. The criterion of a free separation affecting the external flow as a 17° wedge is new, and although it will not be true for all cases, particularly at low Mach number, it does provide a useful reference point for discussion.

We may now proceed with an analysis of the cases in which the flare height is small enough to affect the separation patterns. A useful starting point would be to analyse the flow about a forward facing step. This case has been investigated by a number of authors[1][8][12] although the most useful information appears in reference [12]. The flow pattern is significantly different from that appearing in Kuehn's work.

As shown by Figure 3 the step represents a change in flow direction that could never be accomplished via a shock. Consequently there is no flare shock, and flow pattern is governed by the single separation shock as shown in Fig 8. Re-attachment in this case occurs at the step via an expansion fan. As might be expected, the model geometry, i.e. step height, plays a significant role in determining the flow parameters. It is of interest to relate the results to the constant 17^o angle observed in the analysis of Kuehn's results.

Table 3 Flow Separation Angle for Flow over a Forward Facing Step

The angle, in degrees, is calculated from the data of Bogdonoff[12] using

$$\theta_{sep} = \tan^{-1}\left\{\frac{\text{Step Height}}{\text{Distance inflection point to step}}\right\}$$

h	M=2.35	M=2.9	M=3.85	
0.05	6.6	8.4	9	
0.1	8.9	9.1	10.1	
0.15	9.9	10.3	10.3	
0.2	10.4	10.4	10.4	
0.25	10.7	10.6	10.6	
0.3	10.9	11	10.9	
0.35	11	11.3	11	
0.4	--	--	11.1	
δ_s inches	0.162	0.214	0.074	For definition see text
Effective angle for all h	12.1^o	12.8^o	11.7^o	

Table 3 shows an analysis of some results from Bogdonoff's [12] paper. Since it is difficult to define the exact point at which the separation occurs, the criteria for the position of the separation need to be chosen so that a unique point may be clearly defined rather than attempting to predict the point of zero wall shear or some similar exact criterion. In this case the angle of the separation has been calculated from the ratio of step height to the distance between the lower point of inflection of the pressure distribution and the forward face of the step. It will be observed in Table 3 that the apparent angle reduces with reduction in step height. However, if it is arbitrarily assumed that there is some constant effective boundary layer thickness up the step (δ_s as shown) then it is found that for the value of δ_s given in Table 3 the angle of separation comes out very nearly constant at the angle shown. The validity of this form of analysis is unknown, but it does give a single uniform result for flow deflection angle.

The effect of Mach number of this angle is small, but the fact that it peaks at a Mach number of 2.9 is consistent with trends reported by Erdos and Pallone [13], although the source of their results is not entirely clear. Charwat et al [14] have also carried out analyses based on the pressures reported in Ref 8 and find angles varying between 10° and 14°. K. Johnston has made some preliminary analyses of the separated flows occurring in the tests at Ames, and one of his graphs is reproduced as Fig 9. This again indicates a constancy of angle of separation for a given step height. Note in Fig 9 that a change in flare angle from 45° to 90° seems to have a negligible effect on separation geometry. The trend to lower angles for Mach numbers below 1.6 is a consistent trend in all the reported data and may be accepted as an experimental fact. Clearly the representation of the separation as a constant angle fillet cannot apply at very low Mach numbers (< M 1.4 say) as the external flow would then undergo inviscid separation (c.f. Figs 3 and 4).

Figure 9 also shows an effect of step height (h) on the results. The result is not always duplicated in experiment, but it is believed to be a real effect, and shows a trend to approach the 17° value indicated by Kuehn's experiments for 'free interactions' at high step heights. Since the values of undisturbed boundary layer thickness (δ_o) are not currently available for the Ames tests a consideration of using h/δ_o as a unifying parameter must be deferred. Data in general report h/δ_o as a valid parameter for separated flows, e.g. Ref 14.

The peak pressure values found in Bogdonoff's experiments [12] are plotted in Fig 10. Theoretical values of the inviscid pressure increment for various flare angles are also shown. In this case the constant angle criterion is giving only moderate reduction of the data for various values of h/δ_o. In general the geometrical data for any given separation reduce well to give angular criteria, but the pressure data reduce less well. One reason for this may be that the pressure normal to the wall is not constant, as in an unseparated boundary layer.

A major point of interest in a separated flow is the extent of the separation. For flows over steps the question is already answered as it is given by the separation angle and the step height. However, for free double shock interactions as described by Kuehn [9], the problem poses difficulties. The difficulty of defining separation point has already been mentioned, however Kuehn has made estimates of the separation point in his report. The distance of this point from the cylinder-flare junction is given (to one significant figure) in Table 2. The figures show that separation length increases with

- (i) increase in flare angle (Fig 5 of Kuehn's [9] report)
- (ii) decrease in Mach number (Fig 8 of Kuehn's [9] report)
- (iii) increase in Reynolds number (Fig 10 of Kuehn's [9] report)

The first two effects might be expected from previous experience. However, it is surprising to find such a marked dependency of separation length on Reynolds number, although Kuehn did mention a similar effect in Ref 10 where he found a major effect of Reynolds number on the pressure rise for incipient turbulent separation. It is very desirable to find some physical reason for this marked dependence on Reynolds number.

One possibility is that the proper Reynolds number for a separated flow should be based on a typical velocity in the separated region, say $0.2U_o$, so that at low Reynolds numbers some sort of reverse transition is taking place, and part of the separation region contains laminar flow. This and other hypotheses could be investigated by tests at higher Reynolds numbers where, hopefully, the effect of Reynolds number will be found to be less marked. An interesting, though possibly fortuitous observation is that the separation length cannot be defined for the three lowest values of h/δ_o recorded in Kuehn's (9) work. (The value of Fig 15d is excluded since its boundary layer is not typical.) The prediction of turbulent separation length by Erdos and Pallone (13) does not tie in with these results. In their work the effect of flare angle is in agreement with Kuehn, but the effect of Mach number is reversed, and the effect of Reynolds number ignored.

The exact process by which the flow separates and reattaches is somewhat vague. It is known that at the separation point the velocity profile will contain a point of inflection, and that $\partial u/\partial y$ at the wall will equal zero. This velocity profile then develops into a reverse flow profile over some distance which is approximately equal to $3\delta_o$ where δ_o is the undisturbed boundary layer thickness. Analysis of Kuehn's data (9) indicates that this adjustment region increases in length as Mach number is decreased. The reattachment mechanism which has yielded the correct trends for the laminar separation case is that the velocity along the separation streamline increases until its total pressure is sufficient to balance the static pressure at the reattachment point. In order to obtain quantitatively accurate results some efficiency factor must be arbitrarily assumed, but the mechanism does seem reasonable. However, no estimate of the length of the reattachment region seems practicable with the present data. In fact, it is extremely difficult to provide any valid criteria for the position of the reattachment point.

From this discussion, it is now possible to make some general predictions about the separated flow pattern that will occur for any given flare geometry and Mach number. The first consideration is whether the flow is liable to an inviscid separation (Figs 3 and 4.) This will depend on Mach number and flare angle. If the flow is liable to inviscid separation then the flow pattern will be similar to that over a step with a single shock and parameters depending on the ratio h/δ_o as shown in Figs 9 and 10. If inviscid separation is not expected then a double shock flow like those investigated by Kuehn will result. The exact length of the separation region cannot be predicted at this stage, but it is possible that the step height would be too small to enable the full flow to form, and the flow would thus appear as identical to an inviscid separation. In both types of separation the effect of flare angle will be small, unless the angle is approaching 15^o or less. This is shown by the analysis of Kuehn's data for the double shock case, and by Fig 9 for the single shock case.

3. Theoretical Work on the Mean Flow

It is desirable to have theoretical predictions against which experimental data on turbulent separations can be compared. Unfortunately, little theoretical work is available. Ref 13 presents a theory which results from extensive linearizing and employment of a large number of empirical conditions. Some work on laminar separations has met with moderate success, the most thorough analysis being that of Lees and Reeves [15]. Their work gives a clear indication of the importance of choosing the correct family of velocity profiles in any theoretical study. For this reason laminar calculations cannot be extended to turbulent flow as suggested by Pinkus [16] for example. Unfortunately, there is no information on the nature of the correct profiles for turbulent separated flow. One approach is to use profiles which have proved successful in studies of other turbulent flows in an analysis of the turbulent separation. An interesting paper on these lines is that by Dem'ianov and Shmanenkov [17]. Their method relies on extension of Tollmein's work on the turbulent shear layer [18]. In this and other Russian work the existence of separated flows at constant angles is taken for granted. It seems surprising that this view of the flow has not developed in Western literature.

It will be recalled that the analysis of Kuehn's work indicates that the separated region was equivalent to a wedge of approximately 17^{o}. Dem'ianov and Shmanenkov [17] predict that the separated turbulent flow will form a constant angle of 17^{o} 42' ! In addition, they predict that the maximum negative velocity in the stagnation region is $0.207U_o$. Unfortunately, although the angular result is highly encouraging, there are a number of basic short-comings to this method. All the velocity profiles are assumed similar, and also the velocity is assumed constant on straight lines through the separation point. Neither of these assumptions agree with experiment. Further, they assume that the separation region has a finite negative velocity at the wall. Although this effect will not occur in a real flow, the effect of this assumption on the total solution may not be large. The theory also neglects the effect of the approaching boundary layer.

With these assumptions, it may be reasonable to suppose that the theory gives the development of the separated region under constant pressure in positions remote from the separation or re-attachment point. Kuehn's work was on flows where the influence of the separation and re-attachment points were minimized, and this may give part of the reason for the agreement of experiment and theory. However, the theory of Ref 17 is not amenable to prediction of the effect of h/δ_o on the separation region, nor will it enable estimates of the separation length to be made. Neyland and Taganov [19] have extended the work of Ref 17 to give a family of profiles corresponding to various magnitudes of negative velocity in the separated region. The authors' own interpretation of their results seems somewhat dubious, but this extension does provide a possible starting point for a more complete theory. The same authors have published a further paper on the subject [20]. This paper is difficult to analyse since the calculation methods are not described and little attempt is made to correlate the results with experiment. One interesting result is that the flow reattaches at a maximum angle of 13^{o}.

A difficulty in the theoretical work is the lack of sufficiently detailed experimental data in the separated flow region. The problem of choosing a correct family of profiles to start a theory has already been mentioned. The lack of data to which the theoretical results may be compared is equally inconvenient. It is hoped that Wyle Laboratories' program which includes both theoretical and experimental work will enable a more satisfactory position to be reached in the near future.

4. The Pressure Fluctuations in the Supersonic Separation

Little information on the pressure fluctuations in supersonic turbulent separated flow is yet available. The only published account is due to Kistler [1]. Some information is also starting to appear from the current series of tests at Ames Research Centre. All these tests are on the step-induced single shock wave type of separation (Figure 8). Actual separations may be of the single or double shock wave type (Figure 5). In the second type there is the possibility of two oscillating shock waves, each producing large fluctuating pressures. Examination of Kuehn's [9] shadow graph pictures shows that there are often many small sub-shocks within the separation region, which must be assumed to be moving and hence causing intense pressure fluctuations. The need for comprehensive tests covering this type of flow is apparent.

A plot of the rms pressure fluctuation level found in Kistler's experiments is shown in Figure 11b. Also shown are the rms levels resulting after filtering out the low frequency content. This is assumed to correspond with the removal of the oscillating shock effects. Figure 11b indicates that the initial peak magnitudes near the front of the separation region are due to the oscillating shock effects, whereas the even higher levels reached well within the separation region are due entirely to the separated turbulent flow. If this is so, then clearly both sources of fluctuation are worthy of investigation. However, there is probably considerable coupling between the two effects. Kister's work [1] was aimed at an intensive investigation of a few cases and no variation of step height was made. Results of an analysis by K. Johnson showing this effect from the Ames results are shown in Figure 12. Two conclusions may be drawn, firstly that the magnitude of the pressure fluctuations increases with step height, and secondly that the maximum for all cases occurs near Mach 2. The correct parameter for the variation of step height is probably the ratio of step height to undisturbed boundary layer thickness.

Kistler has made an analysis of the magnitude of the peak rms pressure level near the separation point, i.e. in the region of the oscillating shock. He relates the peak magnitude to a step like change in pressure between two levels. The low level corresponds to the static pressure before the separation, i.e., the forward limit of shock oscillation, and the high level to the static pressure at the point in the separation at the backward limit of oscillation. This interpretation is reasonable and Kistler shows that it gives consistent results for both the static and fluctuating parts of the pressure. It also agrees with similar interpretations made in Refs 5 and 6. However, one additional conclusion of Kistler does not seem justified. He claims to relate this second pressure to an inflection point in the mean pressure distribution which does in fact show on his Figure 1. (Figure 11a of the present report.) However a plot of the same (presumably) distribution in his Figure 2 does not show this inflection point, and neither is it noticeable in the published results for step induced pressure fluctuation e.g. Ref 8, as he claims.

All that can be concluded at the moment is that the pressure fluctuates between the static pressure exterior to the separation and some high proportion of the maximum pressure recorded within the separation. It will be recalled from Table 3 that the separation was found to occur at an approximately constant angle between 10° and 15° for a step. Kistler's results correspond to an angle of about 12.5° at M 3.01 and 11° at M 4.54. The value of the inviscid static pressure rise due to a wedge of any given angle is known from theory and will give a first estimate of the probable magnitude of the peak to peak pressure fluctuations for a separated case. Figure 13, from Ref 11, shows the ratio of the pressure difference to total head as a function of wedge angle and Mach number. It seems that the highest values of p_{rms}/q may be expected in the range M 1.5-2.0. Amplitudes (based on square waves) of 0.2q seem quite possible. Note that both this argument and Fig 12 indicate the probable maximum magnitudes near Mach 2. This coincides with the Saturn range of maximum total head.

5. The Transonic Case

Theory and experiment show that shock waves may be divided into two classes as 'strong' shocks and 'weak' shocks. The pressure fluctuations for the supersonic case are caused by the oscillations of weak shocks, and consequently, the values of p_{rms}/q are moderate. The pressure fluctuations in transonic flow are associated with strong shocks and this accounts for the high values of p_{rms}/q recorded in transonic buffet tests. Transonic flow in general presents exceptionally difficult theoretical problems, and transonic prediction techniques are invariably based on very extensive experimental work. There is no reason to expect that the prediction of transonic pressure fluctuations will depart from this pattern. Figure 14 shows sketches of the shock and separation pattern of transonic flow on a Saturn model taken from shadowgraphs in Ref 7. Any asymmetry between the top and bottom surfaces e.g. behind the forward shoulder at M=0.9, probably implies oscillatory phenomena. Clearly the possibility of predicting the flow field in detail is remote. Even prediction of mean shock portion is formidable.

Fortunately, from our point of view, transonic buffet has presented an important aerodynamic problem for several years, and consequently a good foundation of experimental experience is available. Transonic tests on space vehicle models are reported in Refs 5, 6 and 7, and Ref 5 contains a useful definition of the problem into three areas. Figure 15 is taken from Ref 5 and shows (a) the flow separating at the shoulders for low subsonic Mach number, (b) the flow attached at the shoulders but with a probably oscillating shock positioned downstream, and (c) the intermediate case of alternating flow separation and attachment as the flow oscillates between conditions (a) and (c). The highest levels of fluctuating pressure are found for case (b), generally near M 0.9. In this type of flow the shock wave and separation should not be disassociated.

Although this breakdown is helpful, the difficulties of applying it to a real flow as in Figure 14 are still considerable. It is probable that every shock visible in Figure 14 has some oscillation near the surface which could cause unfortunate effects in particular circumstances. Some prediction of magnitude may be obtained from the experimental work, but an additional important parameter is frequency. Ref 5 indicates that the oscillating shock and separated flow phenomena are essentially random for the large fluctuation cases, but it is conceivable that discrete frequency input from some part of the system could cause a damaging oscillation of definite frequency. Some of the shocks existing on vehicle are probably associated with discrete or quasi-discrete frequencies, particularly since a definite frequency seems to be associated with the supersonic case [4]. As has been pointed out previously, transonic shocks are essentially associated with the shoulder and supersonic shocks with the flare. It is very desirable to investigate the mutual interaction of flares and shoulders in transonic flows and to find the effect of flare-shoulder distance for example. It is possible that some combination of flare-shoulder geometry and Mach number would lead to particularly severe fluctuation as a result of the interaction of several inherent types of separated flow pattern.

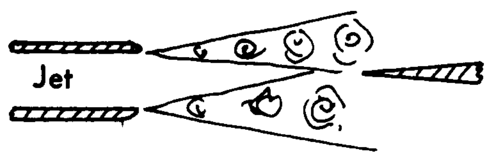
6. Mechanisms within the Fluctuating Region

In order to make any estimate of the frequency or correlation patterns of the flow it becomes necessary to know something of the mechanisms which cause the pressure fluctuations. The following discussion is intended to point out the various mechanisms that could exist and, where possible, how they might be distinguished. The fluctuations may be either random or contain discrete frequencies. The balance of the experimental evidence to date indicates that transonic oscillations are random [5] and that it is the supersonic separations which possess discrete frequencies [4]. The mechanisms causing discrete frequencies are generally of more interest and will be considered first.

A separation is a naturally unstable phenomenon. The velocity profile at separation contains a point of inflection and it was shown in 1880 by Lord Rayleigh that this provides a necessary condition for inviscid instability. Tollmein showed that all boundary layer profiles with points of inflection were unstable. A theoretical discussion of these phenomena appears in the Chapter by Stuart in Ref 21, and experiments by Nikuradse indicating the occurrence of separation instability at low speeds are reported by Schlichting [22]. It is of interest to note that the inflection point criterion also implies instability of the reattachment point. These instabilities imply frequency boundaries which may be of relevance in the prediction of the frequency spectrum of separated flows and oscillating shocks. Trilling [23] has produced a theory which shows the natural instabilities of a shock wave/laminar boundary layer interaction. His analysis includes much simplification but the fact that he was able to predict instability frequencies is in itself significant. The extension of this work to a turbulent case is not obvious.

Both of these mechanisms give rise to instabilities depending only on parameters near the separation point. However, there is a further class of possible mechanisms which depend on interaction of the whole separated flow region.

The most obvious mechanism involves acoustic resonances of the flow region. One may imagine the oscillation sending out sound waves which are reflected from the step or flare and return to provide the triggering mechanism for the next phase of the cycle. The frequencies in this case would depend upon the separation length and the local speed of sound. However, the local speed of sound depends on the local temperature, which may be very different from the free stream temperature. It will therefore be necessary to make measurements of local temperature before the possible existence of this mechanism can be determined. Another mechanism which is extremely common is acoustic phenomena is the vortex/sound wave interaction which has been exhaustively investigated by Powell. An abbreviated summary of his work appears in Ref 24. A typical process is in the 'edge-tone', which gives rise to high levels of acoustic power in whistles, for instance. The mechanism of the edge-tone is as follows.



A sharp edge is placed in a jet of air. Eddies (vortices) develop in the shear layer and proceed with the flow until they meet the edge where an acoustic pulse is developed. The acoustic pulsefeeds back to the jet exit and triggers the development of the next eddy. The total feedback loop is characterized by vortex action in the downstream path and acoustic action in the upstream path. This process occurs in many aero-acoustic phenomena, including the 'screeching' of jet engines, all reed type wind instruments, whistles, the discrete frequency noise of jet ejectors, cavity resonances, etc. It is a likely mechanism for many oscillating shock/separated flow phenomena. An unfortunate characteristic of this mechanism is shown in Fig 16 taken from a characteristic edge-tone phenomena of Ref 24. The frequency, although definite, may occur on a number of different branches. These branches correspond to a different number of vortices in the downstream path. Close control of experimental conditions is required in order that the scatter is reduced sufficiently to render each branch of the solution distinct. Often there is a possibility of two or three distinct frequencies at any given mean flow condition depending on how the flow was set up.

As was mentioned above, the possible mechanisms of oscillation fall into two groups, one dependent only on local parameters near the separation point, and the second involving the whole flow region. It is reasonably simple to devise experiments which will indicate to which group the oscillatory phenomena observed belong. An important parameter of the first group must be boundary layer thickness. If an artificial thickening of the boundary layer causes a marked change in frequency, then it is likely that the oscillation mechanism is in the first group. A very strong indication of this will occur if the frequency change is actually proportional to boundary layer thickness. The second group of mechanisms will be dependent on the distance from the oscillation point to the corner. The experiments to determine membership of this group are best done with a forward facing step in the first instance, as this will provide a definite regeneration point for the return path. The separation length is generally proportional to step height, as shown above. Thus if the frequency of oscillation is found to depend significantly on step height, the mechanism is probably in the second group described. The exact mechanism can then be elucidated by further analysis, e.g. an investigation of the phase of the oscillation frequency down the separation region. An analysis by K. Johnston indicates that the magnitude (see Fig 12) and extent of the oscillation is dependent on step height. Although the frequency would be a more critical parameter, this effect would tend to indicate the second group of mechanisms as being the more likely. On the other hand, Bogdonoff (12) thought that the extent was proportional to boundary layer thickness. Clearly, more information will be required.

The other possibility is that the oscillation is random. In that case the frequency spectrum may be predicted theoretically, and is in fact the 'random telegraph signal' reported by Rice [25]. Fig 17, taken from Ref 5, shows this theoretical spectrum together with a typical actual transonic spectrum. It is apparent that this transonic phenomenon was random. Frequency spectra with the general shape shown in Fig 17 are good indications of random phenomena. However, discrete frequencies are easily masked under pseudo-random conditions and some caution should be observed in reaching a conclusion. It may be desirable to conduct some tests incorporating discrete frequency excitation at various points of the separation - representing panel flutter for instance - since the separation may be quick to couple with such inputs.

The other major source of pressure fluctuations is due to the turbulence within the separated region. Kistler's [1] work indicates that the pressure fluctuations due to this cause may be even higher than those due to oscillating shocks. The frequency specimen of this excitation will probably be broad, and the correlation pattern will be that typical of convected eddies. Kistler's work indicates that the mean convection velocity is about 0.6 of the velocity outside the boundary layer at all positions through the separated region. The magnitude of these turbulent pressure fluctuations is high, and it is difficult to understand the mechanisms behind it. The only reported work containing pressure fluctuations of the same order of magnitude is in the 'wall jet' [26]. A close comparison of these two cases, the separated flow and the wall jet, may reveal a parameter in common which is the cause of the high levels of pressure fluctuation. One possibility is the presence of a point of inflection in the velocity profile for each case. A theoretical investigation of the pressure fluctuations in turbulent flows should also give an indication of the leading causes of pressure fluctuations in the separated region.

7. Conclusions

Relatively little information on the aerodynamically induced pressure fluctuations on space vehicles is at present available, and final conclusions cannot be drawn at this stage. However it is clear that the major sources of pressure fluctuation will be in the regions of separated flow and oscillating shocks. The phenomena are conveniently divided into two regimes, the transonic ($0.8 < M < 1.4$) and supersonic ($1.4 < M < 1.5$). Phenomena in the transonic regime are best investigated by experiment, and the experience gained in the testing of aircraft and other transonic models will be of basic value. The evidence indicates that on the fluctuation phenomena in the transonic regime will be essentially random, and governed by the geometry of the shoulders. In the range $1.1 < M < 1.4$ the mutual effect of shoulder and flare may be important.

In the true supersonic range ($1.4 < M < 2.5$) the separation and its associated shocks will occur in the compression corners of the flares, and the shock oscillation may occur at discrete frequencies. The separation in the supersonic range may be divided into two classes. The first class has one shock associated with separation and a second shock with reattachment whereas in the second class reattachment is associated with an expansion fan. The first class, with two shocks, corresponds to corners which are large compared to the undisturbed boundary layer thickness and have flare angles which are not large enough to provoke inviscid separation. The separation in this case has the effect on the external flow of a 17^{o} fillet between cylinder and flare. The effect of Mach number, Reynolds number, and flare angle seem to have a significant effect only on separation length. The effect of Reynolds number will be particularly relevant to experimental work. The second class of separated flows, with a single shock, correspond to small ratios of step height to undisturbed boundary layer thickness and to flare angle /Mach number combinations which provoke inviscid separation. Reattachment for this class occurs at the top, expansion, corner and the position of this point will dominate the flow. The separation region will form an angle of approximately 12^{o} in front of the corner, but the exact value of the angle will depend on the ratio of step height to boundary layer thickness. For small values the angle tends to about 10^{o} and for large values the angle will tend to 17^{o}, as in the first class. For either class the effect of flare angle will be small unless it is less than about 15^{o}, or the Mach number is low.

It would be desirable to produce a theory for the mean flow showing the effects described above. A body of Russian work showing a possible simple approach has been described, and an alternative is the extension to the turbulent problem of the well developed, but complex, theories for laminar separation. In either case more detailed experimental information on the mean flow field will be required before a successful theory can be compounded.

The fluctuating pressures in a region of supersonic separated flow have been investigated by Kister (1), and he has shown that both oscillating shocks and convected turbulence in the separated region can cause high levels of fluctuating pressure. Using his analysis of the oscillating shock phenomena together with the constant angle results reported above, it is possible to make a preliminary estimate of the probable magnitudes of pressure fluctuation. It seems likely that maximum values of p_{rms}/q will occur near M 2.0. This agrees with an analysis of data from the Ames test and coincides with the max q range for Saturn. It is therefore possible that Saturn type vehicles will encounter particularly large aerodynamic pressure fluctuation phenomena.

Possible mechanisms causing discrete frequency oscillations have been discussed, and have been divided into two classes. The first class depends on local conditions at the separation point, in particular on undisturbed boundary layer thickness. The second class depends on the whole separated flow, in particular on separation length. An experimental investigation of the effect of these two reference lengths on the discrete frequencies observed should indicate to which class the oscillating mechanism belongs. However it is still difficult to understand from first principles the reasons for the occurence of such large pressure fluctuations in the separated region since these are presumably due to the convected turbulence. Further work will be required on this problem.

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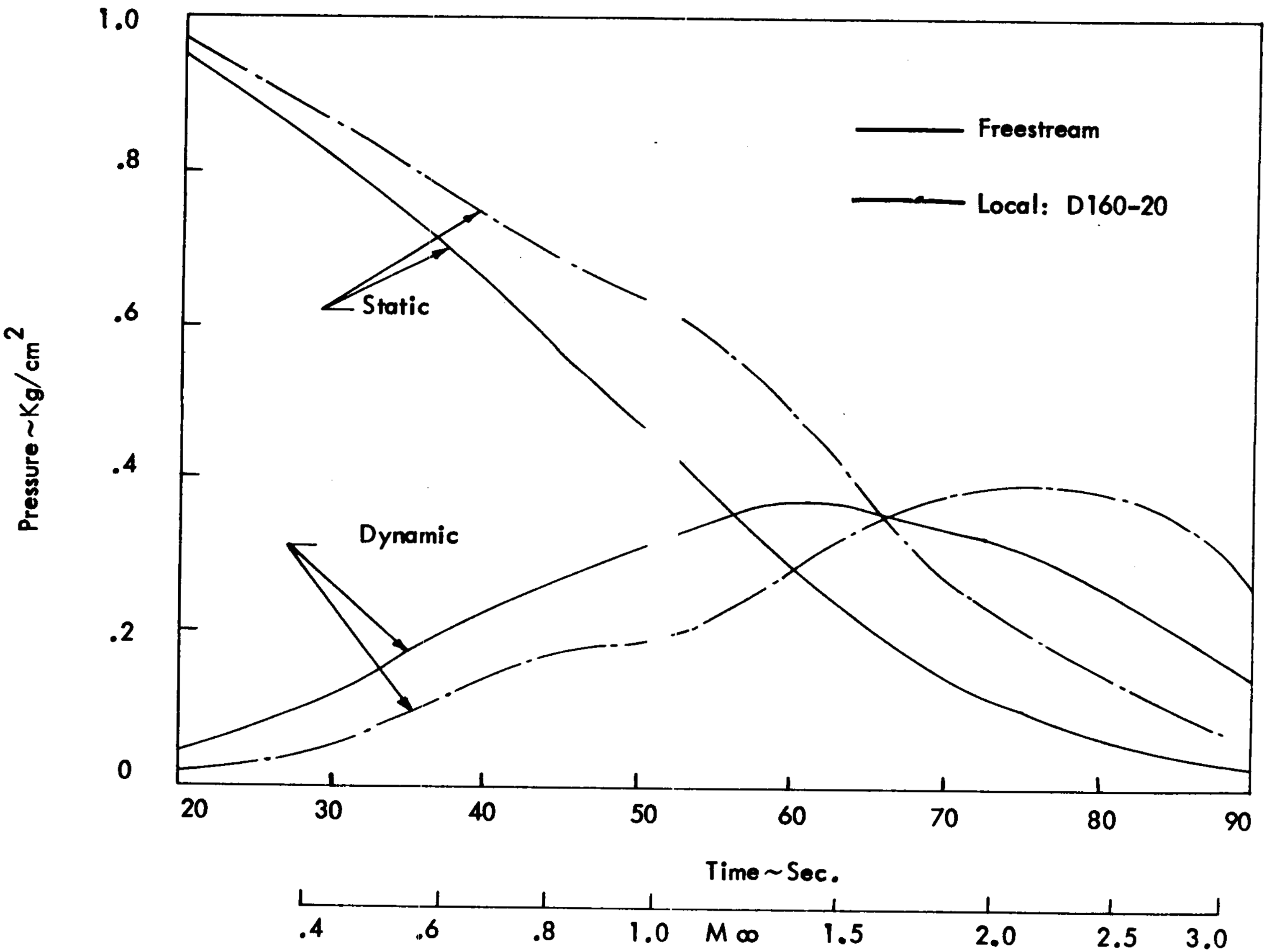


Figure 1: SA - 4 Flight Local and Free Stream Pressures From Flight Trajectory From Ref 4.

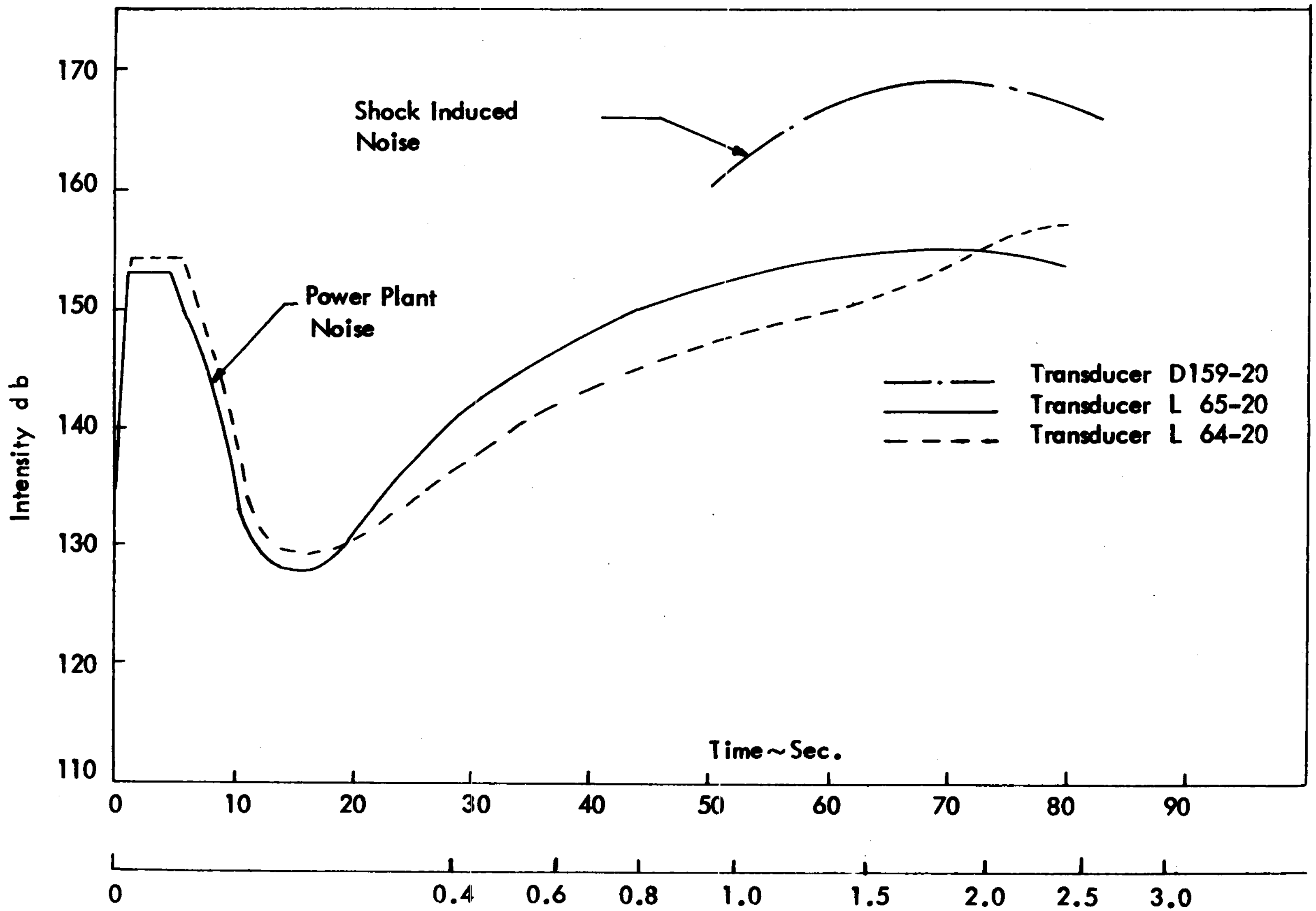


Figure 2 : Root Mean Square Pressure Fluctuations During SA-4 Flight From Ref 4.

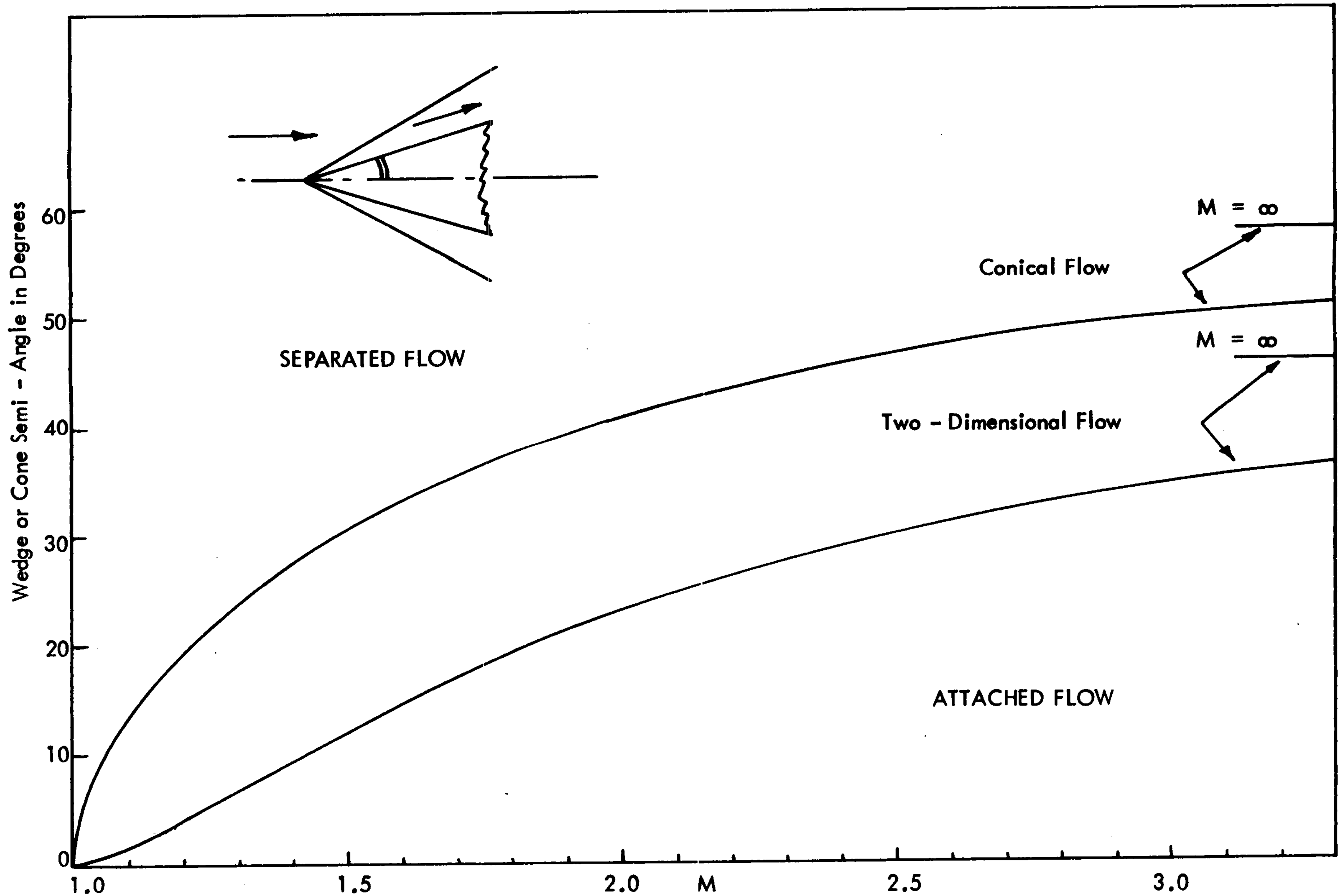


Figure 3 : Critical Angle for Inviscid Separation

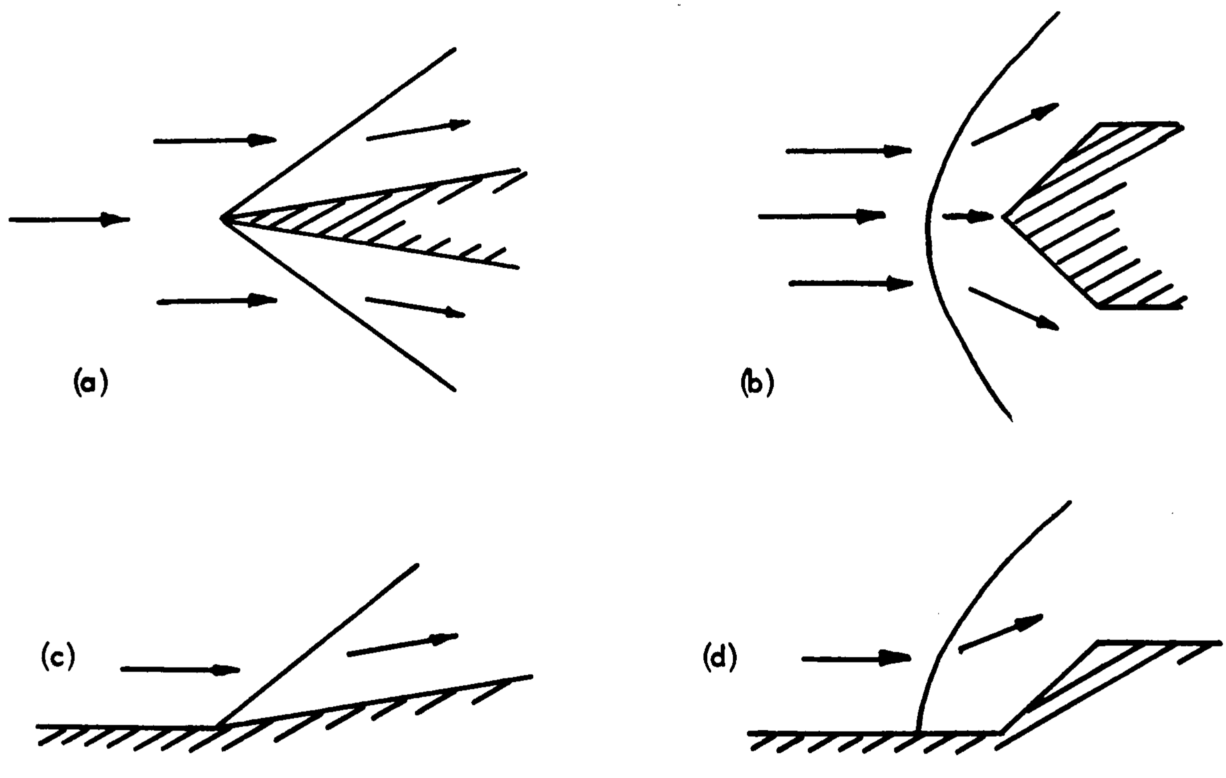


Figure 4 : Types of "Inviscid" Flow

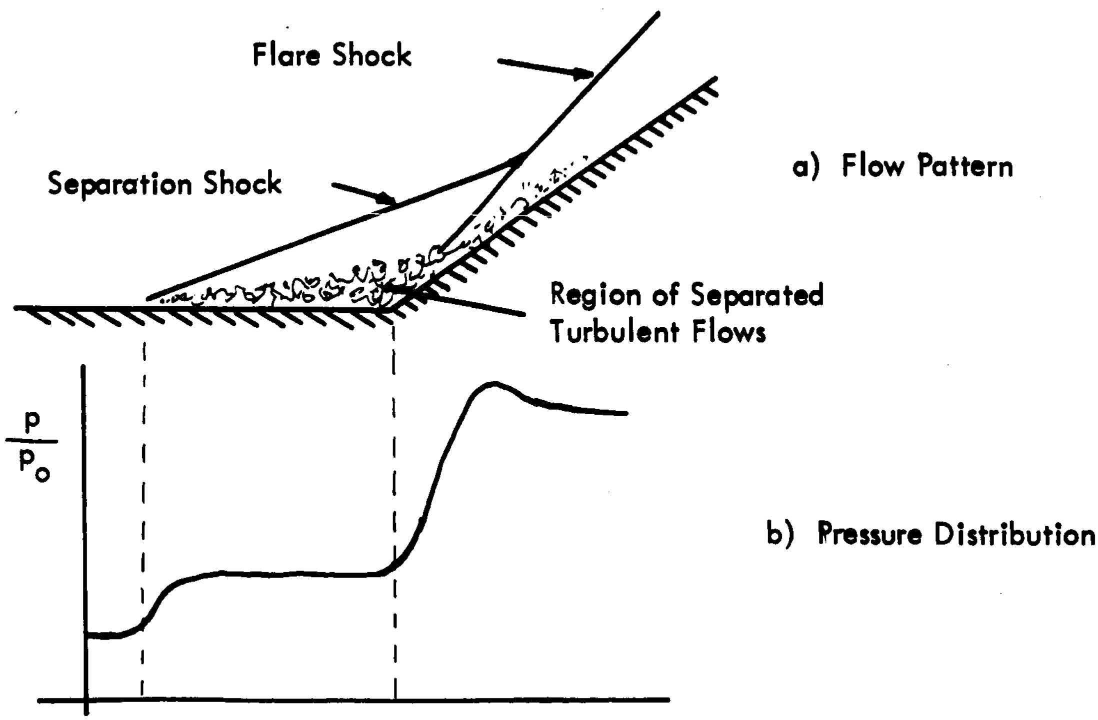


Figure 5: "Two-Shock" Separation Flow in a Compression Corner

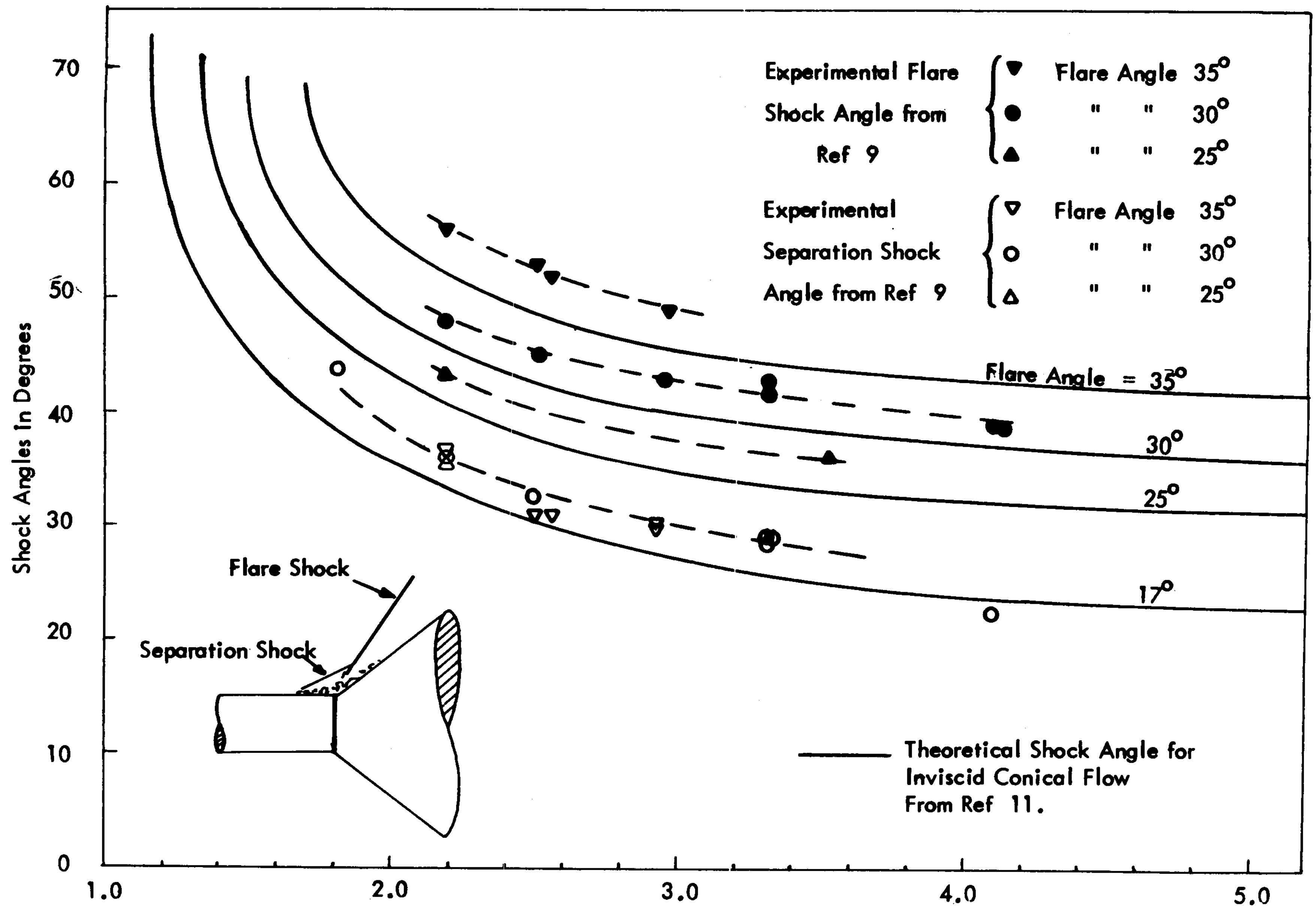


Figure 6 : Shock Angles vs Mach No. For Various Flare Angles

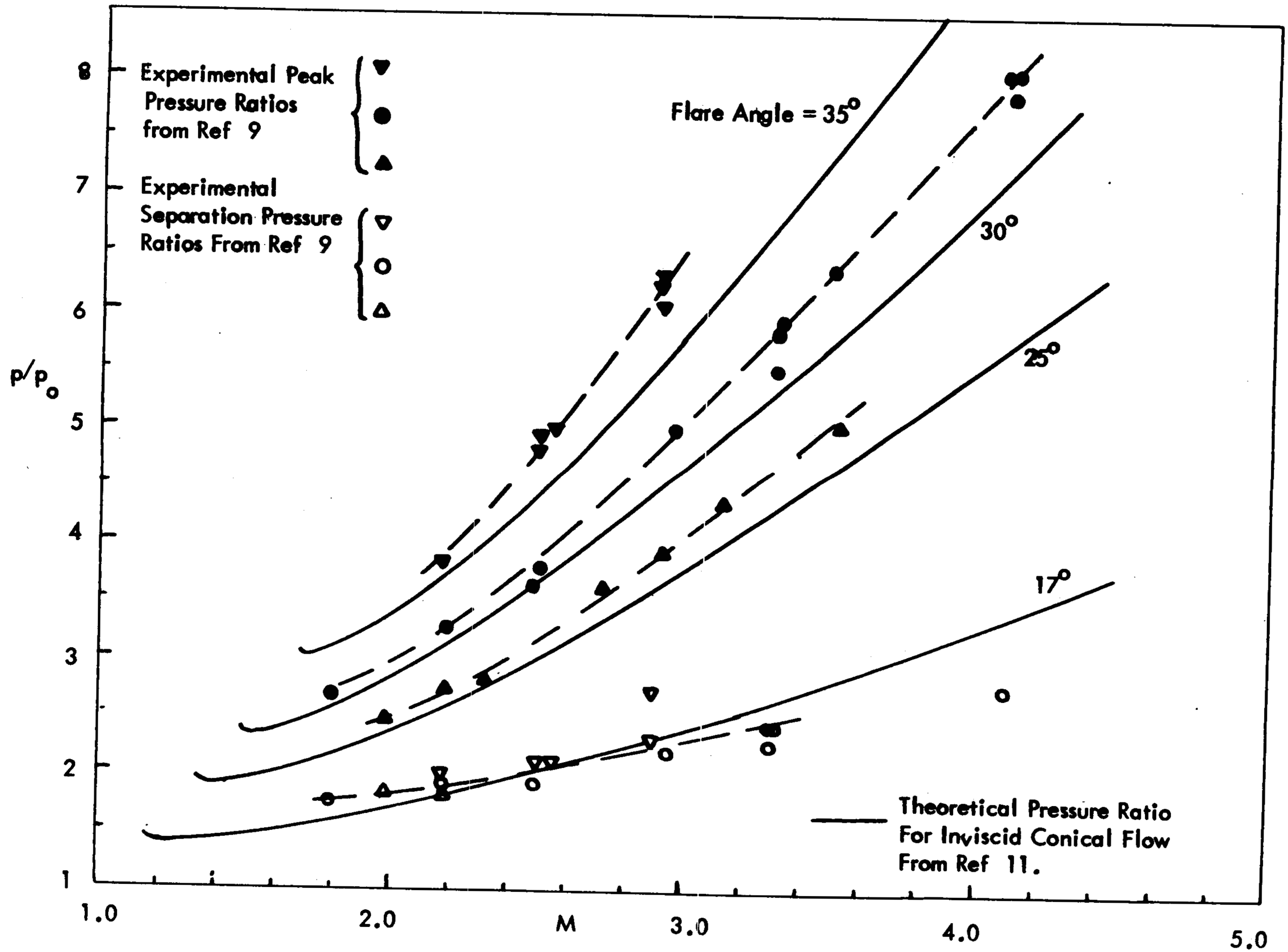
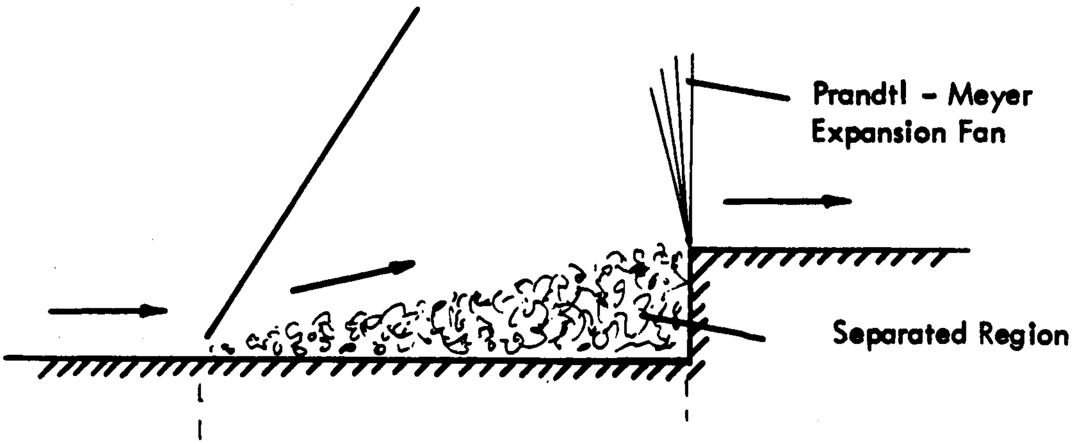
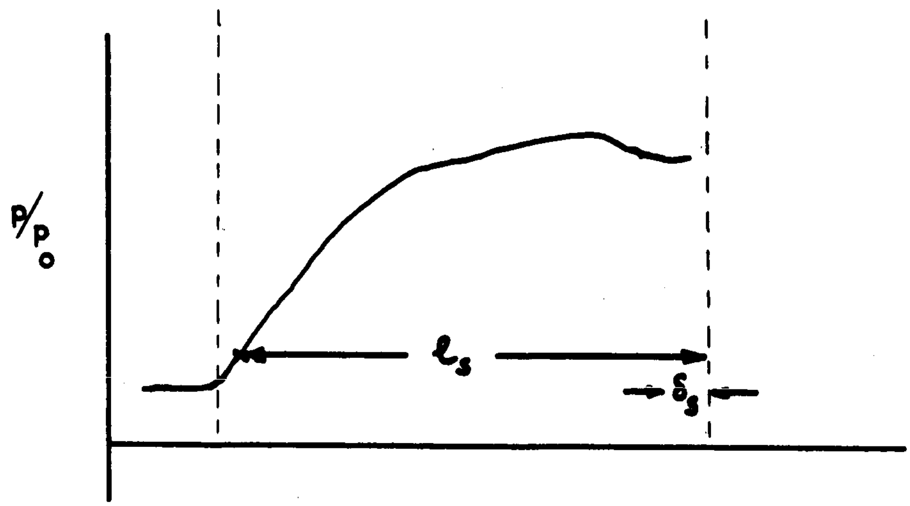


Figure 7: Pressure Ratio vs Mach Number for Various Flare Angles



a) Flow Pattern



b) Pressure Distribution

Figure 8: "Single Shock" Separated Flow Around A Forward Facing Step

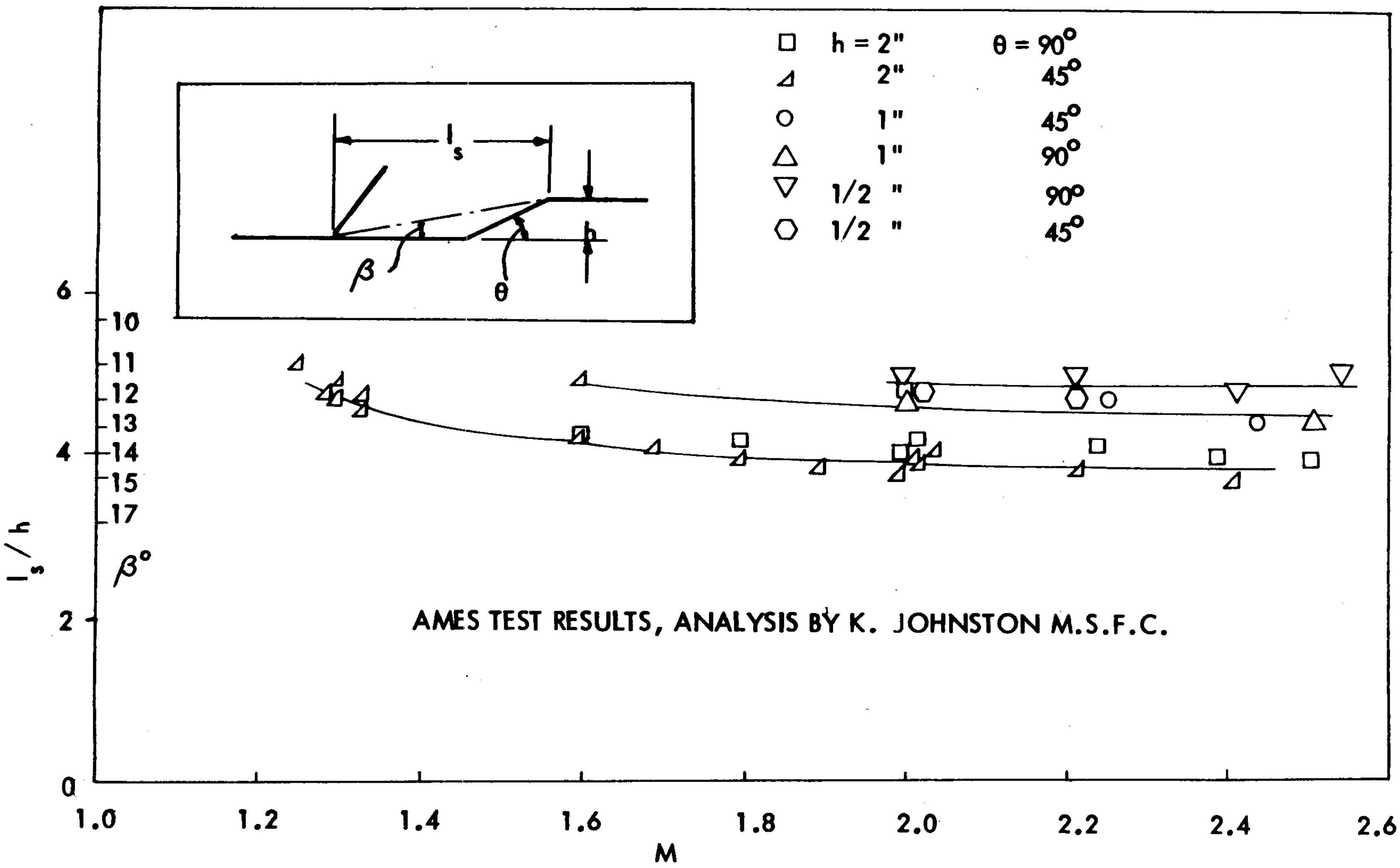


Figure 9 : Separation Length vs Mach Number

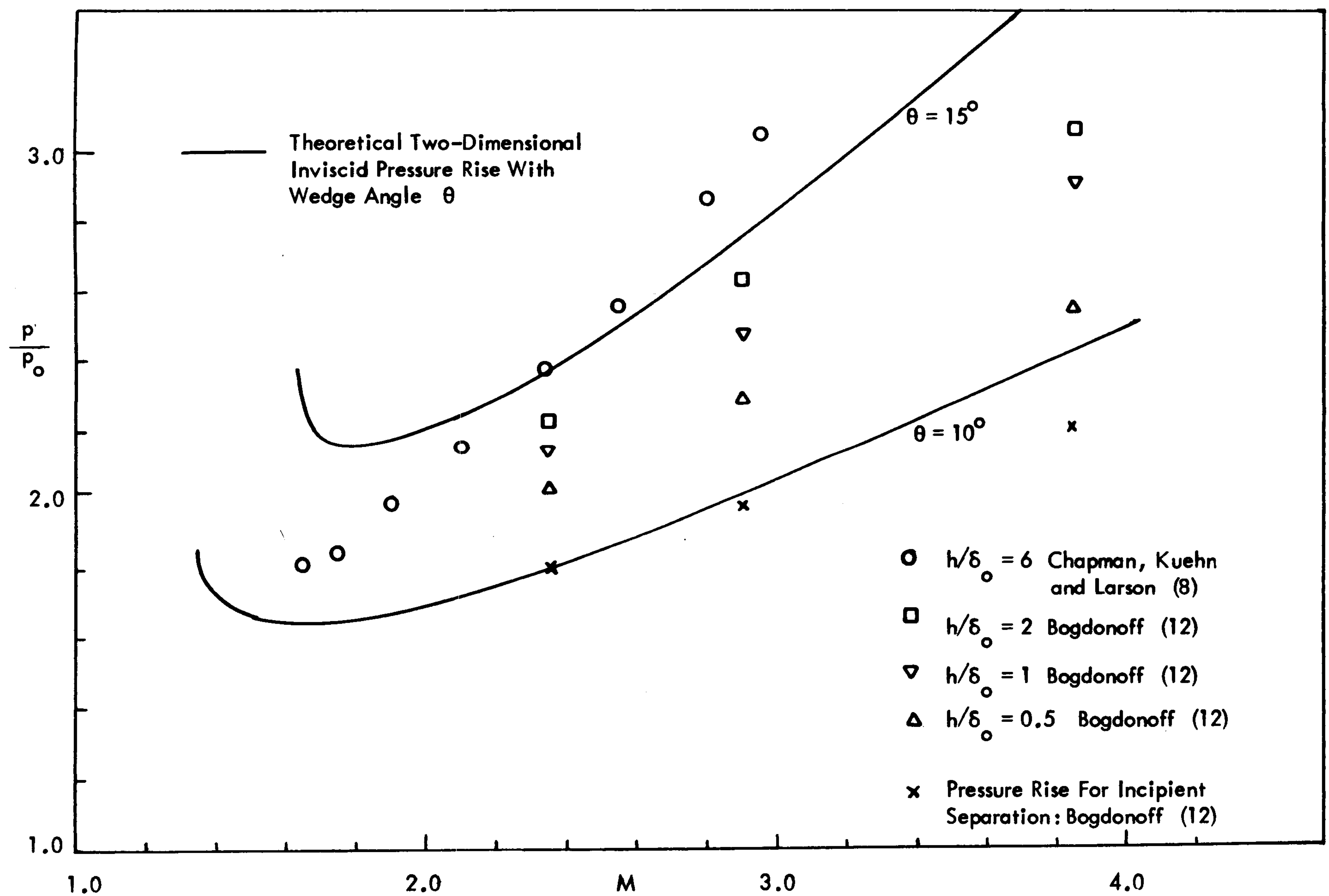
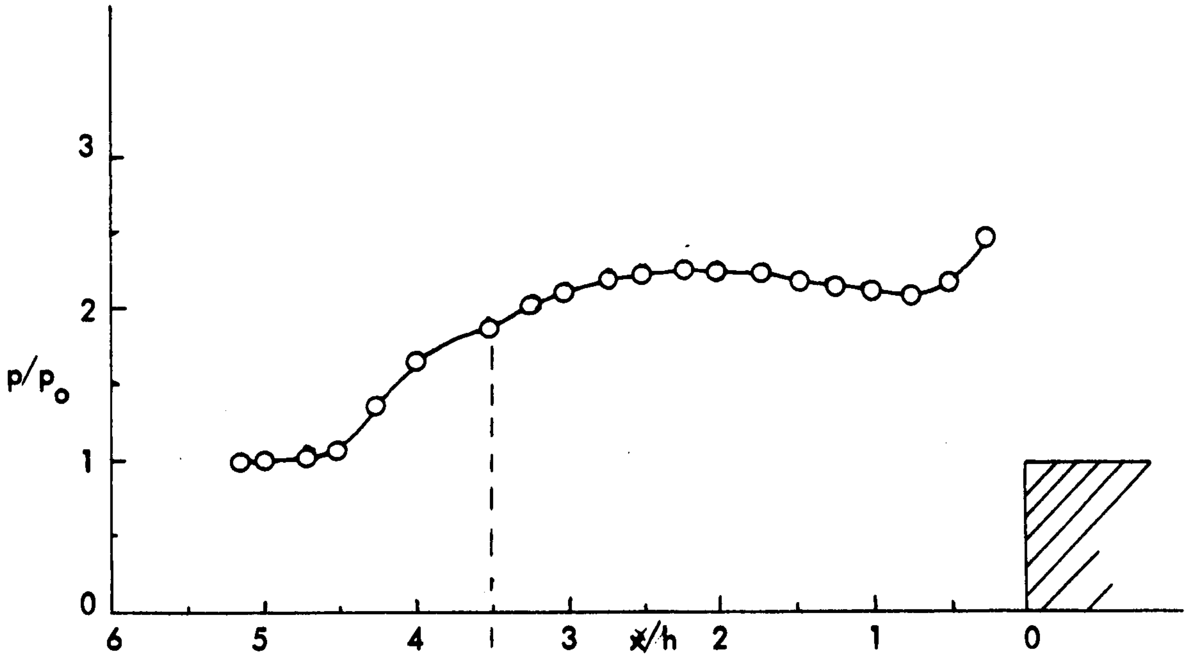
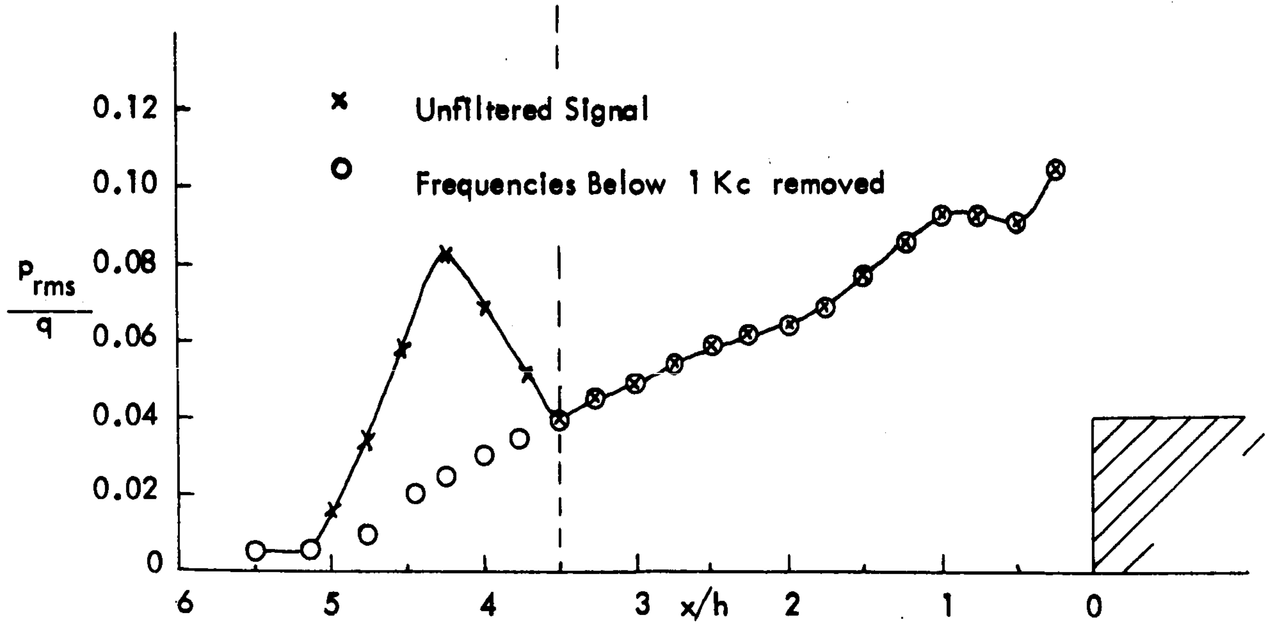


Figure 10: Peak Pressure Ratio vs Mach Number For Forward Facing Steps



a) Mean Pressure Distribution



b) R.M.S. Pressure Fluctuation Level

Figure 11: Kister's Results (1) For a Forward Facing Step M = 3.01

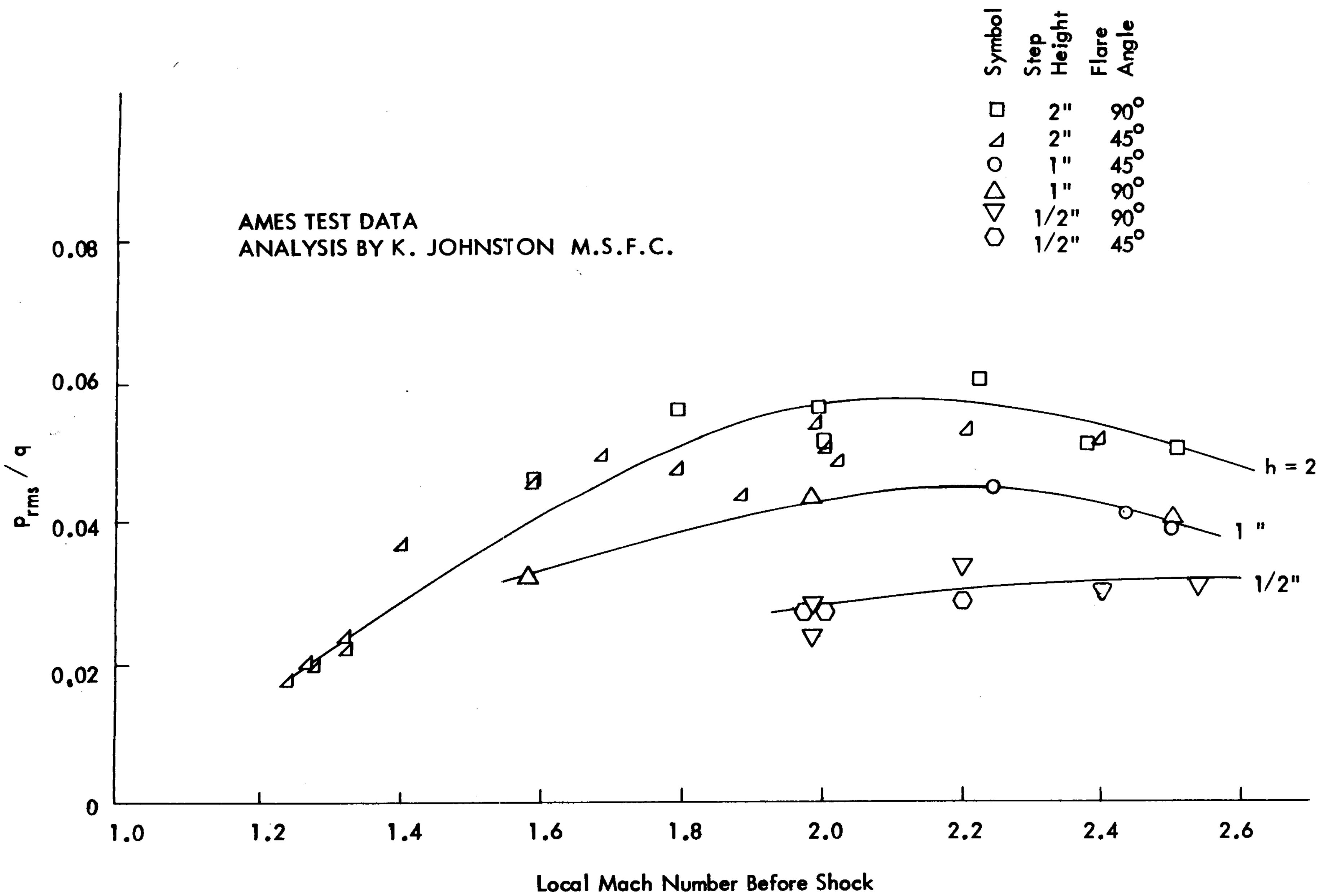


Figure 12: Forward Peak Pressure Fluctuation Level vs Mach Number

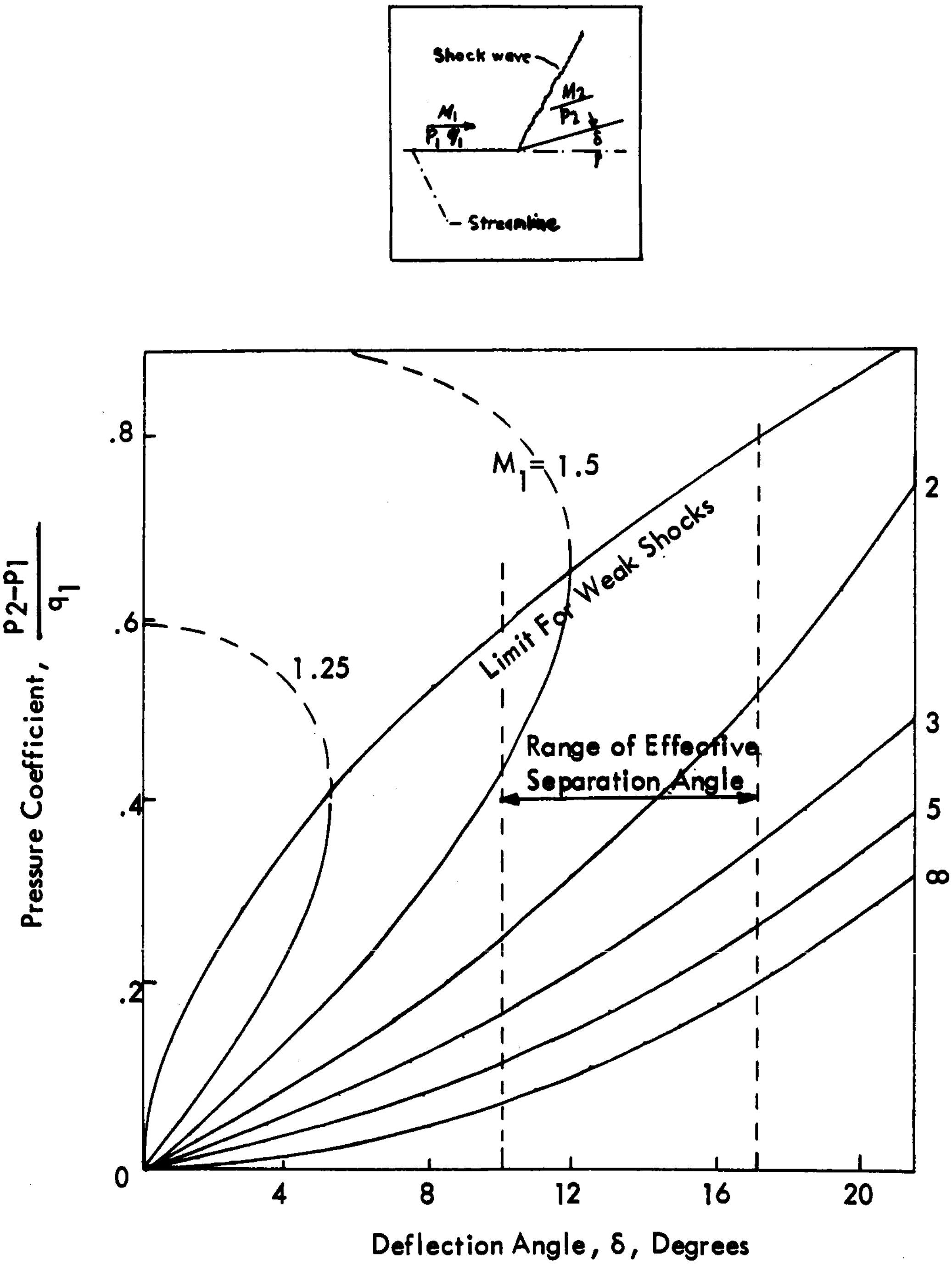


Figure 13: Pressure Coefficient vs Deflection Angle (11)
- Giving Potential Peak to Peak Amplitude
For Oscillating Shocks

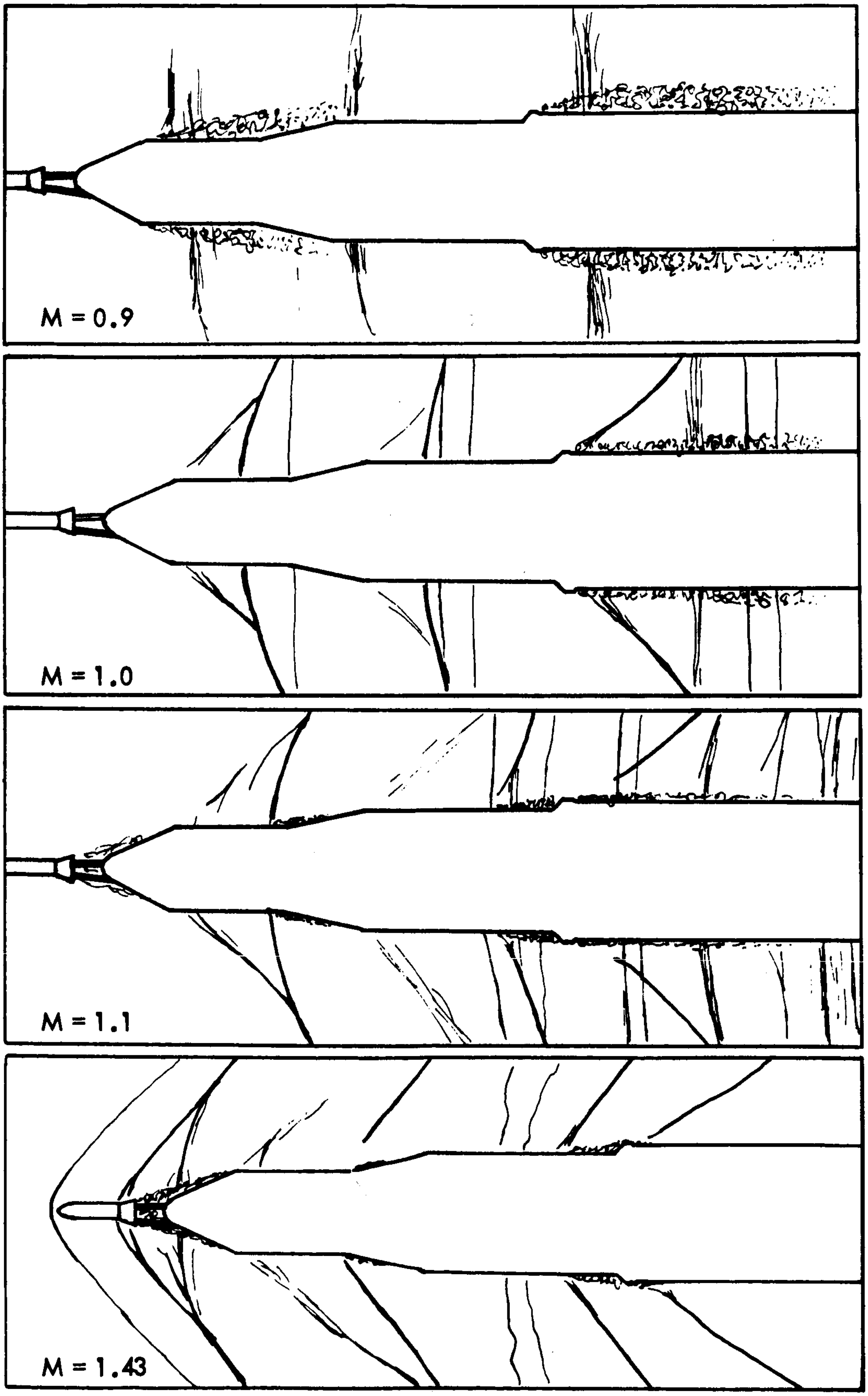
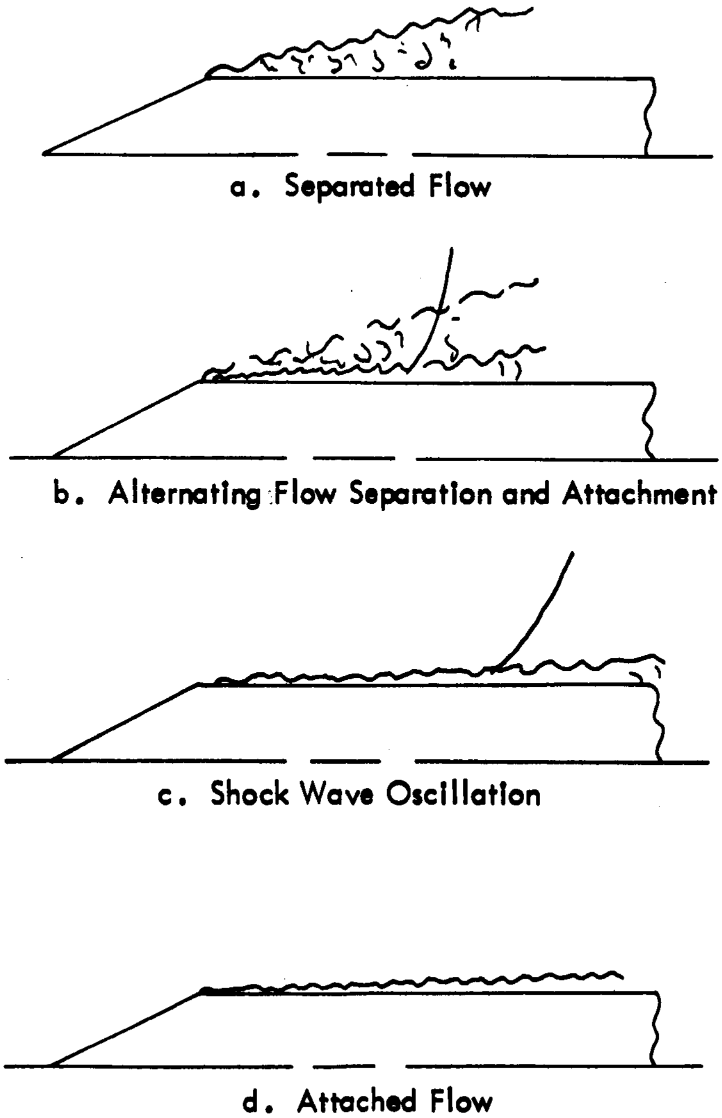


Figure 14: Transonic Shock and Separated Flow Patterns on a Model Saturn Vehicle – From Ref. 7



a. Separated Flow

b. Alternating Flow Separation and Attachment

c. Shock Wave Oscillation

d. Attached Flow

Figure 15 : Types of Transonic Separated Flow From Ref 5.

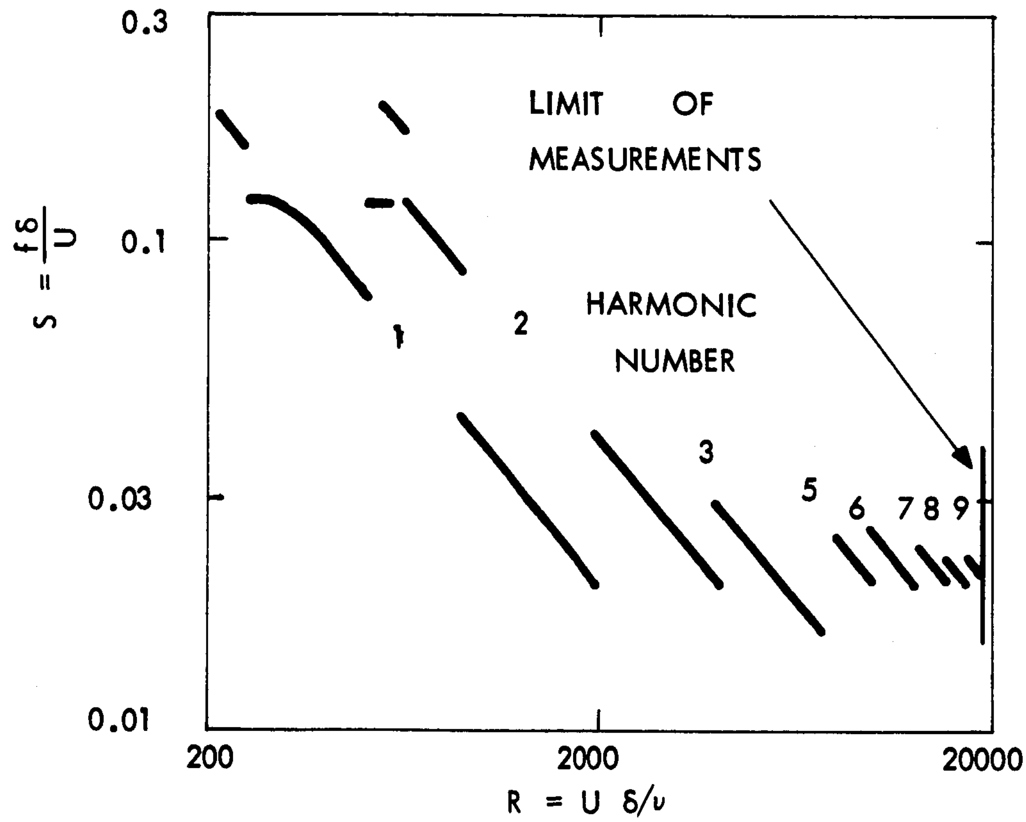


Figure 16: Frequencies occuring in a Typical Edge Tone Flow, Ref. 24.

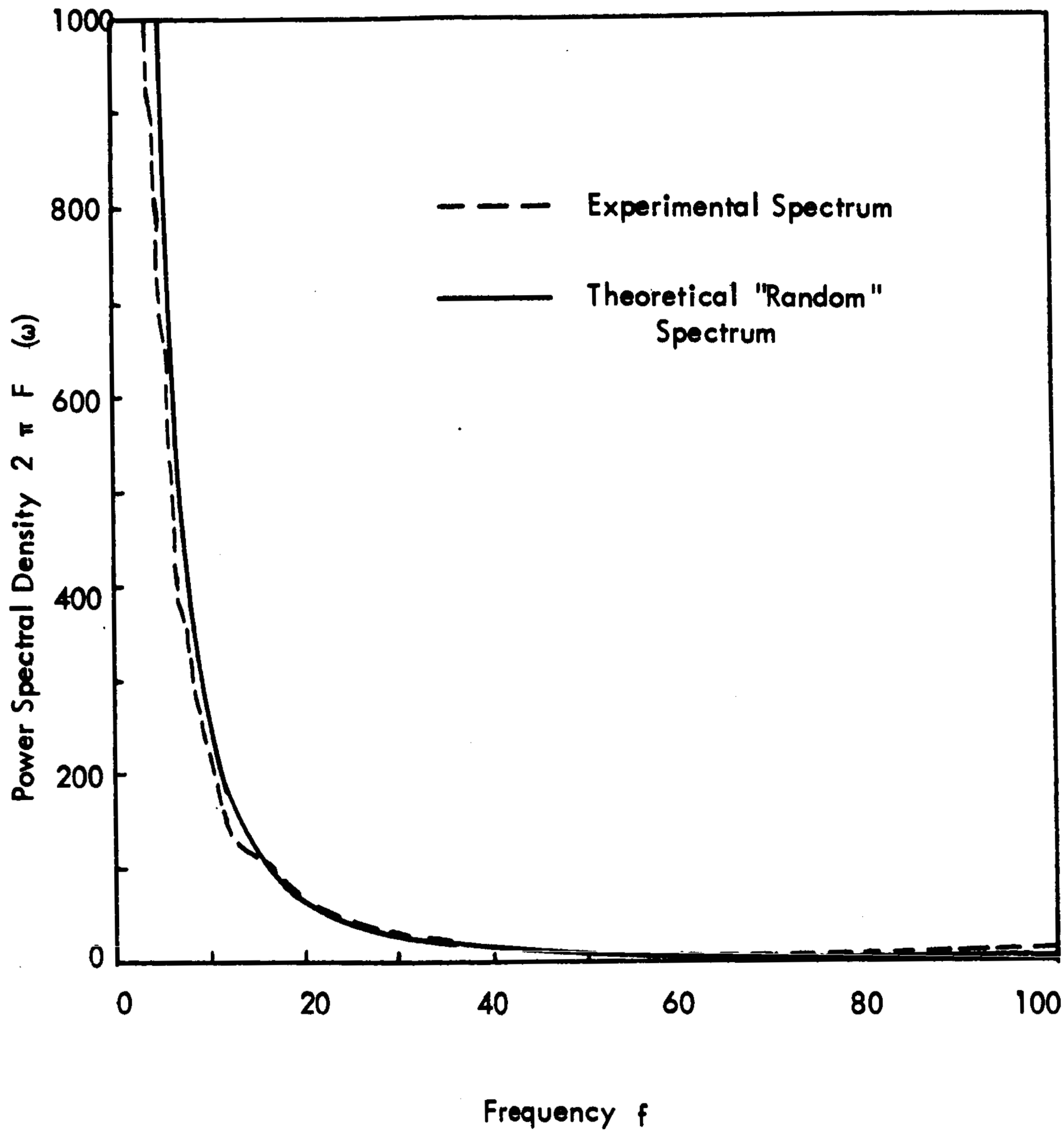


Figure 17: Typical Transonic Power Spectrum From Reference 5