31. THE PROBLEM OF ROUGHNESS DRAG AT SUPERSONIC SPEEDS

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SUMMARY

An assessment has been made of the problem of roughness drag at supersonic speeds. The study indicates that no reliable methods are available at present for estimating roughness drag for general shapes at supersonic speeds. It appears, however, that research on the drag of surface roughness has progressed sufficiently to indicate that the basic parameters involved can be delineated and that the overall problem of roughness drag can probably be put on a more solid theoretical foundation. Some additional experimentation is still needed concerning certain parameters that have not been investigated sufficiently. From the present assessment, it is apparent that roughness drag depends upon local boundary-layer characteristics and that methods for calculating these characteristics in practical-type three-dimensional flows must generally be improved; the usual procedure of calculating roughness drag on the basis of the boundary layer on a flat plate generally will not be adequate. Finally, considerably more analytical work is required to reduce the complete problem to a rational basis, and a rational basis for predicting roughness effects can greatly improve airplane-performance calculations.

INTRODUCTION

Research results from past conferences of NASA have shown that surface roughness can make significant contributions to the drag of a typical supersonic aircraft. For example, in reference 1 Peterson and Braslow estimated that the typical fabrication-type surface roughness prevalent on military airplanes at the time could increase the cruise drag of a supersonic transport by about $3\frac{1}{2}$ percent and could decrease the potential payload by 3500 pounds. More recent assessments indicate that distortion of the airplane surfaces under aerodynamic heating and loading, and the deterioration of the surface smoothness with time in service will also pose difficult problems. Thus, there is a definite need for developing reliable methods for estimating roughness drag at supersonic speeds. The objective of this paper is to assess the overall problem, to delineate areas where design data may or may not be available, and, in particular, to show some of the progress being made to rationalize the overall roughness-drag problem and to put it on a more solid theoretical foundation.

SYMBOLS

C_D	drag coefficient
ΔC_p	incremental pressure coefficient
k	roughness height
k'	height from reference surface to experimental reattachment point for dividing streamline on round-cornered forward-facing steps (see fig. 9)
M	Mach number
q	dynamic pressure
r	radius of upper corner of forward-facing step
R_x	Reynolds number, $\frac{u_\infty x}{\nu_\infty}$
R^*	Reynolds number, $\frac{u^* k}{\nu_k}$
t	time
u	velocity
u^*	friction velocity, $\sqrt{\frac{\tau_w}{\rho_w}}$
x	longitudinal distance from virtual origin or axial distance from body nose
y	lateral distance
z	distance normal to reference surface
β	Mach number parameter, $\sqrt{M_\infty^2 - 1}$
δ^*	boundary-layer displacement thickness
ρ	density
τ	surface shear
ν	kinematic viscosity

Subscripts:

av,δ	average condition in undisturbed boundary layer over complete boundary-layer thickness at location of roughness element
k	at top of roughness element
p	based on pressure integrations
$q_{av,k}$	average dynamic pressure in undisturbed boundary layer (roughness element removed) over height of roughness
$q_{av,k'}$	average dynamic pressure in undisturbed boundary layer between reference surface and reattachment point for dividing streamline at location of roughness element
w	wall
∞	free stream
1	modified drag coefficient, defined in figure 7
2	modified drag coefficient, defined in figure 7

ASSESSMENT OF OVERALL PROBLEM

The status of knowledge of roughness drag at supersonic speeds is summarized in figure 1. For convenience the surface roughnesses have been divided into three types: uniformly distributed or equivalent-sand-grain roughness; two-dimensional, square-cornered, essentially unswept steps, either forward- or rearward-facing; and the general arbitrarily shaped roughness, of which the other roughnesses are special cases. For the uniformly distributed roughness the critical roughness criterion is usually taken as the Reynolds number formed from the local friction velocity, the roughness height, and the kinematic viscosity corresponding to the top of the roughness. This criterion was developed from subsonic pipe-flow tests (ref. 2) but analyses and supersonic tests indicate that the criterion usually applies reasonably well at supersonic speeds provided the roughness height does not exceed approximately 300 to 400 microinches. Theoretical considerations and some unpublished results (also, see data for 480 in. model in refs. 3 and 4) indicate the possibility of more than negligible roughness wave drag for roughness heights exceeding this value even when the roughness Reynolds number is below the critical value. In general, neither criterion poses any severe restrictions on surface manufacturing tolerances, and hence surface-roughness drag of this type should not be any problem. Consequently, the knowledge in this area is considered fairly satisfactory even though the theoretical and experimental results at supersonic speeds are somewhat limited, and no further discussion of this type of roughness is included herein.

For the two-dimensional, square-cornered, essentially unswept step-type roughness there is no critical height below which drag due to roughness is not present. Considerable experimental data exist for this type of roughness (ref. 5 provides a short list of references), and some success has been attained in correlating effects of Reynolds number (or, more accurately, the effects of the ratio of roughness height to boundary-layer thickness) on roughness drag. (For example, see ref. 6.) The effects of Mach number have not yet been fully resolved. The ultimate objective in this research is to develop a universal correlation procedure wherein a theoretical or experimental drag coefficient for a particular type of roughness can be blended with the correct scale and dynamic-pressure parameters to calculate the correct drag under any set of boundary-layer and free-stream Mach number conditions.

Research on the general roughness shapes, exclusive of the two types just discussed, is in the preliminary phases only, and very little experimental data are available. Unfortunately, most of the roughnesses that will be present on the supersonic transport and other supersonic airplanes will probably fall into this category.

In the remaining part of this discussion the object is to show some of the progress being made in rationalizing the overall drag problem in the last two roughness-configuration areas illustrated in figure 1. Because of the complexity of the drag problem for the general arbitrarily shaped roughnesses and the lack of experimental data thereon, much of the emphasis is, of necessity, on the extension of correlations for the two-dimensional unswept steps and the effects of gradual modifications of the steps toward the general arbitrary shape.

MODELS AND TESTS

The experimental results from which the illustrations presented herein are drawn were obtained, as shown in figure 2, on many different types of models, on many types of configurations, in various wind tunnels, and by many different techniques. The Mach number range was from a subsonic Mach number of 0.7 to a hypersonic Mach number of 10.0, and a range of free-stream Reynolds number per foot from 0.7×10^6 to 20×10^6, which can be translated to a range of Reynolds number based on length from 2×10^6 to 200×10^6. Some effects of heat transfer were explored. Although some laminar-flow data were obtained, most of the emphasis was on turbulent boundary-layer flow, and the data presented are limited to that type of boundary layer.

RESULTS AND DISCUSSION

Definition of Problems

For purposes of orientation and for definition of the general problems involved, some typical pressure-drag results obtained on a single cycle of a repeating series of approximately sinusoidal-wave surface roughness on an ogive-cylinder model with a turbulent boundary layer are presented in figure 3. The cross-hatched line represents a linearized, two-dimensional, potential-flow theory which utilizes an experimental local Mach number. Inasmuch as this local Mach number does not vary exactly as M_∞, extrapolation from one free-stream Mach number to another results in a narrow band of values rather than a single line. The two dashed lines labeled "subsonic theory" will be explained shortly. It should be noted that the roughness height of 0.053 inch (which is exaggerated by a factor of 20 in the vertical scale of the sketch) is well within the boundary layer which is estimated to vary at this test station from about 0.25 to 0.35 inch.

The experimental results in figure 3 show a drag variation with Mach number that is typical of an object in a uniform free stream without boundary layer except for a rather high form drag at subsonic speeds and a powerful Reynolds number effect at the transonic and supersonic speeds. It should be noted that at the highest test Mach numbers and the highest Reynolds number, the experimental drag appears to approach agreement with the theoretical predictions. The truly significant feature is, however, that on an actual airplane, because of attempts to minimize roughness drag, most roughness elements will be in an area corresponding to the lowest curve or even lower and, thus, indicate the great need for a proper understanding of Reynolds number effects.

The theoretical subsonic form drag was obtained by assuming that the drag was due both to the pressure gradient existing on the basic smooth model and to the growth of the boundary-layer displacement thickness along the length of the roughness element. The latter increment in drag was determined by calculating the potential-flow pressure distribution for the roughness-element shape, as modified by the growth of the boundary-layer displacement thickness on a flat plate, and superimposing this pressure distribution directly to the actual physical contours of the element. The results of these calculations, shown in the lower left part of figure 3, indicate the proper trend in form drag with Mach number but are too low. Allowance for the thinner boundary layers existing on the test model relative to a flat plate would greatly improve the agreement between theory and experiment. In general, it appears the approach may be fundamentally valid but the details need considerably more development. It should be mentioned at this point that an understanding of subsonic roughness drag is necessary to the interpretation of supersonic-speed drag results for highly swept roughness configurations.

Drag at Transonic and Supersonic Speeds

At transonic speeds the calculation of theoretical pressure distributions, and hence drags, is formidable enough a problem without the introduction of boundary layers. Nevertheless, the prospects for obtaining at least empirical correlations in this speed regime do not appear to be hopeless. This possibility is illustrated in figures 4 and 5. In figure 4 are shown the effects of changes in Mach number and in figure 5 are shown the effects of changes in Reynolds number on the pressure distributions over the same approximately sinusoidal roughness element considered in figure 4. The increment ΔC_p is the difference in pressure coefficient existing between the smooth reference body and the model with surface roughness at identical test conditions. As the Mach number is increased (fig. 4), the pressure distribution changes from one similar in shape (except for a vertical scale factor) and in phase with the surface roughness shape to one approximately similar in shape, in this case, but now increasingly out of phase with the surface roughness shape. At the highest test Mach number, the negative and positive pressure peaks tend to approach the inflections in surface slope as required by the supersonic linearized potential-flow theory, although the magnitude of the experimental pressure coefficients remains considerably below the theoretical predictions which, however, are not shown. This type of change in pressure distribution with increase in Mach number is typical (except for the deficiency in magnitude of pressure coefficients relative to the theoretical values) of similarly shaped bodies in a uniform free stream without the boundary layer.

The significant feature at this point is that these changes in pressure distribution are very similar to those due to increasing Reynolds number shown in figure 5. Note that at the lower test Reynolds number, the shape of the pressure distribution tends toward similarity with the shape of the roughness and in phase with it. At the higher Reynolds number the supersonic flow has developed somewhat further, and the negative and positive pressure peaks tend to approach the inflection points. The shape of the pressure distribution is increasingly out of phase with the shape of the roughness. This similarity in Reynolds number and Mach number effects suggests that it may be possible ultimately to predict at least the first-order combined effects on the basis of an effective Mach number and effective dynamic pressure, in which the effective Mach number and dynamic pressure are derived from the local boundary-layer characteristics. Although it is not presented, this problem of a flow fully expanded supersonically to the inflections in surface slope, but deficient in magnitude of pressure coefficients predicted in terms of free-stream Mach number, extends continuously into the higher free-stream Mach number regimes. The problem that exists at these higher Mach numbers is to devise methods for predicting the effective Mach numbers and effective dynamic pressures. Satisfactory methods for estimating the effective values of these parameters for wave-type configurations have not yet been developed, but several promising leads have been uncovered.

Development of Typical Correlation Procedures

The emphasis thus far in this discussion has generally been on the types of surface roughness for which potential-flow calculations appear feasible because flow separation is nonexistent or the separation is on an insignificant scale. As indicated in figure 6, work is also proceeding on types of roughness involving separation. In this figure, which incidentally has been shown in a previous conference (ref. 6), the pressure drag on a two-dimensional forward-facing step is plotted as a function of the ratio of roughness height to boundary-layer displacement thickness. These data are for a step mounted on a tunnel wall at a Mach number of 2.20, with k ranging from 0 to 1.006 inches and R_x ranging from 11×10^6 to 103×10^6. As indicated, a drag correlation was obtained (that is, C_D is constant) over most of the k/δ^* range when the drag coefficient C_D was based on the average dynamic pressure existing in the basic boundary layer over the height of the step when the step is nonexistent. For the lowest step heights, when the top of the step approaches the height of sonic flow, the correlation breaks down. This area has not yet been intensely analyzed. There is also a residual Mach number effect on the level of the average drag coefficient in the range of correlated data, as illustrated in the left-hand part of figure 7. An attempt to correlate the Mach number effect on the basis of the parameter $\sqrt{\beta_\infty}$ derived from the turbulent boundary-layer separation correlation developed by Erdos and Pallone (ref. 5) was not successful, as is indicated by the data in the upper part of the right-hand plot. A successful universal correlation, good for all conditions of boundary layer and free-stream Mach number, appears to result, however, if the parameter $\sqrt{\beta}$ is based on the average Mach number in the boundary layer and if an allowance is made for the reduced dynamic pressures within the shear layer. This apparent universal correlation needs to be tested, however, over a much wider range of Mach number before it can be accepted with any confidence.

Similar universal correlations, which are not shown, are possible for the Reynolds number and Mach number effects for the rearward-facing two-dimensional steps, but all the average dynamic pressures and Mach numbers must be replaced by the free-stream values. It should be mentioned that the correlation of Mach number effect is not quite as good for the rearward-facing step as that shown for the forward-facing step. The essential point to be made is that the rearward-facing steps have other basic controlling parameters for the effective Mach number and dynamic pressure than the forward-facing steps.

Most step-type roughnesses on a supersonic airplane probably will not have perfectly square corners. In figure 8 are shown the effects of rounding off the corners of the forward-facing step on the drag correlation. The ordinates and abscissa are the same as in figure 6 for the square-cornered, forward-facing step. The lines represent curves drawn through the average data in figure 6 and in other similar figures with the corner radius r being held constant. The experimental data were obtained over a wide range of corner radii, roughness height k, and Reynolds number R_x.

The results in figure 8 indicate that rounding off the upper corner of the forward-facing step prevents all steps from being universally correlated on the basis of the parameters of figure 6. It is to be noted that the data for each step configuration having a constant radius do correlate in the form of a curve of C_D as a function of k/δ^*, but the drag coefficient is no longer constant over most of the k/δ^* range. For the square corner, the flow phenomena on the forward face and upon the upper roughness surface downstream of the corner appear to be effectively separated from one another because of the very small subsonic-flow connection through the boundary layer. With the rounding of the corners this point for the division of the two flows moves forward and below the total roughness height, so that the roughness height is no longer the proper parameter for obtaining the correlating effective dynamic pressure.

The possibility of obtaining the desired correlation by suitably picking the effective roughness height is shown in figure 9. The roughness height k' used in this figure was taken to be at the location of the dividing streamline for the boundary layer as indicated by the experimental pressure distributions on the rounded corners. The drag integrations extended only from the reference surface to this point, with some drag component left to be accounted for above the point. The main objective is to determine whether the overall flow over the roughness element can be simplified into component flows more suitable for theoretical treatment. The successful correlation shown in figure 9 indicates that such simplification is possible, although the correlation of the drag component existing above the reattachment point has not yet been attempted.

Effects of Roughness Sweep

At this point it is desirable to conclude the discussion of those areas where substantial progress is being made and to give some attention to a pertinent item for which only a rough preliminary analysis has been applied. In figure 10 are presented some typical pressure-drag results showing the effect of sweeping the roughness element. The drag coefficient is, as usual, based on roughness frontal area. The theory is based on the normal components of the local surface slopes and experimental local flows and is best represented by a band for the same reasons as mentioned previously. The approximate shape of the roughness with the vertical scale exaggerated is illustrated in figure 10. The roughness-drag results of this figure indicate that the onset of wave drag on the roughness element has been delayed and the peak drag coefficient has been reduced (in comparison with the drag of a similar unswept configuration) by the sweep of the element. These effects are precisely those expected for the element in a uniform free stream with no boundary layer.

Another important effect resulting from the sweep is that the region of maximum Reynolds number effects, which occurs just above a Mach number of 1 for the unswept roughness, has now been delayed to higher free-stream Mach numbers. This phenomeneon results from the fact that the development of the supersonic flow in a plane normal to the element and strongly influenced by changes in boundary-layer thickness, as was shown previously for the unswept roughness, has been delayed to higher free-stream Mach numbers. Furthermore, the tendency toward better agreement between theory and experiment at the higher test Mach numbers is apparently delayed to still higher values. This trend illustrates the need for a better understanding of subsonic- and transonic-flow drag characteristics in making drag calculations at supersonic free-stream Mach numbers.

CONCLUDING REMARKS

From this assessment of the problem of roughness drag at supersonic speeds, it can be said, in summary, that there are at present no reliable methods for estimating roughness drag for general shapes at supersonic speeds. However, research on the drag of surface roughness has progressed sufficiently to indicate that the basic parameters involved can be delineated and that the overall problem of roughness drag can probably be put on a more solid theoretical foundation. Some additional experimentation is needed to investigate certain parameters that have not been investigated sufficiently. From this presentation, it should be obvious that roughness drag depends upon local boundary-layer characteristics and that methods for calculating these characteristics in practical-type three-dimensional flows must generally be improved; the usual approach of calculating roughness drag on the basis of a flat-plate boundary layer generally will not be adequate. Finally, considerably more analytical work is required to reduce the complete problem to a rational basis, and a rational basis for predicting roughness effects can greatly improve airplane-performance calculations.

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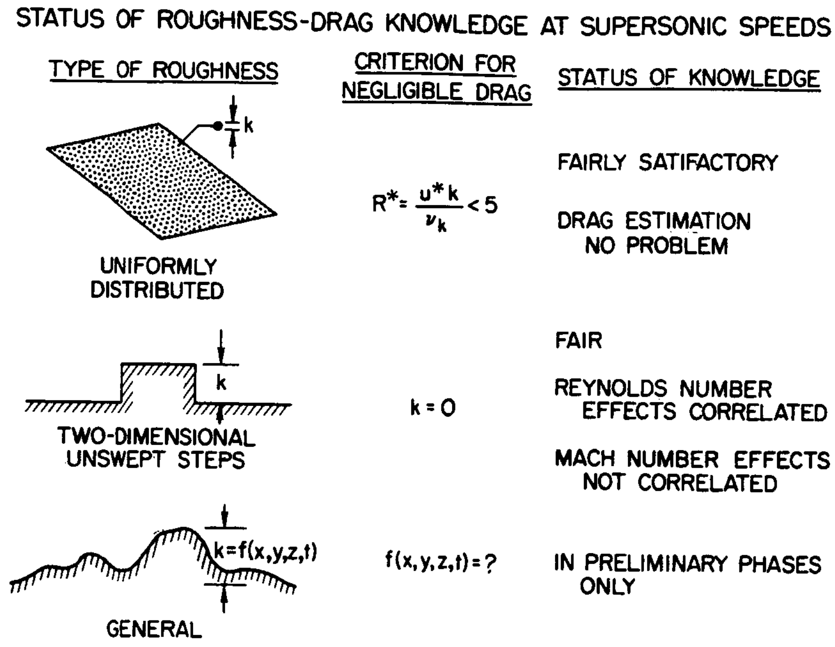

Figure 1

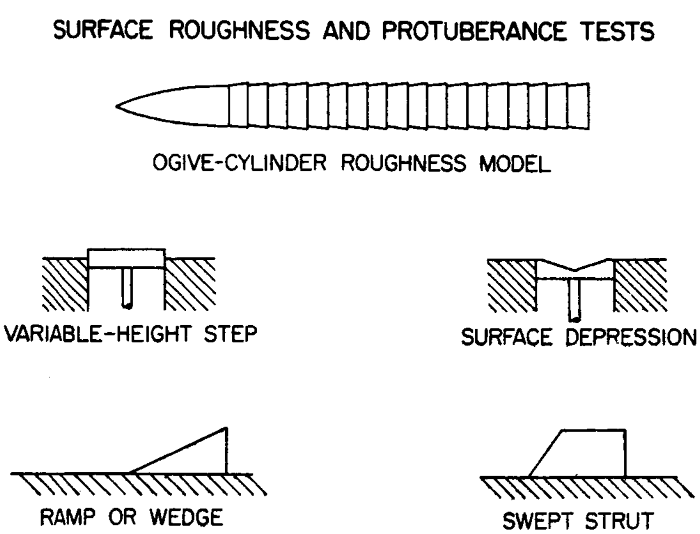

Figure 2

TYPICAL PRESSURE DRAG FOR SINGLE UNSWEPT ROUGHNESS ELEMENT

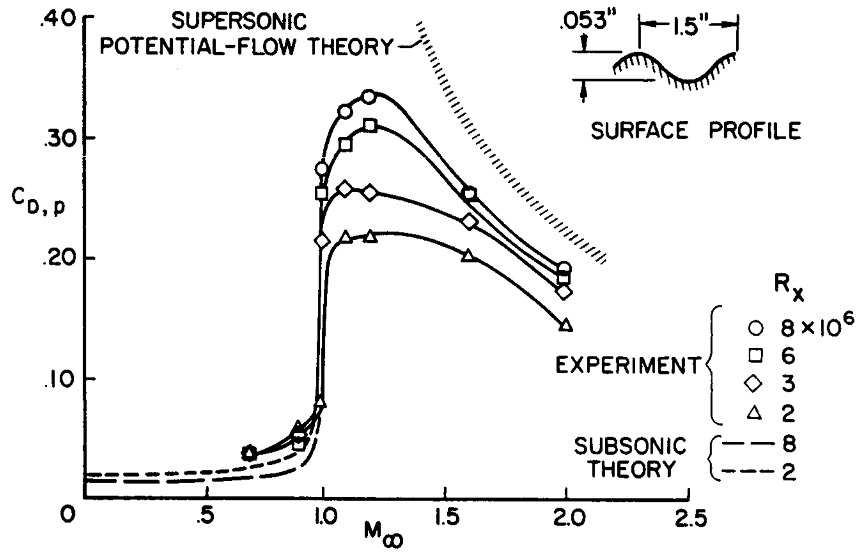

Figure 3

EFFECT OF MACH NUMBER ON ROUGHNESS PRESSURES

0.053-IN. WAVE; $R_x = 8\times10^6$

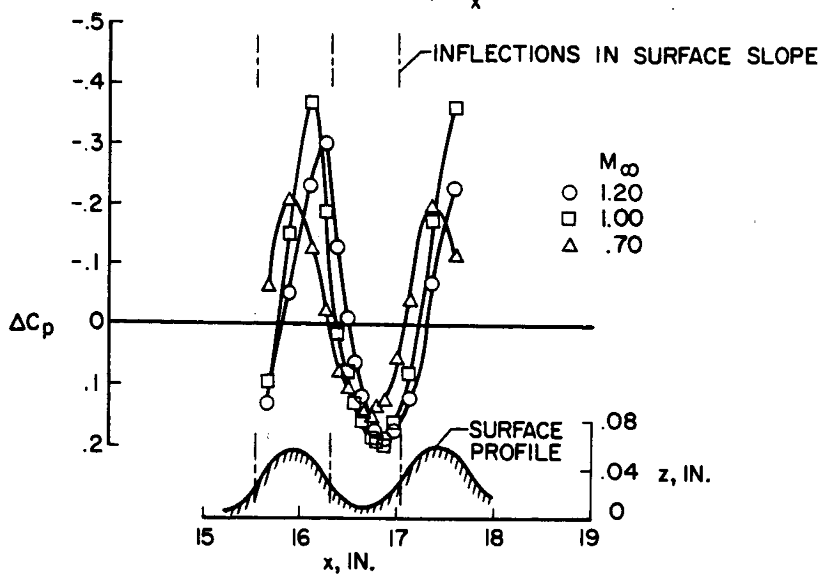

Figure 4

EFFECT OF REYNOLDS NUMBER ON ROUGHNESS PRESSURES

0.053-IN. WAVE; $M_\infty = 1.10$

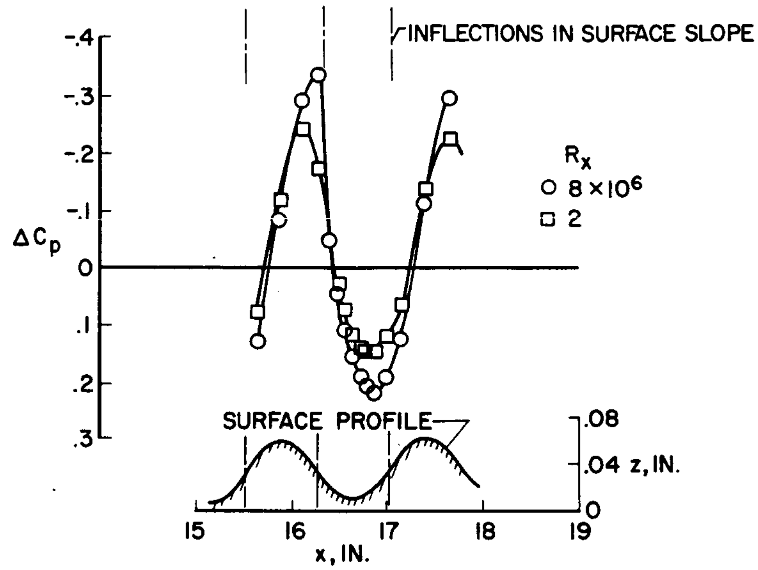

Figure 5

DRAG CORRELATION FOR SINGLE FORWARD-FACING STEPS

SQUARE CORNER; $M_\infty = 2.20$; k = 0 TO 1.006 IN.

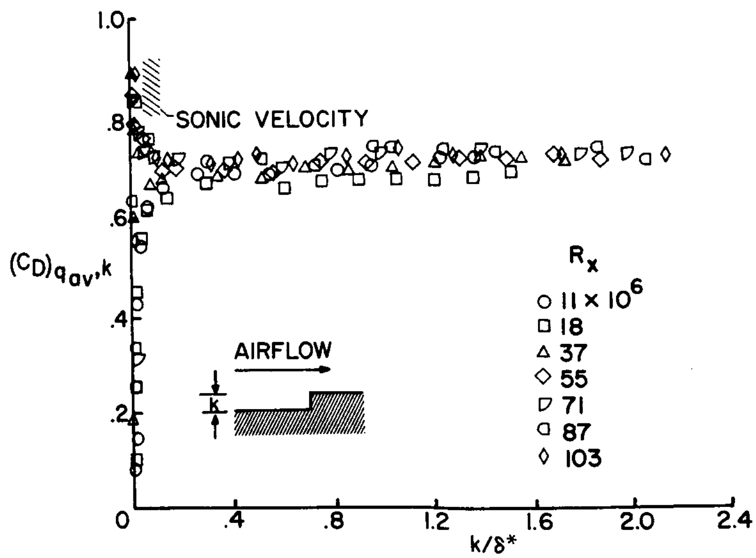

Figure 6

CORRELATION OF MACH NUMBER EFFECTS FOR FORWARD-FACING STEPS

SQUARE CORNERS; $\frac{k}{\delta^*} > 0.2$

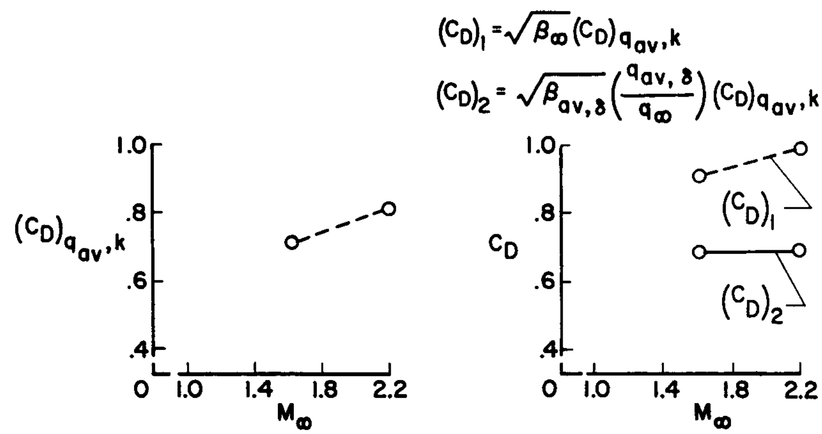

Figure 7

EXPERIMENTAL DRAG CORRELATION FOR SINGLE FORWARD-FACING STEPS

ROUNDED CORNERS; $M_\infty = 2.20$

k = 0 TO 1.006 IN.

$R_x = 11$ TO 103×10^6

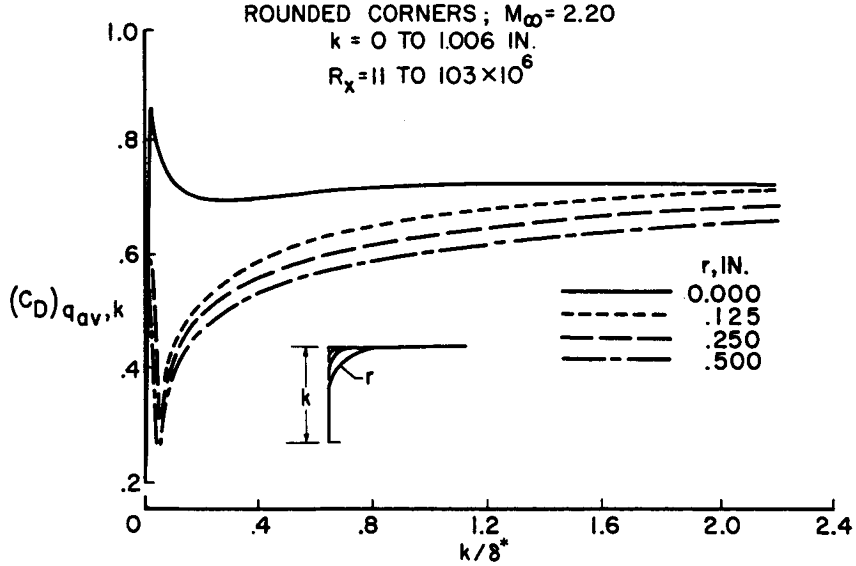

Figure 8

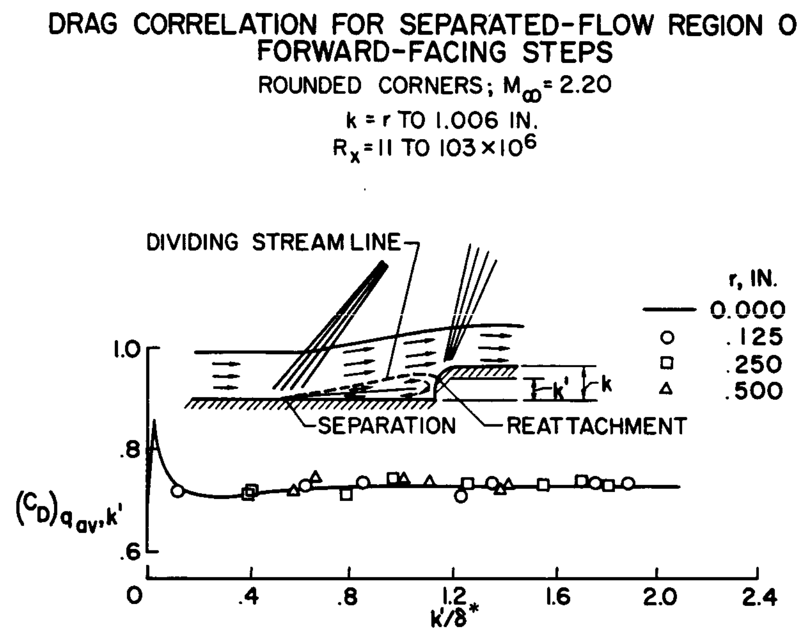

Figure 9

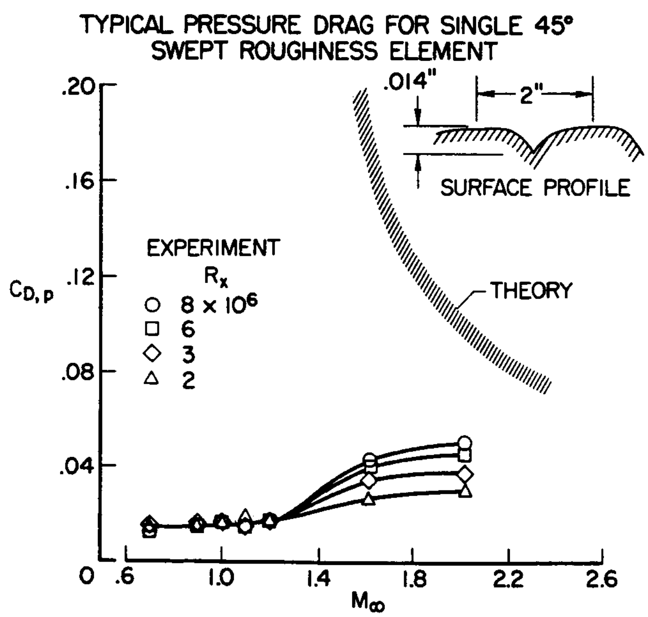

Figure 10