NASA TECHNICAL NOTE

NASA TN D-3579

NASA TN D-3579

N66 36119
(ACCESSION NUMBER)
20
(PAGES)
(NASA CR OR TMX OR AD NUMBER)
(THRU)
/
(CODE)
01
(CATEGORY)
FACILITY FORM 602

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GPO PRICE $ ________

CFSTI PRICE(S) $ 1.00

Hard copy (HC) ________

Microfiche (MF) .50

ff 653 July 65

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1966

NASA TN D-3579

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SUMMARY

Some general guidelines that are applicable to grit-type boundary-layer-transition trips located near the leading edges of model components are presented. Conditions that permit transition to be fixed at the roughness at subsonic and supersonic speeds without a resultant grit drag are reviewed. In certain cases in which grit drag is unavoidable, two methods - the choice of which depends upon the characteristics of the wind tunnel used - for correcting for such drag are discussed. At hypersonic speeds, the problem of fixing boundary-layer transition near the leading edges of the model components without distorting the turbulent-boundary-layer velocity profile has not been solved.

INTRODUCTION

Accurate determination of the low-lift drag characteristics of full-scale aircraft from small-scale wind-tunnel tests usually requires that boundary-layer transition from laminar to turbulent flow be artificially fixed near the leading edges of the various model components. An extrapolation to the full-scale Reynolds number can then be made for completely turbulent flow, after which drag increments must be added for aircraft protuberances and surface irregularities that are not simulated on the model. The use of three-dimensional or grit-type roughness as a boundary-layer-transition trip has met with the most success and is the subject of this paper. The appendix presents some recent information on the use of triangular particles cut from adhesive tape as a trip.

SYMBOLS

C_D drag coefficient

$C_{D,min}$ minimum drag coefficient

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[1]Presented at the classified "Conference on Aircraft Aerodynamics," Langley Research Center, May 23-25, 1966, and published in NASA SP-124.

$C_{D,o}$ zero-lift drag coefficient

C_L lift coefficient

k roughness height

M free-stream Mach number

R/ft unit Reynolds number (Reynolds number per foot based on free-stream velocity and kinematic viscosity), V_∞/ν_∞

R_k roughness Reynolds number based on roughness height and velocity and kinematic viscosity at top of roughness, $u_k k/\nu_k$

$R_{k,cr}$ value of R_k for initiation of artificial transition

R_x Reynolds number based on free-stream conditions and distance of roughness from leading edge, $V_\infty x/\nu_\infty$

$R_{x,min}$ minimum value of R_x below which an increase in roughness height is required to initiate artificial transition

u local streamwise component of velocity inside boundary layer

u_k local streamwise component of velocity inside boundary layer at top of roughness particle

V_∞ free-stream velocity

x distance of roughness from leading edge

δ total thickness of boundary layer

ν_k coefficient of kinematic viscosity at top of roughness particle

ν_∞ free-stream kinematic viscosity

DISCUSSION

No single trip configuration is effective or, in fact, desirable, regardless of tunnel test conditions or model configuration. A single set of specifications for a trip design, therefore, cannot be designated. However, some general guidelines that are applicable to all grit-type trips are

(1) The roughness bands should be narrow. Wide bands are unnecessary, and they create drag if carried to extremes.

(2) The roughness should be sparsely distributed. It is undesirable to pack the roughness densely because a densely packed band will act as a two-dimensional trip. Two-dimensional trips are unsatisfactory because reasonable heights do not fix transition at the trip location.

(3) Care should be taken not to build up layers of adhesive which can form spanwise ridges at the edge of the trip. These ridges also tend to make the trip act as a two-dimensional step.

With these general guidelines in mind, a choice of particle size and location must be made. The proper choice is not an obvious one. Several factors are involved that require careful consideration. The primary factor involved in the artificial fixing of transition is Mach number, and subsonic speeds will be considered first. Before proceeding with the discussion, however, the boundary-layer parameters to be used are defined with the aid of figure 1. Shown, to an exaggerated scale, is the total boundary-layer thickness as the boundary layer grows along a surface. A roughness particle is shown located a distance x from the surface leading edge. The height of the particle is designated as k. Also shown is a sketch of the boundary-layer velocity profile at the roughness location. A roughness Reynolds number is formed based on the roughness height k and the local flow conditions at the top of the roughness - that is, the velocity at the top of the roughness u_k and the kinematic viscosity at the top of the roughness ν_k. For roughness Reynolds numbers less than a certain value, the roughness has no effect on the location of the natural transition. When the roughness Reynolds number reaches a critical value, designated by the subscript cr, transition moves forward of its natural location. At subsonic speeds, transition moves very close to the roughness when the critical value is attained. Many experimental investigations have determined that the value of the critical Reynolds number is approximately 600 at subsonic speeds (for a ratio of particle height to width of 1). (See ref. 1 or 2.) With this value of roughness Reynolds number as a criterion, the minimum roughness height required to initiate artificial transition can be calculated for the given test conditions and for a selected distance of the roughness from the leading edge. A Reynolds number based on this distance x and the free-stream flow conditions has been designated as R_x.

Subsonic Considerations

Figures 2 and 3 present examples of subsonic drag data plotted against roughness height. In figure 2 are results for a rather large range of roughness height on a variable-sweep fighter configuration; whereas, in figure 3 are results for a more limited range of roughness height on fighter and transport configurations. The values of roughness height k for a roughness Reynolds number of 600 are indicated by the vertical tick for each test. For all the configurations presented, an increase in roughness height by a factor of 2 over that indicated by $R_k = 600$ can be tolerated with very little or no drag increase. The drag coefficients measured in this range of roughness height varied within only $\pm 1\frac{1}{2}$ counts, that is, ± 0.00015. Therefore, choice of a roughness grit somewhat larger than that indicated for $R_k = 600$ will enable drag measurements to be made at subsonic speeds without the need for any corrections due to roughness drag. Use of a nominal grit size one size larger than that determined for $R_k = 600$ is recommended to insure a margin of conservatism for transition. This recommendation would appear to be a good one because the average height of roughness in three-dimensional grit has been found to be somewhat smaller than the nominal height. The results of careful measurements of the particles in representative carborundum-grit trips are presented in figures 4 and 5.

The shape of the curve of drag coefficient plotted against roughness height (fig. 2) is a function of particle frontal area and average dynamic pressure over the particles. For each particle that is somewhat higher than the boundary-layer thickness, indicated in figure 2 by the arrow, the drag is about proportional to only the particle frontal area, because the average dynamic pressure over the particle height is approximately constant. As the particle height is changed for each particle immersed in the boundary layer, however, the average dynamic pressure over the particle height changes with a change in height. The drag varies in this region, therefore, with the change in average dynamic pressure as well as with the frontal area. The exact shape of the drag-coefficient curve for carborundum-type grit, then, can be different for different trips because of the variation of particle sizes present in the grit and because of a variation in boundary-layer thickness across the span when the grit location from the leading edge is not constant.

The important point to be reiterated is that for all the examples of subsonic data shown, the drag variation with roughness height approaches a plateau region for nominal grit sizes smaller than the boundary-layer thickness but larger than the value determined for $R_k = 600$. This desirable plateau region occurs only when another important criterion is satisfied. This criterion will be indicated in the following discussion.

Figure 6, which repeats the curve from figure 2 for the variable-sweep configuration that was obtained at a tunnel unit Reynolds number of 5.9×10^6, shows the effect of decreasing unit Reynolds number. When the unit Reynolds number was reduced from 5.9×10^6 to 3.0×10^6, transition was still fixed at the roughness height equivalent to a roughness Reynolds number of 600, and a plateau region was once again obtained. When the unit Reynolds number was further reduced to 1×10^6, it appears that a value of R_x of 600 was not sufficient to fix transition at the roughness. The increase in height required to fix transition prevented the attainment of a plateau region - that is, there was always a large variation of drag coefficient with roughness height. It appears possible to correlate the conditions at which a value of R_k greater than 600 is required to fix transition at the roughness on the basis of R_x, the previously mentioned length Reynolds number based on the distance from the leading edge to the roughness location. Values of R_x based on the distance to the trip at the mean-aerodynamic-chord location are presented in figure 6 for the three unit Reynolds numbers. The effect of R_x on the critical roughness Reynolds number $R_{k,cr}$ is shown by figure 7. The shaded band represents dozens of data points. The value of $R_{k,cr}$ is constant at about 600, except at the low values of the length Reynolds number R_x. At the low values of R_x - resulting from either a decrease in tunnel unit Reynolds number or a decrease in distance - the critical roughness Reynolds number increases; therefore, the roughness height required to induce transition increases. These larger heights will cause roughness drag large enough to eliminate the plateau region, as previously indicated for the low Reynolds number curve in figure 6. For subsonic tests, it is usually possible to locate the roughness at a length Reynolds number of at least 0.1×10^6, while maintaining a location far enough forward to have essentially full-chord turbulent flow. It can be seen that 0.1×10^6 is about the value at which $R_{k,cr}$ departs from the constant value of 600. The previous data showing the plateau region for the fighter and transport configurations (figs. 2 and 3) were obtained for values of R_x greater than 0.1×10^6.

Supersonic Considerations

At supersonic Mach number, selection of grit height and location becomes more complicated. Firstly, as indicated in figure 8, an increase in Mach number increases the value of $R_{x,min}$, which is defined as the value of R_x below which $R_{k,cr}$ increases. (See fig. 7.) For combinations of roughness location and tunnel unit Reynolds number resulting in values of R_x smaller than these minimum values, it becomes increasingly difficult to induce transition. Secondly, for values of R_x greater than $R_{x,min}$, the value of roughness Reynolds number at which transition starts to move forward of its natural position $R_{k,cr}$ also increases with increasing Mach number greater than about 3.6. This, too, results in an increase in required roughness height at the higher Mach numbers. Thirdly, as Mach number increases, the roughness Reynolds number must be increased to a value greater than the critical value in order to move transition forward to the vicinity of the roughness, as indicated by the upper curve in the right-hand plot of figure 8. The increase in R_k to a value greater than the critical value is not required at the lower Mach numbers where $R_{k,cr}$ is sufficient to induce transition in the vicinity of the roughness. Parts of these curves are shown dashed because very few data are available to establish the values quantitatively. The limited data that are available up to Mach 6, however, do indicate the trends plotted.

It is apparent from figure 8 that at hypersonic speeds, fixing transition on wind-tunnel models becomes increasingly difficult. In fact, roughness height several times larger than the boundary-layer thickness was required to fix transition at a trip at a Mach number of 6. Severe, undesirable distortions of the boundary-layer velocity profile accompany such large roughness. Discussion of the significance of the transition-fixing difficulty with regard to hypersonic wind-tunnel testing is included in reference 3.

Further discussion herein of supersonic data will be restricted to Mach numbers up to 3 - the range of interest for the supersonic transport. It has already been indicated that at Mach numbers up to 3, a roughness height equivalent to a value of R_k of about 600 will fix transition very near the roughness so long as the value of R_x at the roughness is greater than the minimum value indicated in figure 8. It is not always possible or practical, however, to locate roughness far enough rearward dimensionally or to operate at a unit Reynolds number high enough to obtain a value of R_x at least that large. In other words, in some supersonic wind tunnels, the maximum tunnel unit Reynolds number or the model scale is not large enough to produce these minimum values of R_x for roughness located as near the leading edge as desired. In tunnels with larger unit Reynolds number capabilities, it may not be feasible to run all tests at the maximum unit Reynolds number condition because of considerations such as angle-of-attack restrictions due to balance limitations at the higher dynamic pressures. For supersonic tests, therefore, a need usually exists for the use of roughness configurations that cause grit drag. A correction for this grit drag must, of course, be determined. Two methods are being used, the choice of which depends upon the characteristics of the wind tunnel used.

Figure 9 illustrates a technique that can be used for determining the grit drag in wind tunnels having a variable Reynolds number capability. The technique is limited, however, to those wind tunnels with a sufficiently high unit Reynolds number and free-stream turbulence level to produce essentially all-turbulent flow on the model surfaces at the highest unit Reynolds number without artificial trips. The data shown in the figure were taken at a Mach number of 2.75 with a delta-wing—body model. Shown on the left-hand side of the figure is a log-scale plot of the zero-lift drag coefficient as a function of the free-stream unit Reynolds number. The circular symbols represent free transition and the square symbols represent measurements with transition trips located near the model leading edges. The roughness particles were sized to produce transition at the trip at the test Reynolds number per foot of 3×10^6, which is the highest unit Reynolds number at which complete lift-drag polars could be taken without exceeding the model balance limits. A comparison with turbulent theory and observation of sublimation material placed on the model surfaces during the tests indicate that the model without trips had essentially all-turbulent flow at unit Reynolds number of about 6×10^6 and greater. By extrapolating along the theoretical turbulent curve for a smooth flat plate back to the test Reynolds number per foot of 3×10^6, the grit drag is obtained as the difference between the extrapolated smooth value and the drag measured with the grit. The increment in drag coefficient due to the grit was 0.0005 in this test. On the right-hand side of figure 9, the square symbols represent the measured variation of drag coefficient with lift coefficient for the model with fixed transition at the Reynolds number per foot of 3×10^6. The solid line is the corrected polar which has been adjusted for the grit-drag increment.

Figure 10 illustrates a technique that can be used for grit-drag determination in wind tunnels which do not have a variable Reynolds number capability or which cannot achieve a sufficiently high Reynolds number to produce all-turbulent flow on the model surfaces without artificial trips. The data shown in this figure were taken with the same delta-wing model as in the previous figure, at the same Mach number of 2.75, and at a unit Reynolds number of 3×10^6. On the left-hand side of the figure is a plot of the variation of the drag coefficient with lift coefficient for the model with artificial trips of different roughness heights. Each of the particle sizes shown was sufficiently large to produce transition at the trip. In order to determine the all-turbulent drag of the model without trips, the data are cross-plotted in the right-hand plot of the figure as a function of the particle size squared at various values of lift coefficient. The parameter k^2 is used rather than k because, for these roughness heights which are all greater than the boundary-layer thickness, the drag is about proportional to a characteristic area as discussed previously. The arrow indicates the roughness height equal to the boundary-layer thickness at zero lift. The all-turbulent drag of the smooth model is obtained by extrapolating linearly to zero roughness height. The corrected all-turbulent drag polar for the model is shown as the solid line in the left-hand plot of the figure.

Figure 11 shows a comparison of the corrected drag polar for the model as determined by the two techniques. The circular symbols represent the corrected drag polar as determined by the variable Reynolds number technique and the square symbols represent the corrected drag polar as determined by the variable roughness height technique. As can be seen in the figure, the agreement in this case is excellent.

Determination of the correct slope of C_D plotted against k^2 in the variable roughness size method, however, is not as simple as the curves of figure 10 may indicate. This fact is explained by figure 12 in which the zero-lift drag-coefficient curve is repeated as the solid line but additional points of larger and smaller roughness heights are included. If the two larger particles are considered in the fairing, as indicated by the dashed line, the lower resultant slope of $C_{D,o}$ plotted against k^2 results in a significant change in the grit-drag correction. These larger particles are over three times as high as the boundary-layer thickness, and other experiments have indicated that particles of such magnitude can either decrease or increase the local skin friction behind the roughness because of distortions in the boundary-layer velocity profiles. Roughness too much larger than the boundary-layer thickness, therefore, should be avoided, but it is not clear at present how large a roughness can be tolerated. Additional work is underway to define better the height limitations. For the smallest roughness height investigated and for natural transition, visual-observation techniques of the boundary-layer condition can be used to determine the amount of laminar flow present. With calculations of the drag decrement associated with the laminar flow, additional points may be provided to help determine the slope of the curve. It is clear that in applying the variable roughness size method for evaluating the roughness drag, extreme care is required in determining the boundary-layer conditions through the range of roughness height so that an educated judgment can be used in fairing the slope of C_D plotted against k^2.

General Considerations

The discussion of the use of transition trips on wind-tunnel models has been restricted in this paper to the problem of determining full-scale low-lift drag characteristics. So long as the flow over the surfaces of wind-tunnel models remains attached, the other force and moment coefficients measured at small scale will, for all practical purposes, be equal to the full-scale characteristics. If, however, regions of flow separation exist at test conditions, the characteristics may be affected by the differences between the test and full-scale Reynolds numbers. Some aspects of the flow-separation problem are discussed in references 4 and 5.

A final point to be made concerns the previously mentioned variation of particle height present in a trip composed of distributed grit. Although this is not a serious problem, further sieving of the grit before application would certainly be helpful. Also, the use of other types of three-dimensional roughness rather than grit in an attempt to provide uniform and more easily controllable trips has been under investigation for some time. Although all pertinent problems have not yet been completely resolved, recent results for one of these types appear encouraging and some of the information on this roughness is included in the appendix.

CONCLUDING REMARKS

It is possible to fix boundary-layer transition far forward on wind-tunnel models at subsonic speeds with grit-type transition trips having little or no grit drag. This is possible also at supersonic speeds, but only if a sufficiently high test Reynolds number is attainable. Testing expediency or tunnel characteristics, however, usually dictate the use of trips, at supersonic speeds, that produce grit drag. Two methods of correcting for this grit drag, depending upon the tunnel characteristics, are currently being used. At hypersonic speeds, the problem of fixing boundary-layer transition near the leading edges of the model components without distorting the turbulent-boundary-layer velocity profile has not been solved.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 23, 1966,
126-13-03-22-23.

APPENDIX

TRIANGULAR PARTICLES OF ADHESIVE TAPE FOR BOUNDARY-LAYER TRANSITION

Two practical difficulties encountered in the use of carborundum roughness particles are the lack of uniformity of the particle pattern (caused by large variations in size and shape of the individual particles) and the length of time required for application. These problems are accentuated when it is necessary to repeat the application of the roughness bands several times as is done in one of the currently used techniques for assessing the particle-drag penalty.

A type of three-dimensional roughness which offers promise of eliminating these difficulties consists of triangular particles cut from adhesive tape. The size and shape of these particles can be accurately controlled and no additional bonding agent is required to affix the particles to the model surface, with a resultant savings in time for application. Triangular particles of this type have been tested at the University of Maryland in a water tunnel (refs. 6 and 7) and at the Ames Research Center in air. In both studies, the triangular roughness particle was shown to be more effective in promoting artificial transition than spherical roughness particles of the same height.

Results obtained from tests at supersonic speeds at Ames are shown in figure 13. The ratio of minimum spherical trip Reynolds number to minimum triangular trip Reynolds number for transition near the roughness is plotted against Mach number for station Reynolds numbers from 0.025×10^6 to 0.6×10^6 and for particles with height greater than the boundary-layer thickness. These results show that for the conditions of figure 13, the particle height required to fix transition near the roughness is less for triangular trips than for spherical trips. At the top of figure 13 is a sketch showing the dimensions and orientation with respect to the free stream of the triangular trips used in the Ames tests. Triangles with apex angles ranging from 45° to 135° were found to produce only small variations in the transition-promoting effectiveness in the studies of reference 7. However, it has been found in both the Ames and the University of Maryland studies that a reduction in effectiveness will be realized if the apex of the triangle does not point into the flow.

Although the use of triangular roughness appears encouraging, further investigation is required in the following problem areas:

(1) The amount of distortion of the boundary layer caused by the triangular trips as compared with the spherical trips

(2) The drag penalty of the triangular trips compared with the spherical trips

(3) The effect of wing leading-edge sweep on the transition-promoting effectiveness of the triangular trips

(4) The effect of pressure gradient on the transition-promoting effectiveness of the triangular trips

(5) The effectiveness of triangular trips with heights less than the boundary-layer thickness

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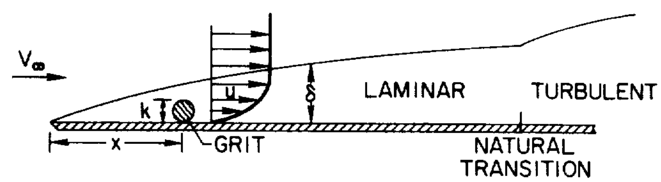
DEFINITION OF BOUNDARY-LAYER PARAMETERS



$R_k = \frac{u_k k}{\nu_k}$ ROUGHNESS REYNOLDS NUMBER

$R_{k,cr}$ VALUE OF R_k FOR FORWARD MOVEMENT OF TRANSITION

$R_x = \frac{V_\infty x}{\nu_\infty}$ REYNOLDS NUMBER BASED ON DISTANCE OF ROUGHNESS FROM LEADING EDGE

Figure 1

SUBSONIC VARIATION OF $C_{D,min}$ WITH ROUGHNESS HEIGHT

VARIABLE-SWEEP FIGHTER, M=0.7

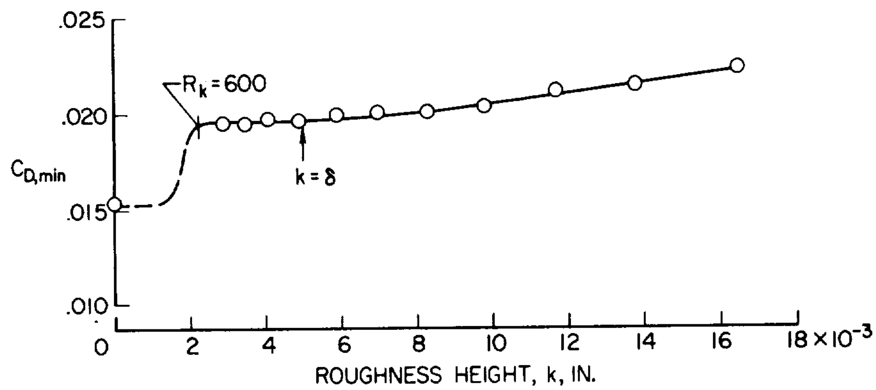


Figure 2

SUBSONIC VARIATION OF $C_{D,min}$ WITH ROUGHNESS HEIGHT

OTHER CONFIGURATIONS; M ≈ 0.7

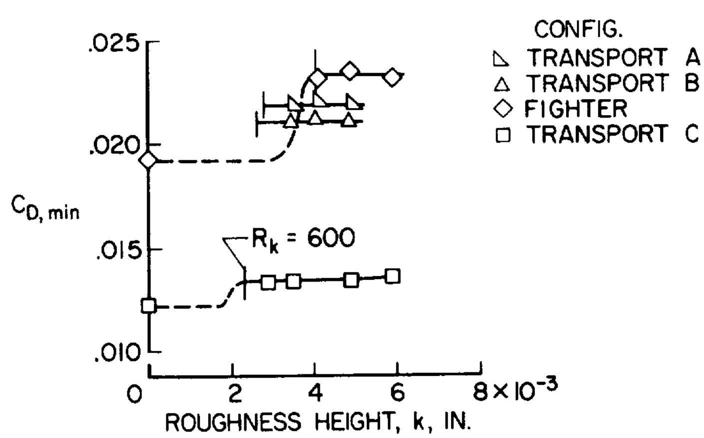


Figure 3

DISTRIBUTION OF MEASURED HEIGHTS OF PARTICLES IN A TYPICAL CARBORUNDUM TRANSITION TRIP
GRIT NO. 30 TO NO. 80

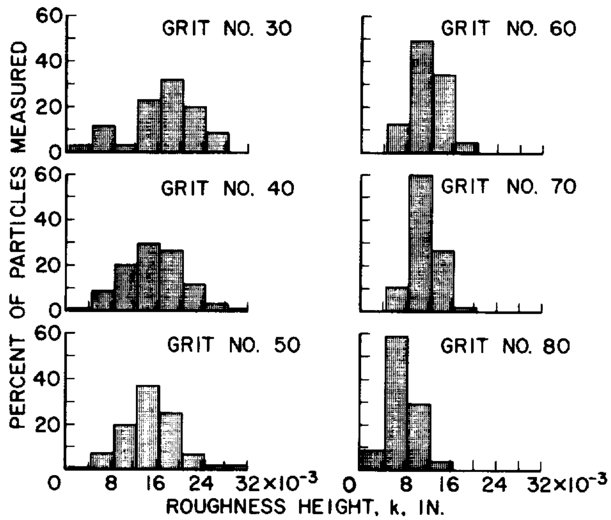


Figure 4

DISTRIBUTION OF MEASURED HEIGHTS OF PARTICLES IN A TYPICAL CARBORUNDUM TRANSITION TRIP
GRIT NO. 90 TO NO. 240

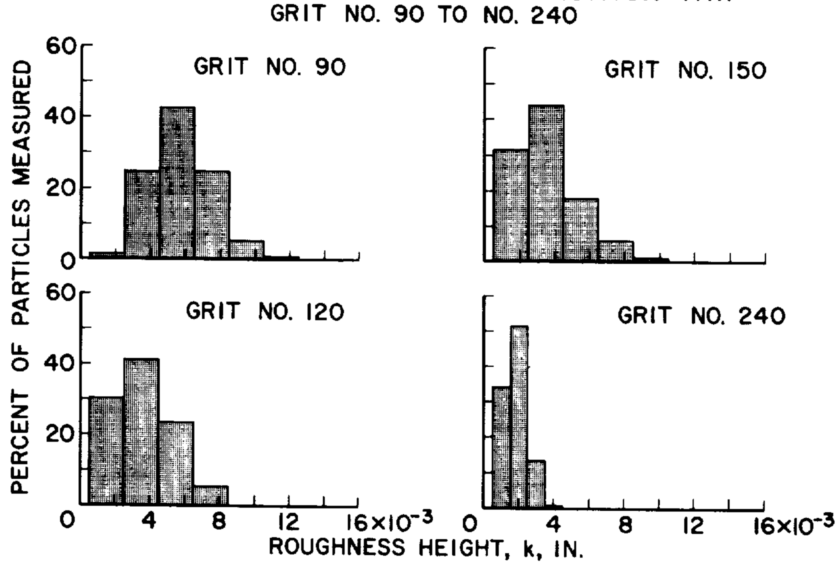


Figure 5

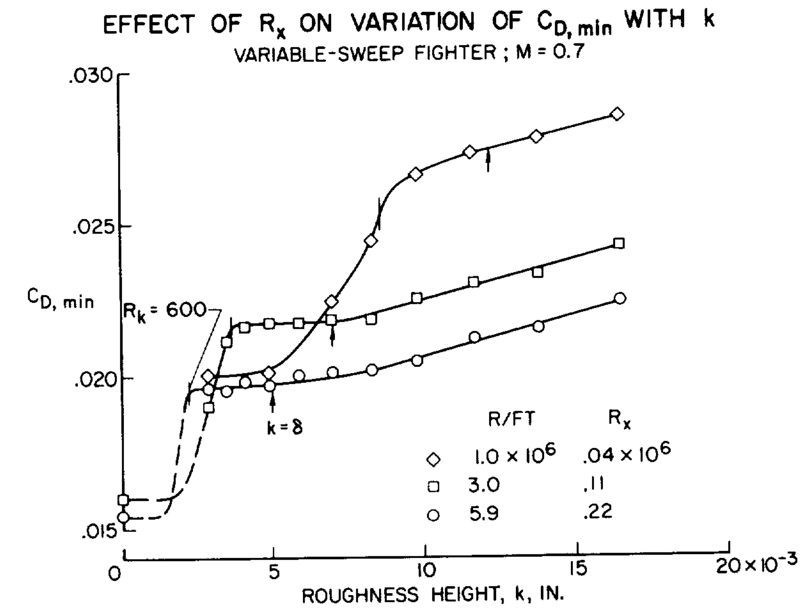


Figure 6

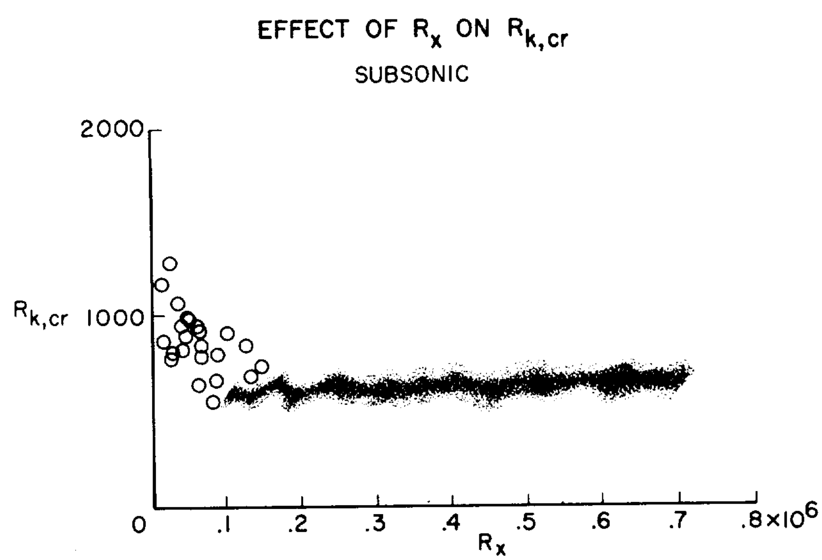


Figure 7

EFFECT OF M ON BOUNDARY-LAYER TRANSITION CRITERIA

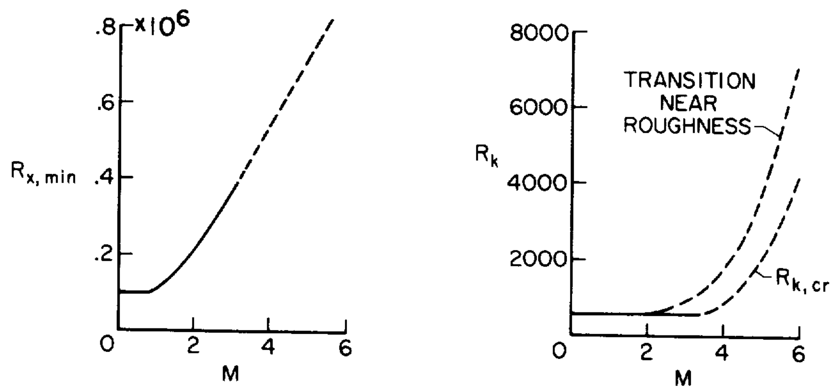


Figure 8

GRIT-DRAG DETERMINATION BY
VARIABLE REYNOLDS NUMBER METHOD

M = 2.75

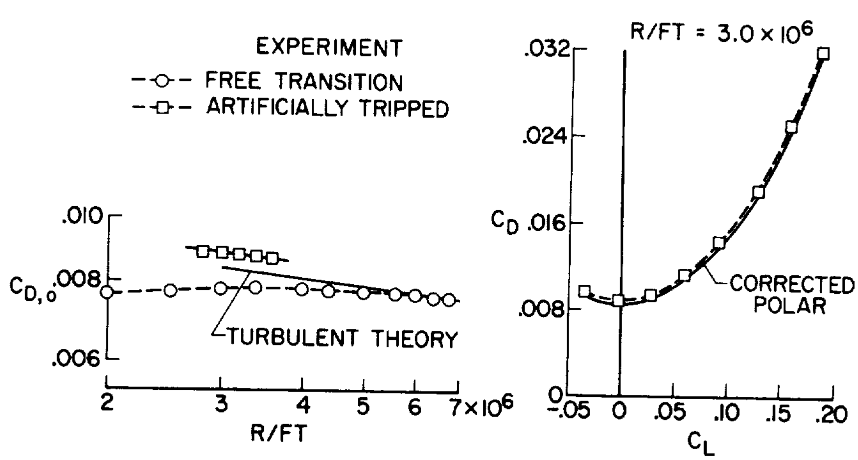


Figure 9

GRIT-DRAG DETERMINATION BY VARIABLE ROUGHNESS SIZE METHOD

M = 2.75 ; R/FT = 3.0 × 10^6

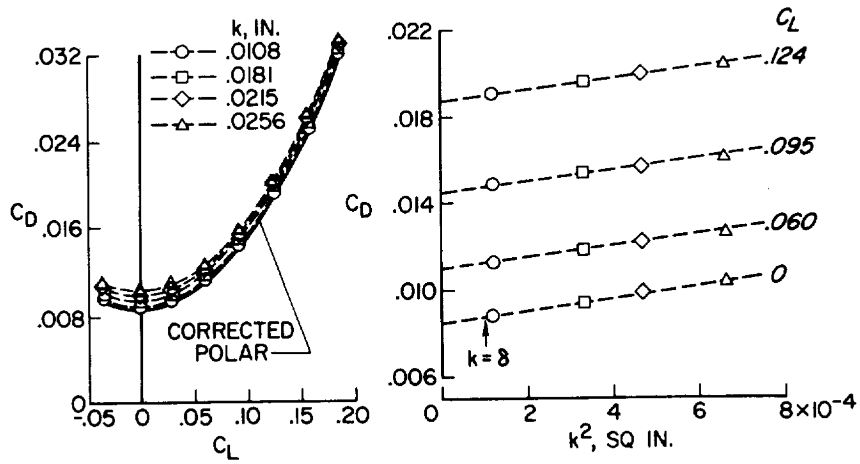


Figure 10

COMPARISON OF CORRECTED POLARS

M = 2.75 ; R/FT = 3.0 × 10^6

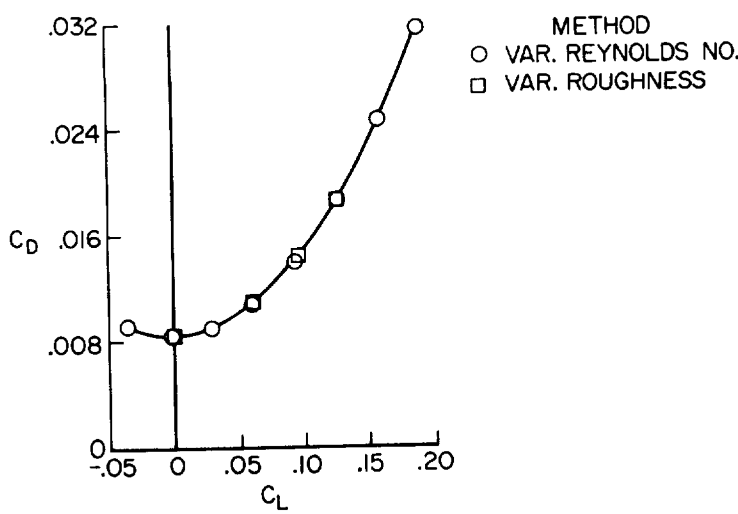


Figure 11

SUPERSONIC VARIATION OF $C_{D,o}$ WITH k^2

$M = 2.75$; $R/FT = 3.0 \times 10^6$

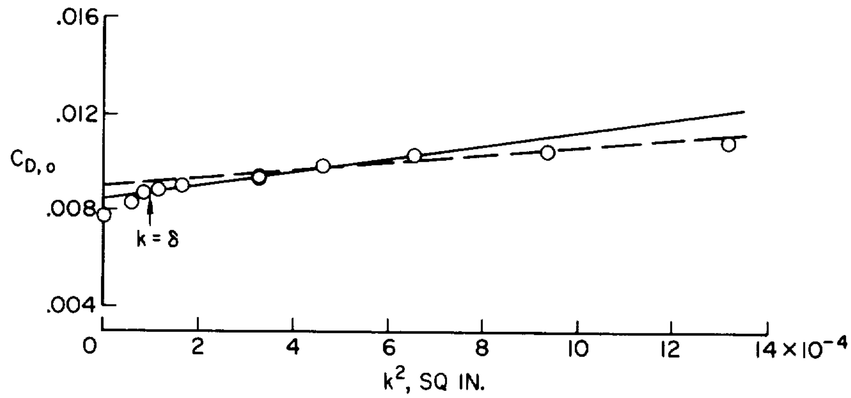


Figure 12

RATIO OF MINIMUM SPHERICAL TRIP REYNOLDS NUMBER TO MINIMUM TRIANGULAR TRIP REYNOLDS NUMBER FOR TRANSITION NEAR ROUGHNESS

$\frac{k}{\delta} > 1$; $R_x = 0.025 \times 10^6$ TO 0.6×10^6

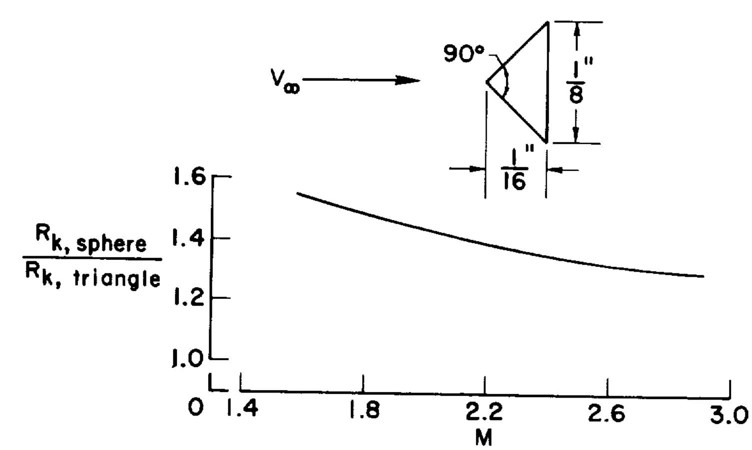


Figure 13

NASA-Langley, 1966 L-5226