Effects of Surface Roughness on Two Shuttle Orbiter Models

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The study addressed the effects of roughness on longitudinal and lateral stability and performance. In addition, asymmetric flow separation (or attachment) due to roughness, vehicle pitch rate, or large, rapid elevon motion was studied. Tests were made using 0.01875- and 0.012-scale Shuttle Orbiter models over a Mach number range from 0.20 to 6.0 in wind tunnels at Langley and in the Vought High-Speed Tunnel. Data indicate that even large asymmetrically placed roughness had little effect on the longitudinal and lateral stability of the models across the Mach range and performance was affected only at subsonic speeds. An empirical performance-estimating technique using the wind-tunnel data gave lift-drag values in the range of values obtained from Shuttle flights. Attempts to cause the flow to separate asymmetrically over the wings of the model were unsuccessful.

Nomenclature

C_D = drag coefficient
C_L = lift coefficient
C_ℓ = rolling-moment coefficient
C_{ℓ_β} = $\partial C_n/\partial\beta$, per degree
C_m = pitching moment coefficient
C_n = yawing moment coefficient
C_{n_β} = $\partial C_n/\partial$, per degree
C_Y = side-force coefficient
D = drag force ℓb
L = lift force ℓb
L/D = lift-drag ratio
M = Mach number
R = Reynolds number per foot
α = angle of attack, deg
β = angle of sideslip, deg
δ_e = elevon deflection, deg

Subscripts

L = left
max = maximum
min = minimum
R = right
untrim = untrimmed conditions, nonzero moments

Introduction

THE National Aeronautics and Space Administration is continuing analytical and experimental studies related to the development of design criteria for vehicles capable of transporting large payloads into near-Earth orbit. During the development of the Space Shuttle, a number of questions about the basic aerodynamics of winged vehicles traveling to and from the Earth's atmosphere were raised. These queries were generally concerns outside those usually addressed in the mainstream Shuttle development program and were handled through a Shuttle Aerodynamics Panel with members from the prime contractor and NASA centers. One of the areas of concern was the effect surface roughness might have on the stability, control, and performance of such spacecraft across the Mach number range. The surface of such vehicles may be covered with some type of thermal protection system (TPS) that might consist of individual tiles or "blankets" like the Space Shuttle Orbiter. Because of the roughness resulting from the steps and gaps in individual tiles or the general character of the TPS surface itself, there was concern that unusual flow phenomena may be triggered that would affect the stability and control characteristics of the vehicle. This could take the form of local flow separation and sudden leading edge stall (or flow attachment as the vehicle pitches down from a high angle of attack). If separation should occur asymmetrically, large rolling moments (snap roll) could result. Roughness could also result in general degradation in performance or stability that is of particular interest at subsonic speeds as the vehicle will probably perform a gliding entry and landing and have no "go-around" capability.

In an attempt to determine the effects of roughness, wind-tunnel investigations were conducted using Shuttle Orbiter models in the Langley Low-Turbulence Pressure Tunnel, 8-foot Transonic Pressure Tunnel, the Unitary Plan Wind Tunnel, 20-inch Mach 6 Tunnel, and the Vought High-Speed Tunnel over a Mach range from 0.20 to 6.0, an angle-of-attack range from −0 to 45 deg, and a sideslip range up to 8 deg (see Refs. 1–5). Surface roughness was simulated by applying grit to the models. Grit was used in narrow bands along the wing leading edge, vertical tail, and around the nose in the normal manner used to force transition from laminar to turbulent flow in wind-tunnel tests. As an extreme case, grit was applied over the entire model.

In conjunction with the study of the effects of roughness, additional tests were made to determine the effects of pitch rate on the aerodynamics of the shuttle model as it transitioned from high angles of attack (spacecraft mode) to low angles (aircraft mode). Again, the concern of asymmetric flow attachment was addressed. It was also postulated that the flow could become attached over one wing before the other or that rapid upward elevon deflections would cause the marginally attached flow over the wing to become detached and roll divergence would result. To investigate the validity of these concerns, tests were made in the Vought High-Speed Tunnel and Langley Unitary Plan Wind Tunnel where flowfield observations were made and pitch rate and elevon motion effects investigated.

The longitudinal data are referred to the stability system of axes, and the lateral-directional data are referred to body system of axes. The model moment reference center was located at 65% of the body length.

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Description of Models

The models were 0.01875- and 0.012-scale models of a combination of Shuttle design iterations. The configuration consisted of a large body, a 45 deg swept trapezoidal wing blending into a 79 deg swept inboard section, and a 45 deg swept centerline vertical tail. Large fairings on the aft upper body on either side of the vertical tail represented the housing for the orbital maneuvering system. The contractor's designation for the model was 139B for the nose section and 089B for the remainder. A sketch and photograph of the configuration are presented in Figs. 1 and 2, respectively. The model control surfaces consisted of the wing-trailing edge elevons deflected together for pitch and differentially for roll and rudder deflection to produce yawing moment. The model was also equipped with a control flap at the base of the body that was fixed for these tests at 0 deg. The vertical tail had a split rudder that was pulled together to form a diamond-shaped cross section (boattailed configuration) at subsonic speeds, opened to form a 10 deg wedge cross section at transonic speeds, and opened further to a 10/40 deg section at supersonic speeds. No attempt was made to simulate the texture of the thousands of individual tiles with associated gaps and steps. Figure 3 is included, however, as an illustration of the appearance of the vehicle surface.

Test Conditions

The tests were conducted in four Langley research facilities and the Vought High-Speed Tunnel. A complete description of these facilities is given in Ref. 6. The model was sting-supported, and forces and moments were measured by use of an internally mounted strain-gage balance. Angle of attack was corrected for the effects of sting and balance deflection under load. Lift interference and tunnel blockage effects were applied as appropriate to each facility. The data presented here represent gross drag in that no correction for base pressure has been made. For the 0.01875-scale model, which was used in tests up to $M = 4.6$, a range of surface roughness was investigated by applying relatively sparse coatings of various size carborundum grit over the complete model. In all cases, the grit was hand-sprinkled onto the model and, therefore, no close tolerance as to the density of the grit was maintained. The density of the largest size grit was checked, however, at between 20–30 grains per square inch. The smaller size grit was more difficult to control and was somewhat more densely applied. This overall roughness is referred to as acreage roughness. Examples of the model with various grit configurations are shown in Fig. 4. For comparison purposes, the model was tested "clean" with no fixed transition and with transition fixed in the normal manner by thin-strips of grit just aft of the leading edge of the wing, vertical tail, and nose. As a most extreme case, the largest size grit was applied over the entire model. To investigate asymmetric effects, one-half of the model was gritted and the other half was left clean. The roughness applied to the 0.012-scale model consisted of large single grains of carborundum placed just aft of the leading edge of the wing on the lower surface only. This model was used only in tests at $M = 6$. The test parameters investigated in the various facilities are presented in Table 1.

Fig. 2 Photograph of 0.01875-scale model used in the investigation.

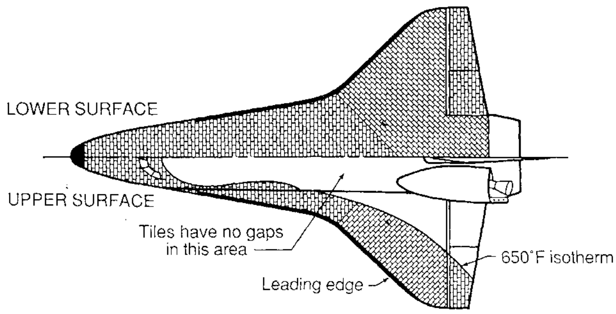

Fig. 3 General arrangements of thermal protection system tiles.

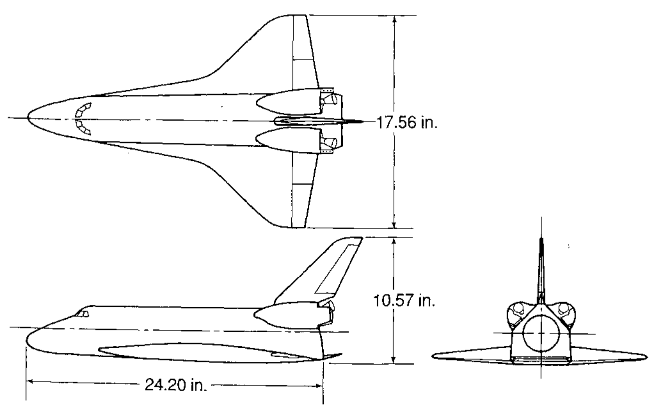

Fig. 1 Sketch of 0.01875-scale Shuttle Orbiter model.

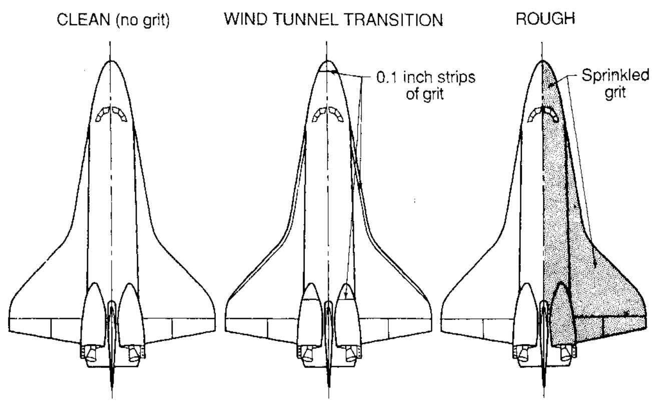

Fig. 4 Roughness arrangement on model.

Table 1 Test Parameters

Facility	Mach	α	β	Maximum $R \times 10^{-6}$
LTPT[a]	0.20	0–20	0, = 5	13
8-ft TPT[b]	0.4–1.2	0–20	0, = 5	7
UPWT[c]	1.6–4.6	0–30	0, = 8	5
20-in.[d]	6.0	0–45	0, = 5	9
Vought HST[e]	2.5–4.6	0–45	0, ± 5	30

[a]Langley Low-Pressure Turbulence Tunnel; [b]Transonic Pressure Tunnel; [c]Unitary Plan Wind Tunnel; [d]Mach 6 Tunnel; [e]Vought High-Speed Tunnel.

Table 2 Physical surface characteristics

Component	Full scale	Roughness	
		0.019 scale[a]	0.012 scale
Leading edge	0.003	0.000056	0.000037
Heading edge gap	0.070	0.0013	0.0087
TPS	0.010	0.00019	0.00012
TPS gap	0.070	0.0013	0.00087
TPS step disp.	0.070	0.0013	0.0087
Tile size	6 × 6	0.11 × 0.11	0.07 × 0.07

[a]For test at M = 4.6 in. UPWT transitions of 0.0117 in height are used to insure turbulent boundary layer. For tests at M = 1.0 in. 8 ft TPT strips of 0.0035 in height are used.

Scaling Roughness

The general tile arrangement of this early Shuttle configuration was estimated to have approximately 54,000 tiles with 37,800 running ft of gaps. The gap width and step height between tiles and surface irregularity are given in Table 2 in full-scale and model-scale dimensions. The full-scale values of roughness are relatively small with the maximum estimated discontinuity of only 0.07 in., although some postflight measurements indicated values of 0.125 in. When these values are scaled to model sizes suitable for wind-tunnel tests over the Mach range, the roughness size becomes very small. In fact, the roughness becomes smaller than the size usually used to trip the boundary layer (to insure turbulent flow) in normal wind-tunnel tests (see Ref. 7). It was obvious that geometrically scaling roughness was not a realistic approach to determine the effect of roughness on the aerodynamic characteristics of the vehicle. It was decided to attempt to bound the problem by testing the models in a clean condition and then adding varying degrees of roughness in the form of grit applied overall. The range of roughness sizes selected for the test had grit diameters that varied from 0.0029 in. (the smallest that could be conveniently handled) to 0.0165 in. (see Table 3). Geometrically scaling these values to full scale indicated that even the smallest grit was larger than the estimated roughness level, and the largest grit would represent heights of 0.88 in. It was felt that tests with grit applied in this manner would give an indication of the effect roughness might have on stability and control, but the effect on actual performance, especially subsonic performance, would be subject to doubt.

Table 3 0.01875-scale model roughness[a] simulation

Grit diameter, in.	Grit scaled to full scale, in.
0.0029	0.155
0.0049	0.261
0.0059	0.315
0.0165	0.880

[a]Maximum full-scale roughness = 0.007 in.

Effect of Roughness on Aerodynamic Characteristics

Selected results of the many wind-tunnel tests are shown in Fig. 5 for Mach numbers of 0.25, 0.98, and 2.36. These data are representative of the effects across the Mach number range for the model in the clean configuration and with the maximum degree of acreage roughness applied. All controls were neutral and the rudder was flared 10 deg in the transonic tests and 40 deg in supersonic tests. The most significant effect of roughness occurred at subsonic speeds where there was a sizable loss in subsonic performance (L/D), but as indicated previously, this was to be expected because of the very large size of the roughness. There was surprisingly little effect of the grit on pitching moment or the lateral stability parameters. Deviations of equal magnitude in C_{n_β} and C_{ℓ_β} at angles of attack near the stall also resulted from changes in Reynolds number and are felt to be a characteristic of the configuration and not attributable totally to roughness (see Ref. 1). At transonic and supersonic speeds, the effects of roughness on performance and stability disappear.

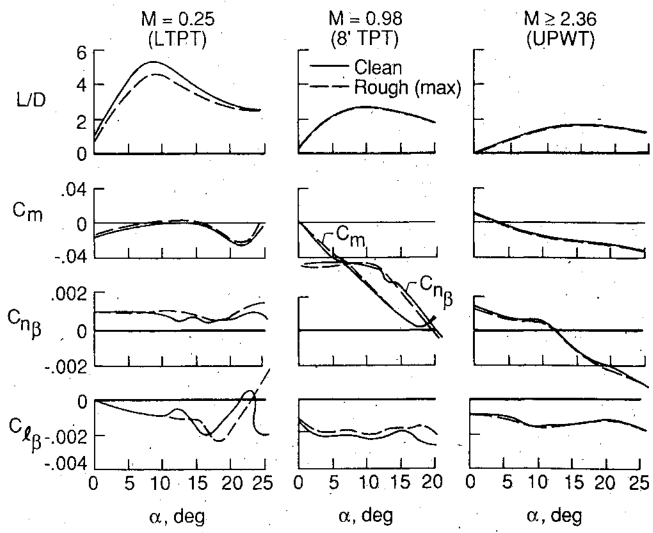

Fig. 5 Effect of roughness on aerodynamic characteristics.

A summary of the simulated roughness effects on the characteristics of the model up through $M = 4.6$ is presented in Fig. 6. The performance and drag data are presented as the variation of the ratio of the values obtained with roughness divided by the values obtained with no roughness plotted against Mach number. There was about a 14% reduction in $(L/D)_{max}$ at low subsonic speeds; however, losses in performance disappear as Mach number approaches 1.0 (as previously observed). Note that drag due to roughness does not decrease as rapidly with increasing Mach number above $M = 1.0$. The indication is that roughness not only influences friction drag, but also, to some extent, drag due to lift in incompressible flow. The diminishing drag due to roughness at the higher Mach numbers occurs in all probability because the grit (on the upper surface of the wing at least) becomes immersed in the thickened boundary layer and, therefore, has no effect. There is essentially no change in the longitudinal stability parameter $\partial C_m/\partial_{C_L}$ across the speed range.

The results obtained in the Langley 20-in. Mach 6 tunnel using the 0.012-scale model are shown in Fig. 7. Roughness was added as discrete roughness particles to the lower surface of the left wing in an attempt to simulate a highly asymmetric condition where thermal protection has been lost on one side (Fig. 8). The angle of attack was varied from 20 to 35 deg, covering the flight range at this Mach number. No roughness was added to the upper surfaces of the model as the surface is shielded from the airstream at these angles of attack. Tests were conducted at Reynolds numbers of ¼ and ⅔ of full-scale values. The longitudinal data of Fig. 7 show no effect of roughness as the deviation in the data are within the experimental accuracy. The lateral data show the effect of the asymmetric roughness, but these effects are small and would be expected. The differences could easily be handled with small control deflections.

Effect of Full-Scale Roughness on Performance

Relatively good results in estimating the drag characteristics of full-scale operational aircraft from wind-tunnel data taken at lower Reynolds numbers have been obtained by the technique described in Ref. 8. Smooth model wind-tunnel data (drag) are used as the initial condition. The smooth model data are then scaled to full-scale Reynolds number values (changes in skin friction), and then a drag increment due to manufacturing tolerances and protuberances is added. This method was selected to estimate the subsonic performance of the Shuttle vehicle. Three cases were investigated based on the following assumptions: a worst case where all tiles have sharp edges and gaps and steps (displacement between tiles), a nominal case where all tiles have sharp edges and gaps, but only one-half of the tiles have steps, and a favorable case where all tiles have rounded edges and gaps and one-half of the tiles have steps. The method of estimating the drag increment of the surface was taken from Hoerner.[9] The results of the estimation are presented in Fig. 9. The estimated untrimmed $(L/D)_{max}$ values obtained using this technique varied from 5.5 for the clean model (no roughness drag added) to 4.5 for the worst roughness case. The $(L/D)_{max}$ from the wind-tunnel test was 5.3 for the clean configuration and 4.0 for the maximum roughness case. Values from actual Space Shuttle flights have indicated subsonic L/D's nearest those for the "favorable" roughness condition. It is interesting to note that there has been an apparent decrease in the Orbiter L/D on subsequent flights when there has been no major surface maintenance performed, indicating that the roughness drag on the vehicle has increased.

From wind-tunnel data, it appears that for configurations similar to the Space Shuttle (highly swept wings, thick airfoils, etc.), there would be no large effect of roughness on stability or control. Performance should not be affected except at low subsonic speeds where roughness will have a detrimental effect. There are methods, however, for estimating this effect with a relatively high degree of confidence.

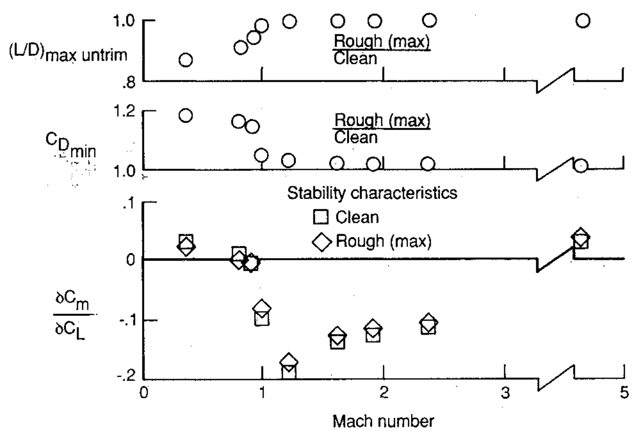

Fig. 6 Summary of roughness effects.

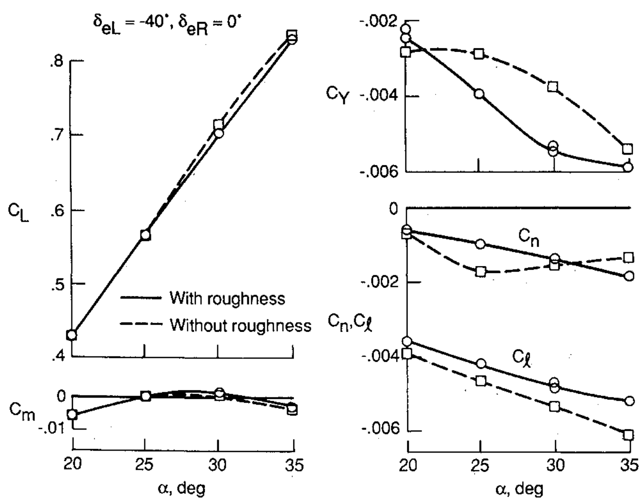

Fig. 7 Effects of roughness at Mach 6, δ_{eL} = 10 deg, δ_{eR} = 0 deg.

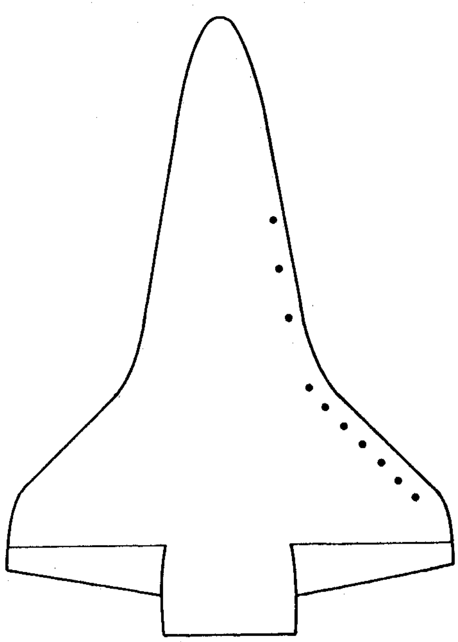

Fig. 8 Roughness locations on 0.012-scale model performance.

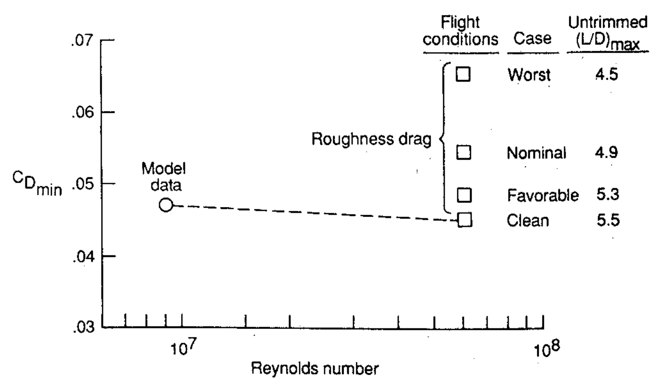

Fig. 9 Estimated low-subsonic aerodynamic performance.

Roll Divergence

A Shuttle Orbiter entry angle-of-attack schedule as a function of Mach number, which would be typical of current manned reentry vehicle trajectories, is presented in Fig. 10. As may be seen, the transition from the high angle-of-attack spacecraft mode to the low-angle aircraft mode occurs at supersonic speeds. It is at these speeds that flow attachment over the upper surface of the wing will occur. Therefore, tests were conducted in this speed range to determine the effect of pitch rate and large elevon deflection angles and the possibility of asymmetric attachment. Before initiating the detailed investigation, an exploratory series of tests were made to define the nature of the flowfield over the model. Small tufts were attached to the model for visual observation. The location of the windows in the Unitary Plan Wind Tunnel limited the viewing range for these preliminary tests to about a 20-deg angle of attack. Sketches of the flow as indicated by the tufts (Fig. 11) showed no discernible difference in their behavior at Mach numbers of 4.6 or 2.5 or at the two test Reynolds numbers. Also, no difference was apparent in the flow character over the model with or without normal transition roughness strips applied.

At an angle of attack of zero, the flow over the wing was attached and smooth; however, there was some outflow at the wing-body junction probably caused by the interference resulting from the presence of the Orbital Maneuvering Systems (OMS) pods. The flow begins to separate at the trailing edge of the wing along the probable interference line generated by the OMS pod at $\alpha = 5$ deg. At an angle of attack of 10 deg, a vortex originating at the leading edge of the highly swept fillet is evident (see Fig. 12), which sweeps up at the wing midspan and scrubs down along the body. This is an indication of the three-dimensionality of the inboard-flow behind fillet. As the angle of attack is increased, the vortex seems to move off the wing surface, and the region of flow separation increases. At an angle of attack of 20 deg, most of the flow over the wing is separated. If asymmetric flow attachment were to occur during the entry phase of flight, it would probably occur at angles of attack of 20 deg or less.

Wind-tunnel tests to investigate the possibility of asymmetric flow attachment were conducted in the Unitary Plan Wind Tunnel and the Vought High Speed Tunnel at Reynolds numbers ranging from very low- to full-scale flight values. During these tests, the model was pitched up at a constant rate from an angle of attack of 0 to 40 deg and then pitched down at the same rate. The data, shown in Fig. 13, are from the Vought tunnel at full-scale Reynolds number. The data are presented as discrete points, but are actually selected points taken from continuously monitored values. These data show excellent repeatability for all parameters with no signs of asymmetric flow attachment even with the large negative right elevon deflection. Again, as indicated in the tuft study, the flow over the vehicle seems to be well behaved, which is typical of highly swept wing configurations with their low-lift curve slope and gentle stall characteristics.

To investigate the possibility of control-induced asymmetric flow separation caused by the rapid deflection of the elevons, the Orbiter model was equipped with remotely controlled pneumatically driven elevon surfaces and tested in the Unitary Plan Wind Tunnel. A typical example of the results of these tests are presented in Fig. 14. The test procedure was to hold the model at a fixed angle of attack and differentially deflect the controls in both the positive and negative directions while recording continuous data. The elevon rate deflection was almost instantaneous, exceeding the actual Orbiter elevon rate. For each test condition, the force-and-moment data repeated consistently with mirror image values resulting from increasing and decreasing control deflections. The data were smooth and no unusual control characteristics were noted. In addition, visual observation from the schlieren system indicated the shock structure was unchanged with no effects feeding forward even at an angle of attack of 0 deg. It is rea-

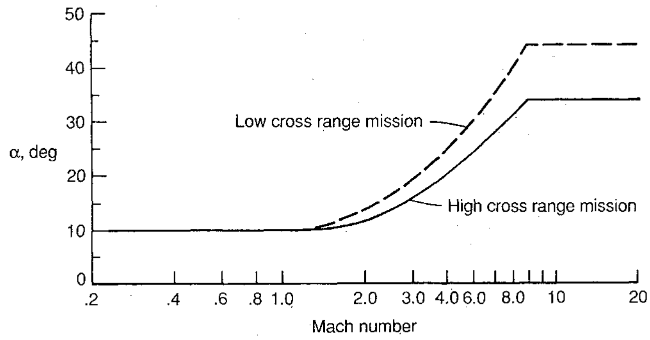

Fig. 10 Nominal entry angle-of-attack schedule.

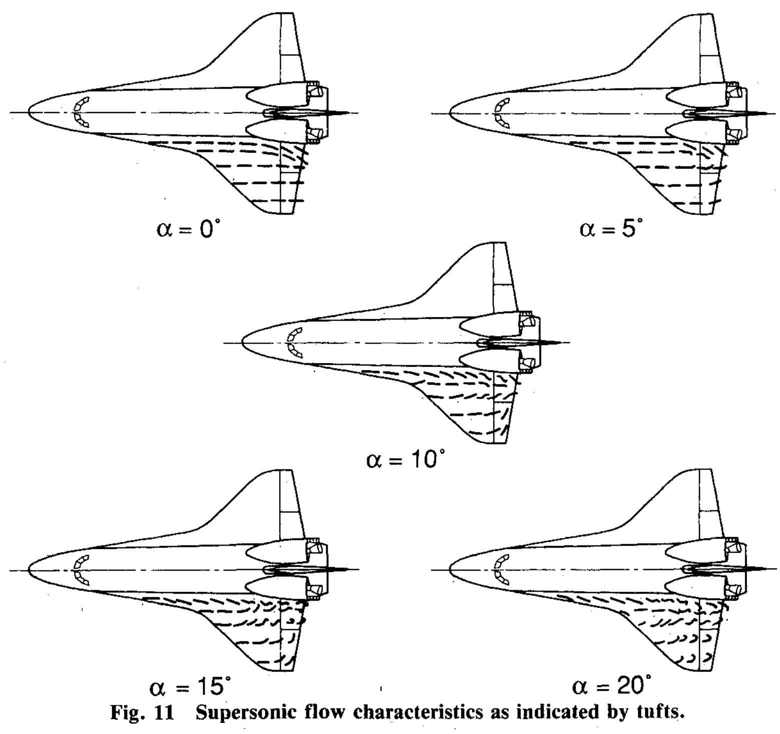

Fig. 11 Supersonic flow characteristics as indicated by tufts.

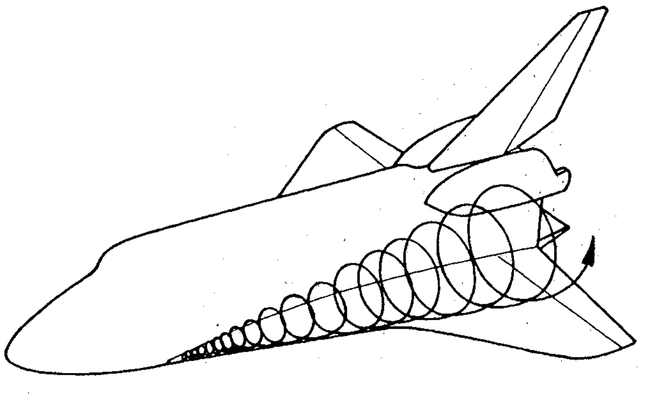

Fig. 12 Wing leading vortex.

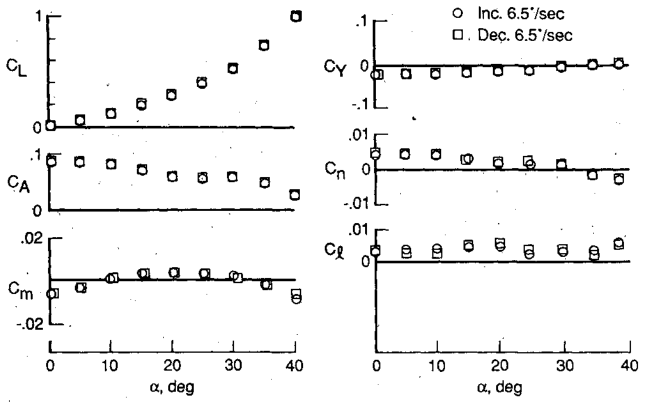

Fig. 13 Effects of increasing/decreasing pitch, δ_{eL} = 0 deg, δ_{eR} = 40 deg.

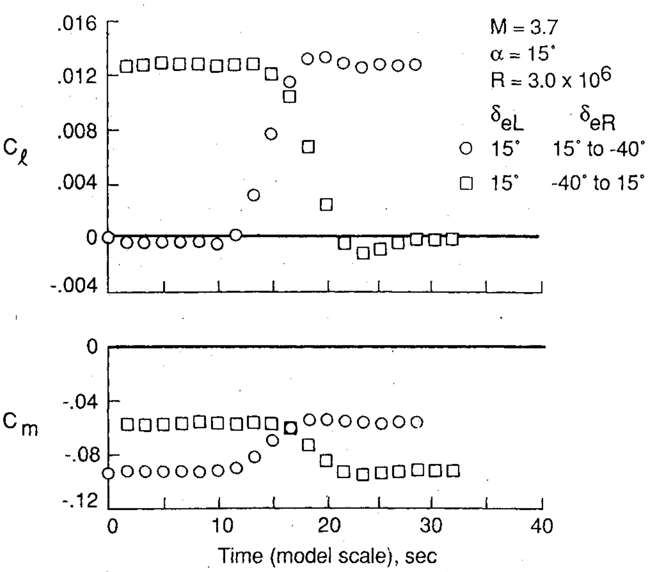

Fig. 14 Effect of rapid full travel elevon deflection.

sonable to conclude, therefore, that no unusual condition should occur where asymmetric flow characteristics would cause "snap roll."

Concluding Remarks

An experimental wind-tunnel test program has been conducted to determine the effects of vehicle surface roughness (corresponding to the external thermal protection system) on the aerodynamic characteristics of two scale models of an early version of the Space Shuttle Orbiter. Surface roughness was simulated by applying a sparse coating of carborundum grit to the complete model. Various grit sizes were investigated. Tests were made with both increasing and decreasing model angles of attack with elevons deflected in an attempt to identify any flow separation potential as the Orbiter traversed from the high angle-of-attack spacecraft mode to the more conventional low angle-of-attack aircraft mode. The tests were conducted over the Mach number range from 0.25 to 6.0 at the Langley Research Center in the Low-Turbulence Pressure Tunnel, 8-foot Transonic Pressure Tunnel, Unitary Plan Wind Tunnel, 20-inch Mach 6 Tunnel, and Vought High-Speed Tunnel.

Geometrically scaling the Orbiter surface roughness characteristics to model size resulted in values that were smaller than the transition roughness usually used to insure turbulent flow over models in wind-tunnel tests. Since geometric scaling was impractical, various-size roughness in the form of carborundum grit was tested. The results of the investigation indicated that surface roughness, even roughness of considerable magnitude, had no significant effect on vehicle stability or control. Comparison of smooth model stability and control data with that of the rough model indicated only small differences at subsonic Mach numbers and no differences above $M = 1$. There was an effect of roughness on performance (L/D), but that effect also disappeared at supersonic Mach numbers. Using the subsonic wind-tunnel data, extrapolating skin friction to full-scale Reynolds numbers, and then adding computed roughness drag resulted in untrimmed $(L/D)_{max}$ values ranging from 5.5 for the clean configuration to 4.5 for the very rough configuration. Actual Shuttle flight values have been estimated to be within this range but nearer the high end.

Attempts to cause the flow to separate over the wing of the model by adding roughness, alternating positive and negative pitch rate, or by large or rapid negative control deflection was unsuccessful. At all times, the flow patterns under these adverse conditions were well behaved, this seems to be typical of highly swept winged configurations with low-lift curve slopes and gentle stall characteristics. It can be inferred that snap roll resulting from flow attachment or detachment over one wing and not the other is not a valid concern.

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