JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 38, No. 5, September–October 2001

Effect of Noise on Roughness-Induced Boundary-Layer Transition for Scramjet Inlet

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Boundary-layer transition was studied on an axisymmetric scramjet-inlet model with compression corners, using the Purdue Mach 4 quiet-flow Ludwieg tube. Although the Reynolds number was not large enough to achieve natural transition under quiet-flow conditions on the smooth model, transition was investigated by applying isolated roughness elements near the nose of the model. Surface hot-film measurements were obtained under both quiet and noisy wind-tunnel conditions. Both the noisy tunnel flow and the roughness elements generated intermittency in the boundary layer. The effect of the tunnel noise was comparable to the effect of the roughness. The change from quiet to noisy flow also changes the character of the intermittency and the effects of the roughness, which suggests that ground tests for boundary-layer transition should be interpreted with care. These results form the first substantial quiet-flow measurements available in the open literature for supersonic boundary-layer transition over compression corners.

Nomenclature

$I(t)$ = smoothed value of $i(t)$, intermittency is average value
$i(t)$ = trace of provisional turbulence/nonturbulence using ε as threshold for the identification
Re = Reynolds number
Re_s = Reynolds number based on freestream conditions and arclength from the leading edge
ε = local difference between two points (proportional to the local first derivative)

Introduction

THE development of a single-stage-to-orbit space plane using horizontal takeoff is a promising long-term goal in space transportation. This difficult concept will require advanced propulsion systems. Development of a successful system will require much additional research and development in the area of hypersonics. Breakthroughs will be required in many technical areas, such as aerodynamics, structures, and propulsion.

The prediction of boundary-layer transition is the most important and the most difficult problem in hypersonic aerodynamics. Transition from a laminar to a turbulent boundary layer increases aerodynamic heating by a factor from roughly 3–5, which may increase requirements for appropriate thermal protection systems (TPS). A TPS weight savings trades kilo-for-kilo with payload. Transition is also critical in the control of boundary-layer separation. However, research into hypersonic boundary-layer transition in ground-test facilities suffers from several difficulties. The chief problem is that conventional hypersonic wind tunnels have noise levels far above flight conditions.[1] In addition, flight measurements are very rare because of the very high associated costs.

This paper summarizes detailed measurements obtained in the Mach 4 Ludwieg tube at Purdue University, which is capable of generating a very quiet uniform flow, with noise levels that are comparable to flight conditions. Thus, this facility is suitable for research in boundary-layer transition. The research was focused on an axisymmetric scramjet inlet that contains compression corners, which can cause separation or transition of the boundary layer.

Transition on Compression Corners in Quiet Flow

Only one quiet-flow test of a scramjet forebody[2] is known to the authors. That test was conducted in the NASA Langley Research Center Mach 3.5 quiet tunnel, and the model incorporated a 0.3-mm-radius nose on a 3.6-deg wedge forebody, followed by unspecified compression ramps. Measurements in the region past the first corner showed length transition Reynolds numbers (Re_s) of about 6×10^6 for quiet conditions and about 3×10^6 under noisy conditions. Forward of the first corner on the centerline, transition did not occur under quiet-flow conditions. Further details for this test were not available in the open literature. However, there are several references available for the more general compression corner problem.[3,4] In addition, Lachowicz et al. measured instability and transition on a smooth compression flare in the NASA Langley Research Center Mach 6 quiet tunnel,[5] although this smooth compression is rather different than the sharp corner studied here.

The authors are aware of only two sets of flight measurements in which a compression corner was present. These were made on the flare of a cone–cylinder–flare configuration. In the first study,[6] it unfortunately appears from the surface heat transfer data that the boundary layer was turbulent before it approached the corner. In the second study,[7] transition may have occurred on the flare at high Mach numbers, but angle-of-attack effects are present, and three-dimensional computations would be required to help determine whether transition occurs.

Quiet-Flow Ludwieg Tube

A schematic of the Purdue quiet-flow Ludwieg tube is shown in Fig. 1. A Ludwieg tube consists of a long pipe with a converging–diverging nozzle on the downstream end, from which flow exits into a test section and diffuser. The diffuser section is connected to a vacuum tank, which is initially isolated from the working gas in the upstream portion of the facility by a diaphragm.[8]

The Purdue facility is based on a 305-mm-diam driver tube that is 20.7 m long. A smooth contraction tapers from the driver tube to the nozzle throat, which is followed by the 90×109 mm Mach 4 rectangular test section. The nozzle is polished to a surface smoothness

Presented as Paper 2000-0284 at the AIAA 38th Aerospace Sciences Meeting, Reno, NV, 10–13 January 2000; received 23 May 2000; revision received 16 April 2001; accepted for publication 17 April 2001.

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of 0.02–0.04 μm in the throat region. Optical access is provided by 76-mm-diam windows in the flat sidewalls.

Flow is initiated when the vacuum tank is evacuated and the diaphragm downstream of the test section is broken. The resulting expansion wave moves upstream into the test section, and supersonic flow is established. Because the expansion of air from the fixed-volume driver tube results in a continual decrease in the stagnation conditions, the test run lasts until the pressure ratio is insufficient for sustaining supersonic flow through the nozzle. Periods of constant test conditions occur between passages of the reflecting expansion wave. Consequently, even though the duration of constant-condition flow in the facility may be relatively brief, numerous segments of constant-condition flow may be obtained at decreasing stagnation conditions and Reynolds numbers. In this paper, the first run segment is used to measure transition phenomena because this segment has the highest Reynolds number and is, therefore, most likely to cause boundary-layer transition.

Total pressure fluctuations in the quiet region of the Purdue nozzle are about 0.05% for driver-tube pressures less than 103 kPa. This noise level is an order of magnitude less than in conventional facilities. Such small fluctuations result from both the natural low noise aspects of the Ludwieg tube design and the ultrasmooth finish on the nozzle walls. The intermittency distribution on the flat sidewalls as a function of driver-tube pressure has been measured using hot-film sensors flush mounted on the sidewall window blanks.[9]

The wind-tunnel total pressure is measured to 0.02% accuracy, and the total temperature is accurate to 0.7%. These stagnation conditions are reduced by the expansion wave in the driver tube, but this effect is neglected here, due to the very low driver-tube Mach number (0.0069). The drop in total temperature during the run is 0.34%. The measurement of freestream pitot pressure at the test section is accurate to about 1.5%. The signal-to-noise ratio for the measurements of pitot-pressure fluctuations is about 2, for the lowest noise measurements; in the present work, no attempt was made to subtract the electronic noise from the measured fluctuations.

Unfortunately, in the present facility this low noise uniform flow can only be maintained at low Reynolds numbers, where the flow on the model is completely laminar under smooth-wall conditions. Therefore, experiments were conducted with roughness elements on the model, to trip the boundary layer to turbulent flow. A similar type of roughness is needed on the Hyper-X scramjet flight-test vehicle to ensure turbulent flow upstream of the cowl entrance.[10] The present work is the first study of roughness-induced transition in compression corners to be carried out under quiet-flow ground-test conditions. For comparison purposes, roughness elements were installed on the wall of the wind-tunnel nozzle to generate the noisy conditions that are characteristic of the conventional facilities used for all other experiments using this model geometry.

Experimental Model

The experiments were performed with a one-fifth scale model of the Central Institute of Aviation Motors (CIAM) axisymmetric scramjet forebody.[11] The model geometry is shown in Fig. 2 and is generally typical of axisymmetric scramjet-inlet designs. The nosetip was made slightly larger than one-fifth scale, to allow inserting a small pressure transducer.

The configuration contains two corners where the air is compressed through oblique shock waves. The tip of the scramjet model was located 237 mm downstream of the nozzle throat, near the beginning of uniform flow in the Ludwieg tube. As already mentioned, the low noise in this wind tunnel combined with the low Reynolds number caused the flow to be completely laminar, under smooth wall conditions.

Because no turbulent intermittency was observed on the smooth model, two kinds of roughness were placed near the nose tip, as shown in Fig. 2, to investigate transition phenomena and also to supply information on the effect of dust on the inlet surface. The width and thickness of the roughness elements are shown in Table 1.

Table 1 Test condition and roughness parameters

Case	Roughness no.	Thickness, mm	Width, mm	Condition
0Q	None	——	——	Quiet
0N	None	——	——	Noisy
1Q	1	0.75	2.2	Quiet
1N	1	0.75	2.2	Noisy
2Q	2	1.50	2.4	Quiet

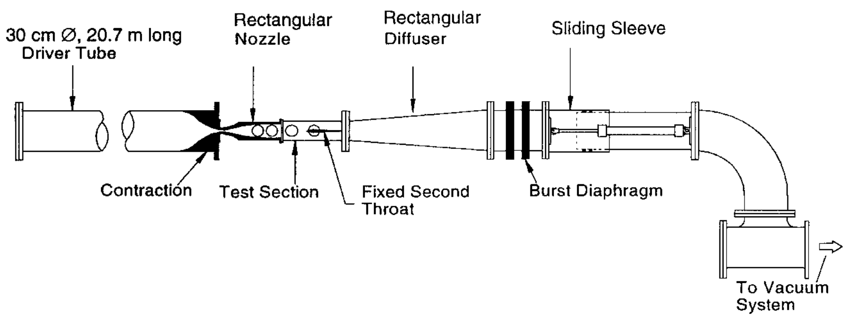


Fig. 1 Mach-4 quiet Ludwieg tube.

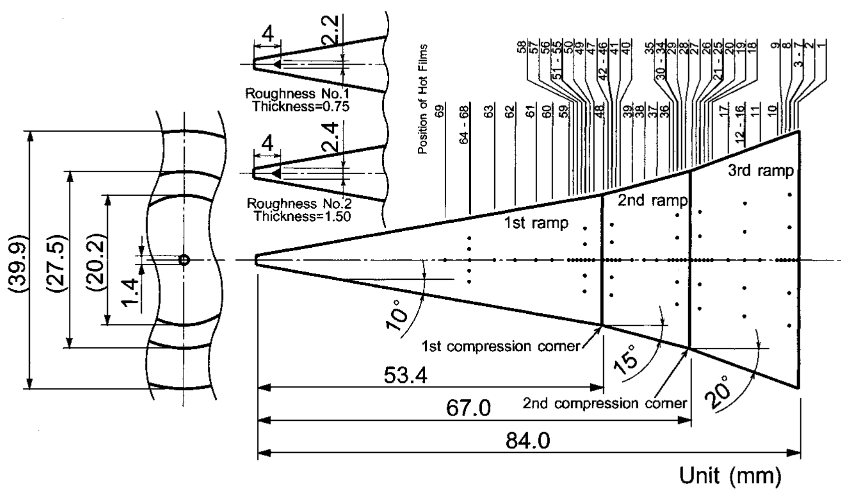


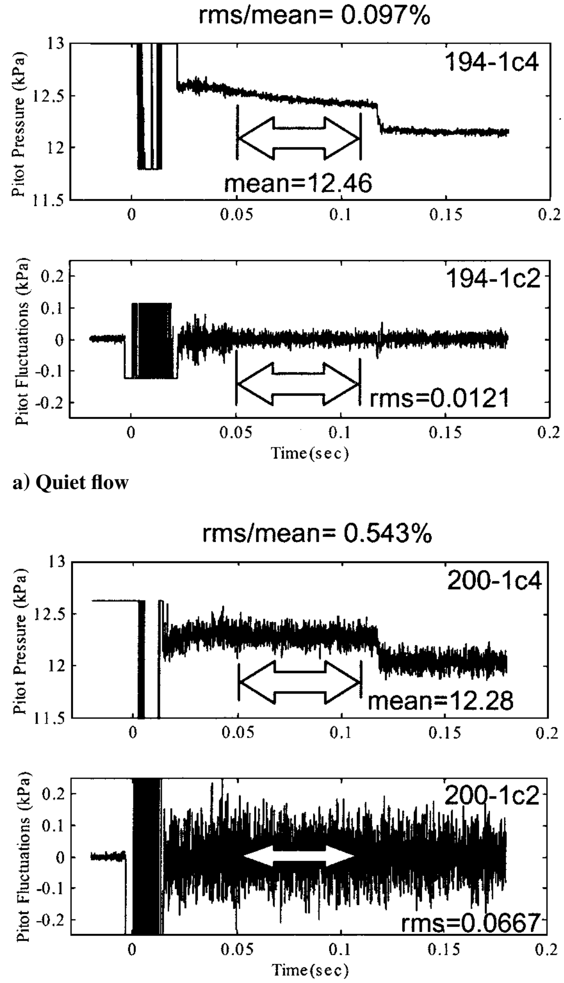
Fig. 2 Experimental model.

The elements were flat equilateral triangles of plastic shim stock, glued to the model and oriented so that they pointed forward, similar to typical Hama-type trips.[12] The uncertainty in the dimensions of these elements is less than 3% in the thickness and less than 5% in the width and length. The trailing edges of the elements were located 4 mm from the forward tip of the cone. Although there are many studies of roughness-induced transition in hypersonic flows,[13,14] there are only a few studies of the effect of tunnel noise on roughness-induced transition.[13,15] None of these studies examine compression corners or scramjet inlets.

There are a total of 69 hot-film sensors arrayed on the scramjet model. These sensors provide qualitative measurements of the heat transfer rate, which changes dramatically during laminar–turbulent transition,[9] and were epoxied to the model. The locations of these hot-film sensors are also shown in Fig. 2. The sensors were connected to constant temperature anemometers that were fabricated at Purdue. The anemometers were an improved version of those used by Schmisseur et al.,[9] because the output was dc coupled, allowing determination of the intermittency by the probability density distribution of the uncalibrated wall shear.[16] Although the bandwidth is only about 20 kHz, the noise level is much lower than that of the commercial TSI IFA100, and it was possible to fabricate eight channels due to the low associated cost. The data were collected on digital oscilloscopes at 1 MHz. All of the hot-film data were dc coupled.

About 200 Ludwieg tube runs were conducted for this project. Eight hot-film sensors were monitored for each run. Quiet-flow wind tunnels can show variations in noise level depending primarily on the cleanliness of the nozzle. To demonstrate that the noise level remained low, so that the data were repeatable, one or two sensors were sampled for all runs. The results for these sensors showed good repeatability, as will be described later. All measurements reported were carried out near 1.0-atm stagnation pressure and 300-K stagnation temperature, for a freestream unit Reynolds number of about 4.5×10^6 m.

The limits of the run-to-run variation of the stagnation pressure were within ±1.5%, and the temperature varied within ±1.6% among the runs. Table 1 also shows the experimental conditions for the various kinds of roughness and wind-tunnel noise studied in the present work.



a) Quiet flow

b) Noisy flow

Fig. 3 Pitot pressure and fluctuations.

Experimental Results and Discussion

Freestream Pitot-Pressure Fluctuations in Quiet Flow and Noisy Flow

The quiet-flow freestream pitot-pressure fluctuations are first shown, for later comparison with the noisy-flow data. These pressures were measured with a fast-response semiconductor pressure transducer, used as a pitot probe. Figure 3a shows typical quiet-flow results on the nozzle centerline at 299 mm from the throat. There is a streamwise variation in pitot pressure due to a streamwise variation in Mach number in the tunnel. The centerline Mach number is about 3.94 ± 1.5%. The timescale begins at the start of the run. The starting process ends at about 0.02 s; before this time, the signal is often clipped by the startup process. The first segment of steady flow begins at about 0.03 s and extends until about 0.11 s. However, some noise was evident during 0.03–0.05 s, apparently due to the wind-tunnel startup. Therefore, the data from 0.05 to 0.11 s are used. The low pitot-pressure fluctuations observed during the steady part of the run are about 0.097% of the mean pitot pressure. This fluctuation level is somewhat higher than the 0.06–0.07% normally observed in the upstream part of the quiet nozzle at this pressure (compare data of Fig. 7 in Ref. 17, at $z = 666$ mm). The higher noise in the present measurements might be because the electronic noise was not subtracted off, as it was in Ref. 17. However, for this particular run, the additional noise was probably due to incipient turbulence from low levels of dust on the tunnel walls.

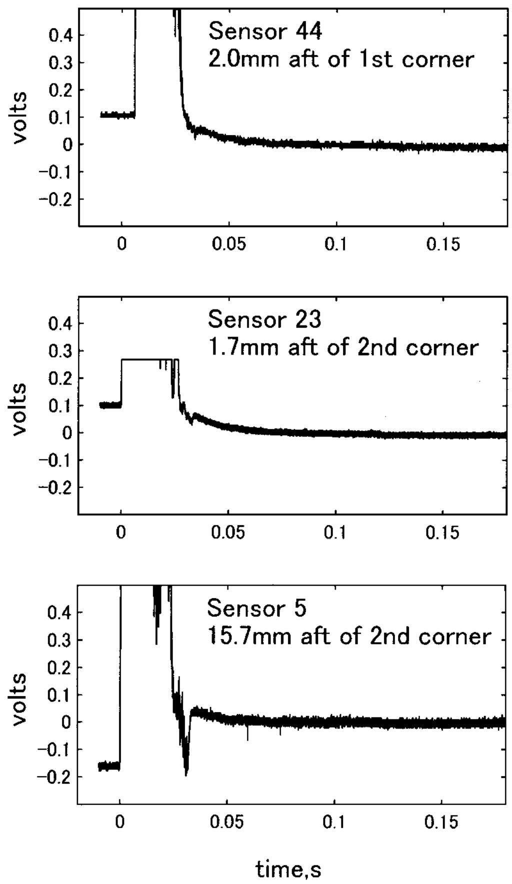
Conventional wind tunnels have high noise levels due to acoustic radiation from the turbulence present on the nozzle walls.[1] To simulate this conventional-test environment, the boundary layer on the wind-tunnel wall was tripped using roughness. The roughness element consisted of 0.3-mm-thick duct tape placed on the upper and lower wall of the wind tunnel, 93 mm downstream of the throat. The duct tape was cut in a saw-toothed pattern, on the leading edge. The increase in noise resulted in a remarkable difference between the data obtained under conventional- and quiet-flow conditions, the latter condition being characteristic of actual flight.[13,18] The effect of the tunnel-wall boundary-layer trip is shown by the pitot-probe measurements presented in Fig. 3b. Figure 3b shows that the freestream fluctuations increased by about a factor of 5–6, compared to the quiet flow. Although this noise level is still lower than that usually achieved in a conventional wind tunnel, the high noise level is sufficient to illustrate the comparative effect.

Basic Characteristics of the Hot-Film Time Traces

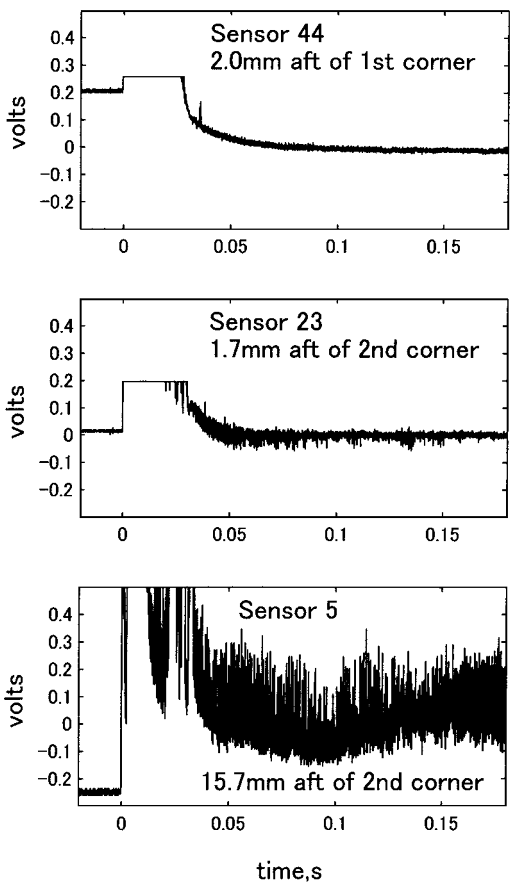
Hot-film data with good temporal resolution includes considerable information about flow structure. Some results are presented to indicate the distinctive characteristics. The hot-film sensors were not calibrated, and so the amplitudes are useful only for qualitative purposes.

In the low noise quiet flow, the left-hand side of Fig. 4 (case 0Q) shows typical hot-film results at three locations. In each trace, the prerun electronic noise is visible for $t < 0$, followed by 30–40 ms of startup noise.

The steady portion from 0.08 to 0.12 s is used to compute the intermittency using a method discussed in the following section. All three traces show the low intermittency levels typical of completely laminar flow. There is no evidence of transition to turbulence. This fully laminar flow was consistently observed under these conditions, when the nozzle wall was carefully maintained, so that the tunnel flow was very quiet. Earlier observations[8] of transition under these conditions were apparently caused by imperfect cleanliness of the nozzle walls. The current test geometry was the most sensitive of any tested in the Purdue facility to date, and great care was needed to obtain repeatable results.



Quiet flow (case 0Q)



Noisy flow (case 0N)

Fig. 4 Hot-film time traces for smooth-wall model.

The right-hand side of Fig. 4 (case 0N) shows the smooth-wall results from the same hot-film sensors in noisy flow. Downstream of the model's second compression corner, large fluctuations were evident when the tunnel was noisy but not when the tunnel was quiet.

Figure 5 shows sample results, for a 0.75-mm isolated roughness (number 1), positioned 4 mm from the tip. The roughness was added to promote transition under both quiet and noisy conditions. The same hot-film sensors were used for both cases. Under quiet conditions the flow (case 1Q) is nearly laminar to the second corner, with the intermittency rising to about 0.2 aft of the second corner. The traces show the intermittent spikes that are characteristic of transitional flow in the boundary layer. Because of the limited Reynolds number, the quiet-tunnel flow is only partially intermittent at the end of the model, as can be seen from the data for sensor 10 in Fig. 5.

Under noisy conditions (case 1N), the flow becomes intermittent aft of the first corner, as shown in the right side of Fig. 5, with always-turbulent flow occurring somewhat forward of the second corner. When transition occurs well downstream of a roughness element, both tunnel noise and roughness are important factors. The detailed character of the quiet and noisy traces is very different. The quiet traces clearly show the signatures of turbulent spots, whereas the noisy traces do not.[3]

Determination of Intermittency Using High-Frequency Portion of Signal

There is no single well-defined procedure for the determination of intermittency from hot-film sensor time traces. There are two classes of procedures for computing intermittency from a given trace. The first procedure, discussed by Schneider,[16] follows an idea used by Hansen and Hoyt[19] and advocated by Narasimha.[20] This class of procedure picks out the portion of the record where the fluctuating wall shear is high and identifies that portion as turbulent. As a first step toward this, a histogram analysis was performed. However, unlike in Ref. 15, no algorithm was found that was able to determine consistent intermittencies for all of the data.

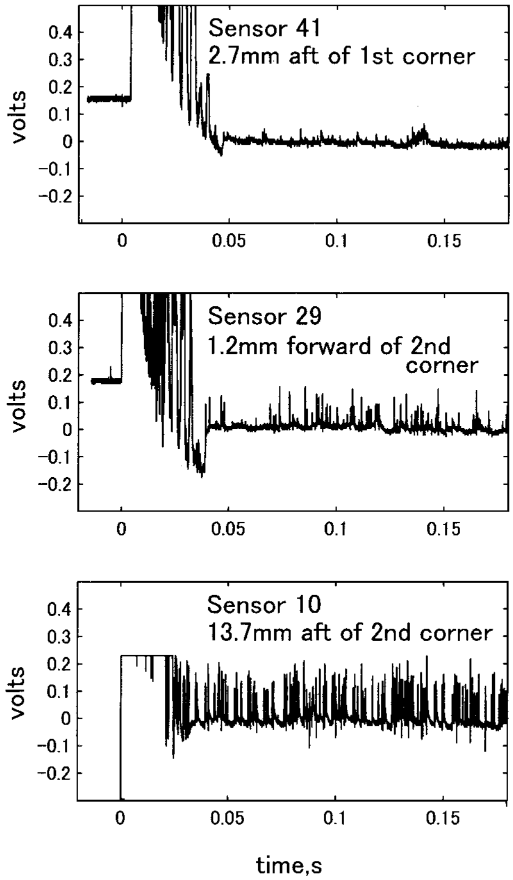
Because the histogram method was not very successful in determining consistent intermittencies, methods based on discriminating the high-frequency parts of the signal were attempted. The frequency-based technique is the more traditional method.[21]

Here, the data from a 1-μs digitization interval were averaged to a 10-μs interval. A parameter ε, defined as the local difference between two points (proportional to the local first derivative, which seemed to work better than the usual method using the second derivative), was then computed. A limiting value of ε was set, and the points in the time trace for ε above the threshold are identified as turbulent. This trace of provisional turbulence/nonturbulence is denoted $i(t)$. The trace was smoothed using a window that passes over the data and within which the center point is called turbulent when the majority of points in the window are turbulent. This smoothed trace is denoted $I(t)$, and labels the parts of the record to be called turbulent. The average value of $I(t)$ over the record is called the intermittency.

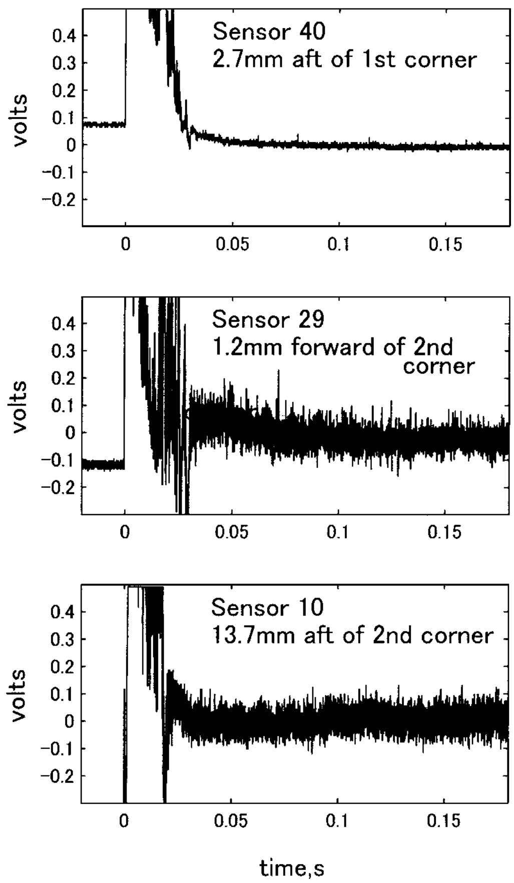
The parameters, namely, the threshold in ε and the window width, are selected so that the routine identifies as turbulent the part of record that appears turbulent, that is, the parts that have high-frequency content. Critically, a single cutoff value of $\varepsilon = 0.007$ V and a single window width of 0.2 ms was found to work adequately for all of the data from all of the sensors. The repeatability of this technique for the repeated sensor measurements was good, as described in the following section. Also, reasonable and consistent trends were observed for all of the data. The uncertainty in the intermittency is best evaluated by looking at the standard deviation of repeated measurements, as will be described.

Intermittency Results and Discussion

Although most of the sensors are located on a single principal ray from the nose to the end of the model, some data were obtained for the sensors that are offset from this ray. Line plots of the intermittency were obtained from data obtained along the principal ray. Limited-resolution contour plots were also obtained, using the rest of the data. Figures 6–9 show both the line and the contour plots. The off-centerline data are also shown with the centerline line plot



Quiet flow (case 1Q)



Noisy flow (case 1N)

Fig. 5 Hot-film time traces with roughness 1.

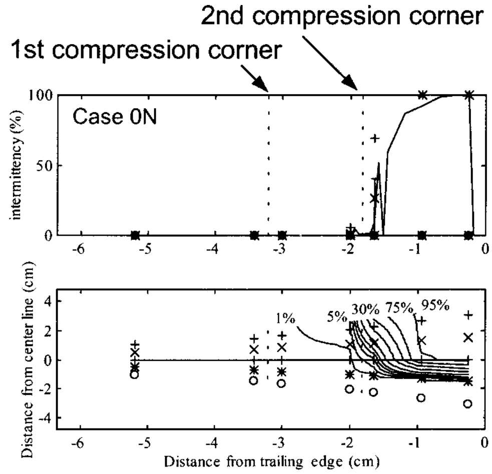


Fig. 6 Intermittency distribution for the smooth-wall model in noisy flow.

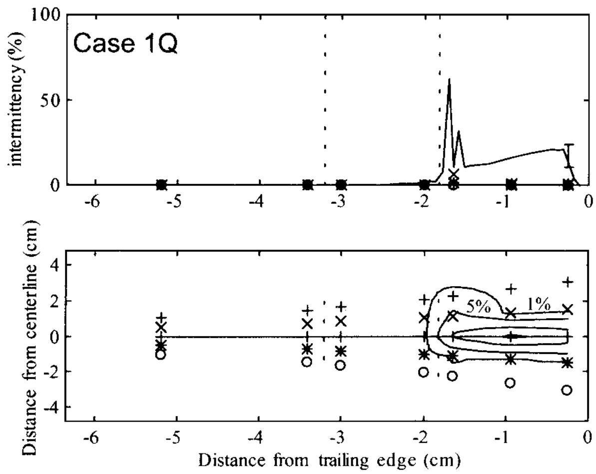


Fig. 7 Intermittency distribution with roughness 1 in quiet flow.

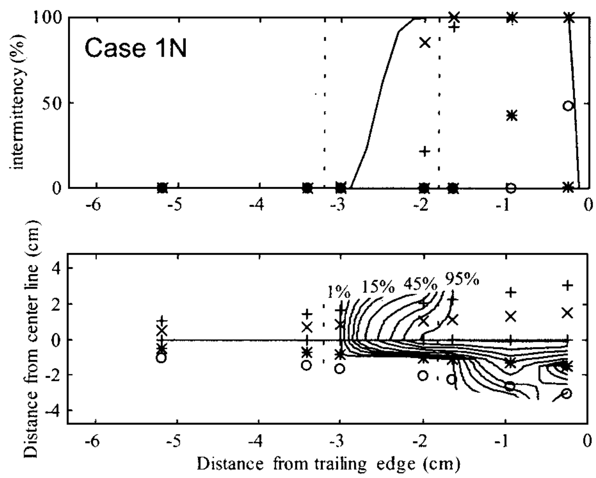


Fig. 8 Intermittency distribution with roughness 1 in noisy flow.

by adding symbols whose location is shown on the contour plot. As shown in Fig. 2, there are not many sensors off the principal sensor ray, so that attention is focused on the better-resolved principal-ray data.

The smooth model remained laminar under the quiet flow (case 0Q). However, Fig. 6 for case 0N shows that noisy flow caused transition downstream of the second compression corner. Note that the transition does not happen smoothly. Instead, we observe a short peak just downstream of the second compression corner, probably caused by fluctuations in the reattachment of a separation bubble.

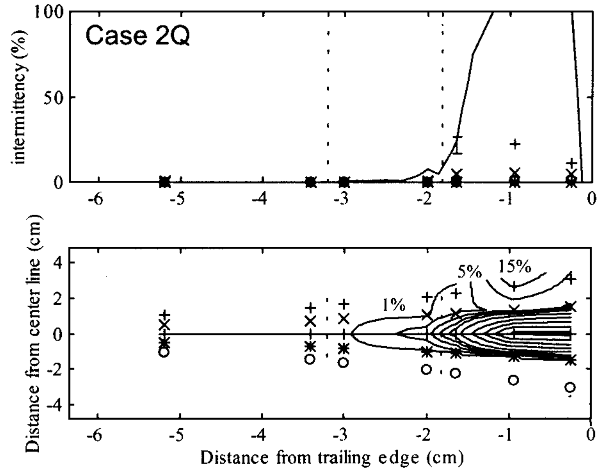


Fig. 9 Intermittency distribution with roughness 2 in quiet flow.

The flow may well relaminarize on reattachment. Although the noisy flow appears to cause earlier transition in the separating shear layer at the second compression corner, the low Reynolds number appears to cause relaminarization on reattachment. This type of relaminarization was discussed by Narasimha and Sreenivasan.[22] Downstream of the corner, the intermittency increases to the turbulent level. Although the wind-tunnel noise level is lower than that achieved in a conventional tunnel, it has a dramatic effect on transition, as compared to the fully laminar smooth-wall quiet-flow case. Substantial asymmetry is evident in the noisy case. Figures 8 and 9 also show higher intermittency on the upper side, for noisy flow. It is well known that transition can be very sensitive to small flow variations. Although the cause of this asymmetry is unknown, it may be due to an asymmetric noise field, caused by asymmetries in the placement of the duct tape on the tunnel wall. The repeatability of the intermittency data shows that the asymmetry is a systematic effect, which could also be caused by slight asymmetries in the roughness element or in the nozzle flowfield.

Figure 7 shows the effect of the 0.75-mm roughness in the quiet flow of case 1Q. A noticeable peak occurs just aft of the second compression corner. This peak is presumably caused by fluctuations in the reattachment of a separated shear layer, as in Fig. 6 for case 0N. Here the roughness appears to cause transition in the separated layer even in the quiet flow, but the low test Reynolds number results in relaminarization on reattachment. After the peak, the intermittency drops and then slowly increases. Fully turbulent flow is not obtained. Intermittency for the same roughness under noisy-flow conditions is shown in Fig. 8 for case 1N. For this condition, transition occurs aft of the first compression corner.

Figure 9 for case 2Q shows the effect of the largest (1.5-mm thickness and 2.4-mm width) roughness element, under quiet-flow conditions. In Fig. 9, transition occurs just aft of the second compression corner. Note that this transition point is about the same as that observed for the smooth model in the noisy flow (Fig. 6 for case 0N). The effect of the wind-tunnel noise is comparable to the effect of the large roughness element. This observation demonstrates the dramatic importance of quiet-flow measurements for this model geometry. Measurements of transition carried out under high noise levels in conventional wind tunnels will be highly uncertain due to the unknown effects of the tunnel noise.

Repeatability

Boundary-layer transition is a very sensitive phenomenon. Very small disturbances can sometimes produce completely different results. In particular, it was found that the flow on the model was very sensitive to changes in noise caused by small dust particles that can deposit in the throat of the quiet-tunnel nozzle. Verification of measurement repeatability is, thus, critical in establishing the reliability of boundary-layer transition measurements. In these experiments, one or two sensors were repeatedly sampled for all runs to demonstrate that the noise level remained uniform.

Table 2 Repeatability of intermittencies computed using hot-film data

Case	Position no.	Number of runs	Intermittency, % Average	Intermittency, % Standard deviation
0N	23	16	17.6	23.05
0N	44	5	0.0	0.0
1Q	5	28	17.26	6.726
1Q	32	28	1.231	1.05
1Q	66	28	0.0	0.0
1N	23	13	100.0	0.0
1N	44	4	0.0	0.0
2Q	23	5	21.62	4.864
2Q	44	16	0.0406	0.1391

The results for these sensors are shown in Table 2. Both the average intermittency and the standard deviation are shown. When the intermittency has a significant value, the results show very good repeatability, except for sensor 23 in case 0N (Fig. 6). This sensor is on the edge of the transition region and the presumed separation bubble (see Figs. 2 and 6), and so it is not surprising that the intermittency would be very sensitive to small fluctuations. The standard deviations shown are small enough to assure the reliability of the general conclusions made in this study.

Conclusions

Boundary-layer transition on a scramjet inlet with compression corners was measured using the Mach 4 quiet-flow Ludwieg tube at Purdue University. Although the Reynolds number under quiet-flow conditions was not large enough to observe natural transition on the smooth model, the effects of isolated roughness and wind-tunnel-generated noise were investigated. Either noisy tunnel flow or the roughness could make the boundary layer intermittent, and the effect of the noisy flow was comparable to the effect of large roughness elements. The character of the transition process clearly changes when the tunnel noise is large. This observation clearly suggests that conventional-tunnel tests for boundary-layer transition should be interpreted with care.

Acknowledgments

Takeshi Ito was supported by a Research Abroad Fellowship from the Science and Technology Agency of the Japanese Government. The work was also supported by the U.S. Air Force Office of Scientific Research, under Grant F49620-97-1-0037. Application of the hot-film sensor arrays to the scramjet forebody model was funded by the Hyper-X Program Office at NASA Langley Research Center, and the sensor arrays were fabricated and installed by NASA Langley Research Center personnel. Some of the facility description was obtained from the work of Dale Ladoon and John Schmisseur.

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