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Görtler Instability and Supersonic Quiet Nozzle Design

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Abstract

TO advance boundary-layer stability and transition research and to ultimately provide reliable predictions of transition for supersonic flight vehicles, a wind tunnel is required with very low stream disturbance levels comparable to free-flight conditions. Previous investigations indicated that the freestream noise in pilot quiet nozzles is primarily caused by transition in the nozzle wall boundary layers that are subjected to Görtler instability. A new concept for nozzle design was developed that provides a large increase in the length of the quiet test core by postponing the initiation and decreasing the growth rate of Görtler vortices and thus delays transition on the nozzle walls. A new advanced Mach 3.5 axisymmetric quiet nozzle was fabricated and tested to prove the new design concept. The Reynolds numbers based on the measured length of the quiet test core for this new nozzle are in excellent agreement with the theoretical predictions.

Contents

The high noise levels in conventional supersonic wind tunnels cause premature boundary-layer transition on test models. There can be many sources for this noise, but at higher Mach numbers (>2.5) the primary source is the eddy-Mach-wave radiation from the turbulent boundary layer on the nozzle wall. The key requirement for the design of a quiet supersonic nozzle is to maintain the nozzle wall boundary layer in a laminar state.

The primary causes of nozzle wall turbulence are 1) continuation onto the nozzle wall of the turbulent boundary layer present on the wall of the upstream piping and settling chamber, and 2) destabilization of the nozzle wall laminar boundary layer by the formation and amplification of instability waves in the nozzle wall boundary-layer flow. The turbulent boundary layer in the subsonic approach to the nozzle is removed by a suction slot upstream of the throat so that a new, laminar boundary layer will develop downstream of the slot and delay transition in the supersonic portion of the nozzle. The technique of the suction slot has been applied to all of the previous pilot quiet nozzles.[1] These pilot quiet nozzles were designed with rapid expansion contours to obtain the design Mach numbers within short distances. Therefore, it was thought that the growth of boundary-layer instability waves along the nozzle wall would be limited and transition to turbulence would be further delayed due to strong favorable pressure gradients. Small quiet test cores with very low noise levels in the upstream regions of the test rhombus have been obtained in the pilot quiet nozzles. These low noise levels were observed only when the corresponding upstream "acoustic origin" regions of the nozzle wall boundary layers were maintained laminar. Hot-wire measurements of the noise field in the Mach 3.5 Two-Dimensional Pilot Quiet Tunnel[2] showed that the maximum length of the quiet test core that could be maintained, up to the highest test freestream unit Reynolds number, $R_\infty \cong 8\times 10^7$/m, was only about 12 cm. The short lengths of quiet test cores in the pilot quiet nozzles impose restrictions on the size of test models and limit the use of the pilot quiet tunnels.

To develop an efficient and economical way to delay the nozzle wall boundary-layer transition, it is essential to understand the instability mechanisms involved and to develop theoretical models that can be used for predictive purposes. The compressible linear stability theory with the e^N method for transition prediction/estimation has been successfully applied to several different flows with proper account of the dominant physical effects in the computations. When this prediction method (a modified version of the COSAL code[3]) was applied to the experimental data from pilot quiet nozzles[1] for Mach numbers from 3 to 5, it was shown that transition in the wall boundary layers of nozzles was caused by the Görtler instability mechanism in the concave curvature regions of the wall rather than Tollmien-Schlichting waves. A simple way to delay the onset of transition is to insert a straight wall, radial flow section upstream of the inflection point of contoured nozzle walls. Thus, the Görtler instability will not be initiated until the beginning of the concave nozzle wall and then a slow expansion can be used to achieve the design Mach number. The slower expansion implies larger radii of curvature that would result in smaller overall growth of Görtler vortices. This is the new concept to be used in the design of the advanced quiet nozzle. As a note of caution, we mention that slower expansion also implies smaller favorable pressure gradients and thus the possibility of Tollmien-Schlichting instability that must be accounted for in the design.

The advanced Mach 3.5 axisymmetric quiet nozzle was designed to be used in the existing pilot quiet tunnel located in the Gas Dynamics Laboratory at the NASA Langley Research Center. Detailed descriptions of the design procedures were given in Ref. 4. Figure 1 shows the wall contours and Mach lines for different flow regions in the nozzle. The radial flow region with its straight line wall section inclined at 6.99 deg is identified. The beginning of the concave curvature along the nozzle wall is located at the upstream point of origin of the Mach line that terminates on the centerline at X_0. Since the Görtler vortices can only form along the concave wall, their onset is delayed until this point is reached. The amplification

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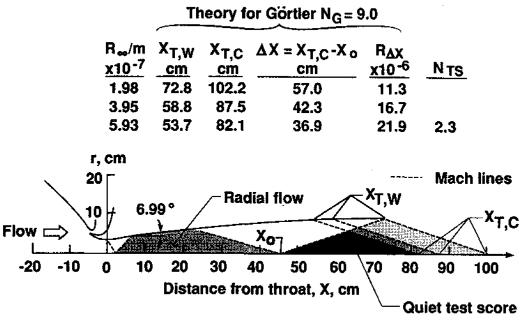

Fig. 1 Advanced Mach 3.5 axisymmetric quiet nozzle.

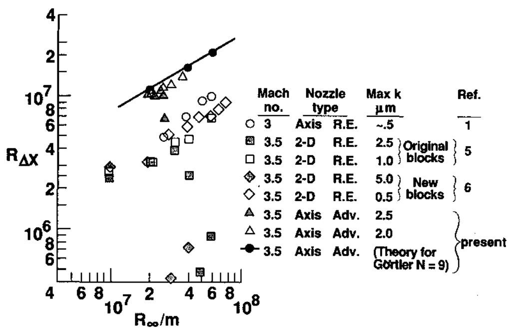

Fig. 2 Quiet test core length Reynolds numbers.

rates of the vortices are then reduced compared with those in the rapid expansion, pilot quiet nozzles[1] due to the larger radii of curvature along the concave wall region of the new advanced quiet nozzle. Therefore, the predicted locations of transition with $N_G = 9.0$ occur far downstream at the indicated $X_{T,W}$ distances that decrease with increasing unit Reynolds numbers. The resulting predicted axial lengths ΔX of the quiet region are then determined by the distances between X_0 and $X_{T,C}$ where the $X_{T,C}$ locations are the downstream points, on the centerline, of the Mach lines that originate from the predicted locations of transition $X_{T,W}$ on the nozzle wall. Listed in the figure are the freestream Reynolds numbers $R_{\Delta X}$, based on the lengths ΔX that are used as a criteria to evaluate the performance of the quiet nozzles. The corresponding largest amplification of Tollmien-Schlichting (TS) waves occurs at the highest unit Reynolds number where $N_{TS} = 2.3$ as listed in the figure. This result confirms the dominance of Görtler instability in the nozzle wall boundary-layer transition.

Figure 2 shows $R_{\Delta X}$ from test data for two rapid-expansion (R.E.) pilot quiet nozzles[1,5,6] for Mach numbers of 3 and 3.5 and for the present advanced Mach 3.5 axisymmetric quiet nozzle (Adv.) over the test range of R_∞. Also, the predicted values of $R_{\Delta X}$ as given in Fig. 1 for the present nozzle are included for comparison with the experimental results. For each nozzle, the measured maximum surface roughness k in the throat region for different sets of test data are listed in the figure to show the effect of surface finish on the performance. The data for the pilot nozzles and the present nozzle indicate an increasing trend of $R_{\Delta X}$ with unit Reynolds number R_∞, except for the larger values of k. This unit Reynolds number effect on $R_{\Delta X}$ is caused by the increasing local favorable pressure gradients that damp the growth of Görtler vortices as transition moves upstream along the nozzle wall with increasing R_∞. The maximum value of $R_{\Delta X}$ obtained from the present nozzle is about 1.4×10^7. This is the highest value of $R_{\Delta X}$ that has ever been achieved in quiet tunnels and is close to the design value of 1.6×10^7. For lower test values of R_∞, the values of $R_{\Delta X}$ for the present nozzle are in even better agreement with the theoretical predictions. It is believed that with further improvement in the surface finish of the nozzle wall, especially in the region of the nozzle throat, higher values of $R_{\Delta X}$ can be obtained at higher values of R_∞. Except for the problem of surface finish, values of $R_{\Delta X}$ for the present nozzle are more than double the values for the previous pilot quiet nozzles. This improved performance verifies the new design concept of the advanced quiet nozzle.

Conclusions

The advanced Mach 3.5 axisymmetric quiet nozzle is the first prototype built to verify the new design concept. This investigation has proved the feasibility of the concept for quiet supersonic nozzles. Stability and transition research in wind tunnels that simulate the low-disturbance conditions in flight can now be extended to higher Reynolds numbers.

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