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Experimental Studies of Instability and Transition in a Mach-6 Quiet Tunnel

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14. ABSTRACT

The Mach-6 tunnel continues to run quiet to moderately high Reynolds numbers. Although the maximum quiet pressure was more variable in the last few years, due to problems with tunnel particulate and nozzle roughness, quiet flow was recently achieved past the nozzle exit to a stagnation pressure of 180 psia. This is the highest quiet Reynolds number ever achieved. Since the nozzle-wall boundary layer remained laminar downstream of the exit to unit Reynolds numbers of more than 10-13 million per meter during the last 4 years, fairly high quiet-flow Reynolds numbers have been achieved on slender models. The tunnel is operated by a single graduate student, with good reliability, and a large amount of data can be obtained during each run using a variety of sensors. Instability and transition measurements were carried out on various models to aid in developing mechanism-based transition-estimation methods that can then be used to predict transition in flight. The research funded under this grant has so far resulted in 22 conference papers, 9 journal papers, 3 Master's theses and 4 Ph.D. theses. Leadership of this tunnel has now passed to the next generation, in the form of Asst. Prof. Joseph Jewell. A brief summary is reported here, along with selected highlights.

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Experimental Studies of Instability and Transition in a Mach-6 Quiet Tunnel

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Summary

The Mach-6 tunnel continues to run quiet to moderately high Reynolds numbers. Although the maximum quiet pressure was more variable in the last few years, due to problems with tunnel particulate and nozzle roughness, quiet flow was recently achieved past the nozzle exit to a stagnation pressure of 180 psia. This is the highest quiet Reynolds number ever achieved. Since the nozzle-wall boundary layer remained laminar downstream of the exit to unit Reynolds numbers of more than 10-13 million per meter during the last 4 years, fairly high quiet-flow Reynolds numbers have been achieved on slender models. The tunnel is operated by a single graduate student, with good reliability, and a large amount of data can be obtained during each run using a variety of sensors. Instability and transition measurements were carried out on various models to aid in developing mechanism-based transition-estimation methods that can then be used to predict transition in flight. The research funded under this grant has so far resulted in 22 conference papers, 9 journal papers, 3 Master's theses and 4 Ph.D. theses. Leadership of this tunnel has now passed to the next generation, in the form of Asst. Prof. Joseph Jewell. A brief summary is reported here, along with selected highlights.

Contents

1 Introduction

The research performed under this grant is documented in a series of AIAA Papers [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22]. Some of the research was jointly funded by NDSEG Fellowships or other sources, and several students were supported in part by various other fellowships. AFOSR funding was the foundation on which these collaborative efforts were built, and often provided critical elements in multi-organization joint efforts. Several of the conference papers were revised into journal forms [23, 24, 25, 26, 27, 28, 29, 30, 31]. A number of students also completed Ph.D. theses [32, 33, 34, 35] and M.S. theses [36, 37, 38]. In addition, Kathryn Gray is to finish her Ph.D thesis in late summer 2022 [39], having acquired all her data with AFOSR funding, and needing only to finish the analysis and writing. Since considerable detail is readily available in these publications, the present final report was written as an overall summary.

As part of a long-term plan for the orderly transition of quiet-tunnel leadership to a new generation, Purdue University hired Asst. Prof. Joseph Jewell in July 2019 to take over the Mach-6 quiet tunnel. Prof. Jewell then wrote all new proposals for work in the Mach-6 quiet tunnel. With the expiration of the present grant, the transitional process is nearly

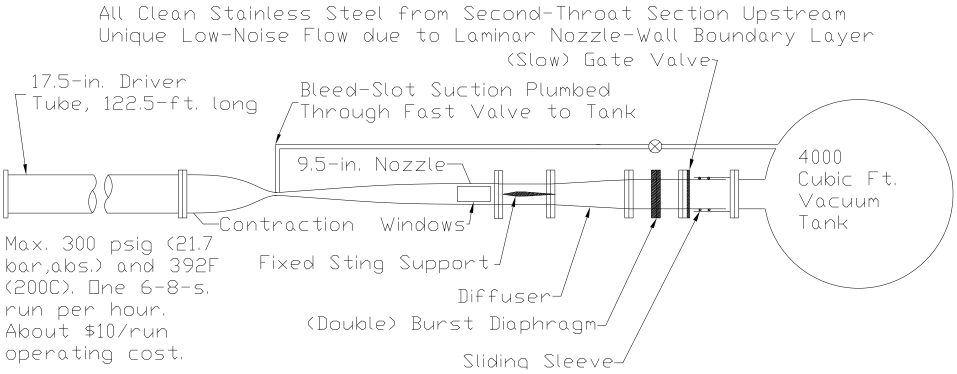

Figure 1: Schematic of Boeing/AFOSR Mach-6 Quiet Tunnel

complete. All the students working in the Mach-6 quiet tunnel are Prof. Jewell's, and he is the principal investigator for all the grants and contracts that fund work in that tunnel. Prof. Schneider has moved to a supporting role, in which he plans to continue for another decade.

2 The Boeing/AFOSR Mach-6 Quiet Tunnel

2.1 General Description

Quiet facilities require low levels of noise in the inviscid flow entering the nozzle through the throat, and laminar boundary layers on the nozzle walls. To reach these low noise levels, conventional blow-down facilities must be extensively modified. Requirements include a 1 micron particle filter, a highly polished nozzle with bleed slots for the contraction-wall boundary layer, and a large settling chamber with screens and sintered-mesh plates for noise reduction [40]. To reach these low noise levels in an affordable way, the Purdue facility has been designed as a Ludwieg tube [41]. A Ludwieg tube is a long pipe with a converging-diverging nozzle on the end, from which flow exits into the nozzle, test section, and second throat, as shown in Fig. 1.

A pair of diaphragms are placed downstream of the test section. When the diaphragms burst, an expansion wave travels upstream through the test section into the driver tube. Since the flow remains quiet after the wave reflects from the contraction, sufficient vacuum can extend the useful runtime to many cycles of expansion-wave reflection, during which the pressure drops quasi-statically.

The contraction-wall boundary layer is bled off just upstream of the throat, beginning a fresh undisturbed boundary layer for the nozzle wall. A fast valve is connected directly between the bleeds and the vacuum tank, allowing the bleed air to be dumped directly into the tank. If the bleed valves remain closed, the air entering the throat is disturbed by passing over the bleed slots, tripping the nozzle-wall boundary layer. Thus, these tunnels can run quiet and noisy at nearly the same operating condition, by opening or closing the bleed valves.

Unless otherwise specified, the initial stagnation temperature in the driver tube is set to

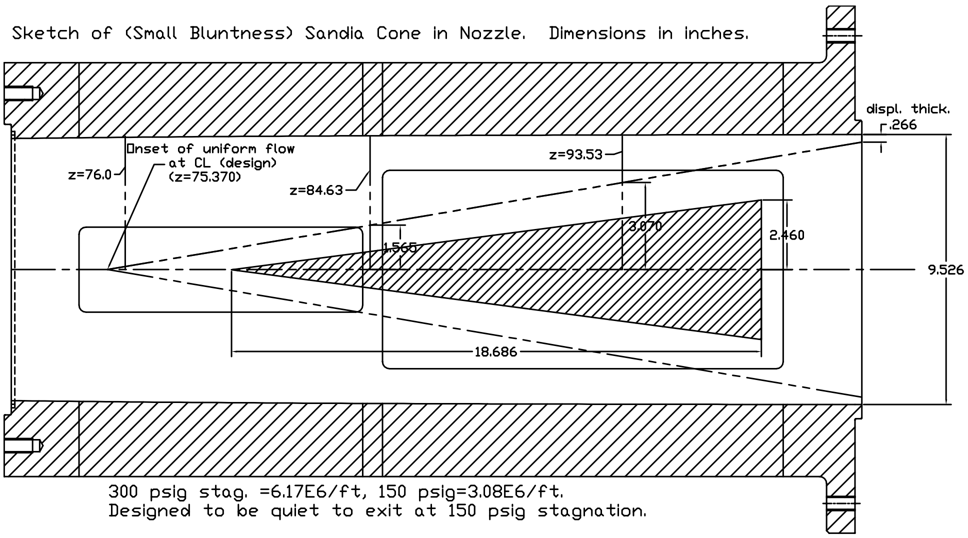

Figure 2: Schematic of Mach-6 Quiet Nozzle with Model

$160^\circ C$. The stagnation temperature drops about 10% during the run, as the air flows out of the driver tube [42]. The air in the nozzle at Mach 6 is supercooled, making Reynolds number computations dependent on the somewhat uncertain value of air viscosity at very low temperatures near 50K, but no evidence of condensation has been observed under these conditions [43], although further studies are needed.

Figure 2 shows the nozzle. Here, z is an axial coordinate whose origin is at the nozzle throat. The region of useful quiet flow lies between the characteristics marking the onset of uniform flow, and the characteristics marking the upstream boundary of acoustic radiation from the onset of turbulence in the nozzle-wall boundary layer. A 7.5-deg. sharp cone is drawn on the figure. The rectangles are drawn on the nozzle at the location of window openings, which can be filled with various windows or with blank metal inserts. Images of the tunnel are available at `https://engineering.purdue.edu/~ aae519/BAM6QT-Mach-6-tunnel/`, along with earlier papers and other documentation.

The tunnel is operated by a single researcher, usually a graduate student, but sometimes an alumnus who has taken refresher training. Available labor has been sufficient to keep the tunnel operating about 45-50 weeks per year, for roughly 25-35 shots per week on average. Although it takes a minimum of about 35 minutes between successive runs under ideal conditions, and 12 runs can be obtained in an 8-hour shift, a substantial portion of a student's occupancy time is usually expended in model setup and adjustment, preliminary assessment of the results of a given run, debugging apparatus, and so on. Thus, about 9 runs is the maximum that is usually feasible in a 10-hour shift with a single tunnel operator.

2.2 Status and Improvements for FY17-22

The Mach-6 quiet tunnel operated reliably from ca. Nov. 2010 through Nov. 2016, without much downtime. The flow was consistently quiet to a total pressure of about 170 psia during those six years. The quiet-flow performance is exquisitely sensitive to the cleanliness and polish in the nozzle throat, but the nozzle, contraction and driver tube were not opened upstream of the nozzle exit during those six years, the cleanliness of the air flow through the throat was maintained, and the quiet performance remained consistent.

However, in Dec. 2016 it became necessary to open the tunnel at the entrance to the contraction, as one of the silicone o-ring seals began to leak, to an extent that had a noticeable effect on the flow. Note that the upstream sections of the tunnel are all sealed with silicone or silicone-teflon o-rings. Since the resilience of these o-rings diminishes with time at high temperature, they will all have to be replaced eventually. Although measures were taken to keep the inside of the tunnel as clean as possible when this o-ring was replaced for the first time in a decade, some dust did of course still enter the tunnel. After about 38 runs, enough dust blew out to return the maximum quiet pressure to 135 psia, but additional tunnel runs shortly after that did not raise the quiet pressure back to 170 psia. This began a long period wherein we repeatedly repolished the electroformed nickel throat assembly, and repeatedly tested its operation.

In January 2017, Matt Borg from AFRL reported quiet flow in our tunnel only at 135 psia. As of Feb. 2017, more than 250 runs had been performed, blowing out dust, but the tunnel was still quiet only at 135 psia. It seems that it ran that way for most of 2017.

A FY2008 DURIP grant was to improve performance and reliability by procuring a new throat, machined from stainless steel [44]. However, difficulties with the vendor and the throat fabrication left this project incomplete, regrettably. Funding to complete this throat was provided in a FY2014 DURIP grant, which enabled the machining to be completed [45]. However, various problems with the machining delayed the work, which was completed only by using additional funds from subsequent AFOSR grants. As of March 2017, the machining was complete, and the new throat was at the polisher for the final stage of the fabrication. A long series of iterations followed, during which the stainless throat was repeatedly tested in the tunnel, and then repeatedly removed and modified to improve its performance. While the stainless throat was being tested, the nickel throat was being repolished, so the tunnel remained in operation. The ability to use two different throats thus became very important to tunnel operability. The details of the stainless throat design and manufacturing are not reported here to improve security for this sensitive technology.

In March 2018, the stainless throat was inserted in the tunnel. Early on, it was only quiet to about 30 psia. The nickel throat was repolished while the stainless throat was being tested. Some tests with controlled roughness were performed using the stainless throat, since it was to be repolished anyway after the nickel throat was re-installed.

In May 2018, the nickel throat was reinstalled. Very rapidly it reached a quiet stagnation pressure of about 155 psia. This remained the maximum quiet pressure for many months.

In July of 2020 the stainless throat was again installed, after a series of modifications and yet another repolish. The nickel throat was again sent for repolishing. Shortly after installation, the quiet pressure was about 80 psia. The quiet pressure of the (unheated) stainless throat remained near 80 psia for months. In Nov. 2020 we swapped the nickel throat back into the tunnel, and achieved a quiet pressure of about 140 psia. The quiet pressure increased to 143 psia over the subsequent months.

In July 2021 we reinstalled the stainless throat. It was at first quiet to about 74 psia, similar to the nearly 80 psia that was observed in summer 2020. Ca. August 2021, we started heating the stainless throat, in accordance with the original plan from the 2008 DURIP proposal. The heated stainless throat was quiet to 170 psia, a dramatic improvement. In Dec. 2021, the quiet pressure suddenly dropped to 125 psia. The malfunctioning heaters were then adjusted, and the quiet pressure increased to about 180 psia. A quiet pressure of 200 psia was later observed with the stainless throat by using even higher temperatures. Although much remains uncertain, much has been learned, and a high quiet Reynolds number remains available.

3 Support for Hypersonic Transition Collaborations within NATO STO

The present AFOSR grant supported the author's work as a co-chair for NATO STO AVT-240, a Task Group supporting improved estimates for Hypersonic Boundary Layer Transition Prediction. This large working group met once per year with the Panel in Europe, and once per year on it's own in the USA. The meetings were very popular, and many younger members stated that they were very helpful. The final report for AVT-240 was mostly completed in 2018. In 2019 it was approved by OSD for public distribution through the NATO STO system. Formal completion of the 400-page final report was hampered by the pandemic. The report became available in Feb. 2021, although it was 'published' in Aug. 2020. AVT-240 received the Panel Excellence Award in June 2020.

In an effort to continue the success of AVT-240, a new NATO STO Task Group for 'Predicting Hypersonic Boundary-Layer Transition on Complex Geometries' was proposed. The present author remains a co-chair. An Exploratory Team was approved by the Panel in Fall 2018, and the formal Task Group was approved in Fall 2019. Unfortunately, the work of this group was hampered by the pandemic that began in Spring 2020, which precluded in-person meetings until the one held at the Von Karman Institute in Belgium in May 2022. Nevertheless, good progress was made in the areas of (1) transition as affected by separation, and (2) transition as induced by multiple instability modes. Work in support of AVT-346 continues under AFOSR Grant FA9550-22-1-0110, at a reduced level of effort.

4 Flow Quality in the Mach-6 Quiet Tunnel

Improved characterization of the tunnel was one of the tasks funded by this grant. Two years of effort towards this goal were reported in Kathryn Gray's M.S. thesis [36]. Katie reported fast-pitot-probe measurements of the mean flow and fluctuations. Modest variations in the nozzle-wall temperature had small effects on the mean flow and the fluctuations. The upper surface of the nozzle is usually about 5-10C warmer, presumably due to free convection between runs. Katie also installed a pitot probe near the base of a model, and verified that the whole model sees quiet flow, not just the nosetip region. The tunnel noise increases somewhat after about 2 sec., while remaining quiet, as was found earlier by Steen [46]. This increase in noise occurs only at downstream locations within the nozzle. The reasons for this increase in noise are not yet clear. Katie also reported the effect of the diameter of the pitot tube on the Kulite fluctuation measurements. Comparisons were made to computations [12].

Derek Mamrol developed a pitot rake for the first part of his M.S. thesis, and made measurements of the spatial distribution of the fluctuations in the tunnel [47]. These measurements showed increases in noise downstream of the cavities that form in front of the flat schlieren windows when they are installed. He also made some preliminary Schlieren measurements of the noise increase that occurs after 2 seconds. Following this work, Derek completed his thesis by making flat plate measurements that were funded by others.

5 Crossflow on a Cone at Angle of Attack

The crossflow instability seems likely to dominate transition on many lifting hypersonic vehicles, since it occurs at lower Reynolds numbers in 3D flows. In flight and in quiet tunnels, the stationary streamwise-vortex form of the crossflow-instability waves seems likely to dominate, since high-frequency noise should be low, and small surface roughness is effective at introducing the initial disturbances [48]. Calculations of the linear and nonlinear growth of this instability are now straightforward, but two research challenges remain: (1) computing the initial amplitude of the waves for a given surface roughness distribution and a given set of flow conditions, and (2) computing the conditions where the saturated crossflow waves break down to turbulence. These challenges must be met in order to develop a mechanism-based prediction method for transition induced by this instability. Loosely coordinated studies on 7-deg. half-angle sharp cones at a 6-deg. angle of attack were initiated by several researchers under NATO STO AVT-240 [29]. Two Purdue students contributed to these studies with measurements in the Mach-6 quiet tunnel using AFOSR support.

Josh Edelman used arrays of small discrete roughness elements to induce stationary crossflow waves in a controlled manner [33]. He then used arrays of fast surface pressure sensors to study the nonlinear breakdown of these crossflow waves. He found two separate modes of nonlinear breakdown. However, when Josh then used a distributed roughness element to induce the stationary waves, the nonlinear breakdown mechanism was markedly different. Further studies are needed to understand the conditions that affect the nonlinear breakdown process.

Varun Viswanathan used the same arrays of small discrete roughness, and the same cone geometry [37]. He was to measure the amplitude of the linear stationary crossflow waves, for various flow conditions and roughness heights, in order to aid in developing a computational approach for predictions. This task turned out to be more difficult than anticipated. Although Varun found a linear relationship between the roughness height and the wave amplitude, much remained uncertain, and much thus remains to be determined. Unfortunately, Varun's work ended with his M.S. thesis, and it was not possible to continue this much-needed effort.

6 Transition Induced by Very Large Second-Mode Waves

In 2008 it was already becoming evident that (1) second-mode waves could reach high and variable amplitudes before breaking down to turbulence, (2) in (nearly) all previous measurements of transition in quiet tunnels, only the front portion of the model was under quiet flow, so that the nonlinear breakdown of the instability occurred under noisy flow [41], (3) fairly complex axisymmetric models could be designed using stability analysis, specifically to achieve the highest possible instability-wave growth under quiet flow [49], (4) fairly complex axisymmetric models could be built on the 2001 CNC lathe in the department machine shop at a very affordable cost, (5) laminar flow seemed to extend past the nozzle exit in the Purdue facility, so the whole model could be studied at fairly high Reynolds number under fully quiet flow, and (6) it was desirable to generate very large second-mode waves under quiet conditions, so they could be measured with the new PCB-132 sensors [50]. Thus, it became both feasible and desirable to try to study transition due to large second-mode waves under fully quiet flow, using a specially designed model. Such studies seem critical to developing a criterion for the amplitude at which the waves break down. With the development of a conventional-tunnel amplitude-based method for predicting transition onset [51], and the award of the MURI for developing estimates of high altitude freestream disturbances, such a criteria for second-mode breakdown appears ever more useful [52].

Brandon Chynoweth continued the flared-cone research, finishing up his Ph.D. thesis under the present grant. Mostly he studied flared cones, which continue to show great promise for studying the nonlinear breakdown of second-mode waves into turbulence. They do suffer from some factors that are not common in applications: (1) Görtler vortices that may influence the nonlinear breakdown, and (2) the same frequency is amplified over a long distance, which is not likely to occur in general. Since the ultimate goal of this work is to identify an algorithm that can predict the critical amplitude of the second-mode waves at the point when they begin to break down to turbulent spots in flight, later measurements focused on the maximum amplitude of the second-mode waves under different conditions. Although most of these measurements were carried out using different microroughness elements on the flared cone under different conditions, very slender straight cones were also studied, in the hope that natural transition can occur under fully quiet flow. Since the very slender straight-cone measurements were at first non-axisymmetric due to very small angles of attack, later straight-cone measurements were obtained using the micro-AoA adjuster to null out differences in PCB-132 measurements of the frequency of second-mode waves at 90-deg. intervals around the circumference of the cone. Chynoweth's work was reported in his Ph.D. thesis [32], shortly after the beginning of the present grant.

Measurements on a very long 3-deg. half-angle cone were carried out by Sebastien Willems from DLR Cologne during a visit in June and July of 2012. More than three years later, these measurements were reported in Refs. [53] and then [23]. Willems et al. observed a nearly-complete breakdown of the second-mode waves under fully quiet flow using the smooth-wall model, although the significance of this was not discussed much, and the papers were not well disseminated at the time.

Chynoweth's work was then continued by Katie Gray for her Ph.D. research. Katie measured natural transition due to second-mode waves on two long slender cones, beginning ca. 2019. A flow-induced vibration was measured on the 2.5-deg. half-angle cone near the second-mode frequency, which was very surprising. Instability and transition were also observed on this cone in the absence of this vibration, as the vibration only appeared for a narrow range of Reynolds numbers. This 110kHz flow-induced vibration was reported in the Transition Open Forum at the AIAA meeting in Jan. 2020. An early report of her instability and transition measurements on the 2.5-deg. cone was presented in Ref. [17]. Efforts were made to modify the 2.5-deg. cone to control the vibration, and efforts were also made to measure it more definitely. However, due to a general lack of interest in this high-frequency vibration, and to difficulties in controlling it on the 2.5-deg. cone, Katie's work then focused on the 3-deg. half-angle cone, where the vibration did not occur. Her Ph.D. thesis is to describe the work she did with both cones, and is to appear ca. August 2022.

Continued efforts to obtain natural transition under fully quiet flow seem critical. To improve on the e^N method using amplitude-based transition predictions, algorithms are needed to estimate the conditions at which the primary instability will break down into turbulence. Since this is a nonlinear process, it should depend on the freestream noise that is incident near transition onset, and require fully quiet flow. Katie's results are showing a very short transition length under quiet flow, in agreement with Chen et al. [54] (see Fig. 15 in [55]), although the details are confusing and remain to be understood.

7 Instability and Transition in the Separated Shear Layer above a Finite-Span Flap on a Generic Cone with a Slice

Maneuvering hypersonic vehicles may use body flaps as control surfaces. As these vehicles descend after being boosted to high altitudes, transition may occur on these flaps, affecting control authority and flap heating. Since this phenomena seems likely to occur at relatively low Reynolds numbers, it seems critical to many possible vehicle designs. Although 2D corners have been used as canonical geometries in the past, they suffer from end effects that are difficult to control in experimental practice. Axisymmetric geometries can be useful for preliminary comparisons [9], but computational methods must be developed for 3D flows in order to be validated for use with real vehicle designs. Very slow transverse flows in the separation bubbles are challenging to simulate, but accurate 3D grids and numerical methods must be developed to meet this challenge. Transitional separated flows are *very* difficult to simulate, but such simulations must be developed and validated by comparison with quiet-tunnel experiments. The separated flow must reattach before the end of the flap to avoid coupling the bubble flow into the wake, which would add additional complexity.

In order to present a suitable test case for computational analyses, Greg McKiernan performed measurements of instability and transition on a generic cone with a slice and flap. An unflyable public-release geometry was developed, building on the work of Oberkampf et al. [56]. McKiernan measured instability and transition on the geometry, modified it to ensure that the separation bubble is fully attached well before the end of the flap, and identified some of the features of the instability and transition process. Surface measurements with fast pressure sensors detected instability-wave packets and turbulent spots downstream of reattachment. Transition Reynolds numbers were a little less than one million, based on freestream conditions and the distance from the nosetip. A pulsed plasma perturber was developed with the assistance of Prof. Bane's group, and used to introduce disturbances into the boundary layer just upstream of the bubble. Although this enabled detection of a convective instability, this convective instability did not seem to dominate transition [20, 34].

The results are being compared to preliminary computations by others [57, 58]. This work continues within Prof. Jewell's group using funding from the Israeli Ministry of Defense.

These flows remain challenging to predict, and good topics for additional research. Quiet tunnels are needed to capture the critical physics, and very high quiet Reynolds numbers are not needed. Computational analyses are challenging but still need to be developed through comparisons to each other and to the experiments.

8 Transition Induced by a Separation Bubble on a Cone-Cylinder-Flare

To address transitional separations with a simplified geometry that was accessible to our NATO STO AVT-346 partners, and to our Israeli collaborators, Liz Benitez studied the flow on a sharp cone that was followed by a cylinder and flare. This flow features an expansion corner followed by a compression corner, rather like a cone with a slice and a flap, but in an axisymmetric form. Although Benitez's work was mostly funded by an NDSEG Fellowship, her experimental expenses were supported by the present AFOSR grant. The cone-cylinder-flare was selected instead of a hollow-cylinder-flare in order to avoid the starting problems that often occur with hollow cylinders.

Initial measurements and computations were carried out using a 3.5-deg. half-angle flare, which avoided separation, and served as a control case [7]. Benitez measured with fast surface pressure sensors, infrared thermography, Schlieren, and a focused laser differential interferometer. The linear theory compared fairly well to the instability measurements on the cone and flare, but there were more difficulties making comparisons on the cylinder.

The primary measurements were then made using a 10-deg. flare, which was sufficient to generate a moderate-sized separation bubble [18]. Above and downstream of the bubble, Benitez detected a low-frequency traveling wave, in addition to the usual second-mode wave. The second-mode wave frequency could be predicted by Navier-Stokes mean-flow analyses and the usual linear instability theory, but the low-frequency traveling wave was not expected. The low-frequency traveling wave appeared to be generated by the shear layer in the separation bubble, so it was called the shear-generated instability. Under quiet flow, natural transition was not observed at the maximum quiet Reynolds number that the tunnel could provide at that time.

Small angles of attack are inevitable with long slender models of this kind, and their effect was then studied in detail [19]. The separation bubble gets shorter on the windward side of the model under quiet laminar flow, but gets longer on the windward side under noisy transitional flow. Reattachment on the windward side moves forward with angle of attack, under quiet laminar flow. Streamwise vortices could be detected at reattachment only very near zero angle of attack, when they were still very weak, leading to suspicions about the generality of the Görtler-like mechanism for transition.

A plasma perturber was then mounted on the cone, upstream of the separation bubble. Pulsed disturbations were introduced. These amplified along the bubble via the shear-generated instability, and not the second-mode instability [21].

Benitez's work is summarized and detailed in her Ph.D. thesis [35]. The shear-generated traveling waves were the major discovery of this work, but remained unexplained from a theoretical or computational point of view.

Computations were then developed by the NASA Langley team to explain the low-frequency shear-generated waves, which turned out to be caused by an oblique first-mode instability [59]. Very good agreement was found for the heat transfer on the flare, the frequencies of the various instabilities, and the Schlieren image of the separation bubble. The amplitude of the instabilities is in most cases in reasonable agreement, although there are some differences at low frequencies, and linear theory of course requires an assumption for the initial amplitude. The heat transfer under the separation bubble is not predicted well, for reasons which remain to be understood.

Another transition mechanism in these flows is of course related to the Görtler-like streamwise-vortex instability that has often been observed. Limited studies of this mechanism were also performed by Lauren Wagner using small controlled roughness, but this work was funded by other sources [60].

Although much has been learned about this simpler flowfield, much remains to be understood. It thus remains a good test case for developing tools for predicting transition in separated flows.

9 Joint-Step Roughness Effects for BOLT

The BOLT geometry was developed in order to flight-test boundary-layer transition on a complex configuration, where several different instabilities could interact and lead to transition. Since tunnel noise is known to affect transition [61], JHU APL planned a series of measurements in the Mach-6 quiet tunnel at Purdue as a part of the ground-testing campaign. Purdue was asked to support this work under the present grant. Initial measurements are reported in Refs. [5] and [10]. At the maximum quiet flow Reynolds number, the smooth-wall flow remained laminar at Purdue near zero angle of attack. In the 2019 paper, small 3D roughnesses near the leading edge trip transition downstream even under quiet flow.

As is common for a hypersonic flight test, different materials were used for the higher-temperature regions near the nose. Differential thermal expansion occurs for these different materials, and forward-facing and backward-facing steps can then develop along the surface. These steps can trip the boundary layer to turbulence. To minimize the risk that these steps could have unintended and overly large consequences, and to help in developing specifications for the allowable steps, a series of measurements were obtained in several wind tunnels. The initial results from the Purdue measurements with the original APL model are reported in Ref. [15]. Transitional wedges were observed downstream of the steps even under quiet flow, for sufficiently large steps and sufficiently large angles of attack. However, the carefully designed nosetip of this model was still not precise enough. When the nosetips were replaced with ones that created larger or smaller steps, the mechanical mounting and alignment process was not accurate enough, and the (small) steps varied significantly across the span, and were not sufficiently repeatable when the nosetips were removed and re-inserted.

This APL model was then modified for a series of experiments that were carried out as part of Chris Yam's M.S. thesis research [22, 38]. Sufficiently large steps produced turbulent wedges downstream, when at sufficient Reynolds numbers and sufficient angles of attack. Strong streamwise streaks were measured upstream of these wedges of turbulence, and secondary instabilities of these laminar streamwise streaks were measured using fast surface pressure transducers. Although the accuracy of the nosetips of the model was improved, the small forward-facing and backward-facing steps were still not as uniform and repeatable as was hoped. The results are of good quality, though, and remain a good subject for computational comparisons.

10 Summary

The Mach-6 wind tunnel remained quiet through most of the grant period. Instability and transition measurements were performed for a variety of geometries under a variety of conditions. The results were reported in detail in 22 conference papers, 9 journal papers, 3 Master's theses, and 4 Ph.D. theses. The present document therefore provides only an overall summary.

Measurements in the Mach-6 quiet tunnel continue to have an impact for a number of transition problems of interest to the DoD. This tunnel is now led by Asst. Prof. J. Jewell. Further measurements in this quiet tunnel should continue to assist the development of mechanism-based transition estimation methods that can be used to design and develop DoD vehicles. Most of the real value comes from detailed comparisons between computations and measurements, which lead to improvements in the computational approaches, and to improved methods for predicting phenomena in flight.

11 Acknowledgements

Most of the present report is summarized from the cited papers, each of which has multiple authors. Portions of the work were also supported by various fellowships. These complex quiet-tunnel experiments would not have been possible without the support of many organizations and individuals. All the quiet tunnel measurements were made by the graduate students whose work is cited above.

12 References

[1] Lian Duan, Meelan Choudhari, Amanda Chou, Munoz, Ali, Rolf Radespiel, Schilden, Schroder, Marineau, Casper, Chaudry, Candler, Kathryn A. Gray, Cameron Sweeney, and Steven P. Schneider. Characterization of freestream disturbances in conventional hypersonic wind tunnels. Paper 2018-0347, AIAA, January 2018.

[2] Brandon Chynoweth, Steven P. Schneider, Christoph Hader, Hermann Fasel, Armani Batista, Joseph Kuehl, Thomas Juliano, and Bradley Wheaton. A history and progress of research on boundary-layer transition on a Mach-6 flared cone. Paper 2018-0060, AIAA, January 2018.

[3] Travis Kocian, Alexander Moyes, Helen Reed, Stuart Craig, William Saric, Steven P. Schneider, and Joshua Edelman. Hypersonic crossflow instability. Paper 2018-0061, AIAA, January 2018.

[4] Eric Marineau, Guillaume Grossir, Alex Wagner, M. Leinemann, Rold Radespiel, H. Tanno, T. Wadhams, Brandon Chynoweth, Steven P. Schneider, Ross Wagnild, and Katya Casper. Compilation and analysis of second-mode amplitudes on sharp cones in hypersonic wind tunnels. Paper 2018-0349, AIAA, January 2018.

[5] Dennis Berridge, Gregory McKiernan, Brandon Chynoweth, Bradley Wheaton, Thomas Wolf, and Steven P. Schneider. Hypersonic ground tests in support of the boundary layer transition (BOLT) flight experiment. Paper 2018-2893, AIAA, June 2018.

[6] Roger Greenwood and Steven P. Schneider. Measurements of entropy-layer instabilities over cone-ogive-cylinders in a Mach-6 quiet tunnel. Paper 2019-0627, AIAA, January 2019.

[7] Sebastien Esquieu, Elizabeth Benitez, Steven P. Schneider, and Jean-Phillippe Brazier. Flow and stability analysis of a hypersonic boundary layer over an axisymmetric cone cylinder flare configuration. Paper 2019-2115, AIAA, January 2019.

[8] Ross Chaudry, Graham Candler, Kathryn Gray, and Steven Schneider. Computations of measured pitot-probe spectra using angled freestream disturbances and comparisons to experiment. Paper 2019-2149, AIAA, January 2019.

[9] Madlen Leinemann, Rolf Radespiel, Federico Munoz, Sebastien Esquieu, Greg McKiernan, and Steven P. Schneider. Boundary layer transition on a generic model of control flaps in hypersonic flow. Paper 2019-1908, AIAA, January 2019.

[10] Dennis Berridge, Heather Kostak, Gregory McKiernan, Rudolph King, Mark Wason, Bradley Wheaton, Thomas Wolf, and Steven Schneider. Hypersonic ground tests with high-frequency instrumentation in support of the boundary-layer transition (BOLT) flight experiment. Paper 2019-0090, AIAA, January 2019.

[11] Mirko Zaccara, Salvatore Cerasoulo, Gennaro Cardone, Joshua Edelman, and Steven Schneider. Infrared thermography data reduction technique for heat transfer measurements in the Boeing/AFOSR Mach-6 quiet tunnel. Paper 2019-0894, AIAA, January 2019.

[12] Ross S. Chaudhry, Graham V. Candler, Kathryn Gray, and Steven P. Schneider. Computations of measured pitot-probe spectra using angled freestream disturbances and comparisons to experiments. Paper 2019-2149, AIAA, January 2019.

[13] E. Vogel, B. Chynoweth, J. Coder, and S. Schneider. Experimental and computational results of a cone-slice-ramp geometry at Mach 6. Paper 2019-3593, AIAA, June 2019.

[14] Joshua Edelman and Steven P. Schneider. Using discrete and distributed roughness to generate stationary crossflow waves in a Mach-6 quiet tunnel. Paper 2019-2968, AIAA, June 2019.

[15] Brandon Chynoweth, Steven P. Schneider, Bradley Wheaton, and T. Wolf. Transition measurements with forward and aft-facing steps on the BOLT geometry at Mach 6. Paper 2020-1560, AIAA, January 2020.

[16] E. Benitez, J. Jewell, and S. Schneider. Focused laser differential interferometry for hypersonic flow instability measurements with contoured tunnel windows. Paper 2020-1282, AIAA, January 2020.

[17] Kathryn Gray and Steven P. Schneider. Measurements of second-mode dominated transition on a straight cone in the Boeing/AFOSR Mach-6 quiet tunnel. Paper 2020-0590, AIAA, January 2020.

[18] Elizabeth Benitez, Joseph Jewell, Steven P. Schneider, and Sebastien Esquieu. Instability measurements on an axisymmetric separation bubble at Mach 6. Paper 2020-3072, AIAA, June 2020.

[19] Elizabeth Benitez, Joseph Jewell, and Steven P. Schneider. Separation bubble variation due to small angles of attack for an axisymmetric model at Mach 6. Paper 2021-0245, AIAA, January 2021.

[20] Gregory R. McKiernan and Steven P. Schneider. Instability and transition on a cone with a slice and ramp at Mach 6. Paper 2021-0249, AIAA, January 2021.

[21] E. Benitez, J. Jewell, and S. Schneider. Propagation of controlled disturbances through an axisymmetric separation bubble at Mach 6. Paper 2021-2844, AIAA, August 2021.

[22] Christopher Yam, Steven P. Schneider, and Joseph Jewell. Effect of forward- and backward-facing steps on BOLT at Mach 6. Paper 2022-0346, AIAA, January 2022.

[23] Sebastian Willems, Ali Gülhan, Christopher A.C. Ward, and Steven P. Schneider. Free transition on a slender cone in a quiet and a conventional wind tunnel and the effect of ultrasonically absorptive materials. *Progress in Flight Physics*, 9:497–516, 2017.

[24] Joshua B. Edelman and Steven P. Schneider. Secondary instabilities of hypersonic stationary crossflow waves. *AIAA Journal*, 56(1):182–192, January 2018.

[25] Amanda Chou and Steven P. Schneider. The azimuthal variation of boundary-layer instabilities generated on a flared cone by freestream laser perturbations. *AIAA Journal*, 56(5):1867–1877, May 2018.

[26] Brandon Chynoweth, Steven P. Schneider, Christoph Hader, Hermann Fasel, Armani Batista, Joseph Kuehl, Thomas J. Juliano, and Bradley M. Wheaton. History and progress of boundary-layer transition on a Mach-6 flared cone. *Journal of Spacecraft and Rockets*, 56(2):333–346, March 2019.

[27] Eric Marineau, Guillaume Grossir, Alexander Wagner, Madlen Leinemann, Rolf Radespiel, Hideyuki Tanno, Brandon Chynoweth, Steven P. Schneider, Ross M. Wagnild, and Katya M. Casper. Analysis of second-mode wave amplitudes on sharp cones in hypersonic wind tunnels. *Journal of Spacecraft and Rockets*, 56(2):307–318, March 2019.

[28] Lian Duan, Meelan M. Choudhari, Amanda Chou, Federico Munoz, Rolf Radespiel, Thomas Schilden, Wolfgang Schroder, Eric Marineau, Katya M. Casper, Ross S.

Chaudhry, Graham V. Candler, Kathryn A. Gray, and Steven P. Schneider. Characterization of freestream disturbances in conventional hypersonic wind tunnels. *Journal of Spacecraft and Rockets*, 56(2):357–368, March 2019.

[29] Travis S. Kocian, Alexander J. Moyes, Helen L. Reed, Stuart A. Craig, William S. Saric, Steven P. Schneider, and Joshua B. Edelman. Hypersonic crossflow instability. *Journal of Spacecraft and Rockets*, 56(2):432–446, March 2019.

[30] Gregory McKiernan, Brandon Chynoweth, Steven P. Schneider, Dennis Berridge, and Bradley Wheaton. Boundary layer transition preflight experiments in a Mach-6 quiet tunnel. *Journal of Spacecraft and Rockets*, 58(1):54–66, January 2021.

[31] Elizabeth K. Benitez, Joseph Jewell, and Steven P. Schneider. Focused laser differential interferometry with contoured windows. *AIAA Journal*, 59(2):419–429, February 2021.

[32] Brandon C. Chynoweth. *Measurements of Transition Dominated by the Second-Mode Instability at Mach-6*. PhD thesis, School of Aeronautics and Astronautics, Purdue University, May 2018.

[33] Joshua B. Edelman. *Nonlinear Growth and Breakdown of the Hypersonic Crossflow Instability*. PhD thesis, School of Aeronautics and Astronautics, Purdue University, August 2019.

[34] Gregory R. McKiernan. *Instability and Transition on a Sliced Cone with a Finite-Span Compression Ramp at Mach 6*. PhD thesis, School of Aeronautics and Astronautics, Purdue University, May 2020.

[35] Elizabeth K. Benitez. *Instability Measurements on Two Cone-Cylinder-Flares at Mach 6*. PhD thesis, School of Aeronautics and Astronautics, Purdue University, August 2021.

[36] Kathryn A. Gray. Flowfield characterization of the Boeing/AFOSR Mach-6 quiet tunnel. Master's thesis, School of Aeronautics and Astronautics, Purdue University, December 2018.

[37] Varun Viswanathan. Hypersonic stationary crossflow waves: Receptivity to roughness. Master's thesis, School of Aeronautics and Astronautics, Purdue University, December 2019.

[38] Christopher Yam. Effects of forward- and backward-facing steps on boundary-layer transition at Mach 6. Master's thesis, School of Aeronautics and Astronautics, Purdue University, May 2022. Deposited Jan. 2022.

[39] Kathryn A. Gray. *Instability and Transition on a Slender Cone under Fully Quiet Mach-6 Flow*. PhD thesis, School of Aeronautics and Astronautics, Purdue University, August 2022. Tentative title. To appear.

[40] I.E. Beckwith and C.G. Miller III. Aerothermodynamics and transition in high-speed wind tunnels at NASA Langley. *Annual Review of Fluid Mechanics*, 22:419–439, 1990.

[41] Steven P. Schneider. Development of hypersonic quiet tunnels. *Journal of Spacecraft and Rockets*, 45(4):641–664, Jul.-Aug. 2008.

[42] Steven P. Schneider, Craig Skoch, Shann Rufer, Shin Matsumura, and Erick Swanson. Transition research in the Boeing/AFOSR Mach-6 quiet tunnel. Paper 2002-0302, AIAA, January 2002.

[43] Steven P. Schneider, Craig Skoch, Shann Rufer, Erick Swanson, and Matt Borg. Bypass transition on the nozzle wall of the Boeing/AFOSR Mach-6 quiet tunnel. Paper 2004-0250, AIAA, January 2004.

[44] Steven P. Schneider. Final report for DURIP grant FA9550-08-1-0437: Towards increased quiet-flow Reynolds number and operability for the 9.5-inch Mach-6 Ludwieg tube. Contractor Report TBD, AFOSR, February 2011. Rev. 1 consists of 21 pages dated 14 Feb. 2011. Not found in DTIC.

[45] Steven P. Schneider. Final report for DURIP grant FA2386-14-1-3024, towards increased quiet-flow Reynolds number and operability for the 9.5-inch Mach-6 Ludwieg tube: Completing the new throat. Contractor Report TBD, AFOSR, February 2017. Rev. 1 comprising 20 pages was submitted 15 Feb. 2017. Not found in DTIC.

[46] Laura-cheri E. Steen. Characterization and development of nozzles for a hypersonic quiet wind tunnel. Master's thesis, School of Aeronautics and Astronautics, Purdue University, December 2010.

[47] Derek V. Mamrol. Characterization of the quiet flow freestream and a flat plate model in the Boeing/AFOSR Mach 6 quiet tunnel. Master's thesis, School of Aeronautics and Astronautics, Purdue University, December 2021.

[48] R.H. Radeztsky, M.S. Reibert, and W.S. Saric. Effect of isolated micron-sized roughness on transition in swept-wing flows. *AIAA J.*, 37(11):1370–1377, November 1999.

[49] Heath Johnson, Christopher Alba, Matthew Bartkowicz, Travis Drayna, and Graham Candler. Design optimization of hypersonic vehicles for boundary layer stability. Paper 2008-6221, AIAA, August 2008.

[50] Malte Estorf, Rolf Radespiel, Steven P. Schneider, Heath B. Johnson, and Stefan Hein. Surface-pressure measurements of second-mode instability in quiet hypersonic flow. Paper 2008-1153, AIAA, January 2008.

[51] Eric Marineau. Prediction methodology for second-mode-dominated boundary-layer transition in wind tunnels. *AIAA Journal*, 55(2):484–499, Feb. 2017.

[52] Steven P. Schneider. Developing mechanism-based methods for estimating hypersonic boundary-layer transition in flight: the role of quiet tunnels. *Progress in Aerospace Sciences*, 72:17–29, 2015.

[53] Sebastian Willems, Ali Gülhan, Christopher A.C. Ward, and Steven P. Schneider. Free transition on a slender cone in a quiet and a conventional wind tunnel and the effect of ultrasonically absorptive materials. In *6th European Conference for Aerospace Sciences*, 2015.

[54] F.J. Chen. Boundary-layer transition extent measurements on a cone and flat plate at Mach 3.5. Paper 93-0342, AIAA, January 1993.

[55] Steven P. Schneider. Effects of high-speed tunnel noise on laminar-turbulent transition. *Journal of Spacecraft and Rockets*, 38(3):323–333, May–June 2001.

[56] William L. Oberkampf, Daniel P. Aeschliman, Roger E. Tate, and John F. Henfling. Experimental aerodynamics research on a hypersonic vehicle. Technical Report SAND92-1411, Sandia National Laboratories, Albuquerque, New Mexico, April 1993.

[57] Siddarth GS, Anubhav Dwivedi, Graham V. Candler, and Joseph Nichols. Global linear stability analysis of high speed flows on compression ramps. Paper 2017-3455, AIAA, June 2017.

[58] Helio Quintanilha Jr. and Vassilis Theofilis. Steady laminar solutions of hypersonic flow over Oberkampf bodies at cruise. Paper 2021-0632, AIAA, January 2021.

[59] Pedro Paredes, Anton Scholten, Meelan Choudhari, Elizabeth Benitez, and Joseph Jewell. Boundary-layer instabilities over a cone-cylinder-flare model at Mach 6. Paper 2022-0600, AIAA, January 2022.

[60] Lauren Wagner. Amplification of streamwise vortices across a separated region at Mach 6. Master's thesis, School of Aeronautics and Astronautics, Purdue University, May 2022. Deposited March 2022.

[61] Katya M. Casper, Heath B. Johnson, and Steven P. Schneider. Effect of freestream noise on roughness-induced transition for a slender cone. *J. Spacecraft and Rockets*, 48(3):406–413, May-June 2011.