REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
04-03-2011

2. REPORT TYPE
Final Technical

3. DATES COVERED *(From - To)*
1 June 2008 to 30 Nov. 2010

4. TITLE AND SUBTITLE
Final Report for AFOSR Grant FA9550-08-1-0290 -- Hypersonic Laminar-Turbulent Transition on Slender Cones at Zero Angle of Attack: Measurements in Support of Mechanism-Based Models for Scaling Ground-Test Data to Flight

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-08-1-0290

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 N. Randolph St.
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2012-0261

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release, Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Maintaining low laminar heating may be critical to hypersonic gliding reentry vehicles such as the several which have been proposed for the Prompt Global Strike (PGS) mission. However, no single ground test can duplicate the Mach number, Reynolds number, enthalpy, surface temperature, scale, roughness, ablation and freestream noise of flight; thus, ground-test measurements of laminar-turbulent transition must be compared and extrapolated to flight using analysis. Fortunately, the first mechanism-based prediction methods are now becoming available for some of the instabilities that lead to transition. Wind-tunnel measurements of these instabilities are being carried out in order to develop and calibrate these new semi-empirical methods. Recently-successful fast-response surface pressure transducers were further developed and applied on a circular cone at zero angle of attack in several hypersonic wind tunnels in order to measure second-mode waves, transition, and the effect of tunnel noise. Results to date are summarized, and plans for future research are outlined.

15. SUBJECT TERMS
Hypersonic laminat-turbulent transition, second-mode instability, wind tunnels, flight

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	none	17	Steven P. Schneider

19b. TELEPHONE NUMBER *(Include area code)*
765-494-3343

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March 4, 2011

Contents

1 Abstract

Maintaining low laminar heating may be critical to hypersonic gliding reentry vehicles such as the several which have been proposed for the Prompt Global Strike (PGS) mission. Transition is also important for scramjet-powered vehicles, interceptor missiles, and other reentry vehicles. However, no single ground test can duplicate the Mach number, Reynolds number, enthalpy, surface temperature, scale, roughness, ablation and freestream noise of flight; thus, ground-test measurements of laminar-turbulent transition must be compared and extrapolated to flight using analysis. Fortunately, the first mechanism-based prediction methods are now becoming available for some of the instabilities that lead to transition. Wind-tunnel measurements of these instabilities are being carried out in order to develop and calibrate these new semi-empirical methods.

The second-mode instability is one mechanism that may be critical for PGS vehicles. Recently-successful fast-response surface pressure transducers were further developed and applied on a circular cone at zero angle of attack in AEDC Tunnel 9, the 15-inch Mach-6, 20-inch Mach-6 and 31-inch Mach-10 tunnels at NASA Langley, the Mach 5, 8 and 14 tunnels at Sandia, and the Purdue Mach-6 quiet tunnel, in order to measure second-mode waves, transition, and the effect of tunnel noise. Some of the results have been analyzed with the

STABL code using an e^N approach. Results to date are summarized, and plans for future research are outlined.

2 Introduction

Laminar-turbulent transition is critical to gliding hypersonic reentry vehicles and hypersonic airbreathing cruise vehicles, such as those presently being developed under the X-51, FALCON, AHW and CSM programs. However, no single ground-test facility can reliably evaluate transition, as none combine the low noise levels, high Mach numbers, high transition Reynolds numbers, and high enthalpy levels that are observed in flight. Reliable test and evaluation of transition-sensitive designs will require development of a new transition-prediction tool. This tool must extrapolate from new and existing ground experiments and existing flight data, to obtain reliable results for new designs in flight, without extensive flight testing. A reliable tool must be based on the actual physical mechanisms that lead to transition; such a tool is now becoming feasible due to continuing computational advances.

This T&E grant helped to develop analysis tools and test methodology necessary to provide improved predictions of hypersonic boundary-layer transition using wind-tunnel test data. Seven factors were brought together for the first time: (1) the STABL code for analyzing the second-mode instability on cones at zero angle of attack [1], (2) the fast pressure sensors which were recently successful in measuring surface fluctuations and 2nd-mode waves in Japan, Germany, and the Purdue quiet tunnel [2], (3) Pate's correlation for transition on sharp cones at zero angle of attack induced by tunnel-wall radiated noise [3], (4) pitot-probe measurements of the tunnel freestream noise, (5) relationships between the noise measured on a pitot probe and the noise measured under the laminar boundary layer on a sharp cone, (6) a model and instrumentation being developed under Sandia leadership to measure the pressure fluctuations on a circular cone in transitional and turbulent flow, and (7) the newly available Mach-6 quiet tunnel at Purdue. For the sake of brevity, the present report assumes the reader has a good general familiarity with hypersonic instability and transition (for additional detail, contact the author, or see Refs. [4, 5, 6, 7, 8, 9, 10, 11]).

This final report summarizes progress towards a large and ambitious goal. The work of many people will be required to develop all the tools and procedures that are sketched out in concept here, and many different groups are already contributing in various ways. More detail regarding the work is reported in Refs. [12, 13, 14]. Other work that is related to the work funded under the present grant is reported in Refs. [12, 15, 16, 17, 18, 19, 20, 21, 22]. Related work continues at JAXA, DLR, NASA Langley, CUBRC, AEDC Tunnel 9, VKI, Purdue and elsewhere, and will be reported later. This report also outlines a general vision for future research.

3 Original Statement of Objectives from 2008

1. Compute the integrated growth of first and second-mode instability waves for use in e^N-type methods for predicting transition
   (a) Compute mean flows using Navier-Stokes on sharp and blunt cones at zero AOA.
   (b) Compute first and second mode instabilities and their integrated growth. Confirm that second-mode waves are dominant.
2. Compute Pate's Correlation for Various Tunnels
3. Calibrate the Fast-Pressure Sensors, in Collaboration with Sandia
   (a) Compare the Kulite and PCB sensors
   (b) Compare sensors mounted under a small hole (to improve spatial resolution) to those mounted flush with the surface (to improve frequency response)
4. Measure Instability and Transition on Hypersonic Cones at Zero AOA
   (a) 9.5-inch Mach-6 Tunnel at Purdue
      i. Measure instability and transition on 7-deg. cone at zero AOA, with a sharp tip and various small-radii nosetips.
      ii. Using fast-response pressure gauges [2] and temperature-sensitive paints
      iii. Measure amplitude, amplification, and nonlinear saturation of 2nd-mode waves
      iv. Measure the amplitude of freestream-induced pressure fluctuations at the cone surface under fully laminar flow
      v. Measure pitot-pressure fluctuations in the freestream using fast pressure sensors
      vi. To compare to Pate's correlation, measure the properties of the turbulent boundary layer on the nozzle wall under noisy conditions
      vii. Using a glow-discharge perturber, generate instability waves that grow enough to cause transition on the cone under fully quiet conditions.
   (b) 60-inch Mach 8, 10, and 14 Nozzles at AEDC Tunnel 9
      i. Perform the same measurements as in the Purdue tunnel (except for the glow-perturber work)
5. Analyze the Data and Report the Results
   (a) Compare the noise radiated to the pitot probe to the estimates contained in Pate's correlation
   (b) Compare the noise measured by the pitot probe to the noise measured under the fully laminar boundary layer on the cone
   (c) Measure the amplitude of linear instability waves on the cones at various conditions. Using e^N methods, determine the amplitude of the initial disturbance where the waves first become unstable
   (d) Compare these initial wave amplitudes to the noise measurements. Develop a method of extrapolating the tunnel noise from measurable low frequencies to unmeasurable high frequencies. Determine if Pate's correlation results from a correlation to these initial wave amplitudes
   (e) Compare the amplitudes of the instability waves at the locations where they become nonlinear and where they break down to turbulence. Determine if these amplitudes are consistent (as they seem to be in Ref. [2]). If possible, develop an amplitude-based criteria for the breakdown of second-mode waves
   (f) Seek a mechanism-based explanation for Pate's correlation. Seek to extend this semi-empirical transition prediction from sharp cones to blunt cones and more complex geometries with second-mode dominated transition

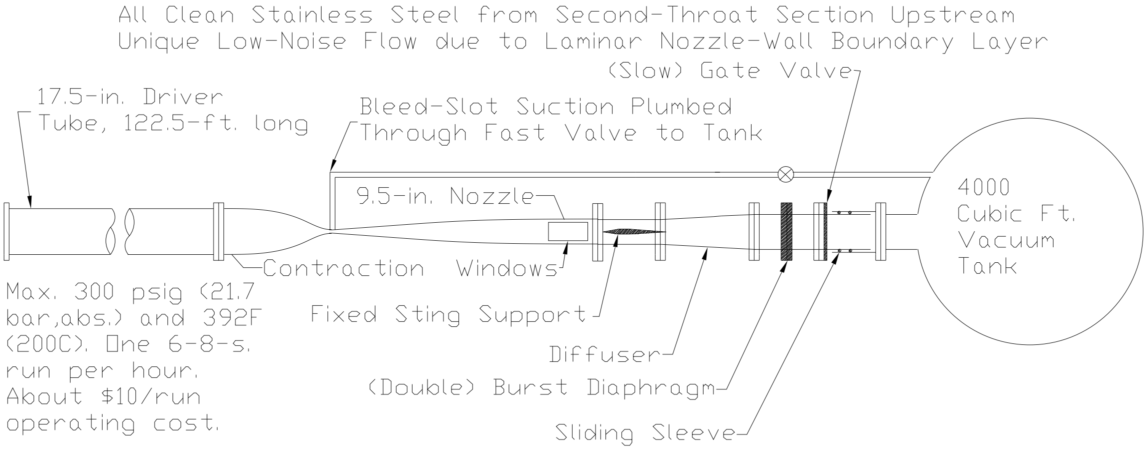

Figure 1: Schematic of Boeing/AFOSR Mach-6 Quiet Tunnel

4 Research Effort

4.1 Brief Summary of Purdue Capabilities

Purdue has developed the larger of two hypersonic quiet tunnels [10]. 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. These features make the noise level in quiet facilities an order of magnitude lower than in conventional facilities. To reach these low noise levels, conventional blow-down facilities must be extensively modified. Requirements have included 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. To reach these low noise levels in an affordable way, the Purdue facility has been designed as a Ludwieg tube. 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 (Figure 1). A diaphragm is placed downstream of the test section. When the diaphragm bursts, an expansion wave travels upstream through the test section into the driver tube, and a fast valve is opened to initiate flow in the bleed slots. 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 tunnel is presently quiet to a stagnation pressure of about 170 psia, or a freestream unit Reynolds number of about 3.5 million per foot.

4.2 Brief Summary of Tunnel 9 Capabilities

AEDC Hypervelocity Wind Tunnel No. 9 (Tunnel 9) located at the White Oak, Maryland site of the Arnold Engineering Development Center (AEDC) is a blowdown facility that utilizes pure nitrogen as the working fluid and currently operates at Mach numbers of 7, 8, 10 and 14. The test section is over 12 ft long and has a diameter of 5 ft, enabling testing of large-scale model configurations. The Mach 10 and 14 nozzles are 40 ft in length with a 60-in.-diam exit. Tunnel 9 is the primary DoD T&E hypersonic wind tunnel and is utilized by most acquisition level reentry programs. Tunnel 9 notable capabilities include the ability to provide high Mach number and high Reynolds number for long run times necessary to collect pitch polar data during a single run. Tunnel 9 is uniquely suited for stability and aerothermal testing of large models (full-scale in some cases), at both fully laminar and fully turbulent conditions due to the large Reynolds number and Mach number range which can be achieved. The successful measurement of second-mode waves in Tunnel 9 has enabled the measurement of such waves on models of real flight vehicles. These measurements then reduce risk in extrapolating ground-test transition measurements to flight.

4.3 Measurements of Second-Mode Instability Using Fast Surface Pressure Sensors

Second-mode waves were first measured using fast pressure transducers by Fujii in the JAXA 0.5-m hypersonic blowdown tunnel in Japan [23]. In hindsight, a measurable pressure signal is not too surprising, since 2nd-mode instabilities are acoustic waves trapped between the wall and the boundary-layer edge. However, it does remain surprising that the PCB M131A32 sensors are able to achieve the required combination of high sensitivity and high frequency response. Even the manufacturer is surprised, according to Mike Holden from CUBRC (private communication, fall 2007), as these sensors were designed to measure the passage of shock waves in guns.

Estorf et al. continued this effort using a 7-deg. half-angle sharp cone [2]. Fig. 2 shows power spectra obtained in the Purdue tunnel under quiet and noisy flow. The second-mode waves are evident at a frequency of a little more than 200kHz. Under quiet flow, the instability waves are about 450 times smaller than under noisy flow, a factor of about e^6. Presumably this is because the freestream noise is two orders of magnitude lower, according to RMS measurements using fast pitot-pressure probes. However, until recently it had not been possible to detect noise in the freestream of any tunnel at the high frequencies corresponding to the second-mode waves [5, 24]; freestream noise decreases dramatically with frequency and the signal-to-noise ratio of the measurement generally falls below 1.0 well before second-mode frequencies are reached. Ref. [15] reports the first measurements of pitot-pressure fluctuations with significant signal-to-noise ratio at the second-mode frequencies, although it is not yet known why this measurement was more successful than previous measurements with other instrumentation.

4.4 Development of a Process for Inferring Second-Mode Wave Amplitudes from Tunnel Noise

The preliminary data shown in Fig. 2 opened up a new set of possibilities for calibrating e^N analyses for various wind tunnels. Beginning in the 1960's, Pate showed that transition on sharp cones at zero angle of attack could be explained by a simple correlation related to the noise radiated from the nozzle wall [25, 3]. Recent measurements support Pate's correlation for the Sandia and Purdue tunnels at Mach 5, 6 and 8 [18, pp. 75-79]. At hypersonic speeds, this transition was almost certainly induced by second-mode instability waves [26]. Hypersonic freestream fluctuations are in principle very complex, being composed of vorticity, sound, and entropy waves [27], along with particulate. However, Pate's correlation suggests

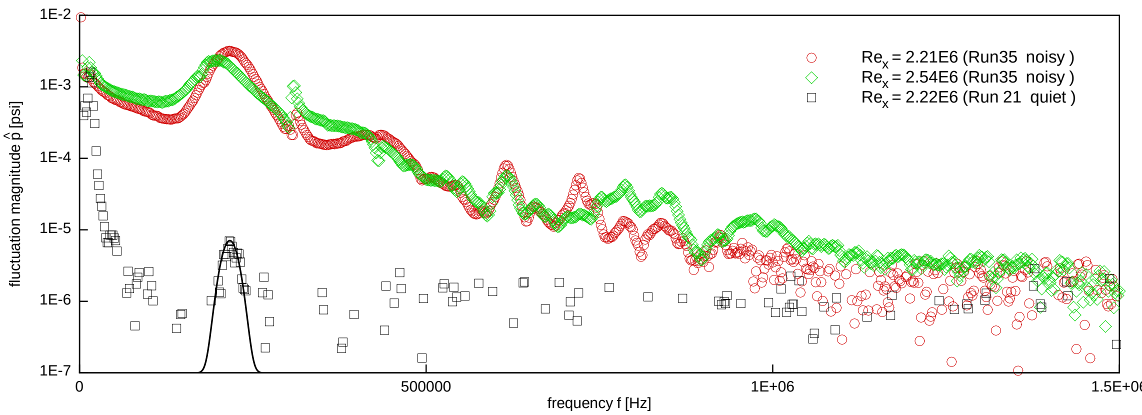

Figure 2: Power Spectra of Pressure Fluctuations Under Quiet and Noisy Flow. From Fig. 8 in Ref. [2]. The solid black line is a curve fit.

that the tunnel-to-tunnel noise variations follow a relatively simple pattern.

With advances in instrumentation and computational analysis, it is now becoming possible to measure and analyze the second-mode instability mechanism that must explain Pate's correlation at hypersonic speeds. Although the noise at the second-mode frequencies is still difficult to measure in the freestream, the instability waves induced on the cone can now be measured using the fast pressure sensors, which are robust enough for routine use. Computer codes for compressible stability analysis, such as STABL [1], are also now becoming fast and readily available. Following recent advances in receptivity theory, one might hypothesize that tunnel noise interacting with the flow near the nose generates an initial amplitude of the second-mode waves at the location where instability begins, A_0. These waves then amplify along the cone until they are large enough to be measurable. Using the measurements and the STABL code, one could infer A_0 for various facilities under various conditions. Measurements of this kind have recently become available in five cold-flow Mach-6 tunnels, at Purdue, VKI, Braunschweig and NASA Langley (two tunnels). Since all the measurements are for 7-deg. half-angle cones at zero angle of attack, the receptivity effects should be nearly the same. If a comparison of A_0 to measurements of the freestream noise shows good correlation, perhaps the differences in the character of the noise can be neglected. An ability to predict A_0 for a given tunnel and geometry would be a major advance in the process of design, test, evaluation and flight.

Tunnel-wall radiated noise can also be inferred from correlations such as Pate's, from measurements with fast pitot-pressure sensors, from measurements with fast pressure sensors under the laminar boundary layer on the front part of the cone, from freestream measurements with hot wires and other instrumentation, and from direct numerical simulations of the turbulent boundary layer on the nozzle wall. It is well known that this tunnel noise is caused primarily by acoustic waves radiated from the turbulent boundary layer on the nozzle wall, at least in well-designed cold-flow tunnels. The power spectra that have been reported seem to vary inversely with the frequency. Can the tunnel-noise power spectra in various conventional tunnels be correlated? Can this correlation be used to extrapolate the measurements at lower frequency to results at higher frequency, perhaps with the aid of selected Direct Numerical Simulations? Would such an extrapolation of the tunnel-wall radiated noise to second-mode frequencies be consistent with the value of A_0 inferred from the stability measurements? If this is possible, then the amplitude of second-mode waves on a sharp cone at zero angle of attack could be determined from the tunnel-noise correlation and STABL.

4.5 Measurements of Nonlinear Breakdown of Second-Mode Waves Using Fast Pressure Sensors

Figs. 3 and 4 show the other promising aspect of Estorf's results. In two separate tunnels running with conventional noise, the second-mode waves saturate downstream and begin to decay, indicating nonlinear effects and the beginning of transition. *This occurs at nearly the same Reynolds number and amplitude for both facilities.* If this is true in general for sharp cones, then it may be possible to determine the amplitude at which second-mode waves become nonlinear and break down, independent of the details of the other disturbances that are present in the tunnels. This would enable an amplitude-based criterion for estimating transition. And, in combination with the tunnel-noise correlation, it might enable an explanation for the mechanism that underlies Pate's 40-year-old correlation.

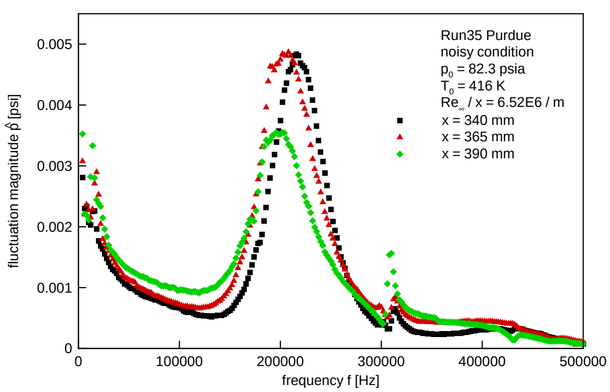

Figure 3: Power Spectra of Pressure Fluctuations Under Noisy Flow at Purdue. From Fig. 7a in Ref. [2]

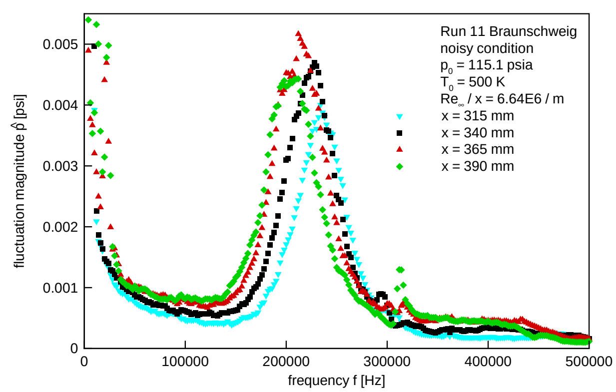

Figure 4: Power Spectra of Pressure Fluctuations Under Noisy Flow at Braunschweig. From Fig. 7b in Ref. [2]

4.6 Development of a Process for Estimating Transition Onset in Conventional Tunnels when Induced by Second-Mode Waves

Of course, both of these hypotheses are speculative, and many hurdles were readily visible when this work was proposed in 2008:

1. There are several forms of fast pressure sensors, and these can be located either flush with the surface (to improve frequency response) or below a small hole (to improve spatial resolution). Which method is best?

2. Can these sensors really measure second-mode waves in most of the larger facilities in the U.S.?
3. Is the response linear to the small amplitudes necessary to measure instability waves?
4. The fast pressure sensors have a spatial extent which is larger than the half-wavelength of the second-mode instability, so integrals of the computed waveforms will be necessary to obtain quantitative wave amplitudes from the pressure signals. Can this be done consistently?
5. Does receptivity happen primarily near the leading edge, and is it fairly consistent for a range of tunnel conditions, even for sharp cones at zero angle of attack?
6. Is nonlinear breakdown really fairly insensitive to the details of the many small disturbances present in the flow?

Fortunately, these questions were addressed not only by Dennis Berridge, the graduate student funded under this T&E grant, but also by collaborating with other researchers funded in other ways.

4.7 Results

4.7.1 Collaboration with Sandia National Laboratories

Sandia is interested in the pressure fluctuations on a cone during reentry and how these generate vibration in the internal components. The largest pressure fluctuations are present during the intermittent portion of the transition process, so Sandia is interested primarily in the region downstream of the onset of transition, although they are also interested in predicting onset. Katya Casper began graduate research at Purdue in fall 2007, working on this problem under NSF and NDSEG fellowships, and also as a Sandia intern.

This Sandia work shares many aspects with the work funded under the T&E grant: (1) the need to calibrate various pressure sensors in various mountings to find the best way of making sensitive high-frequency measurements, (2) the need to measure in various tunnels, (3) the need to measure using arrays of sensors on a cone with sharp and small-radii nosetips. Thus, Katya Casper worked in cooperation with Dennis Berridge in much of this work, with Katya focusing more on the intermittent region downstream of the onset of transition, and Dennis focusing on the instabilities upstream of onset.

A modular cone model was built using funding from the T&E grant to supplement much greater funding that was provided by Sandia. This stainless-steel cone model has a 7-deg. half-angle, a sharp nosetip, small-bluntness nosetips of various radii, and many interchangeable parts for mounting various sensors in various configurations [18]. The model has been successfully used for experiments at NASA Langley, AEDC Tunnel 9, Sandia National Laboratories, and Purdue. The cone was shipped around the U.S. for a variety of experimental efforts, and remains in use [28, Fig. 8].

Working with Steve Beresh, her Sandia advisor, Katya et al. developed improved methods of measuring in various tunnels and with various kinds of pressure sensors in various mounts [18, 17]. They showed that the A-screen Kulites have better frequency response than the B screens. Both Katya and Dennis also found that putting the sensors beneath a small hole reduces the signal by too much, and can also introduce acoustic resonances (private communication, Feb. 2011). Thus, the sensors have been mounted flush with the surface in nearly all cases.

Sandia developed an apparatus for calibrating the Kulite and PCB sensors with high-frequency acoustic waves, but only to about 20kHz [29]. There is general agreement that this is insufficient for measurement of second-mode waves at 200-400kHz. Berridge attempted initial calibrations using the step-response to weak shock waves, identified some of the causes for problems with the sensor measurements, and uncovered some of the sources for possible nonlinearity in the PCB-132 sensors [14]. However, a high-quality calibration for small signals at very high frequencies remains a primary goal of Berridge's continuing work. Berridge et al. are developing a small and precise shock tube wherein these calibrations can be carried out at Purdue.

The cone and these pressure sensors were then used to make measurements in the Sandia tunnels at Mach 5 and 8, and in the Purdue tunnel at Mach 6. These measurements were very successful [12]. Chris Alba from the Air Force Research Laboratory provided the stability computations. Although the factory calibrations of pressure amplitude are not all that relevant at the very low pressures relevant to the second-mode waves, the wave amplitudes were measured under both noisy and quiet conditions. The frequencies of the most unstable waves agreed well with the computations. Under quiet flow at Mach 6, transition did not occur at $N = 10$. Under conventional noise, transition occurred near $N = 5$ at Mach 5 and at $N \simeq 6$ at Mach 6 and 8. At Mach 5, it seems that second-mode waves were not the dominant instability.

In addition, the Sandia work shares the goal of developing a glow-discharge apparatus for introducing instability waves and turbulent spots on the cone. In both cases, this is driven primarily by the need to measure downstream of the linear amplification of instability waves, under quiet conditions comparable to flight. Under quiet flow, with natural freestream disturbances, the initial amplitude of the waves is small and the amplitude at the end of the maximum quiet region is well short of transition. A localized glow perturber on the front of the cone is then to be used to introduce large instability waves whose amplitude is comparable to that generated by conventional tunnel noise. These waves can then grow downstream under quiet conditions, become nonlinear, and break down to turbulence. The breakdown amplitude is critical for the present project.

For the Sandia project, the turbulent spots generated by the breakdown are being studied under quiet conditions, although so far only on the nozzle wall [20]. The glow perturber previously built by Ladoon et al. [30, 31] was first adapted by Matt Borg for measurements on the X-51A, with AFOSR support [32]. It was then developed by Katya Casper and John Phillips for the measurements on the nozzle wall. It is later to be used in the circular cone; the hardware for this is complete, but the actual experiment remains to be performed. It is not clear how difficult it will be to generate waves at the much higher frequencies that are unstable on the Mach-6 cone. It is unlikely that this perturber will be used in Tunnel 9, due to the difficulty of adapting this complex instrument to a large T&E facility with limited access and high occupancy costs.

4.7.2 Collaboration with NASA Langley

Following the completion of the cone, and the successful measurements at Purdue and Sandia, NASA Langley personnel became interested in the proposed measurements of second-mode waves on the cone. In the Fall of 2009, they offered to collaborate in making such measurements in their 31-inch Mach-10 tunnel and 15-inch Mach-6 tunnels. Since the measurements in Tunnel 9 were delayed due to the control-room reconstruction, this was an excellent opportunity. Katya Casper accompanied the cone to Langley and worked with Langley to make the measurements, reported in Ref. [13]. Langley provided tunnel time, some instrumentation, and NASA personnel. The grant funded some travel and shipping costs. Sandia paid to ship and insure the cone.

These experiments were also very successful, almost immediately. Good signal-to-noise ratio was observed. Surprisingly, there were few problems with electrical noise. Second-mode waves were observed at Mach 6 and 10. Large waves with amplitudes of 20-30% were observed at Mach 10, and smaller waves with amplitudes of up to 14% at Mach 6. This increase in maximum amplitude with Mach number was consistent with earlier work. Wave breakdown was observed in the Langley tunnels, as shown by saturation and a decrease in wave amplitudes.

NASA Langley continues to work these issues from the experimental side, performing measurements of tunnel noise and uniformity that have not yet been reported. Second-mode waves have also been measured in the 20-inch Mach-6 tunnel. In addition, Langley has begun efforts towards providing Direct Numerical Simulations of the noise radiated from the turbulent boundary layer on the nozzle wall (private communication, Meelan Choudhari). It seems likely that these simulations will become available in the next few years.

4.7.3 Collaboration with AEDC Tunnel 9

The cone was tested in AEDC Tunnel 9 as a piggyback, following the successful tests at Langley. The Tunnel-9 results are also reported in Ref. [13]. The Tunnel 9 data was obtained at more widely spaced Reynolds numbers, due to the higher costs of Tunnel 9 experiments. At similiar conditions at Mach 10, the waves were somewhat larger in the Langley tunnel, suggesting that the smaller Langley nozzle yields somewhat higher noise levels, as suggested by the Pate correlation.

Although details cannot be reported here, the ideas and methods developed in part under the present grant have already proven useful at Tunnel 9, for a flight program [33]. Tunnel 9 has been measuring their freestream noise with increasing care; they recently obtained the first measurements of freestream noise with significant signal-to-noise ratio at the second-mode frequencies [15].

4.7.4 Other Collaborations

Similar measurements are being attempted in several other international wind tunnels. These include the HEG free-piston high-enthalpy tunnel in Germany, the HIEST free-piston high-enthalpy tunnel in Japan [21, 22], the conventional Ludwieg tube in Braunschweig [34], the Mach-6 blowdown tunnel at the Von Karman Institute (H3), the LENS facilities at CUBRC in Buffalo, New York, and so on. It seems that an informal international cooperation along the lines of the Fisher-Dougherty work is being assembled [35, 36].

4.7.5 Measurements on the Flared Cone in the Mach-6 Quiet Tunnel at Purdue

It has become increasingly obvious that there are probably no measurements of second-mode transition under fully quiet flow, due to the limited Reynolds numbers in the Mach-6 quiet tunnels [10]. It is also becoming obvious that it would be very useful to watch the waves grow and break down to turbulence, to study the nonlinear breakdown, and to improve or develop correlations for it. There are two obvious ways to increase the wave amplitude in order to develop large waves at the low Reynolds numbers and low noise levels available under quiet flow: 1) generate the waves with a glow perturber, and 2) increase the wave amplitude by flaring the cone. Berridge made some initial attempts at using Method (1) on the 7-deg. cone, but was not able to run the glow perturber at sufficiently high frequencies with the electronics at hand. Method (2) was then applied using the STABL code to find a flare geometry with an attached boundary layer and the largest N factor, given the limited model sizes that can run in the tunnel [37]. Although this first design was far from optimal, it was still very useful. The adverse pressure gradient on the flare acts to (a) increase the local growth rate of the waves, and (b) maintain a nearly-constant boundary-layer thickness on the flare, so that the same wave frequency remains highly amplified over a long fetch, leading to large waves. The simulations indicate that (b) is much more important than (a). Under conditions when the computed N factor was about 13, the second-mode waves were now easily measured with the pressure sensors, even under quiet flow conditions, so they were obviously much larger. The waves reached an amplitude of about 5% of the mean, but to the surprise of many, the boundary layer remained laminar. However, the wave amplitude seemed to decrease with streamwise distance, which may have been due to problems with the reliability and calibration of the sensors.

A new nosetip was then built for the cone, with a smaller nose radius, in order to achieve a larger N factor [38]. Although the new tip was very slender and fragile, it was successfully built, and laminar flow was observed to second-mode N factors of about 15-19 under quiet flow. This was very surprising. In addition, transition was observed only at $N = 9$ even under noisy flow. Under quiet flow, images obtained using temperature-sensitive paints showed streamwise hot streaks that appeared only when the waves were very large, towards the end of the cone, and only under quiet flow. They appear to be an indication of streamwise vorticity induced by early stages in the nonlinear breakdown of the instability waves.

Small roughness dots were then added on the upstream portion of the cone, in an attempt to induce the streamwise streaks in a controlled fashion, following Radetzsky and Saric [39, 40]. When the small dots were placed on top of the leading edge of the paint, the onset of transition appeared to move upstream. Thus, it appears that the nonlinear breakdown of the second-mode waves under quiet flow involves an interaction with weak streamwise vorticity. On the flared cone, this is probably affected by the Görtler instability, and it may be difficult to isolate the Görtler effects without further experiments on another geometry [41]. Transition seemed to occur at about $N = 18$, which remains surprising. The flared cone measurements are described in more detail in Ref. [42].

The flared cone already has produced some very interesting results, and continued research using this geometry seems likely to be useful for sorting out the mechanisms of nonlinear breakdown and transition for the second mode under quiet flow. However, the results to date are all preliminary, and much work remains to be done. Funding for this effort is presently being sought, along with a new graduate student who will focus on this topic for their thesis. The University of Minnesota is to design a new flared cone that is longer and more slender, in order to achieve the largest possible N factor under fully quiet flow.

5 Summary and Outlook

The original Statement of Objectives (SoO) from 2008 was very ambitious (Section 3). The first priority was to see if the second-mode waves could be measured in Test and Evaluation wind tunnels. This objective has been met very successfully, in every cold-flow blowdown tunnel in which it has been attempted. This success has led to the development of wave-based measurement and prediction approaches in several T&E facilities. Thus, objectives 4.a.i to 4.a.v have been successful at Purdue and Tunnel 9, and also at several other facilities, although not yet with well-calibrated sensors. Objectives 1 and 3b have also been carried out.

However, much work remains to be done. The primary goal is now item 3, high-quality calibrations of the PCB sensors. A small shock tube is being constructed at Purdue in order to use weak shock waves as a calibration signal. This is the key issue, for high-quality amplitude measurements are needed for the analysis proposed in SoO item 5. Pate's correlation is being computed for a variety of tunnels, but the results have not yet been reported, and are incomplete.

The questions outlined in Section 4.6 have also been addressed only in part. Experiments addressing (1) seem to show that flush-mounted sensors work better, although it still seems that it may be possible to reduce the active surface area with an ingenious acoustical design. It is now clear that the sensors can be used to measure second-mode waves in cold blowdown tunnels, addressing (2), although it is not yet clear if the waves can be measured in high-enthalpy facilities. Questions 3-6 remain open.

The outlook for continued work in this area is very good. Numerous workers are beginning to measure tunnel noise and second-mode waves under various conditions. NASA Langley is now funding about half of Dennis Berridge's work, since they have begun to employ him as a half-time engineer through their graduate-student cooperative-education program. It seems likely that further research in the general direction outlined here will begin to resolve a number of issues regarding transition induced by second-mode waves. However, the current grant has ended and budgets are tight most everywhere, so continued progress will depend on the continued availability of funding and staff, and on continued cooperation.

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