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Initial Shakedown of the Purdue Mach-6 Quiet-Flow Ludwieg Tube

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Abstract

Purdue University is developing a Mach-6 Ludwieg tube for quiet-flow operation to high Reynolds number. The aerodynamic and mechanical design were reported on earlier. The design predicts laminar flow to the exit of the 9.5-inch nozzle, at a unit Reynolds number of 3 million per foot. The detailed mechanical design, fabrication, and testing are challenging, since maintenance of a laminar boundary layer on the nozzle wall requires very tight tolerances and uniform mirror finishes. Measurements on the final mandrel for the nozzle throat are reported here. The design, fabrication, and testing of other facility systems are also described: these include the support structure, the vacuum system, the diffuser, and the double-wedge fixed second throat.

Introduction

Hypersonic Laminar-Turbulent Transition

Laminar-turbulent transition in hypersonic boundary layers is important for prediction and control of heat transfer, skin friction, and other boundary layer properties. However, the mechanisms leading to transition are still poorly understood, even in low-noise environments. Applications hindered by this lack of understanding include reusable launch vehicles such as the X-33, high-speed interceptor missiles [8], and hypersonic cruise vehicles [1].

Many transition experiments have been carried out in conventional ground-testing facilities over the past 50 years. However, these experiments are contaminated by the high levels of noise that radiate from the turbulent boundary layers normally present on the wind tunnel walls [3]. These noise levels, typically 0.5-1% of the mean, are an order of magnitude larger than those observed in flight [21, 20]. These high noise levels can cause transition to occur an order of magnitude earlier than in flight [3, 20]. In addition, the mechanisms of transition operational in small-disturbance environments can be changed or bypassed altogether in high-noise environments; these changes in the mechanisms change the parametric trends in transition [21]. For example, linear instability theory suggests that the transition Reynolds number on a 5 degree half-angle cone should be 0.7 of that on a flat plate, but noisy tunnel data showed that the cone transition Reynolds number was about twice the flat plate result. Only when quiet tunnel results were obtained was the theory verified [6]. This is critical, since design usually involves consideration of the trend in transition when a parameter is varied. Clearly, transition measurements in conventional ground-test facilities are generally not reliable predictors of flight performance. *Only the study of controlled disturbances in a controlled quiet environment can produce unambiguous data suitable for development of reliable theory.*

Development of Quiet-Flow Wind Tunnels

Only in the last two decades have low-noise supersonic wind tunnels been developed [3, 26]. This development has been difficult, since the test-section wall boundary-layers must be kept laminar in order to avoid high levels of eddy-Mach-wave acoustic radiation from the normally-present turbulent boundary layers. A Mach 3.5 tunnel was the first to be successfully developed at NASA Langley [2]. Langley then developed a Mach 6 quiet nozzle, which was used as a starting point for the new Purdue nozzle [4]. Unfortunately, this nozzle was removed from service due to a space conflict. Langley also attempted to develop a Mach 8 quiet tunnel [26]; how-

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ever, the high temperatures required to reach Mach 8 have made this a very difficult and expensive effort. Shakedown of this tunnel continues, several years after first installation, as yet without success (Steve Wilkinson, private communication, May 2000). The new Purdue Mach-6 quiet flow Ludwieg tube may be the only operational hypersonic quiet tunnel in the world.

Background of the Purdue Mach-6 Quiet-Flow Ludwieg Tube

A Mach-4 Ludwieg tube was constructed at Purdue in 1992, using a 4-inch nozzle of conventional design that was obtained surplus from NASA Langley. By early 1994, quiet-flow operation was demonstrated at the low Reynolds number of about 400,000 [17]. Since then, this facility has been used for development of instrumentation and for measurements of instability waves under quiet-flow conditions [23, 16, 15, 9, 10]. However, the low quiet Reynolds number imposes severe limitations; for example, the growth of instability waves under controlled conditions on a cone at angle of attack was only about a factor of 2 [9]. This is far smaller than the factor of $e^9 - e^{11}$ typically observed prior to transition, and small enough to make quantitative comparisons to computations very difficult.

A facility that remains quiet to higher Reynolds numbers was therefore needed. The low operating costs of the Mach-4 tunnel had to be maintained. However, hypersonic operation was needed in order to provide experiments relevant to the hypersonic transition problems described above. Reference [19] describes the overall design of the facility, and the detailed aerodynamic design of the quiet-flow nozzle, carried out using the e^N method.

Attached flow should be maintained in the contraction of the nozzle, since the separation bubbles sometimes observed in wind tunnel contractions are generally unsteady, and would transmit noise downstream into the Mach-6 nozzle. Therefore, a detailed aerodynamic design of the contraction was also carried out [18]. Reference [18] also supplies a preliminary report on the detailed mechanical design of the nozzle and contraction, which was carried out during 1997-98. This mechanical design is not trivial. The nozzle is 9.5 inches in diameter at the exit, and 8-1/2 feet long, yet the inside surface must be fabricated very accurately, with very tight specifications on contour accuracy, steps and gaps, waviness, and roughness. Any of these flaws can trip the laminar boundary layer on the wall, causing early transition and loss of quiet flow, or generate Mach waves that focus on the centerline and cause marked variations in centerline Mach number. Since there are many possible causes for early transition, careful testing of each possible disturbance source during fabrication will be an essential element in successful development.

The detailed mechanical design of the contraction and nozzle was completed by Dynamic Engineering Inc. (DEI) in late 1998, in cooperation with the author. After some initial tests of fabrication procedures, a purchase order for fabrication of these parts was awarded to DEI in January 1999. Reference [22] reported on design and testing of some of the component parts, including the driver-tube heating, the as-measured contraction contour, the throat-region mandrel fabrication and polishing experience, and so on. The first and second mandrels fabricated for throat-region electroforming had to be scrapped, for reasons detailed in this reference. Ref. [22] also reports the results of numerous measurements of the surface roughness of the mandrel and various test pieces.

Delivery of the nozzle and the remainder of the contraction is currently scheduled for December 2000. This paper will report on many critical design details not described in References [18] and [22].

Of course, the new facility requires much more than simply a nozzle and contraction. The driver tube, air supply, vacuum tank and pumps, burst diaphragm section, and diffuser have already been completed. Tests of the burst-diaphragm apparatus are underway. This paper will report on the design, fabrication, and testing of the throat mandrel, vacuum system, second-throat section, and diffuser, many of which are specially adapted to the requirements of quiet flow.

The Purdue Mach-6 Quiet-Flow Ludwieg Tube

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 in an affordable way, the Purdue facility has been designed as a Ludwieg tube [17]. 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).

Figure 2 shows the nozzle. 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 radia-

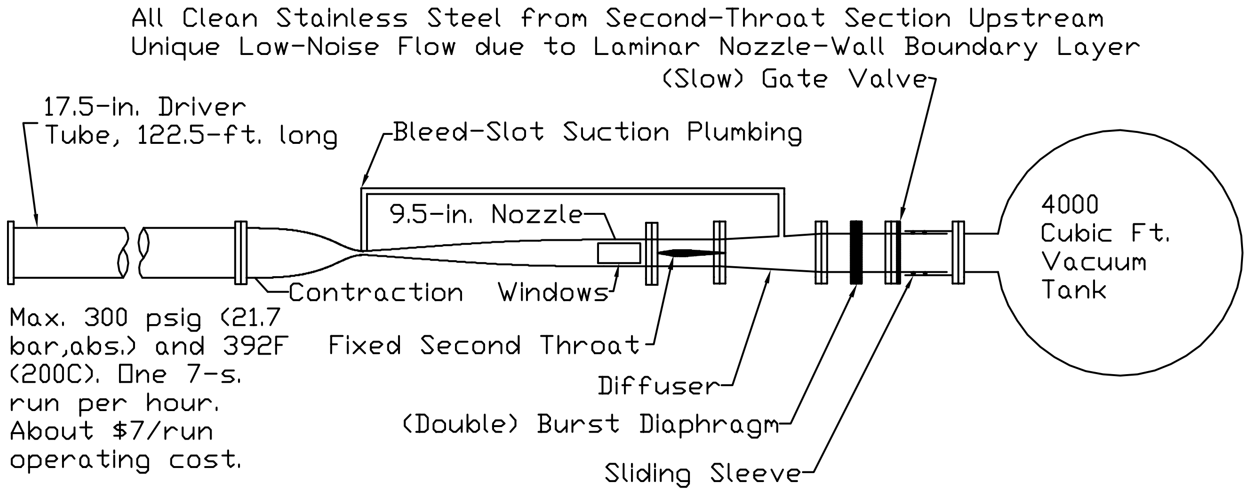

Figure 1: Schematic of Purdue Mach-6 Quiet-Flow Ludwieg Tube

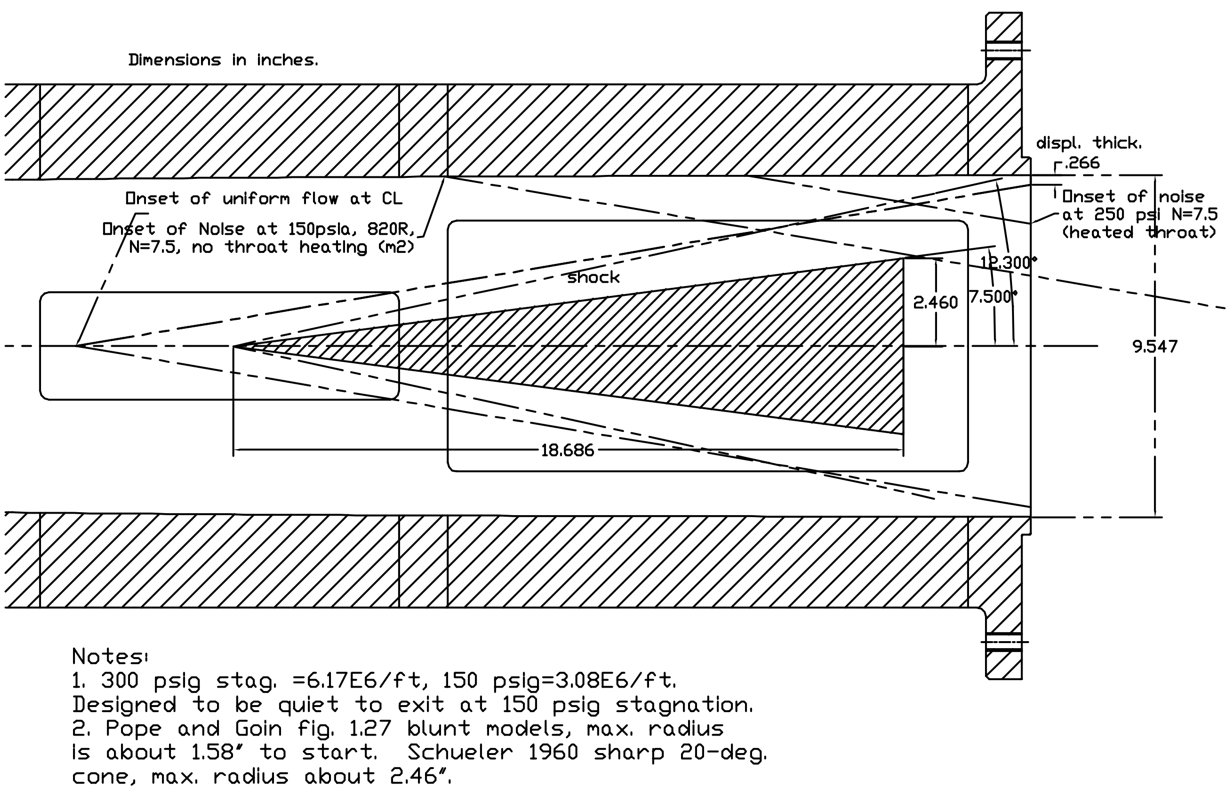

Figure 2: Schematic of Mach-6 Quiet Nozzle with Model

tion from the onset of turbulence in the nozzle-wall boundary layer. A 7.5-deg. sharp cone is also drawn on the figure. The cone is drawn at the largest size for which it is likely to start, according to Schueler [24]. A blunt model of about 3/5 of this size is predicted to start, according to Pope and Goin [14].

The usual quiet-flow length Reynolds number is based on the unit Reynolds number and the length on the centerline between the onset of uniform flow and the first arrival of noise radiated from the nozzle walls. For an axisymmetric nozzle with a nominally uniform transition location, the full quiet uniform-flow region will consist of back-to-back cones, each with a half-angle equal to the Mach angle. Unfortunately, only flat plates and very slender models can make use of the portion downstream of the nozzle exit. Since neither of these flows is of particular interest, this portion was not thought to be very useful. The present facility therefore places the nozzle sting support immediately downstream of the nozzle exit, to shorten the model sting and reduce the cost of the tunnel.

Measurements on Throat-Region Mandrel Number 3

Measurements of contour accuracy, waviness, and roughness are being obtained on the contraction, throat-section mandrel, and nozzle, during fabrication. The contraction results were reported in Ref. [22], along with results on the first two attempts at fabricating the throat-region mandrel. The results for the third (and successful) attempt are shown here; for background, see Ref. [22]. The results for the nozzle will be reported later, since they will not be obtained until fall 2000.

Schmiede Corp. ground the third mandrel attempt, from Optimax, as discussed in Ref. [22, p. 17]. A second test mandrel was first ground, from the same billet of material to be used for the third mandrel. Special efforts were made to grind the mandrel much more finely, to leave smaller grinding gouges. This test mandrel was examined under the 40 power binocular microscope. Typical grinding gouges were perhaps 0.0005 to 0.001 inches wide, and perhaps 0.040 inches long. These are roughly 1/2 to 1/5 the size of the gouges left by Schmiede in mandrel 2, using less refined processes. No pits or material flaws were evident under the microscope, in sharp contrast to mandrel 2, made from 15-5PH vacuum-arc remelt, ultrasonically tested to AAA. The Optimax was clearly better material. A few scratches were evident, besides the circumferential grinding marks – the largest was about 0.0005 inches wide.

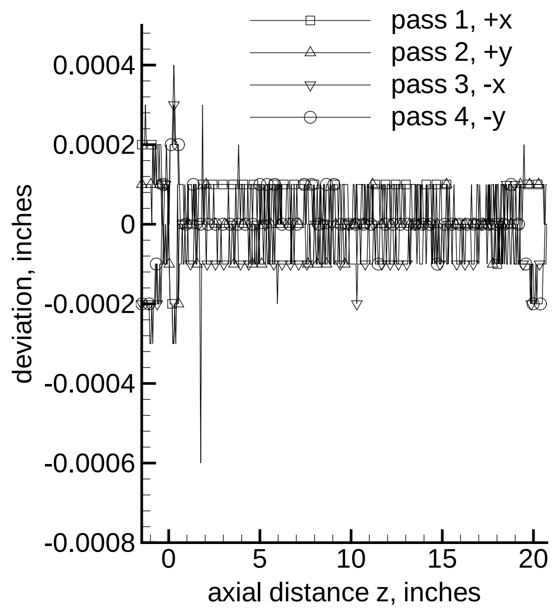

Figure 3: Deviation of Mandrel Coordinates from Design

The second test mandrel was then polished, at Optical Technologies, Franklin Park, Illinois. While grinding tears caused some difficulty, an excellent polish could be obtained, without excessive material removal. The polisher began work with a 400 grit stone, and believed he was able to remove less than 0.001 inch of material. It was very difficult to find flaws in the polished mirror finish, as most apparent flaws were merely dust specks.

The third attempt at fabricating the throat mandrel was then carried out. The mandrel was ground at Schmiede and measured at DEI. Figure 3 shows the deviation of the measured coordinates from the specification. Here, z is the axial tunnel coordinate, where $z = 0$ at the throat, as in Ref. [22]. The deviations are all well within the 0.001 inch specification, with nearly all within 0.0005 inches. Some waviness is evident near the more curved throat.

A detail of the deviations in the throat region is shown in Fig. 4. The single-point deviation near $z = 1.8$ may be erroneous, perhaps due to a dust speck. The waviness was then computed, using the methods described in Ref. [22]. The results are shown in Fig. 5. The waviness is all within the 0.001

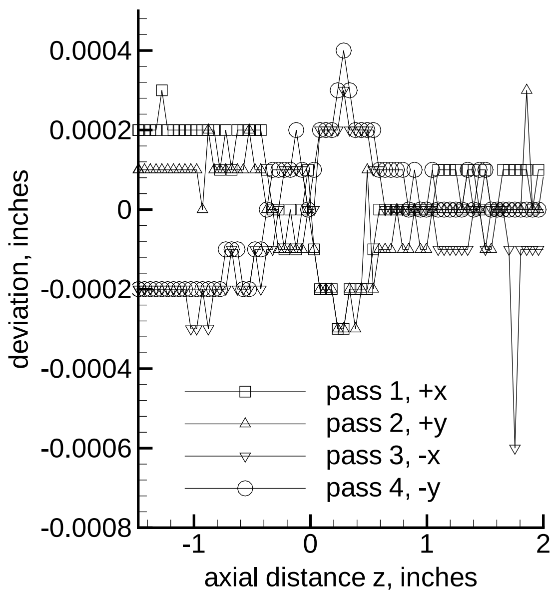

Figure 4: Mandrel Coordinate Deviations: Throat Region

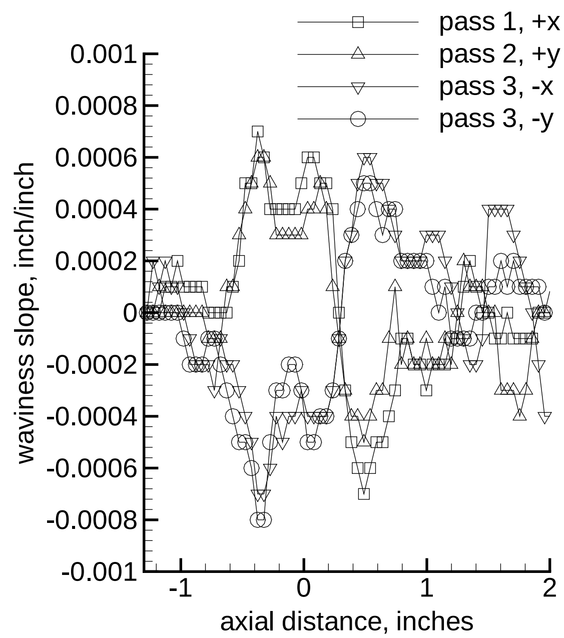

Figure 5: Waviness of Mandrel Coordinates: Throat Region

inch/inch specification.

The part was then shipped to the polisher, who was again able to begin with a 400-grit stone, and who observed no major problems with the material or with grinding tears. The polisher was again comfortable that he did not have to remove excessive amounts of material, probably less than 0.001 inches. On the whole the polished mandrel appeared to have a nearly perfect mirror finish. It almost requires a clean room to inspect the polish, for one is distracted by apparent flaws which turn out to be dust specks when the part is carefully wiped. However, the parting line remained evident to the eye, along with two small flaws. The first, located about 5 inches downstream of the throat, is perhaps 1/16 inch long. It appeared to be perhaps 0.001 inches deep, according to the polisher. The second appeared similar, but was located a few inches from the downstream end of the mandrel.

At 5 inches from the throat, using the $Re_k = 12$ roughness criterion, the allowable peak roughness would be about 0.0005 inches at nominal operating conditions. Since it would introduce waviness to remove this mark, and since it was near the nominal specification, we elected to proceed with electroforming as is. The mark at the downstream end is located where the allowable peak roughness is about 0.0025 inches, so it was not thought to be critical.

The mandrel was then shipped to DEI, inspected, and shipped to GAR Electroforming, Danbury CT. When it was removed from the box, under the observation of DEI quality assurance personnel, a third small ding was observed, again a few inches from the downstream end. Since this raised a small burr, the mandrel was returned to the polisher. The polisher believes that something like an allen wrench was dropped onto the mandrel. The ding was thought to be 0.001 to 0.002 inches deep. The polisher reworked a small area about 2 inches around this ding, thereby introducing some waviness, but reducing the risk of leaving scratches in the electroform on mandrel removal. The mandrel is now scheduled to begin electroforming in June 2000.

Support Structure

The driver tube is supported using insulated pipe supports, as described in Ref. [22, p. 20-21]. The centerline of the tube is 12 feet above ground, allowing normal building operations to be carried out underneath. The trusses of the hangar-like building are about 20 ft. above ground. All driver supports slide on teflon pads, except for a single axial anchor. This is welded to a heavy diagonally-braced

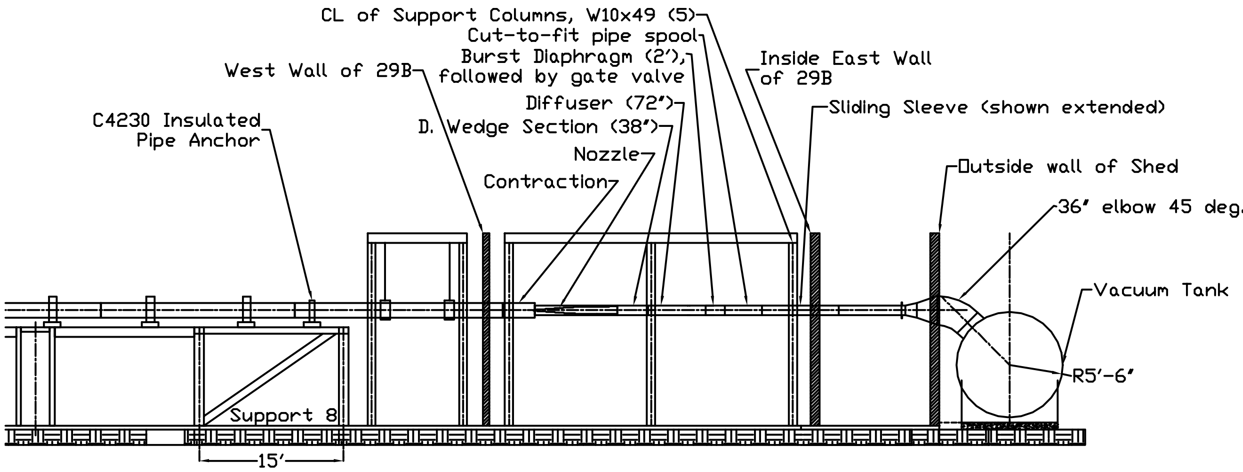

Figure 6: Schematic of Downstream End of Tunnel with Supports

frame, as shown in Fig. 6. The design calls for less than 0.01 inch of lateral deflection under a 10,000 pound axial load. This is to minimize axial model deflection in operation, to ease alignment of optics that are vibration isolated using pneumatic cylinders bolted to the floor. The actual expected axial load is in the neighborhood of 300 pounds; the support was designed for a nozzle three times larger, with safety factors. The last section of pipe is supported differently, by suspension from overhead, since a corridor passes underneath. The structure is in general overdesigned, to allow future flexibility; the additional cost of the extra material is small compared to the labor cost, which changes little.

The 'sliding sleeve' is an adjustable length section, as described below. To change models, the bolts between the nozzle and double-wedge section are removed, and the sleeve is shortened, retracting the model from the nozzle. To change burst diaphragms, a similar process is carried out, but the alignment of the two burst-diaphragm sections is not nearly as critical. The first and second parts of the contraction can also be separated in this way, allowing access to the driver tube and the nozzle throat, for cleaning.

The test area is located in a separate room. Since the various nozzle and contraction sections must be precisely aligned, and must separate and realign during model changes, diaphragm changes, and cleaning, accurate positioning of these sections is critical. Figure 7 shows a schematic of the support arrangement (drawn in a direction perpendicular to the view of Fig. 6). The arrangement is an upgrade to that used successfully on the Mach-4 tunnel. The tunnel sections are supported from above on standard I-beam trolleys that run on two large beams, each set at 30-deg. from vertical. The beams are rated to deflect 0.08 inches under a 20,000 pound load at mid-span. The small deflections allow laser-alignment of sections that are not yet positioned in the correct streamwise location. Standard jaw-end turnbuckles are used for rough positioning of a support bar. However, these do not allow independent control of vertical motion, transverse motion, and rotation. Support bars were therefore fabricated, as shown in the schematic, to ease positioning, by allowing precise control of these three quantities. The structure was completed in summer 1997.

A steel working platform was installed in the test area, about 8 feet off the ground, in Fall 1997. The metal floor sections of the platform span the full 9-foot width between the support beams. They can be lifted out, to allow easy insertion of tunnel components using a 1-ton bridge crane.

Vacuum System

Vacuum is supplied by a 30,000 gallon (4000 cubic foot) propane tank that was obtained surplus from the Radford Army Ammunition Plant in Virginia, in Feb. 1996. Fortunately, it was possible to position the tank outside the building, immediately adjacent to the facility test area. Footings were installed, and the tank was set in place in Oct. 1997. In Feb. 1998, a 36-inch nipple was installed for a vacuum line, and the tank was rerated for 160 psi and full vacuum. An elbow and a reducer (to 12-inch diam.) were installed at the same time. These latter are approved for vacuum only, although made of standard weight carbon steel pipe fittings. The 36-inch

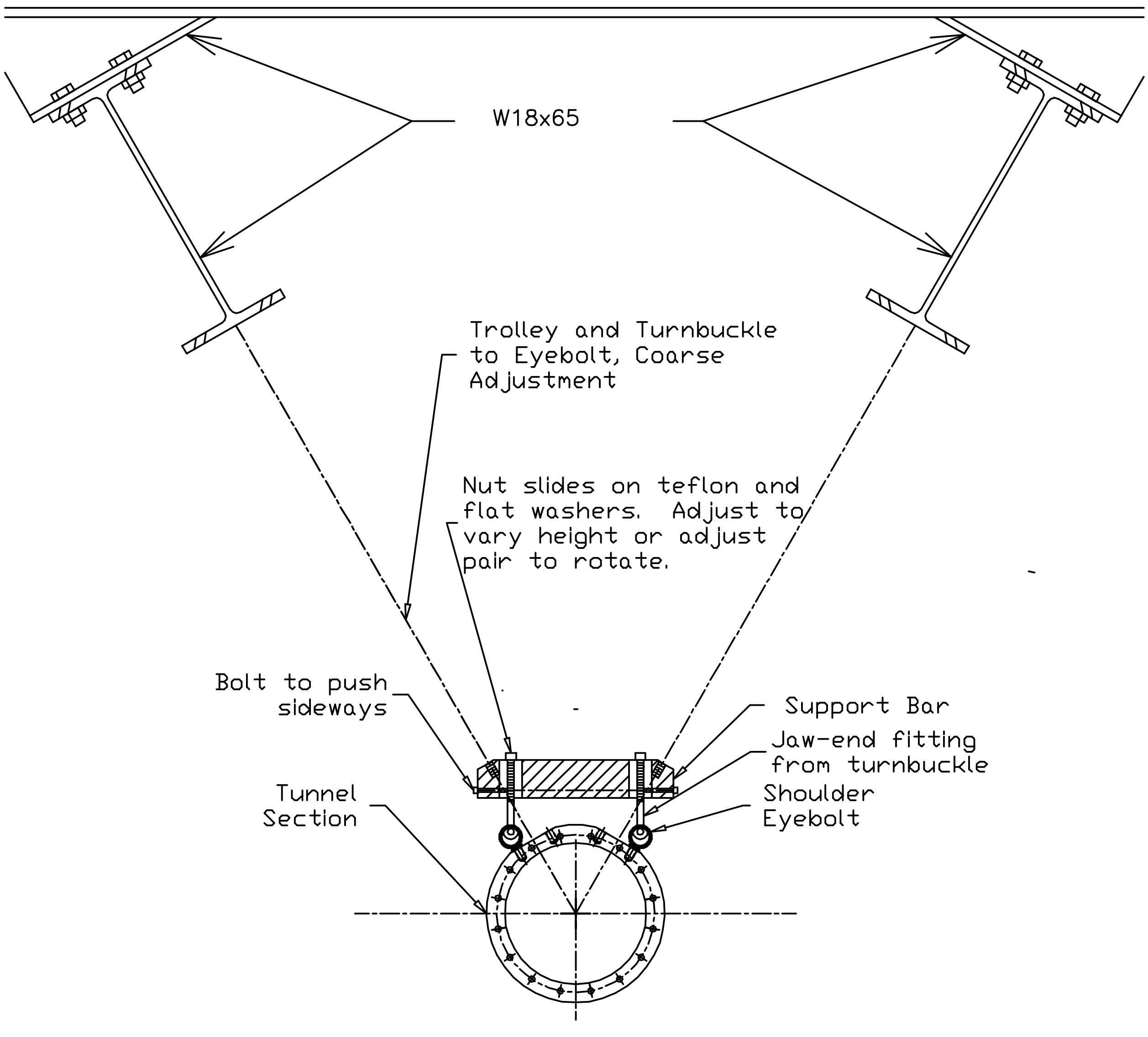

Figure 7: Schematic of Typical Test-Area Support

nipple allows later installation of vacuum lines for a proposed larger tunnel. A 12-inch nipple was also installed, for connection to the vacuum pump. The tank was sandblasted and epoxy painted in fall 1999.

The 12-inch tunnel vacuum line extends only about 15 feet from the reducer to the burst diaphragm section, reducing losses. Computations based on the usual turbulent pipe flow analyses indicate that these losses make up less than 1% of the recovered pressure in the vacuum tank. An adjustable-length section with a stroke of 40 inches was fabricated using thick-walled pipe with external o-rings that inserts into cylinder tubing. It is adjusted with hydraulic cylinders and a hand pump. This allows opening and closing various tunnel sections; its closed length is included in the 15 feet. A hydraulic relief valve is fitted, to allow the section to compress as the nozzle, contraction, and the downstream end of the driver tube heat up.

A Leybold SV630 mechanical vacuum pump was installed in spring 1998. It is rated for 444 CFM at 25HP, to an ultimate vacuum of 0.06 torr, with gas ballast closed. The pump brings the tank from atmospheric to 1-2 torr in 60 minutes; rated speed is 64 minutes to 1 torr. Initial operation in fall 1998 and summer 1999 revealed a problem with rusty dust getting into the pump oil. This was not expected, because no such problem was encountered with the Mach-4 facility. The difference must be the much higher rust level in the interior of the 26-year-old surplus tank that was used for the new facility. A vacuum inlet filter was installed in fall 1999, after which the pump has operated normally with no maintenance problems. A total of 400 hours of operating experience have been accumulated so far.

About 50-100 of these pumps are sold yearly, for industrial vacuum applications. The manufacturer estimates that the exhaust oil-vapor filters must be changed once a year in continuous operation, at a cost of about \$0.05/hour. Overhauls are required about every 5 years, in continuous operation, at a cost of about \$0.05/hour. Allowing for inefficiencies in our operation and maintenance, an operating cost of about \$1/shot seems conservative. Power costs can be estimated at roughly \$2/hour, but electrical power at Purdue is currently not metered, as it is considered an overhead expense.

Although the vacuum tank required for the large short-duration tunnel is not inexpensive to install, the low operational duty cycle allows low operating costs to be achieved.

The burst diaphragm and associated vacuum valve will be discussed in a future paper. The diffuser and second-throat section is described below.

Diffuser

An efficient diffuser is critical to long-duration operation of the Ludwieg tube, as the driver-tube stagnation pressure drops, before the tunnel goes subsonic. Such a diffuser would also allow operation at low Reynolds numbers. Supersonic diffuser design is reviewed in Refs. [25, Sect. 5.11], [14, Sect. 2.24], and [5]. The classic review by Lukasiewicz [11] makes clear that a long straight section is needed for supersonic recovery, followed by a slow subsonic small-angle diffuser. In the subsonic region, Pope recommends keeping the angle between opposing walls below 6.0 deg [14]; which is slightly more conservative than Lukasiewicz. Fortunately, the test area building layout, planned for a 24-inch diam. tunnel, left plenty of room for a long diffuser.

Merkli et al [12, 13] achieve 58-77% of normal-shock pressure recovery at Mach 3, using a constant-area duct about 5 diameters long. Hanus et al. [7] achieved nearly 90% of normal-shock pressure recovery, for straight ducts about 7 diameters long, at $Re_D \simeq 3 \times 10^5$, where D is the nozzle diameter. Their exit Mach number was 7.8. For the Purdue facility at 200 psig total pressure, $Re_D \simeq 3 \times 10^6$, so the high end of Hanus et al. is the low end of Purdue operation. Model blockage reduced efficiency from roughly 90% to roughly 65-80%. This agrees with experience in the Purdue Mach-4 Ludwieg tube, where runtime is observed to decrease with increasing model blockage.

Since Merkli [12] shows that efficiency decreases only slowly when diffuser length increases above optimum, while it decreases rapidly below optimum, a long diffuser was selected. This was also in part due to available space, and the small overall cost of a longer pipe. The principal diffuser section is shown in Fig. 8. The diffuser is about 72 inches long, and was made by welding and machining pipe sections with various diameters and thicknesses. The initial straight section is about 43 inches long and 9.56 inches in diameter. It is followed by a conical section that tapers to a 12-inch diameter with a total included angle of about 4.9 degrees. While the straight section is only about 4.5 diameters, the double-wedge section located upstream will add about 38 inches or 4 diameters of nearly-straight converging-diverging second throat.

The diffuser has an unusual feature – the two 2-inch pipes that enter into the subsonic tapered region at a 10-deg. angle. These lead the suction

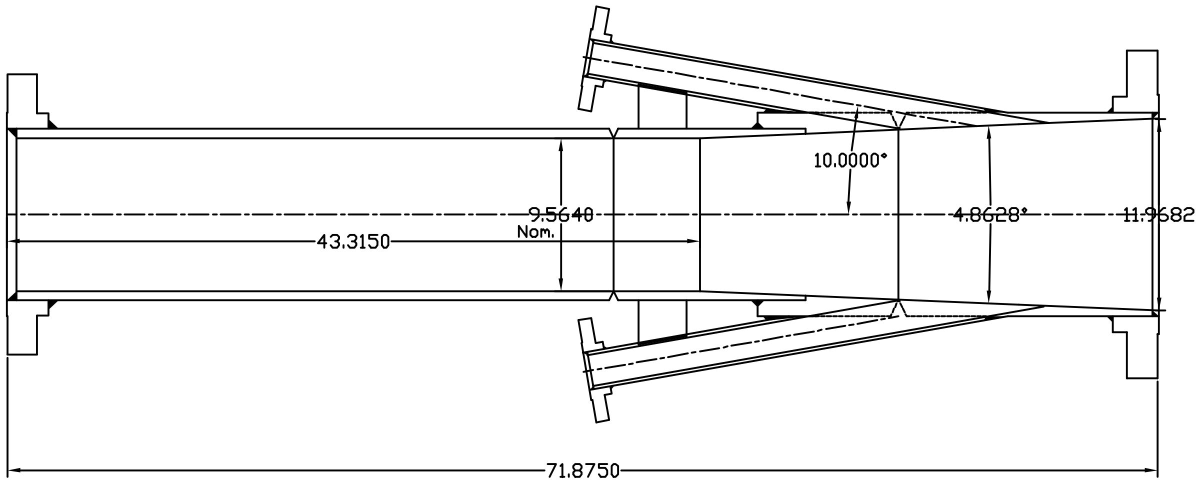

Figure 8: Principal Diffuser, 1/12 Scale. Dimensions in Inches

air from the throat-region bleed slots into the vacuum region (Fig. 1). The entire section upstream of the burst diaphragm is pressurized, before the run starts. When the burst diaphragm breaks, expansion waves travel upstream through the main nozzle, and also through the 2-inch bleed lines. Due to the longer hosing required, vacuum conditions should begin in the bleed-slot region slightly after flow is established in the throat. This simple passive timing of the slot suction is a critical feature of the present design. If suction is established too early, noise may propagate upstream into the driver tube; if too late, a significant part of the run may be lost due to noise from flow spilling over the nozzle bleed lips. A fast high-temperature pressure transducer is inserted in the contraction side of the bleed-slot suction region, to allow measuring this timing.

Given that these suction lines had to enter the main flowpath somewhere between the second throat and the burst diaphragm section, the diffuser was the obvious choice for a location. The subsonic region, where the area is increasing anyway, could be modified by adding in the suction flow. A critical design influence was an observation from the Mach-4 quiet Ludwieg tube: when a burst diaphragm was incompletely broken, supersonic flow could be established in the nozzle, but high levels of noise were sometimes observed. This is believed to be due to upstream propagation of high downstream noise levels, through the subsonic part of the wall boundary layer, to induce early tripping of the laminar nozzle-wall boundary layer. Very high downstream disturbance levels can thus influence the extent of upstream quiet flow. The flow from the suction lines could not be introduced at a 90-deg. angle to the main flow, as would be easiest to fabricate, for a high risk of excessive noise levels would be present from these transverse jets.

It was thus desirable to fit the 2-inch lines at a minimum angle to the main flow. The 10-deg. angle achieved was a balance between desired small angles, and the difficulty of fabricating and welding the pipes at excessively small angles. The diffuser is an ASME code-stamped pressure vessel rated for full tunnel pressure, so pressure-vessel code issues also entered the tradeoff. The diffuser is welded and machined from standard pipe sections, to reduce cost. Achieving the end result at low cost required a complex interaction between tunnel and pressure vessel designers, working with both pressure-vessel welders and precision machinists.

Second-Throat Section

A second throat is needed for efficient tunnel operation. An fixed double-wedge insert is used in a straight pipe section, as on the Mach-4 tunnel. This also serves to support the model stings. To reduce cost, the section was again designed and built from standard pipe sections. This involved another complex set of welding and machining operations, and close cooperation with a local ASME pressure-vessel fabricator.

A schematic of the double wedge is shown in Fig. 9. Pope and Goin [14, p. 32] give a maximum second-throat area for a Mach-6 facility as about 63% of the test section area. The core diameter of the test section is about 9.0 in., since the laminar boundary layer displacement thicknesses are computed to be about 0.25 in. The maximum blockage

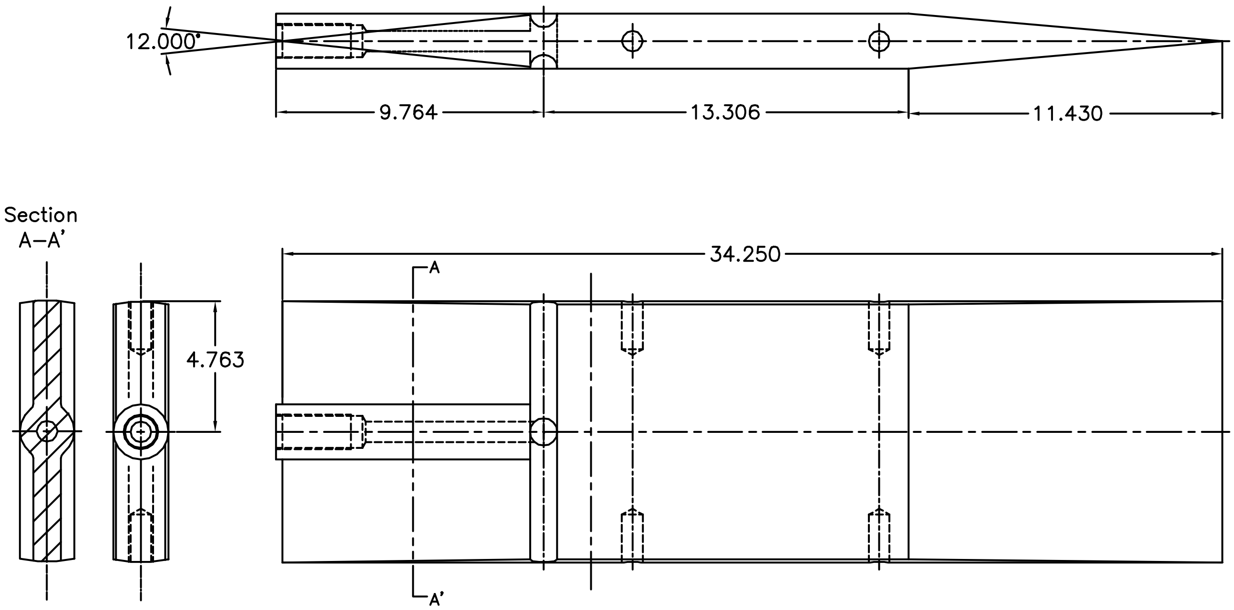

Figure 9: Double Wedge, 1/7 Scale. Dimensions in Inches

area of the second throat itself is then about 23.5 inches. The blockage area of the 2-inch thick double wedge is about 18 sq. in., leaving a margin of about 20%, similar to what was used on the Mach-4 facility. A cone with a base radius as large as 2.4 inches will still have blockage less than the second throat. For very large models, increases in the second-throat area may be desirable, and may be obtained by bolting plates to the side of the double wedge.

The included angle of the trailing edge is 10 deg. For the passages on each side, this leaves included angles less than the 6.0 deg. specified by Pope and Goin [14, p. 127]. The leading-edge included angle of 12 deg. was selected based on part on Lukasiewicz's survey [11, p. 624], which indicated that half-angles of less than 10 deg. were desirable. The constant-area length of 13.3 in. is about 1.5 diameters. Although this is much less than the 5-7 diameters suggested in the references above, the present design includes the slowly tapered second-throat and the long straight section in the initial part of the diffuser, neither of which is present in the studies of Ref. [12] and [7]. The overall design was thus thought to be conservatively long, with good likelihood of excellent pressure recovery.

The double wedge is fitted into a straight section that was welded and machined from thick-wall stainless steel pipe. A custom flange is fitted to the front face, to mate accurately with the end of the nozzle. Six-inch side ports are provided at the base of the sting mount, for access to the model instrumentation wiring. This wiring passes from the sting along grooves in the double-wedge, and out of holes bored in the pipe. The access ports are sealed with close-fitting plugs that were machined to match the internal contour of the pipe.

For a round cone near zero angle of attack, alignment with the flow is critical. An error of 0.1 deg. for a 5-deg. half-angle cone is a large error, for stability experiments. It was thus critical to accurately align the sting with the nozzle centerline. While the nozzle is precision machined, the mating flange surface on the double-wedge section must also be accurately parallel to the attachment boss for the 2-inch dia. sting. To ensure this, the assembly was shimmed precisely into position in a horizontal milling machine, so that the mating flange indicated +0.0000 on the top and bottom, and +0.0004 and -0.0004 on the left and right sides. These measurements show that the flange cupped slightly due to stress-relieving, from machining operations carried out after the flange was faced. The mating boss was then cut true with a facing head. Since the mating flange diameter is 10 inches, this suggests that the sting can be mounted true to within 0.0004/5 inches, or 0.0001 inch/inch, or 0.006 deg. The 1.25-12 threads on the sting are cut slightly looser than normal, to allow shimming the sting about 0.06 deg. in any direction. It thus appears than an unshimmed sting will be within about 0.01 deg. of true zero angle of attack, and that small 0.004 in. shims can be used to zero out any residual angles of attack which may be measured on the model. The sting is very thick, to reduce model deflections under load.

Burst-Diaphragm and Probe-Traversing Apparatus

The pressure-vessel section has been completed, and the two generations of apparatus for holding the diaphragms have been completed. Tests of the burst diaphragms continue as part of Shann Rufer's M.S. thesis, and are to be reported in Jan. 2001. The probe traversing mechanism is presently being designed and is also to be reported in Jan. 2001.

Summary

A high-quality mandrel for electroforming the nozzle throat has been produced, on the third attempt. Electroforming will begin in June. Testing of the other facility components continues. Here, the design and testing of the support structure, vacuum system, diffuser, and second-throat section are described.

Nozzle fabrication currently scheduled for completion in Dec. 2000. Tests of the burst diaphragm and driver-tube heating apparatus continue, along with hot-wire calibrations. These are to be reported in Jan. 2001, along with the measurements on the as-built nozzle contour.

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