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Development of a Supersonic Aerodynamic Test Section Using Computational Modeling

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The design of a supersonic aerodynamic test section was implemented using computational modeling. Initial two-dimensional computational flow simulations revealed critical design issues such as starting the test section and model placement. These issues were resolved to provide a test section capable of operating throughout the Mach number range of the tunnel, with reduced flow blockage and substantial optical access. The final test section inlet design, tunnel starting data and optical access are shown.

I. Introduction

THE primary focus of this paper is the synergistic approach to experimental fluid dynamics (EFD) and computational fluid dynamics (CFD). There is increasing confidence in CFD for supporting wind tunnel testing in a desire to reduce cost and test time, and improve data quality and productivity.[1,2] The pressures to reduce cost and test time, and to improve data quality and productivity, are particularly evident in large, industrial facilities. However, some of these pressures also apply to small research wind tunnels where flexibility in test conditions and model configurations are of utmost importance.[3] These requirements also pose interesting challenges on their own.

Some uses of CFD has been in the design of wind tunnel nozzles,[4–6] for understanding the flow in high-enthalpy facilities[7,8] and for understanding the effects of model blockage and model mounts.[9,10] The use of CFD for simulating the flow in an entire wind tunnel, particularly at low speeds, has also been reported.[11,12] These uses can be classified as (i) designing a new facility component, usually the nozzle and the diffuser, (ii) design a test article to minimize wall interference, including understanding the effect of mounts and (iii) flow conditioning devices. CFD can thus be used to anticipate potential design flaws, and issues related to tunnel interference and tunnel starting and stopping. Note that these are not strictly efforts in code validation and verification although the data may be used for such purposes. Instead, there is an implicit assumption that computer modeling can be used to support wind tunnel and test model design, with various levels of fidelity. One can argue that computer-based design procedures provide an extra check against traditional design procedures.[13,14]

Specifically, this paper addresses the design of a test section for a supersonic blowdown wind tunnel[14,15] for boundary-layer studies. An important requirement of the new test section is extensive access for optical diagnostics. The tunnel is equipped with a two-dimensional nozzle with a continuous Mach number capability of 1.5–4.0. It can operate with total pressures of up to 1.7 MPa (250 psia) and Reynolds numbers between 60–140 million/m. A combination of CAD and CFD was used to design the new test section.

II. Test Section Design

The original configuration of the supersonic blowdown tunnel for aero-propulsion testing is shown in Figure 1.[15] This set-up allowed for semi-free jet testing of propulsion systems installed in a test cabin but did not lend itself to other types of aerodynamic testing, including boundary-layer studies. Thus, a new test section was required. For the new test section, the requirements are that the test section can be started over the entire Mach number range, that there is good flow quality over the test plate and that there is sufficient space and between the test surface and tunnel for mounting models for eventual shock/boundary-layer interaction studies. In the original aero-propulsion

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configuration, the variable Mach number capability is achieved by flexing the top and bottom nozzle walls. The play required for the nozzle liners means that there is a gap between the nozzle and the test section. Such a gap is usually not important for aero-propulsion testing but will produce severe interference for aerodynamic testing. Thus, a decision was made to forgo the variable Mach number capability. Instead, adapter plates were used for setting the nozzle to fixed Mach numbers. These adapter plates removed the gap between the nozzle and the test section to ensure a good core flow into the test section.

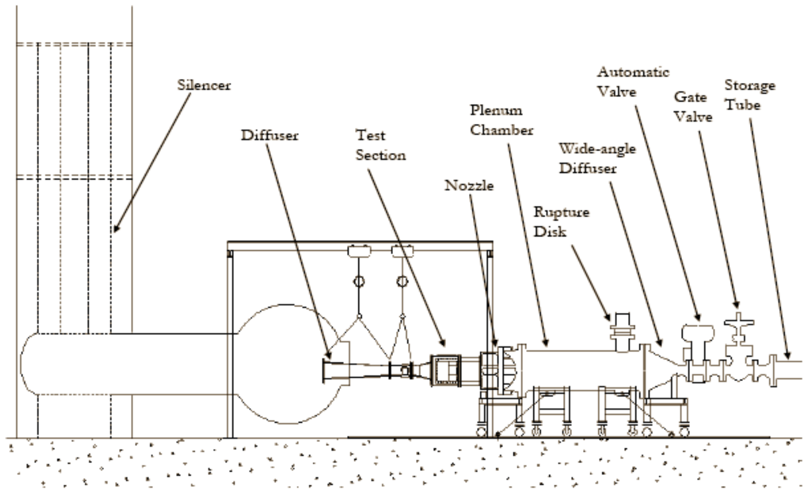


Figure 1. Schematic of supersonic wind tunnel.[15]

A. Inlet Adapter Plates

The first step in the design process was to create an inlet adapter system that would capture the flow from the nozzle into the test section with a minimum of interference or distortion at a desired Mach number, in this case, nominally 2.5. This adapter system has to be installed around the tunnel nozzle and be connected to the test section to create a continuous surface through the length of the test section. Figure 2 shows the free jet nozzle in the original aero-propulsion configuration. The horizontal arrows points to the stationary side walls that are fixed. The vertical arrows point to the top and bottom flexible nozzle liners. These flexible liners move into or away from the test section ceiling and floor when the Mach number is changed. The contours of these flexible liners are such that they are flat at the nozzle exit. However, a gap will generally be present to accommodate the aforementioned length changes.

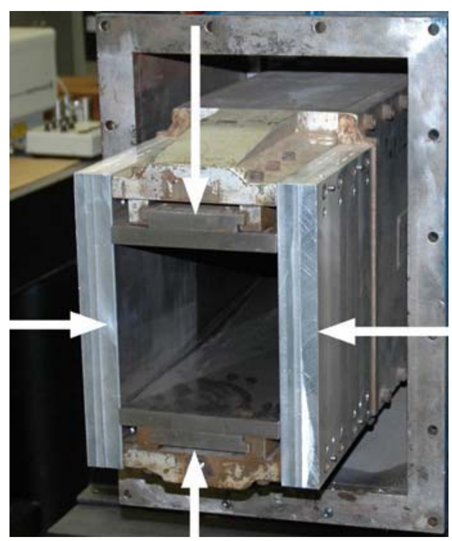
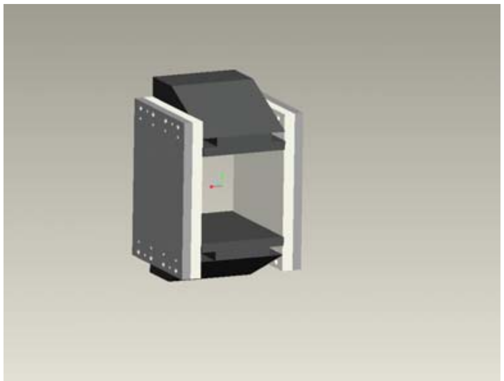


Figure 2. Photograph of nozzle exit of the supersonic blowdown tunnel.

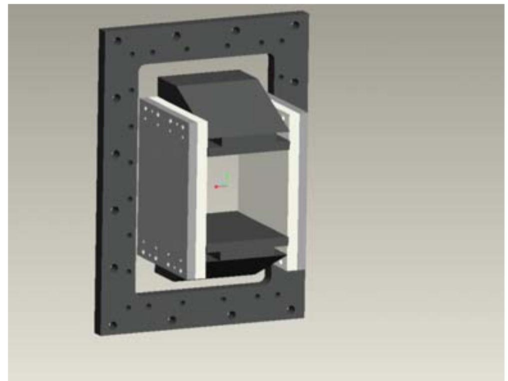
The CAD modeling sequence is shown in Fig. 3. Of note is that only minor modifications are needed for accommodating Mach number changes. For example, Fig. 3(e) shows that four plates need to replaced to change the Mach number. The final design of the inlet adapter assembly, shown in Fig. 4, included a frame made of 1.00 in. (25.4 mm) thick aluminum to surround the nozzle and support the weight of the rest of assembly. The assembly gasket plates were machined from 0.5 in. (12.7 mm) thick aluminum. Note again that this modification by necessity removes the continuous Mach number capability of the nozzle.

B. Test Section with Optical Access

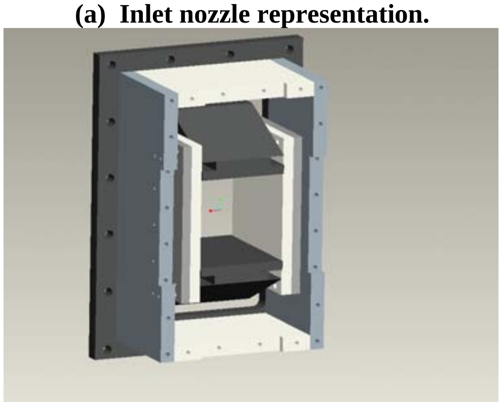
Once the inlet adapter system was designed, the next step was to design an optical test section. It is desirable to have a large amount of optical access to accommodate schlieren, PIV and PSP diagnostics. Other considerations include ensuring that the transparencies are mounted flush with the walls and ensure the integrity of the transparencies when subjected to subatmospheric pressure within the test section and to isolated loading (typically toward the rear of the test section) of as much as the total pressure. To address these requirements, a unique compound angle design was employed as shown in Fig. 5. The transparencies are held in place with a frame on the outside. The final result is extensive optical access from the sides and the top, as seen in Fig. 6.



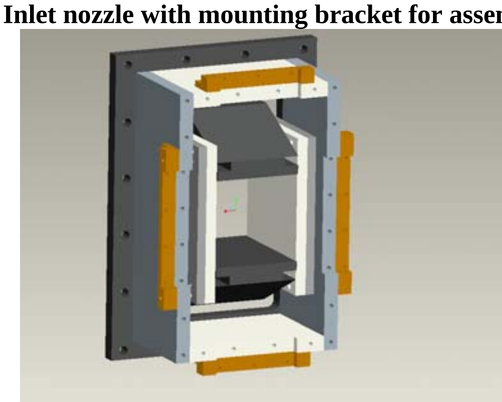
(a) Inlet nozzle representation.



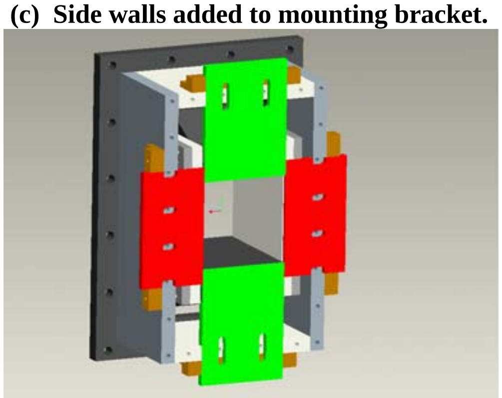
(b) Inlet nozzle with mounting bracket for assembly.



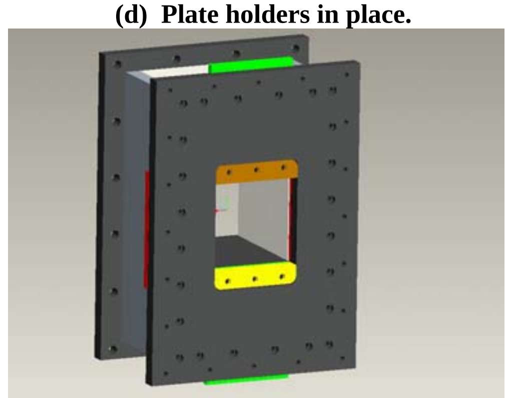
(c) Side walls added to mounting bracket.



(d) Plate holders in place.



(e) Mach number plate in place (M = 2.5).



(f) Final inlet plate with 90 deg. inlet lip blocks.

Figure 3. Building up the CAD model for the inlet adapter.

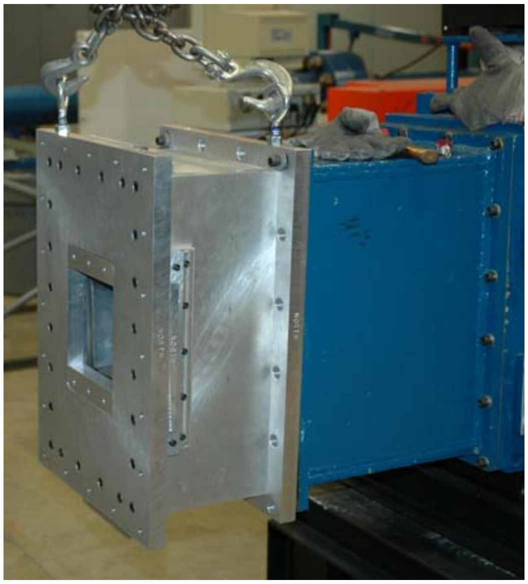
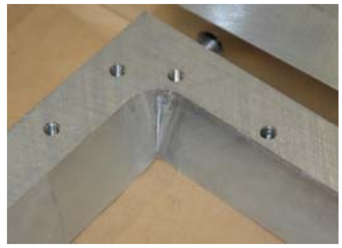


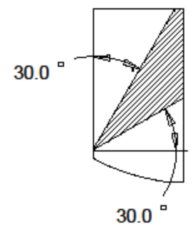
Figure 4. Photograph of inlet adapter section on the blowdown supersonic tunnel.



(a) Front view.

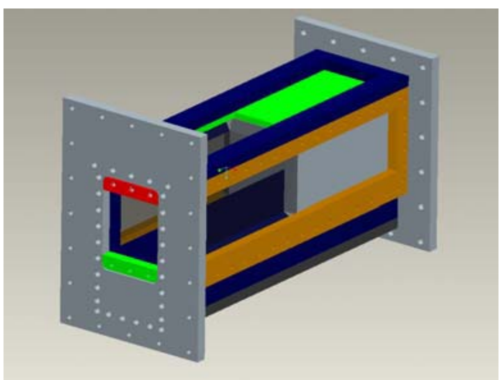
(b) Top view.

(c) Side view

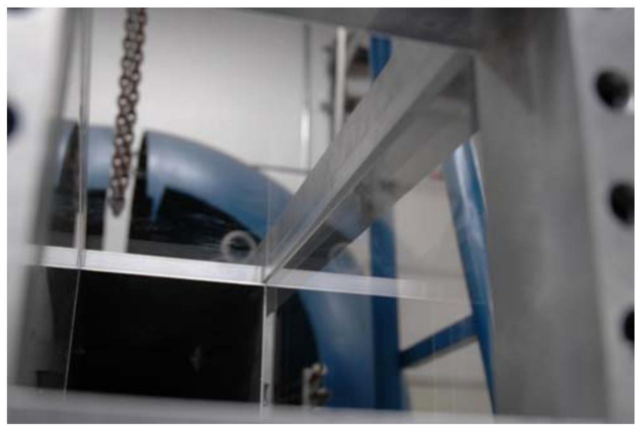


(d) Details.

Figure 5. Detailed photographs of the compound angle side walls.



(a) CAD mockup showing half transparency



(b) Photograph of the test section with its extensive optical access. View from inside looking up and toward the back.

Figure 6. The test section with extensive optical access.

C. Diffuser

Supersonic blowdown wind tunnels generally require the diffuser to recover the pressure and slow the flow to subsonic speeds. A wide angle constant area diffuser was previously utilized with the free-jet test section. A new small angle diffuser was implemented to allow for easier starting of the test section. Such a diffuser also allows a variety of models to be tested by allowing the starting shock to be passed through readily.

The diffuser is shown schematically in Fig. 7 attached to the test section. The total length of the diffuser is 120 in. (3 m) and tt consists of three sections. The mating section to the test section transitions from a 12 in. (304.8 mm) high by 6.6 in (167.6) wide section to a 10 in. (254 mm) height and a 6 in. (152 mm) width, giving contraction angles of 3.6 deg in the vertical and 1.5 deg in the horizontal.[‡] A constant area rectangular duct, 10 in. (254 mm) high, 6 in. (152 mm) wide and 72 in. (1.82 m) long comprises the subsonic diffuser. These two sections were constructed from A36 steel sheets, 0.375 in. (9.52 mm) thick. The rest of the diffuser downstream is a pre-existing, thick walled, rectangular duct.

[‡]These are all external dimensions.

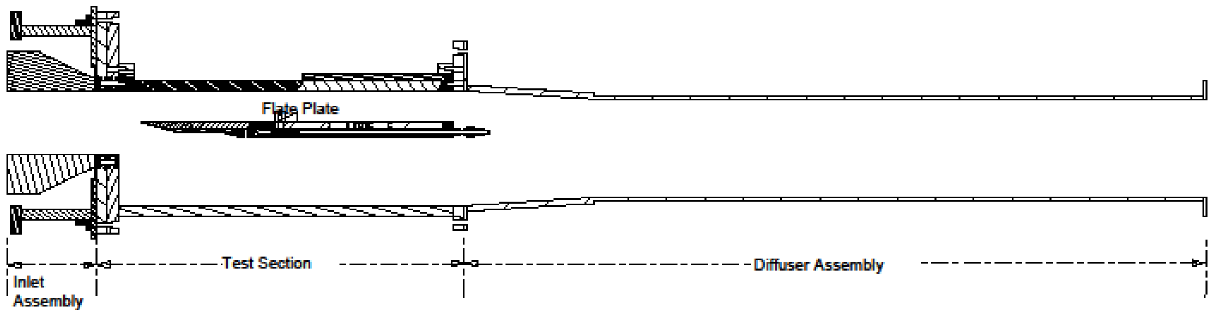


Figure 7. Full inlet, test section and diffuser assembly.

III. Computational Model

According to Ref.13, whenever a supersonic tunnel is started or stopped, a normal shock system passes through the test section and large forces are imposed on the test model. The model oscillates violently at the natural frequency of the model support system and normal force loads of five times those which the model would experience during steady flow are not uncommon. In the present situation where a large flat plate spans in the test section, the situation is different in that the flat plate should present as small a blockage in the cross section as possible to ensure that the test section will start. A flat plate 8 in. (203 mm) wide by 32 in. (813 mm) long, originally used for shock tunnel studies,[17,18] was modified for use in the supersonic tunnel. The flat plate had a thin rectangular cavity for housing instrumentation. The plate was made of stainless steel but the redesigned components were made of aluminum.

The original flat plate had a step at its rear, as shown in Fig. 8. As revealed in the two-dimensional flow modeling, this step apparently caused a large blockage which prevented the flow below the flat plate from starting. Figure 8 shows the existence of large subsonic regions toward the rear of the test section.

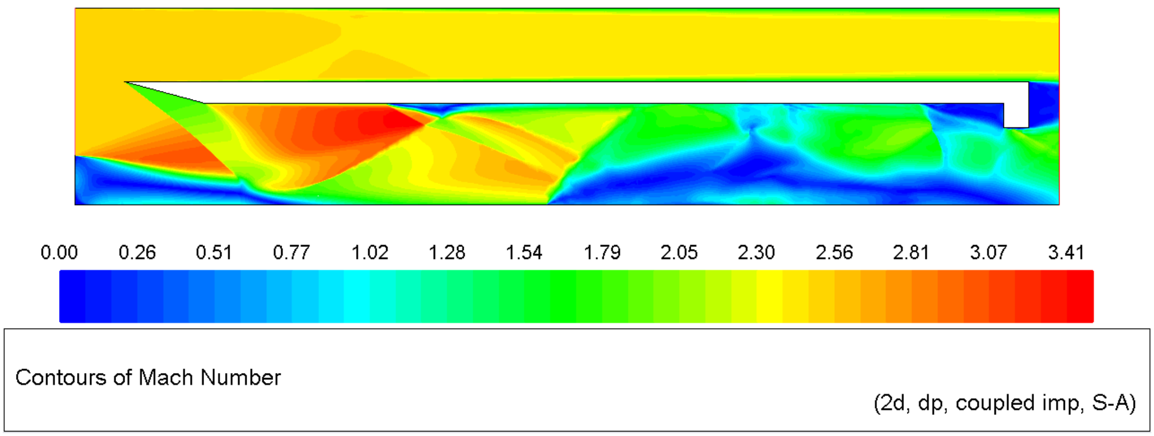
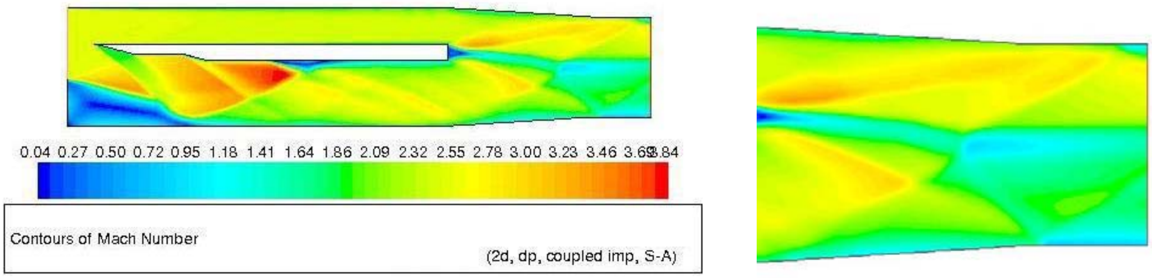


Figure 3. Mach number contours of initial flat plate design and test section dimensions ($M = 2.5$).

The purpose of this step originally was to accommodate a sting for channeling instrumentation cables out of the shock tunnel. To accomplish this, a thicker cavity was incorporated with a streamlined front, as shown in Fig. 9. To accommodate this thicker cavity, the tunnel floor was dropped down to provide additional relief for the incoming flow. As is obvious from the figure, the test section shows a well-established supersonic flow over both the top and bottom portions. The figure also shows that the position of the flat plate does not create undue performance penalties in the diffuser.

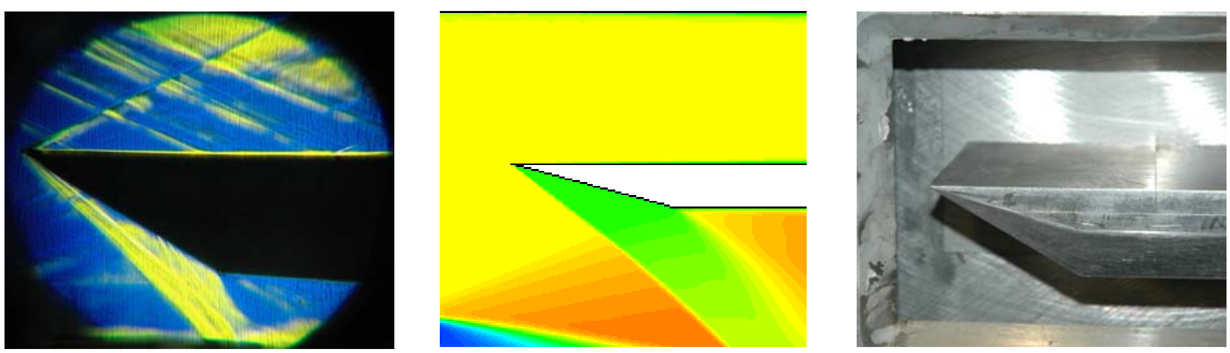


(a) Test section and diffuser. **(b) Close-up of flow into diffuser**

Figure 9. Two-dimensional simulation of Mach 2.5 flow past the new test plate.

IV. Results

The test section performed properly with the flat plate installed. Pressure data from the plenum chamber and a static port in the ceiling of the test section indicated that the test section Mach number was 2.43. In addition, a color schlieren image of the front portion of the flat plate was compared with the two-dimensional simulations in Fig. 10. The schlieren image indicates that the flow was indeed started on both the upper and lower portions of the test section. Note that the leading edge was cut at an angle of 15 deg. The larger angle seen in Fig. 12(a) is due to the sidewall rails used for mounting the flat plate..



(a) Schlieren image of front part of the flat plate showing that the test section has started (*M* = 2.43). **(b) The Mach number contours at the front part of the flat plate (*M* = 2.5).** **(c) Photograph of the front part of the flat plate. Note the unique mounting arrangement through the use of sidewall rails.**

Figure 4. Validation of the numerical modeling process.

V. Conclusions

A new test section with a large flat plate was developed through the use of CAD and CFD techniques. The CFD modeling revealed that adapting a previous flat plate would have prevented the test section from starting. A new design produced a started flow and this was confirmed in the experiment. The CAD mockups enabled the pieces to be assembled virtually to identify areas where parts did not fit well. This experience indicates that wind tunnel components can be designed and tested virtually prior to actual manufacture.

Acknowledgments

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