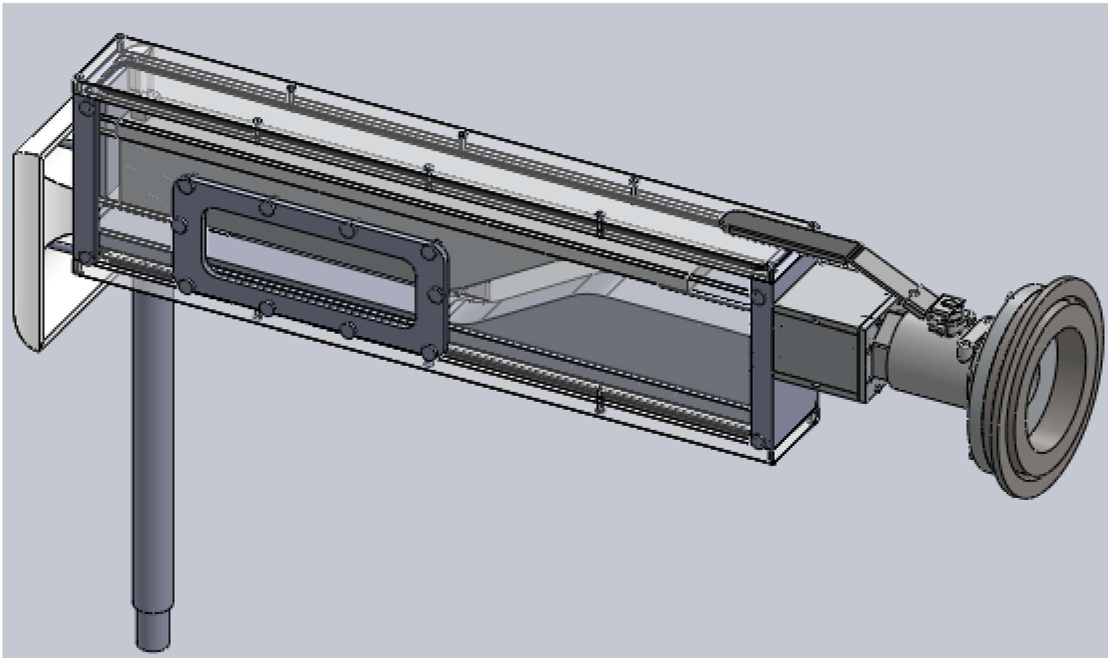
Design of a Variable Speed Vacuum Driven Transonic Wind Tunnel



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1. **Motivation**

WPI does not have a method of testing air speeds around .2<M <1.5; the high of the subsonic end can be found in the recirculating tunnel in the Fluids Laboratory and the supersonic side comes from the Supersonic Indraft Tunnel. This tunnel was designed to bridge that gap on the subsonic side from .3<M <.9. The original test to be performed in the tunnel is to be on plasma actuators to explore their viability and scaling mechanisms with increasing speeds to better match flow speeds of importance in aerospace applications including aircraft wings (0.75 < M < 1.1) aeroengines (0.6 < M < 1.0) helicopter rotor blades (0.5 < M < 1.0) and aeroengine inlets (0.6 < M < 1.2).

2. Design Constraints and Considerations

The constraints of the high-subsonic wind tunnel design are as follows:

- Test section Mach number ~.3-.9
- Runtime as great as possible, at least >5 seconds
- Must fit to existing 6" diameter flange on vacuum chamber, HL 016
- Able to be machined on campus
- Capability of allowing for various measurement techniques
- Minimize unnecessary losses and disturbances
- Maximize sealing so as to prevent whistling during operation, and maximize runtime

3. Variable Mach Number Mechanism

The tunnel is affixed to the vacuum chamber via an external flange with the downstream valve closed. The chamber is then pumped down to an extremely low pressure to create a near vacuum; the valve is then opened creating a large pressure difference between the chamber and the atmosphere. This pressure difference is enough to make the throat go sonic. This fixes the mass flow rate. As air passes through the tunnel, the pressure in the vacuum chamber rises until the pressure inside rises above the level required to choke the throat. The time this takes to occur is based on the area of the throat: a larger throat means a shorter run time and vice versa. The tunnel is swan necked so that the throat is the flat portion which sits on an angle (see diagram). This is so that changing the throat size is just an axial motion of the top piece which opens and closes the throat to increase and decrease the speed in the test section accordingly. The test section is upstream of the throat, in the subsonic portion of the flow path. Downstream of the throat, the flow is supersonic. Moving the top adjustable piece of the tunnel (see Figure 1) downstream closes the throat, decreasing the speed in the test section and increasing the runtime. Moving the adjustable top piece (see Figure 1) upstream opens the throat, increasing the test section speed and decreasing the runtime.

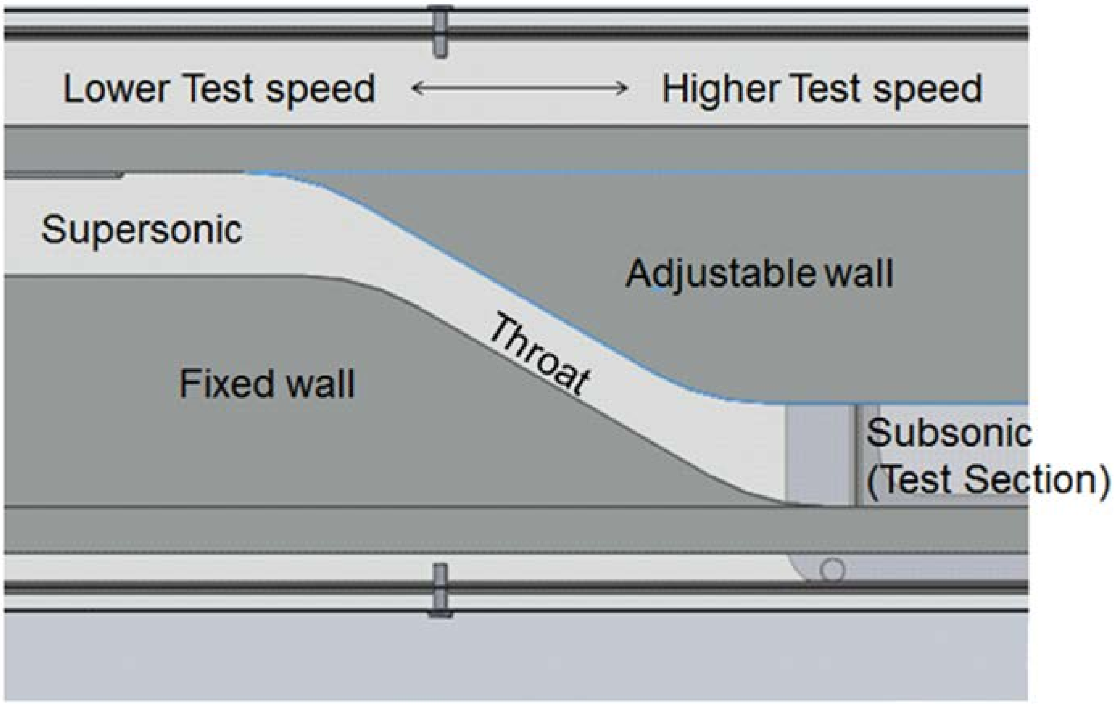

Figure 1: Diagram of the mechanism that controls the Mach number in the test section.

4. Sizing Calculations

Sizing calculations based on those from the Design of a Supersonic Wind Tunnel project paper by Peter Moore (see the paper for greater detail in original derivation); this section will focus how the calculations were implemented to determine the sizing and runtime of the tunnel (see excel spread sheet for full calculations and numbers used).

The starting point calculation is for the throat area for various runtimes (using standard symbols for compressible flow):

$$A^* = \frac{Volume_{tank} P_f}{R T_0 t P_{atm}} \frac{\left(1 - \frac{P_i}{P_f}\right)^{\frac{1}{n}}}{\sqrt{\frac{\gamma}{R T_0}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}}$$

This equation comes to a single value for selected runtimes. The Area-Mach relation is then used to find the ratio of throat area to the test section for various Mach numbers. These two sets of values along with a set width give a test section height. These values are then converted to inches and plotted against time to find the height that gives an adequate balance between height and runtime.

The final result of the calculation was a test section of 1.5” by 1.125” with a runtime varying from about six to ten seconds. The length was determined around the stock dimensions and trying to keep a sizable length for downstream measurement techniques. The test section has an absolute length of 12.3” with a window length of 7.5”.

5. Material Selection

Material selection was based on price and ease of machining while maintaining strength and the modular nature of design. Half inch acrylic was used to allow for sizable modifications and maintaining strength in the transparent parts. Aluminum was used for parts that did not need to be transparent, due to its cost, strength, weight and ease of machining. Other materials were used, including ABS plastic. The choice of material in these locations is explained below, when the component is described in detail.

6. Tunnel Assembly Components

The following sections describe the design of the main components of the tunnel. Some of the design choices are explained, but not all. Early design iterations have been excluded.

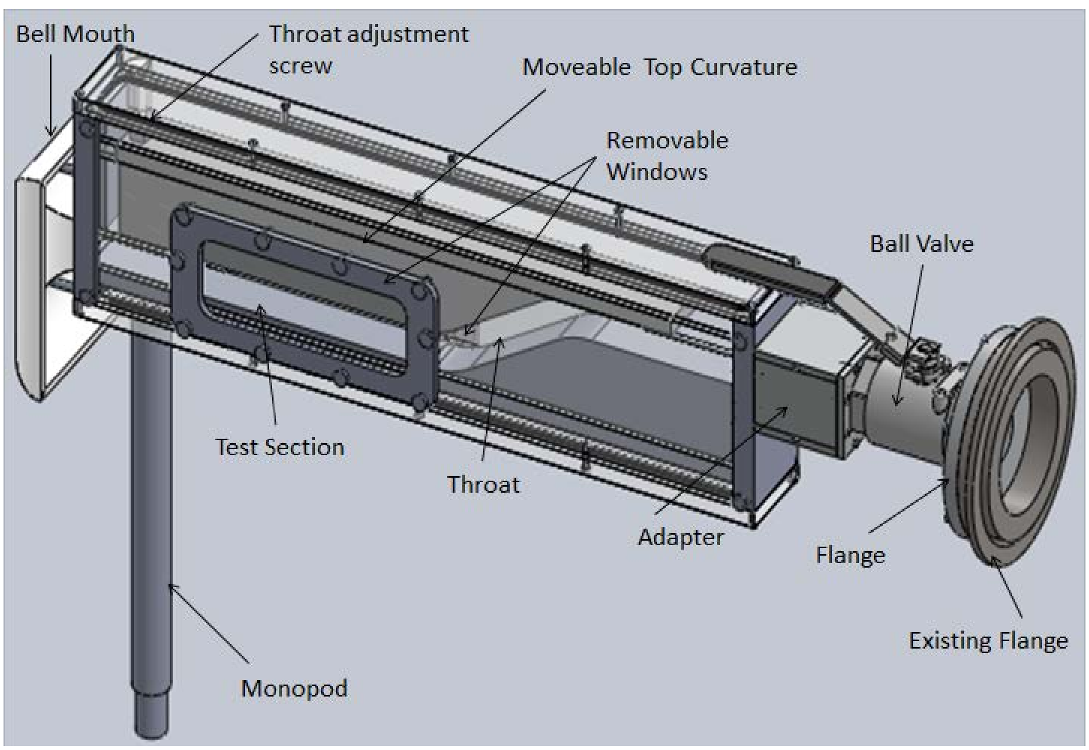

Figure 2: Diagram labeling the main components of the tunnel.

6.1 Ball Valve and Piping

The tunnel requires a valve downstream so that the vacuum chamber may be pumped down to low pressure and then the valve may be opened to let the air flow. To connect the valve to the assembly pipe must be used. A ball valve was chosen for this application due to its clean, wide aperture while being able to sustain the seal needed and simple to operate. The size of the valve was dictated by the test area calculation. The valve cannot, under any flow condition, become the throat. The size was also constrained in an attempt to limit the speed of the flow thought it (which is supersonic). Hence, the size was chosen as the smallest standard size above the aforementioned limitation. The pipe was bought to match the valve and minimize length.

6.2 Flange

This was designed to match the existing 6″ diameter opening on the vacuum chamber and seal properly to it. It was analyzed for the stress it would experience under a loading of a full atmosphere, and shown to exhibit a deflection of less than .0008" and experience a stress of less than 1100 psi., less than 8% of the yield strength of Aluminum. (see Figure 4).

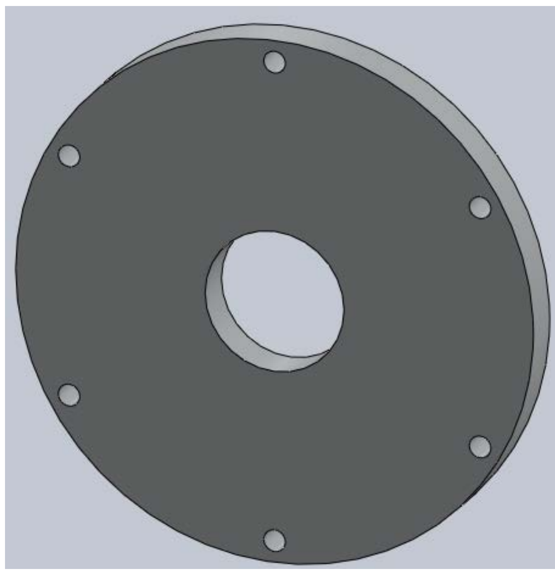

Figure 3: Picture of the CAD model of the flange.

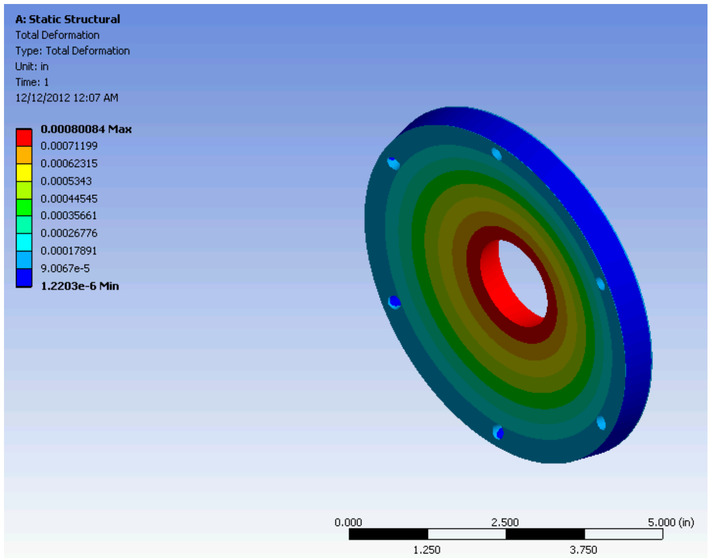

Figure 4: Stress analysis results diagram for the flange.

6.3 Throat and Test Section

The shape and sizing of the throat and test section were based on aforementioned sizing calculations (section 4). The surface curvature was designed to be simple. The rails in the side walls were introduced to aid in sealing and to provide a well seated place for the linear motion which controls the throat area and test section Mach number. A screw action was chosen to drive the linear motion of the tunnel upper wall for its simplicity and ease of calibration. Removable windows were designed to allow for laser measurements (i.e. allow for the use of optical quality glass) and more standard measurement techniques (i.e. hotwires or pressure probes, inserted using slots cut into the acrylic or metal windows) and to allow for easy access to change experiments. The seals above and below the test section were moved from original in rail design to additional covers to create better seals via a set face seal. Thin plates are used to cover the gaps that open at the end of the travel of the top wall. These plates have been analyzed for stress of a full atmosphere of pressure with a deflection of less than .005” (see Figure 6).

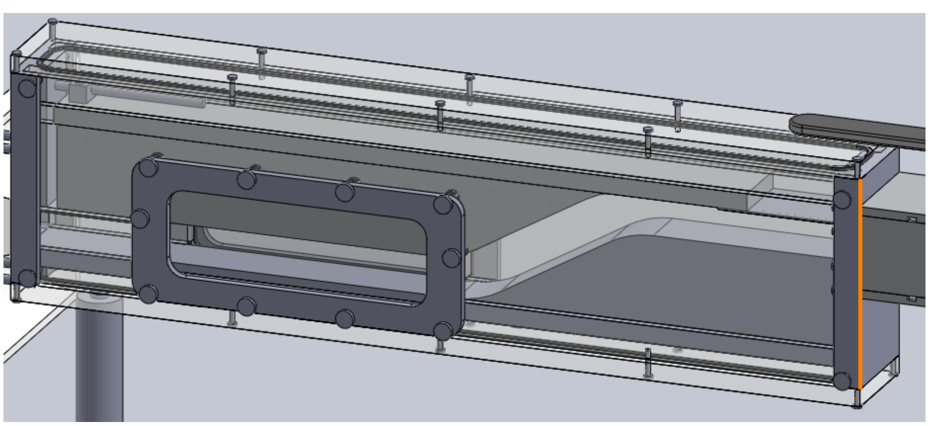

Figure 5: Picture of the CAD model depicting the test section and the main portion of the tunnel.

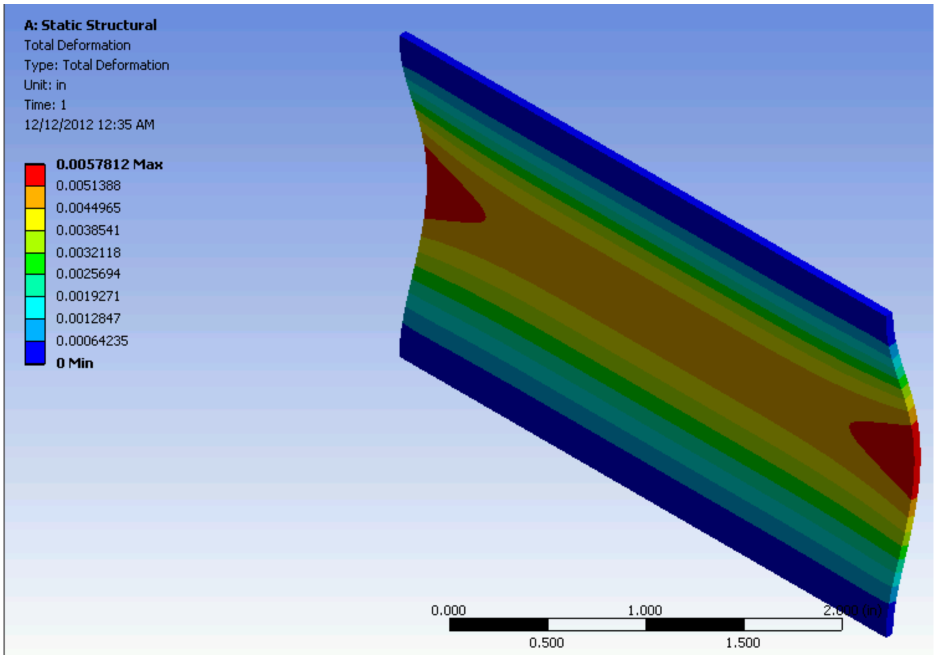

Figure 6: Stress analysis results diagram for the plate that covers the motion of the top piece.

6.4 Adapter

The adapter was incorporated into the design to smooth the transition between the rectangular test section and the circular pipe. The aluminum box is meant to provide structural support and a place for the valve pipe to be threaded into.

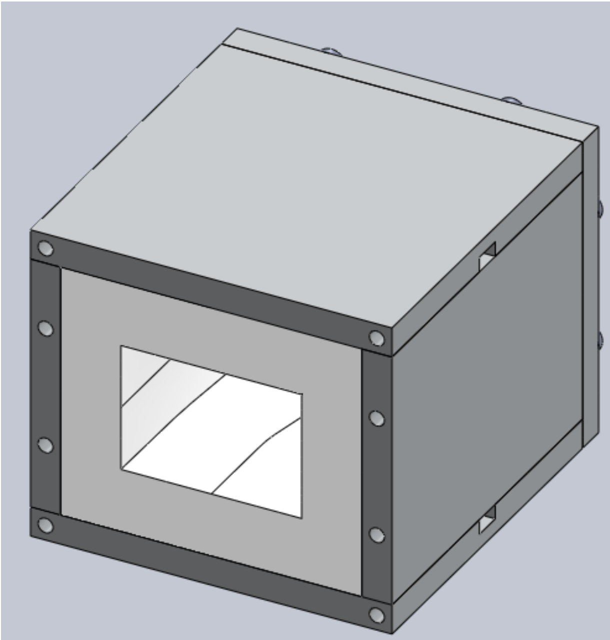

Figure 7: Picture of the CAD model of the adapter externally.

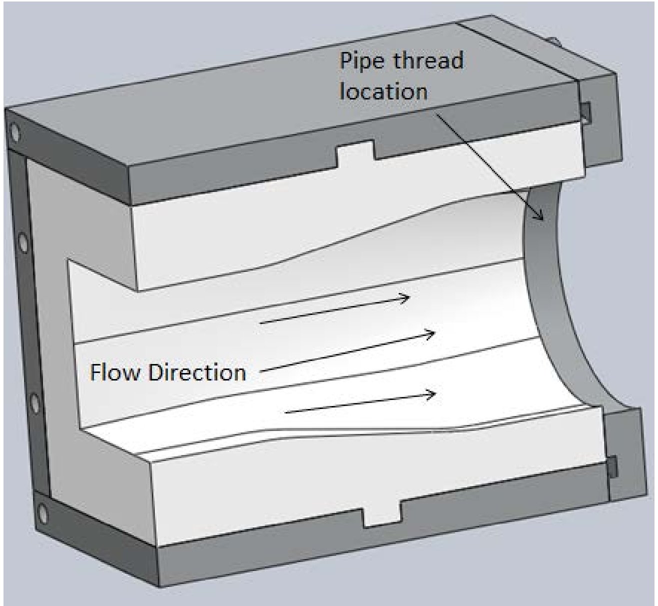

Figure 8: Picture of the CAD model of the adapter as seen with a cut through it to show it internally.

6.5 Bellmouth

The bellmouth was designed to be simple and cheap to make while smoothing air into the test section adequately. It is made of PVC pipe cut in half lengthwise and then cut at 45 degree angles to create the desired shape.

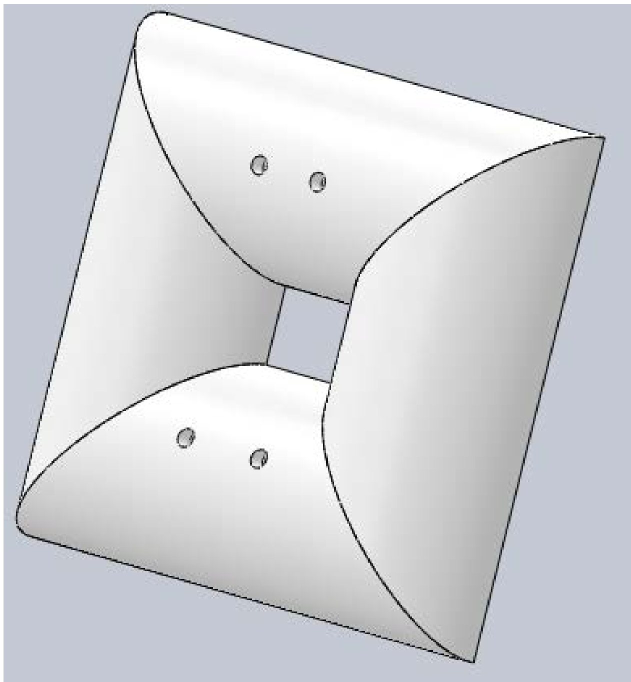

Figure 9: Picture of the CAD model of the bellmouth.

6.6 Monopod

The simple camera monopod was added as a cost effective and simple way to avoid having to cantilever the tunnel from the flange.