

General Motors' New Reduced Scale Wind Tunnel Center

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ABSTRACT

The General Motors Reduced Scale Wind Tunnel Facility, which came into operation in the fall of 2015, is a new state-of-the-art scale model aerodynamic test facility that expands GM's test capabilities. The new facility also increases GM's aerodynamic testing throughput and provides the resources needed to achieve the growing demand for higher fuel economy requirements for next generation of vehicles. The wind tunnel was designed for a nominal model scale of 40%. The nozzle and test section were sized to keep wind tunnel interference effects to a minimum. Flow quality and other wind tunnel performance parameters are on par with or better than the latest industry standards. A 5-belt system with a long center belt and boundary layer suction and blowing system are used to model underbody flow conditions. An overhead probe traverse system is installed in the test section along with a model positioning robot used to move the model in and out of the test section. The facility includes a model shop area and an office section for aero development and CFD engineers. The close proximity to the full size wind tunnel and the Global Design Center support the workflow of the vehicle design and development process.

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INTRODUCTION

In 1980 General Motor was the first American automotive manufacturer to build its own wind tunnel in the Detroit area, a full scale closed jet wind tunnel with a static ground and weigh beam balance [19]. After 36 years GM continues to lead the way in aerodynamic testing by again being the first American automotive manufacturer to build a wind tunnel with a moving ground plane, or rolling road. This time, a reduced scale, $\frac{3}{4}$ open jet wind tunnel optimized for 40% models. The new Reduced Scale Wind Tunnel (RSWT) reinforces General Motors' continuing dedication to improving vehicle aerodynamics and delivering more fuel efficient vehicles to its customers.

As the increasing demands for better fuel economy continue to demand more test hours it became clear that GM needed additional wind tunnel capability. Prior to the construction of the RSWT all reduced scale aerodynamic testing had been conducted in the full scale wind tunnel, and when reduced scale testing demands increased further, some testing was sent to an outside facility. It became clear that an additional facility specifically tailored to reduced scale aerodynamic testing was necessary.

The wind tunnel now runs two shifts per day, five days per week and has not only increased testing capacity, but also increased testing capability with the new moving ground plane, an overhead probe traverse and automated model installer.

The wind tunnel is a $\frac{3}{4}$ open jet, closed return wind tunnel. The test section is 7 m long, has a 4.8 m² nozzle, and scoop primary boundary layer removal system coupled with a suction and tangential blowing secondary boundary layer removal system. The road simulation consists of a 5-belt moving ground plane system and an underfloor six degree of freedom force and moment balance integrated into the turntable. The wind tunnel along with the moving ground plane is capable of achieving a maximum design speed of 250 km/h.

An overhead probe traverse system further increases the testing capabilities by providing the means to make pressure measurements during a wind-on run. The probe traverse was also instrumental in the flow quality measurements during commissioning.

Improved test setup and testing efficiencies were achieved via an Automated Model Installer (AMI) which can pick up a model from the side of the test section and automatically install it on the balance. For a model change the model can be quickly removed from the test section and moved to the adjacent room for clay changes.

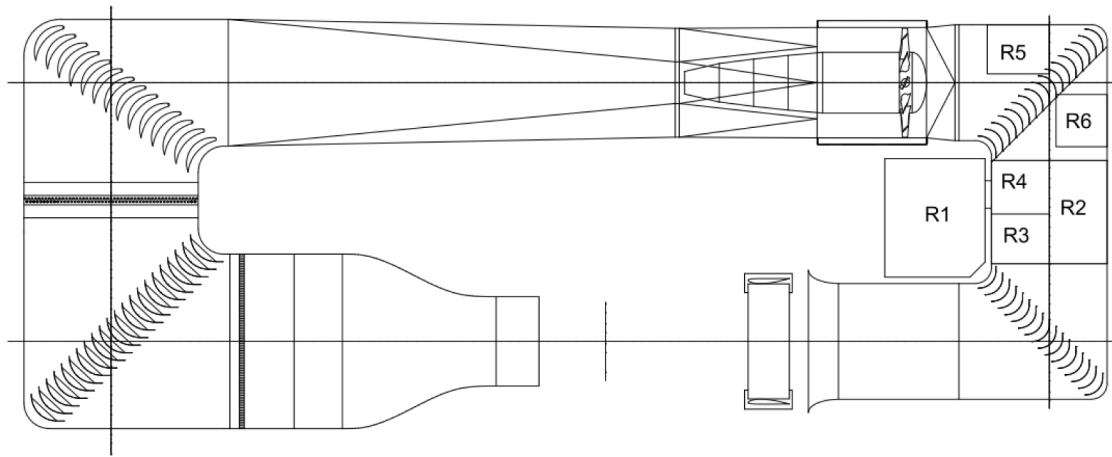


Figure 1. GM Reduced Scale Wind Tunnel airline plan view. The locations of the six Helmholtz resonators (R1-R6) for the attenuation of low-frequency pressure pulsations are shown

WIND TUNNEL DESIGN FEATURES

General Motors contracted Jacobs to design and build the new Reduced Scale Wind Tunnel. Figure 1 shows the general airline arrangement of the wind tunnel in plan view. It is designed as a horizontal return, $\frac{3}{4}$ open jet wind tunnel circuit designed to test scale models with a nominal scale of 40% scale. The design focused on keeping circuit pressure losses low and avoiding the occurrence of flow separation. The result is an aerodynamically efficient airline that minimizes fan power and cooling requirements while still maintaining a small overall foot print. Helmholtz Resonators are used to suppress low frequency (infrasonic) pressure fluctuations. They are located in the first cross-leg and corner 2.

Wind Tunnel Circuit Components

The RSWT was specifically designed to achieve GM's desire for a wind tunnel with exceptional flow quality and performance capabilities. The resulting facility meets or exceeds all of GM's requirements. The airline utilizes several of Jacobs proven design features as well as some new design solutions. The result is an aerodynamically efficient airline that minimizes fan power and cooling requirements while still maintaining a small overall foot print.

The GM RSWT is a horizontal return $\frac{3}{4}$ open jet wind tunnel circuit. Following traditional objectives, the GM RSWT design focused on minimizing circuit pressure losses and minimizing the occurrence of separation with the goal of providing a facility with excellent flow quality in as small and effectual a foot-print as possible.

Test Section and Plenum

The test section is open to a large conditioned space in which the entire RSWT wind tunnel circuit is housed. This large space essentially becomes the plenum and ensures that the test section remains at or near atmospheric pressures. The large conditioned space itself is contained within a larger building that also houses the mechanical room, electrical room, control room, model storage and

work areas, offices and meeting rooms. Other facilities of similar design have shown that this design simplifies model installation and integration into the test section, and provides good visual access [1].

The nozzle exit area is 4.8 m^2 and was designed with an aspect ratio of 1.7 to meet GM requirements. The effective open jet length from the nozzle exit plane to the start of the collector is 6.7 m. The collector design includes the addition of flow stabilizers which have been utilized in several recent wind tunnels [1, 7]. The flow stabilizers are airfoil shaped and aid in maintaining and sustaining a constant static pressure distribution at the downstream end of the test section, prior to entering the high speed diffuser. The farther downstream the static pressure can remain constant, the less interaction it has with the vehicle wake and resulting drag measurements.

The test section contains a 5-belt moving ground plane and turntable for testing scale model vehicles. The turntable has a yaw capability of $\pm 30^\circ$ and can be rotated during wind on conditions. The turntable is based on a double radius design which allows a more compact system than traditional single radius turntables, and allows the model center to be closer to the nozzle exit plane where the jet core is larger. Integrated into the turntable is a six component force balance. The balance and moving ground plane were supplied by MTS Systems Corporations.

The control room is in a separate room adjacent to the test section and plenum. The control room has clear visual access to the test section. Personnel have direct access the test section through a man door that connects the two spaces. The test section is raised approximately 1m above the control room floor and can be accessed by a set of portable stairs. A light curtain is installed across the length of the raised test section floor on the control room side to ensure that no one can enter the test section during a test. The light curtain is interlocked with the main fan drive and if the curtain is broken an e-stop is sent to the drive and the fan is stopped.

Additionally, other safety measures to limit personnel entering the wind tunnel during operation are also included. A Kirk Key interlock system is installed on all air circuit access doors. The Kirk Key interlock is a 2-key system which requires a master key to open a door. Once turned the master key is trapped, in turn releasing the unique door key. The unique key is then removed and held by the individual entering the circuit, thereby ensuring the access door cannot be relocked. Once the master key is removed from its home location in the control room the facility is in an e-stop condition and as a result the fan is locked out and unable to start until the door is relocked and the system is reset. Resetting the system is completed in the control room.

Boundary Layer Removal System

Both, primary and secondary boundary layer removal systems are provided to more accurately model the underbody flow of the vehicle. The primary system is located within the nozzle and removes the boundary layer created within the contraction. The primary system is a suction only system which has a 30 mm high scoop that extends across the entire width of the nozzle. The flow removed from the primary suction is discharged into the conditioned space that houses the wind tunnel. The air is eventually re-entrained by the jet and re-enters the wind tunnel circuit at the collector.

The secondary boundary layer removal system supplements the primary system and is located just upstream of the turntable. The secondary system is a suction- and blowing slots system. This type system [13] has been shown to minimize or eliminate flow induced effects on flow angularity and axial static pressure distribution that are typically encountered with suction only boundary layer removal systems.

Traverse System and Model Positioning Robot

The test section is equipped with an overhead probe traverse system that can move a flow probe such as a Pitot-static probe, hotwire probe or other flow measurement devices to locations around the test vehicle. This allows for localized flow measurements around the vehicle envelope such as vehicle wakes and shear layers.

The test section is also equipped with an Automated Model Installation (AMI) robot, shown in [Figure 2](#). This allows for quick and repeatable model installation and removals. A typical test shift will install and remove the model 20 times throughout the test shift for clay model changes. The AMI robot also improves test efficiencies by enabling two models to be tested in tandem. While one model is undergoing clay changes, a second model can be installed in the test section for a test run. Then the first model is tested while the second model undergoes clay changes.



Figure 2. Automatic Model Installer (AMI)

Active Open Jet Wind Tunnel Corrections

In recent years, many wind tunnel facilities have utilized the techniques developed by Mercker and Wiedemann, also known as the Mercker method [10, 11, 12, 16], for correcting air speed and dynamic pressure in open jet wind tunnels. These corrections utilize potential flow theory for their development and take into account several factors including but not limited to nozzle interference, jet expansion and deflection and collector interference. Most often, the Mercker Method correction is applied post testing because at least one of the correction schemes is iterative in its determination.

Online blockage corrections to adjust the measured dynamic pressures to an interference-free value are provided in the GM RSWT. The techniques developed by Mercker, Cooper, Wiedemann, and co-workers [10, 11, 12, 22], also known as the Mercker Method, are implemented. A succinct summary of the calculation steps is provided by Walter et al. [16]. The facility's supervisor control system actively controls the wind tunnel air speed and dynamic pressure using the corrected parameters as closed loop feedback signals. The calculation process occurs in real time, which requires an iterative numerical scheme that works concurrently within the facility's PLC controller. The real-time approach assures that when the wind tunnel is controlled to the corrected airspeed, this value then matches equivalent translational wheel speed generated by the moving ground plane, which is inherently interference-free.

For the process to work, the wind tunnel must be equipped with both the nozzle and plenum dynamic pressure measurement methods [12]. Additionally, care was taken to locate the nozzle pressure taps at a point upstream in the contraction that is not significantly influenced by vehicle blockage.

Pressure gradient corrections for horizontal buoyancy and wake distortion [17, 23] are not implemented online in the GM RSWT because it was designed to have a very small axial static pressure gradient (see Figure 10 and associated discussion).

High Speed Diffuser to the Main Fan

The high-speed diffuser located downstream of the test section begins the expansion process of the flow from the test section. The high speed diffuser is a two-dimensional diffuser because only the top and bottom walls diverge and the side walls remain straight. The area at the diffuser inlet is 8.38m² and its exit area is 11.1 m² bringing the overall area ratio for this diffuser to 1.325. The total length of the high-speed diffuser is 3.68 m and the resulting diffuser half angle is 2.93°.

Corners 1 and 2 are constant area corners and have a flow area of 11.1 m² and 13.2 m², respectively. Both corners include 17 flat plate turning vanes with leading and trailing edge extensions and gap to chord ratios of 0.34. Corner 2 also is equipped with a Foreign Object Debris (FOD) screen which is located on the leading edge of the turning vanes. The FOD screen is a combination of a coarse screen which spans the entire cross-sectional area of the corner and the fine screen which covers the area from the floor up to an elevation of approximately 250 mm. The coarse screen is used to catch larger pieces of debris that becomes detached from the model during the course of testing. The fine mesh screen collects the heavier and generally smaller debris such as screws and washers.

The Cross-leg diffuser between Corners 1 and 2 continues the diffusion process from the test section. Similar to the High Speed diffuser the Cross-leg diffuser also expands in two-dimensions from 11.1 m² to approximately 13.2 m² to the inlet of Corner 2 with an area ratio of 1.186. The length of the Cross-leg diffuser is 3.3 m, which corresponds to a 2.91° diffuser half-angle.

The fan inlet, located downstream of Corner 2, transitions the wind tunnel circuit from a rectangle cross-section to a circular cross section. It is important for the fan to have uniform inlet flow. A combination of a contracting fan inlet and the fan nose cone help to accelerate the flow entering the fan. As the flow accelerates, the boundary layer is thinned and the inflow becomes more uniform. The result is more efficient operation and lower fan noise.

Main Fan and Annular Diffuser

The fan size was based on established guidelines that consider the fan's performance matched against the air circuit's efficiency and cost. The Twin City Clarage fan has a diameter of 3.53 m with 18 blades and 13 stators. The fan's overall efficiency is greater than 88% with a maximum operating speed of approximately 550 RPM and a supplied 820 kW water cooled motor.

The annular diffuser transitions from a circular cross-section at the fan section outlet to an octagonal cross-section at the interface with the back-leg diffuser. The annular diffuser works in combination with the fan's tail cone that is attached directly to the back of the fan nacelle housing.

The design of the tail-cone is based on maintaining, as close as possible, a 3° diffusion angle throughout the entire length of the diffuser. The diffusion angle was accomplished by dividing the tail cone into four equal length segments and then iteratively adjusting the tail-cone diameter and diffuser cross section until each segment is close to the desired diffusion angle. As shown in Figure 3, the final geometry is verified using CFD to ensure that the flow remains attached.

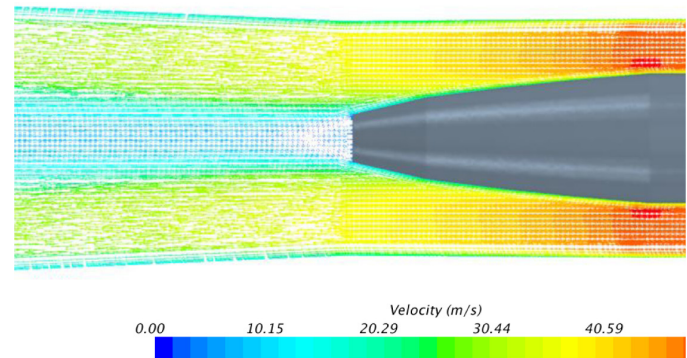


Figure 3. CFD of GM RSWT Tail cone geometry

During commissioning an audible resonance was measured that occurred at a frequency of approximately 289 Hz. The resonance occurred at a test section air speed of approximately 120 km/h. The resonance was associated with the fan's nacelle supports. There are a total of seven fan supports. The two bottom supports are thicker to allow for electrical and cooling water to the motor. The remaining five supports, four along the side and one at the top, were 15 mm thick and approximately 89 mm long. Calculation of the Strouhal shedding frequency for these top five supports matched the audible 289 Hz resonant frequency.

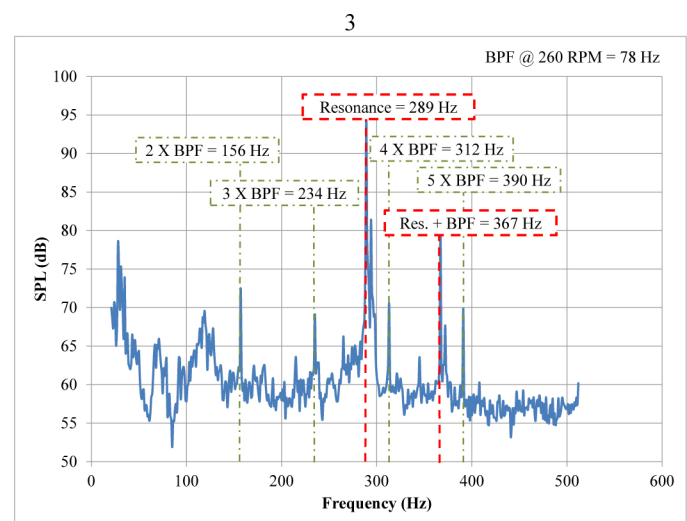


Figure 4. Frequency plot showing the Blade Passing Frequency modes, the resonant frequency of the five nacelle support plates and one side mode of the BPF and resonant frequency. Note: BPF = 78 Hz

Figure 4 shows an acoustic spectrum between 20 and 500 Hz measured in the Plenum. The frequency modes associated with the Blade Passing Frequency ($BPF = 78 \text{ Hz}$) are shown along with the Strouhal shedding frequency associated with the support struts. Additionally, a side frequency which is the sum of the first mode of the BPF and Strouhal shedding frequency is also present. The resonant frequency's peak is more than 15 dB larger than the surrounding frequencies.

The solution to the fan resonance was the application of a Styrofoam covering on the full length of the leading edge of each support. The cross-section of the covering is as shown in Figure 5.



Figure 5. Styrofoam leading edge covering for the fan nacelle supports

It is interesting to note, that originally a hard rubber covering was used instead of the Styrofoam covering. The hard rubber covering had a different leading edge shape which was more aerodynamically smooth than the Styrofoam shape. The original thinking was by simply changing the thickness of the leading edge of the support, would change the shedding frequency at the trailing edge. However, using the rubber covering the resonance was not affected. It is speculated that the hard rubber did not provide sufficient flow unsteadiness over the entire length of the support. The foam shape, on the other hand, was able to generate unsteadiness that extended all the way down the length of the support.

Back-leg Diffuser

The back-leg diffuser transitions from an octagonal cross-section to a rectangular cross-section at the inlet to Corner 3. The area ratio of this back-leg diffuser is 1.91 and the length of the diffuser is 14.3 m. This corresponds to a conical equivalent half-angle of 2.74° . Again, the design philosophy of the back-leg diffuser is to keep the transition angle low to avoid flow separation, flow non-uniformities and unsteady flow issues.

Expanding Corner 3 & Heat Exchanger

Corner 3 is an expanding or diffusing corner with 14 double-arc turning vanes that help turn the flow as it expands around the corner and to provide the heat exchanger with uniform airflow. The main purpose of the diffusing Corner 3 is to keep the overall foot print of the wind tunnel small while maintaining the back leg diffusion angle in a range to avoid flow separation.

The heat exchanger is located in the constant area cross-leg between corners 3 and 4. It is a two pass arrangement with staggered tubes and has a face area that limits the local air speed to 18% of the maximum test section air speed. The result of the lower local velocity through the heat exchanger is a more efficient wind tunnel circuit with less turbulence generation. The cooling system is thermally designed to maintain the wind tunnel circuit at 22°C for a continuous test section velocity of 250 km/h.

Aerodynamic wind tunnels are sometimes prone to flow induced acoustic resonance associated with flow through the heat exchanger [14]. The resonance occurs when a heat exchanger tube's, periodic Strouhal shedding frequency coincides with one of the traverse duct mode natural frequencies. The result is an intense tonal noise that can quickly become disturbing and in some instances harmful as the loudness of the tone exceeds acceptable noise exposure limits. Figure 6 shows a typical sound spectrum from recent wind tunnel measurements completed on other projects. The spectrum is characterized by a dominant frequency, usually in the range of frequencies between 200 and 400Hz, and several side lobe frequencies on either side. The side lobes are acoustic modes of the duct cross-section at the location of the heat exchanger.

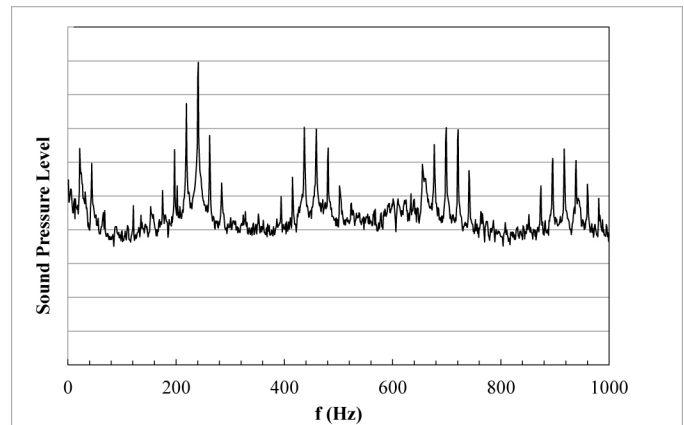


Figure 6. Typical sound spectrum with a heat exchanger resonance in a wind tunnel circuit

One solution to suppress such resonance is the installation of a baffle along the downstream face of the heat exchanger that is parallel to the air flow [15]. The purpose of the baffle is to shift the duct's fundamental natural frequency up and away from the tube Strouhal shedding frequency thus avoiding resonance. The problem with this solution is that it tends to delay or shift the point where resonance occurs especially if the first resonance occurred at a test section speed less than maximum. The result may be multiple baffles, which can have a negative effect on flow quality in the test section.