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DESIGN AND CONSTRUCTION OF AN ACOUSTIC SHOCK TUBE FOR GENERATING HIGH-LEVEL IMPULSES TO TEST HEARING PROTECTION DEVICES

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DEVELOPMENT AND DESIGN OF AN ACOUSTIC SHOCK TUBE FOR GENERATING HIGH-LEVEL IMPULSES FOR TESTING OF HEARING PROTECTION DEVICES

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Executive Summary

Background: The noise reduction performances of Hearing Protection Devices (HPDs) have normally been evaluated at or near the threshold of hearing because the performance of the device was assumed to be constant across the typical range of occupational noise exposure levels. With the advent of new technologies in hearing protection and electronics, the noise reduction performance for some HPDs was found to increase with the increase in the sound levels (Parmentier et al. 2002; Zera and Mlynski, 2007; Berger and Hamery 2008; Murphy et al., 2012). These HPDs are typically described as amplitude-sensitive, non-linear, sound-restoration or level-limiting. The electronic level-limiting or sound restoration HPDs detect the external exposure level and then adjust the gain of the amplification circuit to limit the level of sound played back underneath the protector. Passive HPDs with a non-linear valve or orifice rely increased acoustic impedance with an increased pressure differential across the two sides of the orifice or valve.

In order to accurately assess the performance of these types of protectors, the American National Standards Institute revised the ANSI/ASA S12.42 (ANSI, 2010) standard to include a method to measure the impulse peak insertion loss of all hearing protector over a wide range of impulse levels using a dual ear acoustic test fixture and a field microphone. The ANSI/ASA S12.42-2010 requires that impulse tests be performed at three ranges of impulse peak sound pressure levels. The low-level impulse range is between 130 and134 dB peak SPL; the mid-level range is between 148 and152 dB peak SPL; the high-level range is between 166 and 170 dB peak SPL. For all impulses, the duration of the initial positive pressure phase of the waveform (A-duration) is required to be between 0.5 and 2.0 milliseconds. The standard recommends generating the required impulse sound events using explosive charges or an acoustic shock tube.

Description: This report describes the design and construction of the NIOSH acoustic shock tube. The first prototype shock tube was built under a contract to the University of Cincinnati, but suffered from design flaws that prevented it from achieving the specified impulse ranges. A second prototype shock tube was designed and constructed by Cauble Precision Machine Inc. of Lawrenceburg, IN. The second prototype could generate the specified impulse ranges, but was unwieldy to use for a sustained period due to the manual clamping system. NIOSH modified the pressure control and pneumatic clamping systems to create the third prototype shock tube. Safety features were integrated into the pneumatic clamping system and an acoustic horn was designed and manufactured to provide impedance matching between the shock tube and the room. The horn provided a small amount of gain necessary to generate impulses at the highest peak pressure levels 166 to 170 dB SPL. In summary, the operational performance of the third shock tube was significantly improved. The modifications to the acoustic shock tube have been incorporated into subsequent versions of the shock tube manufactured and sold by B/C Precision Tool (formerly Cauble Precision Machine Inc.).

Conclusions: The NIOSH acoustic shock tube successfully generates impulse noise levels in the range of 130 to 170 dB SPL using 1 and 2 mil polyester film. The operational requirements specified in the ANSI S12.42-2010 standard can be met using this equipment developed by the NIOSH in support of the EPA's effort to revise the hearing protector labeling regulation. This report describes the design, construction and basic operation of shock tube.

I. Introduction

A. Background

In 2003, the US Environmental Protection Agency held a public meeting to gather input from representatives of hearing protector manufacturers, testing laboratories, academic researchers and government officials regarding the need to revise the Noise Reduction Rating (NRR) (EPA, 2003). The major outcome of this meeting was the identification of a need to provide a rating for hearing protection devices that are designed to provide increasing noise reduction as the sound exposure level increases. The noise reduction of Hearing Protection Devices (HPDs) have typically been evaluated at or near the threshold of hearing because the performance of the device was not believed to change significantly over the range of occupational exposure levels for noise. With the advent of new technologies in hearing protection and electronics, some HPDs provide small amounts of noise reduction at low sound pressure levels and yield increasing noise reduction as the exposure level increases. These HPDs can be amplitude-sensitive, non-linear, sound-restoration or level-limiting.

Electronic level-limiting or sound restoration HPDs sense the external exposure level and then adjust the gain of the amplification circuit to limit the level of sound played back underneath the protector. Passive nonlinear HPDs use a valve or orifice to provide increased acoustic resistance as the pressure differential across the valve increases. In order to assess the performance of these types of protectors, the American National Standards Institute has revised the ANSI/ASA S12.42-2010 (ANSI/ASA, 2010) standard which defines a method for measuring the impulse peak insertion loss of a hearing protector over a range of impulsive sound events using an acoustic test fixture and a field microphone. ANSI/ASA S12.42-2010 stipulates that the ranges of levels shall be 130 to 134, 148 to 152, and 166 to 170 dB peak SPL. The duration of the initial blast overpressure (A-duration) was required to be between 0.5 and 2.0 milliseconds. The standard describes creating the requisite impulse events by using either explosive charges or an acoustic shock tube (ANSI, 2010).

Explosive charges require a dedicated range sufficiently remote from surrounding communities to minimize annoyance. The charges range anywhere from blasting caps to a few hundred grams of explosive material such as C4 or Semtex. Handling of these explosives requires extensive training and precautions that are impractical for most hearing protector testing laboratories outside of the military. Small-caliber weapons can generate the required impulse levels, but the A-durations tend to be shorter than 0.5 milliseconds, which is outside the allowable range. Small caliber weapons pose hazards for ventilation of combustion gases, remediation of toxic dusts as well as safety associated with firing a weapon indoors.

Acoustic shock tubes are cited in the standard as having greater operational flexibility in generating impulses at different levels. The major component of the shock tube design consists of a pressure chamber sealed on one end by a membrane. The chamber is pressurized by manually opening up the compressed airflow valve and observing the pressure buildup inside the chamber via a pressure gauge. Once the desired pressure is reached, the membrane is punctured to produce the impulse. If the pressure in the chamber is too low relative to the thickness of the membrane, the cylinder depressurizes with a hiss rather than an explosive release of the gas. Generally, as the peak pressure is increased, the impulse peak sound pressure level increases.

Two acoustic shock tubes are commercially available: one developed by NIOSH and another was developed by Professor Jan Zera in Poland (Zera and Mlynski, 2007). The design, operation and the performances of these shock tubes differ from each other. The Polish shock tube is vertically oriented and does not utilize a horn or an extension of the shock tube. The lack of an exit tube and a horn on the Polish shock tube inhibits the development of a shock wave for impulses below about 150 dB peak SPL. The NIOSH acoustic shock tube is horizontally oriented and can accommodate extensions and a horn to adjust characteristics of the impulse. The extension of the exhaust tube facilitates the formation of a shock wave in the duct and the horn provides impedance matching between the duct and the open space. The NIOSH shock tube can be fitted with a catenoidal, exponential, or linear horn. A linear horn provides finite transmission across all frequencies; an exponential horn has a sharp lower cutoff frequency for energy transmission; and a catenoidal horn has better high-frequency transmission than a linear horn but has a cutoff frequency that is similar to an exponential horn (Blackstock, 2000).

This report describes the design, construction and operation of the NIOSH acoustic shock tube. Early versions of the NIOSH shock tube and subsequent improvements are described. The manufacturer, part number and normal operating parameters for the shock tube components are provided.

II. Shock Tube Design:

A. Prototype Development

The first prototype of the NIOSH shock tube was developed under a contract with the University of Cincinnati. Due to significant design and operational deficiencies, a second shock tube was developed building on the experience with the first prototype. Bids for the design and fabrication of the second shock tube were obtained from local Cincinnati-area machine shops. Cauble Precision Machine Inc. constructed the second prototype of the NIOSH shock tube (see Figure 1).

During extensive use of the second prototype of the shock tube, several operational deficiencies were identified. The manual clamping system for sealing the plastic membrane between the flanges was not ergonomic and impractical to use for more than an hour or two. The pressure controls were imprecise and failed after several months of use. The flat gaskets used to seal the membrane with the flanges would leak at pressures above about 45 psi. Positioning the shock tube in the laboratory was cumbersome.

The second prototype was modified to include pneumatic clamping, improved air controls, a mobile base for accommodating the shock tube assembly and an acoustic horn to provide gain to the impulse (see Figure 2). The sealing of the plastic membrane in between the flanges was automated to use four pneumatic air cylinders (100 psi) capable of delivering over 3000 lbs of force. The airflow controls were upgraded to provide better control of the pressure in the shock tube chamber. The gasket material was changed to a softer material that provided the ability to reach higher pressures before leaks would develop between the plastic membrane and the flanges. The shock tube assembly was mounted on a mobile cart base which allowed the shock tube to be easily maneuvered from one position to another. Finally the airflow circuit was modified to be more serviceable and to improve the safety of the operation of the pneumatically operated clamping system.

B. Theory

The NIOSH acoustic shock tube consists of three major components:

i. The compressed airflow system pressurizes the shock tube to the desired level.

ii. The shock tube pressure chamber contains the pressurized air and generates an impulse when the membrane is burst.
iii. The acoustic horn provides impedance matching between the exhaust tube and the open air.

The essential design of the shock tube clamps a membrane material (foil, paper, plastic film) between flanges with sufficient force to create an airtight seal in the pressure chamber. The chamber is pressurized with air and a trigger activates a lance to explosively burst the membrane. The sudden release of the compressed air forms a shock wave as it propagates along the exhaust tube and into the acoustic horn. The horn reduces the reflection of energy at the interface between the horn and the room (open air). The horn minimizes a downstream flow-induced turbulent vortex for chamber pressures above about 20 psi when the horn is absent.

C. Design Description

The description of the equipment, their operational performance and ranges associated with the compressed airflow system, the shock tube and the horn are briefly described below.

1. Compressed Airflow System

The Impulsive Noise Laboratory has a dedicated compressed airflow system housed in a mechanical room located in the High Bay Area of the Robert A. Taft Laboratories. Conditioned room air is filtered and compressed to supply 100 psi airflow for operating the shock tube. The compressed airflow system has a large compressor with a three-stage-filtration system and is piped into the Impulse Noise Laboratory.

The main compressor is an Ingersoll Rand, Model 2475N, 7 ½ HP premium reciprocating air compressor with an 80 gallon vertical tank. The compressor is housed in a mechanical room outside the Impulsive Noise Laboratory which reduces the noise of the compressor in the high bay area, in the adjacent office spaces and in the Impulse Noise lab. The compressor is shown in Figure 7.

A three-stage filter panel located inside the mechanical room cleans and conditions the compressed airflow prior to exiting the mechanical room (Figure 8). The compressed airflow is filtered in the first stage by a coalescing standard oil removal SPEEDAIRE filter (Model

4ZL45, ½ inch National Pipe Thread (NPT), 35 cubic feet per minute (CFM) maximum airflow, 250 psi maximum pressure,150°F maximum temperature). The second stage regulates the pressure with a SPEEDAIRE airline regulator (Model 4ZL49, ½ inch NPT, 80 CFM, 150 PSI, 125°F). The pressure can be adjusted between 5 and 150 psi. The third stage lubricates the air via a SPEEDAIRE mist intermediate lubricator (Model 4ZL77, ½ inch NPT, 95 CFM, 150 psi 125°F).

The clean and conditioned compressed airflow is supplied at 100 psi to the airflow panel in the Impulse Noise Laboratory using ½ inch black pipe coupled to A53A S40 iron pipe. Once the airflow enters the Impulse Noise Laboratory, the flow is regulated with an FNW 410 shutoff valve (Figure 9). The air pressure supplied to the shock tube is indicated on an Ashcroft pressure gauge (Model 50-1008S-02L-XFF-160#, ¼" NPT, stainless steel case, 0-160 psi, lower connection, flush panel flange, 50 mm dial). The gauge is installed upstream of the shut-off valve FNW410. The airflow panel is connected to the shock tube with HITACHI ¼" ID flexible rubber tubing rated at 300 psi. Both ends of the rubber tubing are male quick-disconnect which are coupled to the female connectors on the shock tube inlet and the airflow panel outlet.

A DeWalt D55146 portable air compressor is the backup for the large compressor (Figure 10). The DeWalt compressor has a 4.5 gallon reservoir and a 1.6 HP motor capable of providing 200 psi.

Three pneumatic systems of the shock-tube clamp the membrane material, pressurize the shock-tube chamber, and trigger the pneumatic lance. These systems together with other additional parts of the shock tube (e.g. such as flanges, linear bearings, extruded aluminum frame, mounting plates, extension pipe and the mobile base) are briefly described below.

a) Pneumatic clamping system

The membrane must be securely clamped to create seal and pressurize the shock tube pressure chamber before bursting the membrane. Four SPEEDAIRE air cylinders (model 6D886) are installed on the four corners of the moveable plate which is bolted to the moveable flange and mounted on to the open end of the shock tube chamber. The actuators' arms pass through the mounting plate affixed to the shock tube pressure chamber and are bolted to a fixed plate. The Wilkerson regulator (model R12-02-F000) provides a constant pressure level airflow to the Ingersoll Rand 4-way 2-position valve (model M212LS-G) for the operation of the four air cylinders. When the valve is activated, the air cylinders retract the actuator arms and clamp the membrane material in between the fixed flange and the gasket of the moveable flange. When the valve is deactivated, the actuator arms will extend and open the space between the flanges. An inherent safety feature forces the cylinders open when the pressure is not applied by operating the hand lever. Furthermore, the hand lever is located near the flanges so that the operator's free hand is less likely to be caught in between the flanges when the pressure chamber is in the act of closing

The valve has a maximum operating pressure of 150 psi, maximum operating temperature of 122°F and maximum airflow of 26 CFM. The Wilkerson Regulator has a range of 0-125 psi and ¼ inch ports. The airflow exhaust noise is silenced by an Arrow 1EJW1 muffler. The SPEEDAIRE cylinders are 10.69 inches long, have a diameter of 2 inches and a 6-inch stroke. Each cylinder is double acting and can provide a maximum load of 785 Lbs. The operating temperature for the air cylinder ranges from 20 to 200^{0}F with the maximum operating pressure of 250 psi. The air cylinders are nose mounted with a 1 ¼-12 thread with a rod diameter of 5/8 inches and a rod thread of ½ -20 inches with rod and a rod thread length of 7/8 inches and tang width of 1 ¼ inches.

The airflow circuit for the unpressurized shock tube and unclamped membrane are illustrated in Figure 16. When the Ingersoll Rand valve is in the OFF position, compressed air exits the valve and opens all four air cylinders. The SPEEDAIRE actuator arms default to the extended position to prevent accidental crushing of fingers or hands in between the moveable and fixed flanges. Figure 17 illustrates the pressurized shock tube with the clamping system closed. When the Ingersoll Rand valve is in ON position, compressed air exits the valve and retracts the actuators to seal the membrane between the moveable flange and the fixed flange. The shock tube chamber is now ready for pressurization.

b) Pressurization system

Once the clamping system is activated and the shock tube chamber is sealed, the chamber can be pressurized (see Figure 18). The airflow is controlled by the Deltrol (model EF-30-B) needle valve and the chamber pressure is regulated by a Norgren R72G-2AT-RMG regulator.

A dust and moisture filter conditions the compressed air before entering the chamber. The Deltrol valve responsible for adjusting the flow rate to the pressure chamber is installed in between the regulator and the chamber. When the regulator is opened, the pressure inside the chamber will increase rapidly and then slow as it reaches the regulator's setting. Pressure can be increased or decreased by adjusting the regulator in small increments. All of the components of pressurization system are connected using ¼"brass fittings, ¼" brass tubing and ¼" nylon tubing. The regulator has ¼" port size, pressure range of 5-125 psi, maximum inlet pressure rating of 300 psi, maximum outlet pressure rating of 150 psi with a maximum temperature rating of 150^0F.

c) Pneumatic lance system

The MAC palm button (model 180001-112-0038) manually activates the pneumatic lance system consisting of the MAC button assembly and the Clippard Minimatic actuator. The MAC palm button has a 3-way, 2-position valve, spring return and button guard with five, ¼ inch NPT threaded ports. One port is connected to the compressed air and two ports are connected to the actuator. The remaining two ports are exhausted into the room via a muffler. Once the palm button is depressed, compressed air enters the Clippard Minimatic piston and extends the actuator to make contact with the membrane material. The original lance design used a razor knife to pierce the membrane; however, the razor knife was not sufficiently robust for sustained use. A stainless steel bolt was ground to produce a sharp tip and was threaded into the socket which held the razor knife; this lance has operated flawlessly. The stainless steel Clippard Minimatic actuator has a 4-inch stroke, operating pressure of 250 psi and temperature range of 32 to 230°F. The pneumatic circuit is illustrated in Figure 19.

Other membrane materials were evaluated in the shock tube. The paper and foil membranes produced impulses below 150 dB. The low tensile strength of the materials yielded inconsistent peak pressure levels. Consistent peak impulse sound pressure levels have been achieved with 1 mil (0.001") and 2 mil (0.002") thick polyester films. The 1-mil polyester film pressurized to 8 psi produced 130-134 dB peak levels when burst. The 2-mil polyester film yielded about 150 dB peak levels when burst at 10 psi and yielded the 168 dB peak levels when burst at 40 psi. The 3-mil (0.003") polyester films tended to burst with a slit and produced impulses that lacked a single wavefront. Polyester or acrylic films thicker than 5 mils (0.005”) tended to produce a hissy leak due to a lack of pressure to catastrophically rupture the membrane.

2. Shock tube pressure chamber

The shock tube pressure chamber is constructed of steel pipe with an inside diameter (ID) of 4”and outside diameter (OD) of 4½” with an overall length of approximately 34”. The chamber is open on one end and closed on the other side. A 4” pipe flange is welded flush to the open end of the chamber and a second 4” pipe flange is welded to the chamber approximately 10 ½” from the closed end. The bottom two bolt holes of the movable flanges are aligned to receive linear bearings for the turned ground polished (TGP) rods. The shock tube chamber is equipped with a safety relief valve, a digital pressure indicator and a handle. The Steuby safety valve (model AS250M) will vent when the pressure exceeds 100 psi. (Figure 14). The Omega digital pressure gauge (model DPG8000-200) can measure pressures up to 200 psi and has a wide range of settings which can be displayed on to the pressure gauge. The instantaneous chamber pressure is most commonly used setting and displays a precision of 0.1 psi. The Omega gauge is battery operated and automatically shuts off after about 15 minutes.

Three 4-inch pipe flanges (U.V. International, LLC) manufactured from the ductile iron were used in the sliding mechanism of the shock tube pressure chamber. The first fixed flange is bolted to the larger mounting plate by three ½” x 1 ½” long socket head cap screw. The second moveable flange is welded flush to the open end of the pressure chamber and bolted to the air cylinder support plate using six ½” bolts. The third moveable flange is welded to the pressure chamber, approximately 10.5 inches away from the closed end with its bolt holes aligned with the second flange. The two bottom bolt holes of the fixed flange support the two sliding TGP rods which pass through the linear bearings inserted into the corresponding bolt holes of the second and third moveable flanges. The flanges are carefully aligned along with the actuator arms of the air cylinders to make the surfaces of the first and second flanges parallel.

In order to seal of membrane between the first fixed and the second moveable flanges, a round 5 ⅛” flat gasket approximately 3/8” thick with a 4” concentric hole was removed is affixed to the face of the second flange using Permatex-2 gasket sealer. In subsequent versions of the shock tube built by B/C Precision Tools, an O-ring groove was machined into the flange and a ¼" O-ring was used in place of the flat gasket material. The O-ring(s) can achieve a higher pressure on the membrane and therefore a higher peak impulse pressure.

The supporting frame of the shock tube is built from T-slotted extruded aluminum manufactured by 80/20 Inc. (model 1515). The framing material is 1.5" x 1.5" and has T-slots on all four sides that are compatible with the 15-Series fasteners and accessories. The supporting frame consists of two 56" front vertical legs and two 37" rear vertical legs. These legs are connected together by four horizontal side bars and two end bars. The bottom shelf of the cart is supported by two horizontal side bars, approximately 33.5" long and two horizontal end bars, approximately 13" long. The top shelf is supported by two side bars; approximately 36.5" long which accommodates the air flow controls of the shock tube (see Figure 2, Figure 3,

Figure 4, and Figure 5) for dimensions and connectors).

Three different sized mounting plates are incorporated in the overall design of the shock tube. Two of the plates surround the open end of the pressure chamber and the fixed flange/exhaust tube (see Figure 2). The third plate supports the TGP rods on which the pressure chambers moves laterally. The largest mounting plate with overall dimensions of 16"x 16" x ½" has a 4" hole in the center of this plate. The fixed flange is bolted to the mounting plate and is welded to the 4" ID exhaust pipe, approximately 24" long. Four ½" holes were drilled and tapped to accommodate the tangs from the four air cylinders. The second mounting plate with overall dimensions of 12"x12"x ¼" is bolted to the flange at the open end of the shock tube. Each of the air cylinders is mounted in a corner of this plate and aligned with the respective holes of the first mounting plate. The plate is divided into two halves and the corners rounded to allow it to be mounted on the second flange using six ¾" bolts. The heads of these bolts were machined down to provide adequate clearance for the flanges to appropriately seal with the plastic membrane when they are in the closed position. Parts of the bottom section of both halves have been removed to eliminate any obstruction associated with the movement of the pressurized chamber. The third mounting plate with overall dimensions of 16"x 5.25"x1" supports the chamber sliding system on the other end.

The 24" long extension pipe is a 4" ID steel pipe welded to the fixed flange (see Figure 2). The extension pipe provides a connection for the acoustic horn and serves as a one dimensional duct in which the shock wave can fully develop.

The NIOSH acoustic shock tube was delivered without any integral wheels. An HTC Products mobile base (model HTC-2000) was purchased and adjusted to fit the shock tube frame. Subsequent versions of the shock tube have a pair of wheels installed at the front end of the tube to facilitate relocating the tube in the laboratory environment.

3. Acoustic horn

The propagation of the shock wave from a cylindrical duct into an open room presents two problems. First, the abrupt change in cross-sectional area from the cylindrical duct of the exhaust tube to the open room is a step function that results in a large impedance mismatch and causes a significant amount of acoustic energy to be reflected back into the tube. Second, the wave front exiting the exhaust tube generates a vortex that creates a significant flow noise downstream from the exhaust tube. Consequently, a solution to both the impedance mismatch and the vortex was to design a horn which could be attached to the exhaust tube. In this section, the mathematical formulae are detailed and measurement tables used to construct the NIOSH exponential and catenoidal horns are provided.

a) Design:

Two different profile rectangular horns were developed for the acoustic shock-tube: exponential and catenoidal. The exponential horn has more discontinuity at the juncture of the exhaust pipe and the horn than the catenoidal horn. The catenoidal horn has a more gradual increase in cross-sectional area than the exponential horn and is longer than the exponential horn. The cross sectional profiles of the two horns are shown in Figure 20. The blue outline is the exponential cross section through the center line. The red outline is the catenoidal cross section through the center line of the horn's axis. The horn amplifies the acoustic impulse allowing the generation of higher level impulses. The highest levels produced by the NIOSH acoustic shock tube are around 166 to 170 dB peak SPL.

The exponential and catenoidal horns were designed using the Webster horn equation. The horns had four identical sides and the flat sheet projection drawing of one side was made using Matlab program (Zechmann, 2011). The flat-sheet projections for both horns are shown in Figure 21. The three-dimensional renderings of the "assembled horns are shown in Figure 22 and Figure 23 for the exponential and catenoidal horns, respectively.

b) Exponential Horn

The distance from the center line of the horn to the wall increases exponentially as one moves from the throat to the end of the horn,

$$y = r_0 e^{\frac{mx}{2}}, \qquad (1)$$

where x is the distance along the centerline of the horn, m is a constant that controls the flare of the horn and r_0=2.25" is the throat radius. For an exponential horn the cutoff frequency was chosen to be 100 Hz. The cutoff frequency is related to the flare constant,

$$f_c = \frac{m c_0}{4\pi}, \quad (2)$$

where m = 3.6637 is the flare constant and c_0 is the speed of sound (typically c_0 = 343 m/s). Using the cutoff frequency f_c = 100 Hz and substituting into Equation 1, m can be computed as follow:

$$m = \frac{4\pi f_c}{c_0} \quad (3)$$

The distance from the centerline describes the cross section of the horn, but does not provide sufficient information to construct the actual sides of the horn to form the rectangular cross section. The distance along the surface of the side of the horn must be integrated to yield the arc length. Then a second arc length must be integrated to find the distance between the centerline of the surface to the edge of the horn.

The general arc length integral is

$$s_{center}(x) = \int_0^x \sqrt{d\hat{x}^2 + dy^2} = \int_0^x \sqrt{1 + \left(\frac{dy(\hat{x})}{d\hat{x}}\right)^2}\, d\hat{x} = \int_0^x \sqrt{1 + y'(\hat{x})^2}\, d\hat{x} \quad (4)$$

where *s(x)* is the arc length as a function of *x* and *y'(x)* is the derivative of the horn's cross sectional profile, in this case the exponential function. Next the arc of the edge is defined in terms of the arc length, *s(x)*, of the profile,

$$y_{EDGE} = y(s_{CENTER}(x)). \quad (5)$$

The arc length along the edge can be computed using the arc length of the centerline,

$$s_{EDGE}(x) = \int_0^x \sqrt{1 + y'(s_{CENTER}(\hat{x}))^2}\, ds_{EDGE}(\hat{x}) \quad (6)$$

where $s_{EDGE}(x)$ is the arc length along the edge. The integral in Eq. 4 can be determined analytically. The arc length integral in Eq. (6) is numerically integrated to yield the final profile. The coordinates for the exponential horn calculated in increments of 1 inch along the center axis are provided in Table 1 of the Appendix. The x coordinates should be plotted along the centerline of the sheet metal material and the y coordinates are the positive and negative distance from the center line. The outline describes the sides for an exponential horn with a throat of 2.25" radius to be coupled to the exhaust of the acoustic shock tube or an extension. Nominally a 4-inch diameter cast iron pipe is assumed to be the size of the shock tube's exit.

c) Catenoidal Horn

The catenoidal profile horn has been extensively used by the NIOSH Impulse Noise Laboratory. The cross sectional area of the horn increases as a hyperbolic cosine from the throat to the end of the horn,

$$y = r_0 \cosh(\frac{mx}{2}) \tag{7}$$

where r_0 is the radius of the throat and m is the flare constant calculated from Eq. 3. Using the theory described for the exponential profile horn, the arc-length of the catenoidal horn can be determined. The x and y coordinates for the horn profiles are given Table 2 in Appendix A.

d) Horn Construction

Four identical catenoidal flat-projection profiles were cut from 16-gauge steel. The four profiles were welded together at the corners to create a square cross-section for the catenoidal horn. A rotary grinder was used to remove sharp edges at the seams and along the edges of the horn's opening. Using the coordinates provided in Table 1 or Table 2, the sides in Figure 21 can be laid out. The programs used to calculate the horn shapes are provided in the archive available on Matlab Central File Exchange (Zechmann, 2011).

The coordinates pairs for [s(x)], y_2(x)] were calculated and saved in a *.dxf file. A computer numerical control (CNC) machine can read the .dxf file and cut the sheet metal within a tolerance of 0.0001 inch. Alternatively, the profiles were imported into Microsoft Visio software, printed with a larger format printer and then transferred to the metal for cutting the sides.

The throat of the horn was joined to the exhaust tube of the shock tube. A square cap was constructed to fit over the end of the horn and was welded to the horn. A 4½ inch diameter was cut in the cap to join the square cap to a 4 3/8 inch long pipe. These pieces were welded together. The horn and the exhaust tube for the shock tube were connected by a PVC 4½ inch coupler.

The horn is mounted on a wheeled frame of 2-inch angle iron to support the horn and allow it to be mobile. The overall dimensions of the base of the cart is approximately 26 ½ inches by 46 ¼ inches. The front side of the horn is welded to the base of the cart using two 2”x2” angle irons approximately 31 ½ inch long and installed 22 inches apart. The bottom of these angle iron frame are welded to the front two corners of the base of the cart while the upper ends are vertically welded to the two sides of the horn, approximately 24 ½ inches away from the outlet of the horn. The rear of the horn is welded to the cart using two 2”x2” angle iron approximately 38 ¼ inch long and installed 5 ¾ inch apart. The bottom of these angle iron are welded to the back of the base of the cart, approximately 10 inches away from the two back corners of the base of the cart while the upper ends are vertically welded to the two sides of the horn, approximately 11 inches away from the inlet of the horn. The base of the cart is equipped with four 2” castors with lock-in mechanism, which increases the mobility of the horn.

Figure 22 and Figure 23 illustrate a three-dimensional rendering of the catenoidal and exponential horns. The NIOSH horns were manufactured by D & D Metal Supply Inc., located in Cincinnati, Ohio. The external surface of the horn should be covered with an extensional damping material to reduce the ringing and vibration of the horn when the shock tube is fired. While the NIOSH horn is covered with a material purchased from McMaster Carr, the damping material is somewhat brittle and has cracked at the edges and seams of the material. B/C Precision Tool has manufactured three shock tubes and catenoidal horns using the NIOSH design and at least one of the horns used the E-A-R C2003 extensional damping material to cover the external surfaces of the horn. The increased flexibility of the E-A-R material seems to reduce the cracking observed with the NIOSH horn.

III. Shock Tube Operation

A. Activation (Start-up)

Step-by-step instructions for the activation of the shock tube are listed below:

1. Turn the FNW 410 valve on to the “ON” position to allow flow of compressed air to the shock tube.

2. Adjust the compressed airflow pressure to 100 psi at the airflow panel.
3. Turn on the OMEGA pressure indicator by pressing the first button on top of the digital readout screen to “ON” setting.
4. Press the first button on the bottom of the digital readout screen to ”Max” setting which will set the pressure indicator to read the maximum chamber pressure at any time during operation of the shock tube.
5. Press the third button on the bottom of the digital readout screen to ”PSI” setting which will set the pressure indicator to read the pressure inside the shock tube chamber in psi.

B. Operation (Firing)

Step-by-step instructions for firing the shock tube are listed below:

1. Insert a membrane between the flanges
2. Close the shock tube with the Ingersoll Rand red handled lever.
3. Pressurize the shock tube with the Norgren R72G regulator
4. Watch the OMEGA pressure gauge until the desired pressure is reached.
5. Press the MAC palm button to activate the pneumatic lance.
6. If the pressure is sufficient, the membrane will be catastrophically ruptured resulting in a shock wave propagating out of the tube and horn assembly. If the membrane is too thick or the pressure too low, the membrane will only be punctured and air will be released slowly with a hissing sound.

C. Termination (Shut-Down)

Step-by-step instructions for shutting-down the shock tube operation are listed below:.

1. The operation of the shock tube is shut-down by turning the FNW 410 valve on to the “OFF” position.
2. Completely “OPEN” the Norgren 2"Pressure Regulator to allow for the compressed airflow to completely bleed out of the shock tube chamber and the clamping system.
3. Make sure the shock tube is in “OPEN” position.

D. Environment and Periodic Maintenance

(1) Compressed Air System maintenance

The oil level in the compressor frame should be checked on a monthly interval. If oil level is below proper level add lubricant to restore the level to the proper level. The stage 1 filter (4ZL45) needs to be bled on a weekly basis to remove coalescing oil residue collected from the compressor airflow. The stage 3 filter (4ZL77) should be bled on a weekly basis to remove oil mist produced in stage 2 filter (4ZL49).

Prior to daily use of the shock tube, purge the water from the shock tube system by bleeding off the Wilkerson regulator located on the bottom of the top shelf of the shock tube cart. On a monthly basis clean the viewing glass bowl installed on the shock tube pressure regulator with soap and water. Daily inspect the rubber gasket install on the moveable flange of the shock tube chamber to ensure proper sealing of the shock tube with the plastic membrane. If the gasket is lose then re-glue the gasket appropriately on to the moveable flange using Permatex 2 gasket sealer. If the shock tube cannot be sealed because of the degradation of the rubber gasket, then it should be replaced with a new gasket.

(2) Horn maintenance

Periodically inspect the exterior surface of the horn to make sure the dampening material has not peeled off from the horn due to the vibration of the horn. Replace the damage dampening material with a new material. 3M manufactures the E•A•R C2003 extensional damping material that can be applied to the exterior surface of the horn to reduce ringing.

The laboratory space should be maintained at a temperature of 75^{0}F ± 5^{0}F and a relative humidity of 50% ± 10% to minimize operational variability.

IV. References:

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V. Appendix

Table 1. The following table provides the coordinates for laying out the sides of the exponential horn on a flat sheet of material. Four identical sheets of material should be cut from 14 gauge sheet metal to be welded together at the corner seams. The x values are the distance along the center line of the 48 x 96 inch sheet metal. The ±y values describe the layout line above and below centerline.

X	+Y	-Y
0.0	2.25	-2.25
1.0	2.35	-2.35
2.0	2.45	-2.45
3.0	2.55	-2.55
4.0	2.66	-2.66
5.0	2.77	-2.77
6.0	2.89	-2.89
7.0	3.01	-3.01
8.0	3.13	-3.13
9.0	3.26	-3.26
10.0	3.40	-3.40
11.0	3.54	-3.54
12.0	3.68	-3.68
13.0	3.83	-3.83
14.0	3.98	-3.98
15.0	4.14	-4.14
16.0	4.30	-4.30
17.0	4.47	-4.47
18.0	4.65	-4.65
19.0	4.83	-4.83
20.0	5.02	-5.02
21.0	5.21	-5.21
22.0	5.41	-5.41
23.0	5.61	-5.61
24.0	5.82	-5.82
25.0	6.04	-6.04
26.0	6.26	-6.26
27.0	6.49	-6.49
28.0	6.72	-6.72
29.0	6.96	-6.96
30.0	7.21	-7.21
31.0	7.47	-7.47
32.0	7.73	-7.73
33.0	8.00	-8.00
34.0	8.27	-8.27

X	+Y	-Y
35.0	8.55	-8.55
36.0	8.84	-8.84
37.0	9.13	-9.13
38.0	9.43	-9.43
39.0	9.74	-9.74
40.0	10.06	-10.06
41.0	10.38	-10.38
42.0	10.71	-10.71
43.0	11.05	-11.05
44.0	11.39	-11.39
45.0	11.74	-11.74
46.0	12.09	-12.09
47.0	12.46	-12.46
48.0	12.83	-12.83
49.0	13.20	-13.20
50.0	13.59	-13.59
51.0	13.98	-13.98
52.0	14.38	-14.38
53.0	14.78	-14.78
54.0	15.19	-15.19
55.0	15.61	-15.61
56.0	16.03	-16.03
57.0	16.46	-16.46
58.0	16.90	-16.90
59.0	17.34	-17.34
60.0	17.79	-17.79
61.0	18.25	-18.25
62.0	18.71	-18.71
63.0	19.18	-19.18
64.0	19.65	-19.65
65.0	20.13	-20.13
66.0	20.62	-20.62
67.0	21.11	-21.11
67.6	21.41	-21.41

Table 2. The following table provides the coordinates for laying out the sides of the catenoidal horn on a flat sheet of material. Four identical sheets of material should be cut from 14 gauge sheet metal to be welded together at the corner seams. The x values are the distance along the center line of the 48 x 96 inch sheet metal. The ±y values describe the layout line above and below centerline.

X	+Y	-Y
0.0	2.25	-2.25
1.0	2.25	-2.25
2.0	2.26	-2.26
3.0	2.27	-2.27
4.0	2.29	-2.29
5.0	2.31	-2.31
6.0	2.34	-2.34
7.0	2.37	-2.37
8.0	2.40	-2.40
9.0	2.44	-2.44
10.0	2.49	-2.49
11.0	2.54	-2.54
12.0	2.59	-2.59
13.0	2.65	-2.65
14.0	2.71	-2.71
15.0	2.78	-2.78
16.0	2.85	-2.85
17.0	2.93	-2.93
18.0	3.01	-3.01
19.0	3.10	-3.10
20.0	3.19	-3.19
21.0	3.29	-3.29
22.0	3.39	-3.39
23.0	3.50	-3.50
24.0	3.62	-3.62
25.0	3.74	-3.74
26.0	3.86	-3.86
27.0	3.99	-3.99
28.0	4.13	-4.13
29.0	4.27	-4.27
30.0	4.42	-4.42
31.0	4.57	-4.57
32.0	4.73	-4.73
33.0	4.89	-4.89
34.0	5.06	-5.06
35.0	5.24	-5.24
36.0	5.42	-5.42
37.0	5.61	-5.61
38.0	5.81	-5.81
39.0	6.01	-6.01
40.0	6.22	-6.22
41.0	6.44	-6.44

X	+Y	-Y
42.0	6.66	-6.66
43.0	6.89	-6.89
44.0	7.13	-7.13
45.0	7.37	-7.37
46.0	7.62	-7.62
47.0	7.87	-7.87
48.0	8.14	-8.14
49.0	8.41	-8.41
50.0	8.68	-8.68
51.0	8.97	-8.97
52.0	9.26	-9.26
53.0	9.56	-9.56
54.0	9.86	-9.86
55.0	10.17	-10.17
56.0	10.49	-10.49
57.0	10.82	-10.82
58.0	11.15	-11.15
59.0	11.49	-11.49
60.0	11.84	-11.84
61.0	12.20	-12.20
62.0	12.56	-12.56
63.0	12.93	-12.93
64.0	13.30	-13.30
65.0	13.68	-13.68
66.0	14.07	-14.07
67.0	14.47	-14.47
68.0	14.87	-14.87
69.0	15.28	-15.28
70.0	15.69	-15.69
71.0	16.12	-16.12
72.0	16.55	-16.55
73.0	16.98	-16.98
74.0	17.42	-17.42
75.0	17.87	-17.87
76.0	18.33	-18.33
77.0	18.79	-18.79
78.0	19.26	-19.26
79.0	19.73	-19.73
80.0	20.21	-20.21
81.0	20.70	-20.70
82.0	21.19	-21.19
82.5	21.43	-21.43

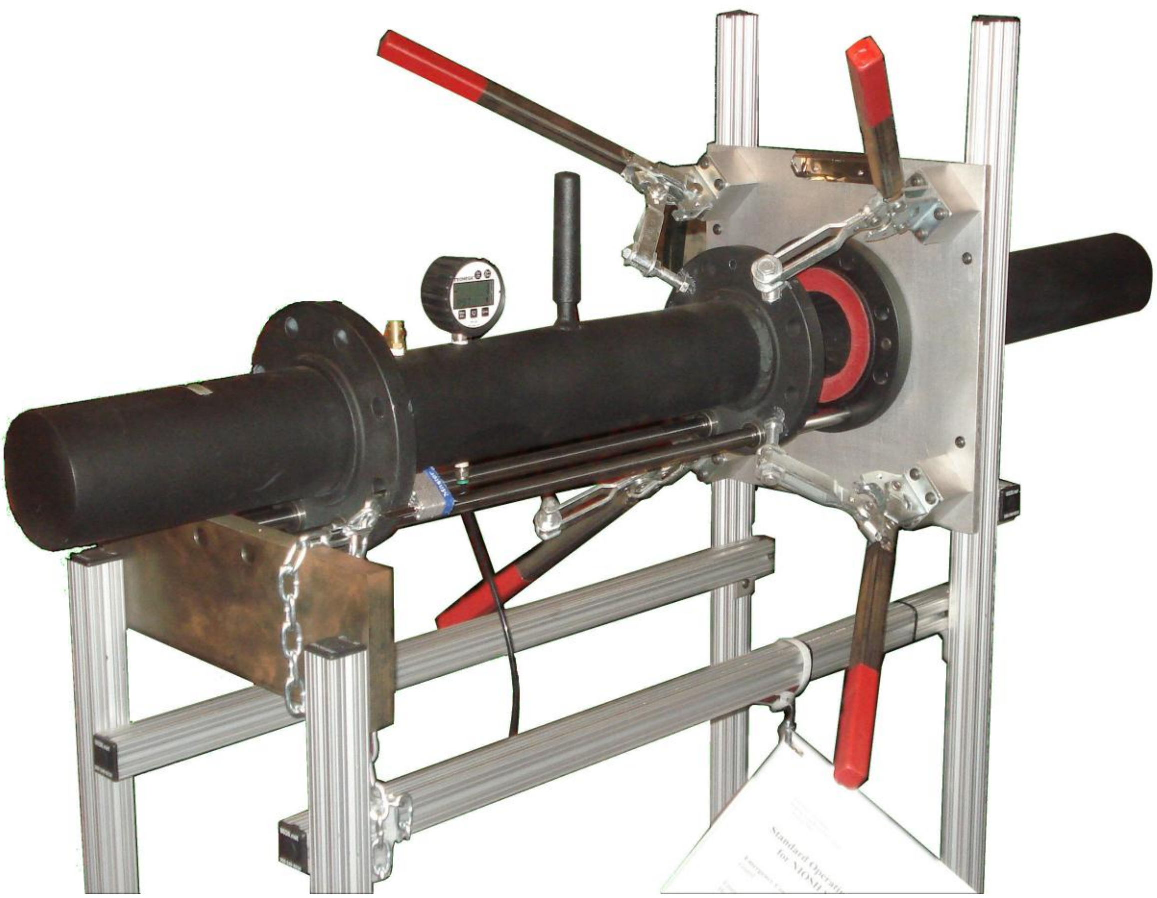

Figure 1: Second prototype of the acoustic shock tube

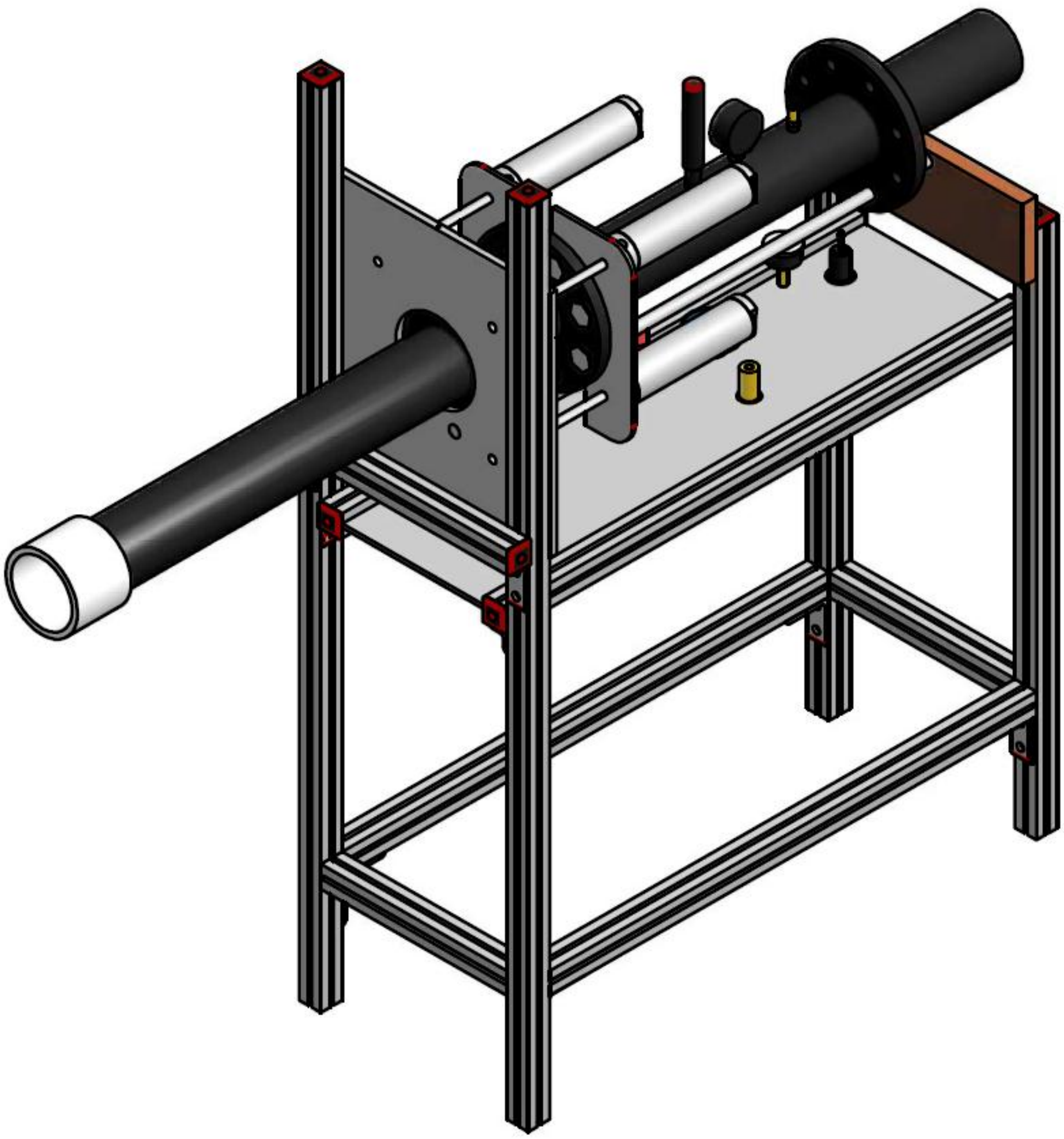

Figure 2: Three dimensional mechanical rendering of the NIOSH acoustic shock tube

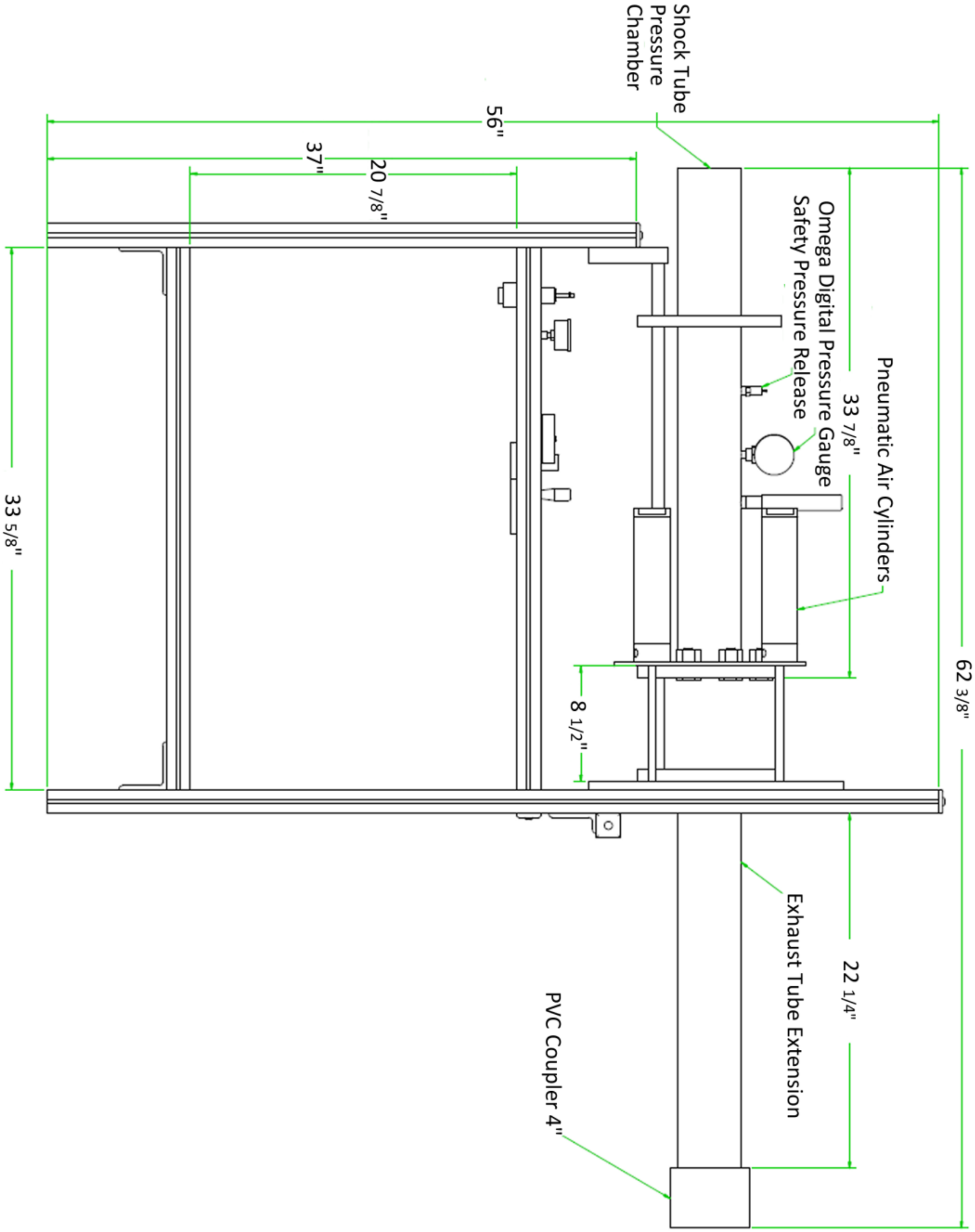

Figure 3: Side view of the acoustic shock tube

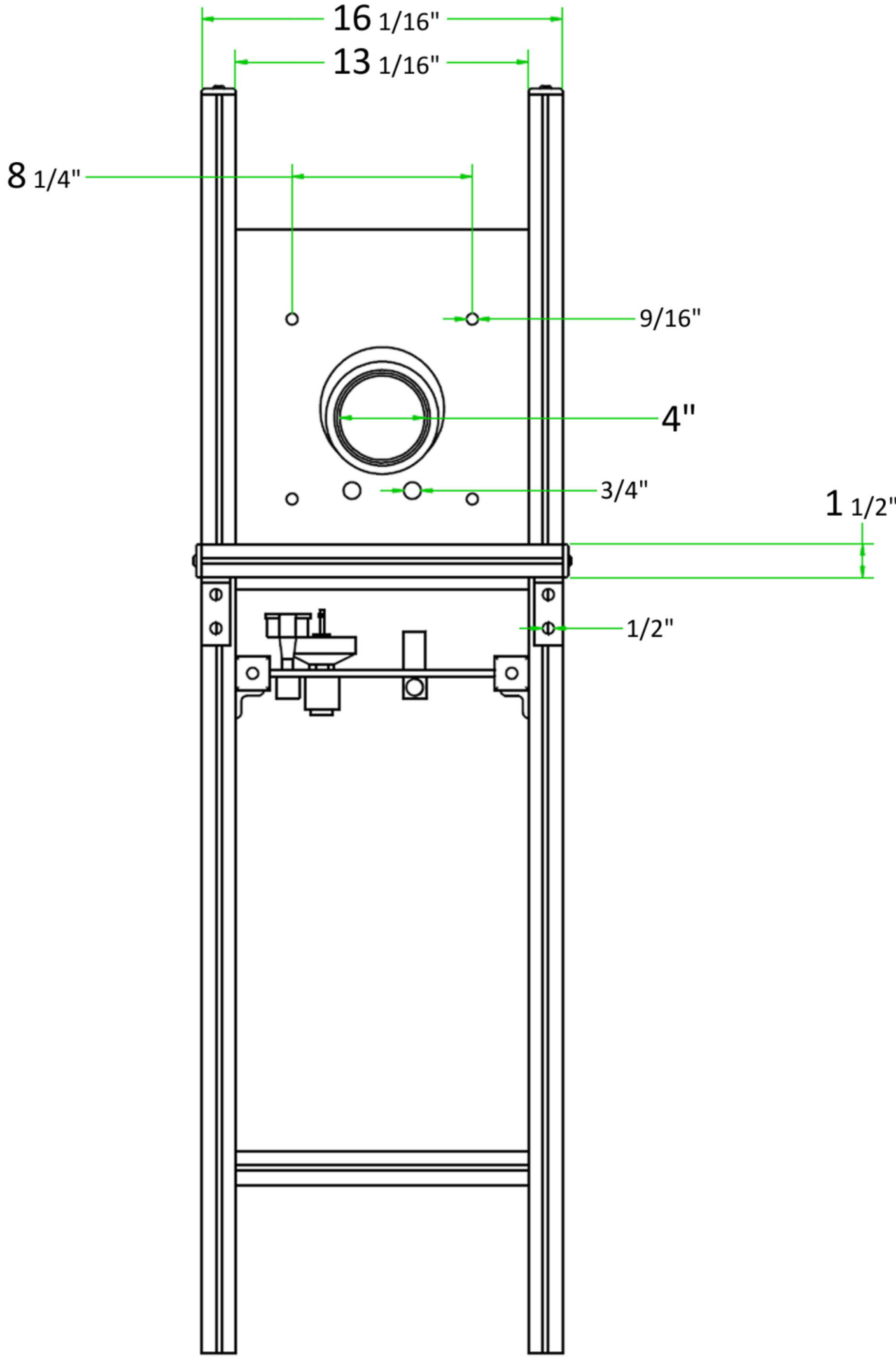

Figure 4: Front view of acoustic shock tube

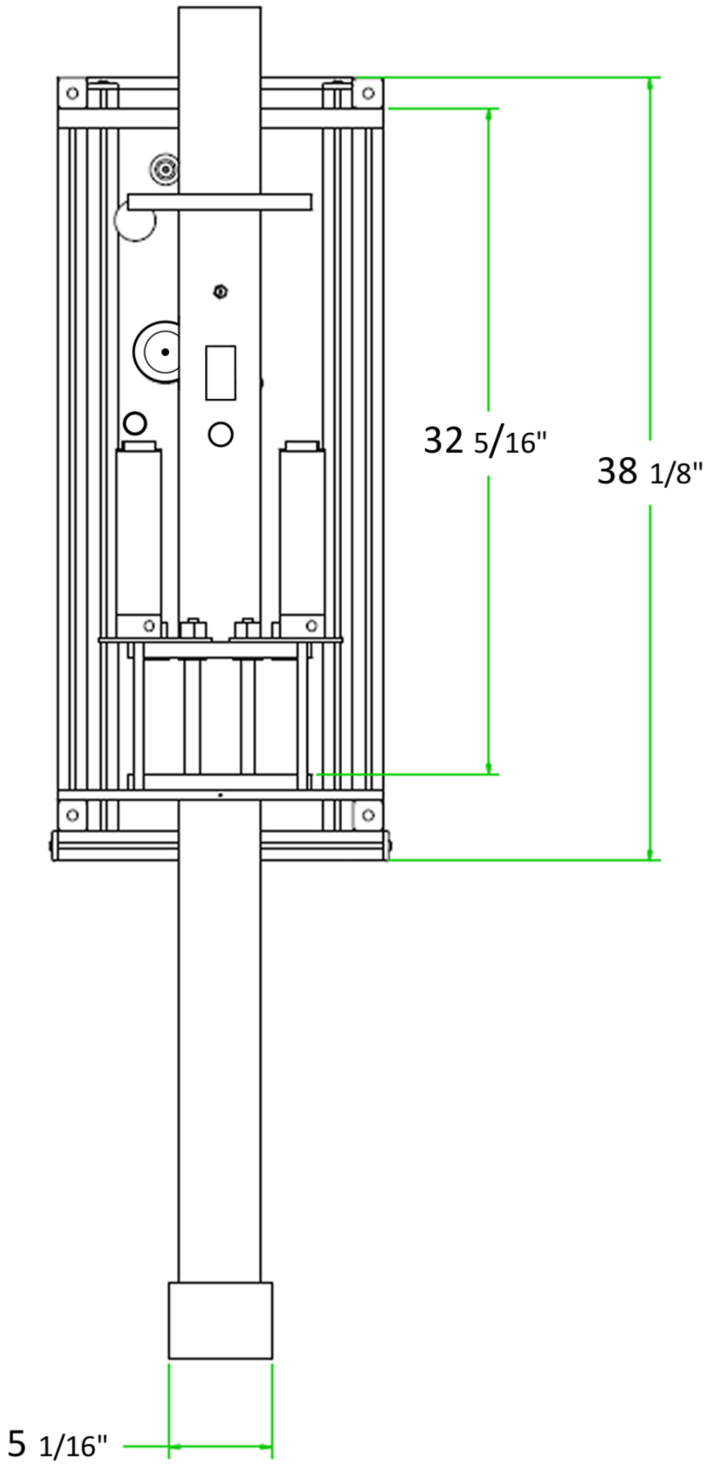

Figure 5: Front view of acoustic shock tube

Figure 6: Top view of acoustic shock tube

Figure 7: Ingersoll Rand, Model 2475N, 7 ½ HP air compressor

Figure 8: SPEEDAIRE three-stage filter for the compressed airflow system

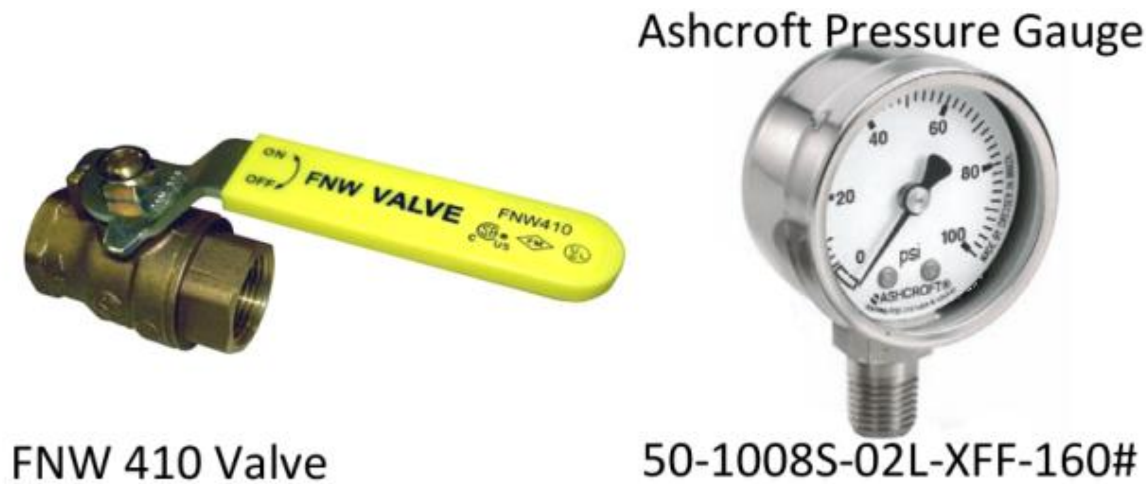

Figure 9: The FNW 410 valve and the Ashcroft analog pressure gauge

Figure 10: DeWalt model D55146 portable air compressor

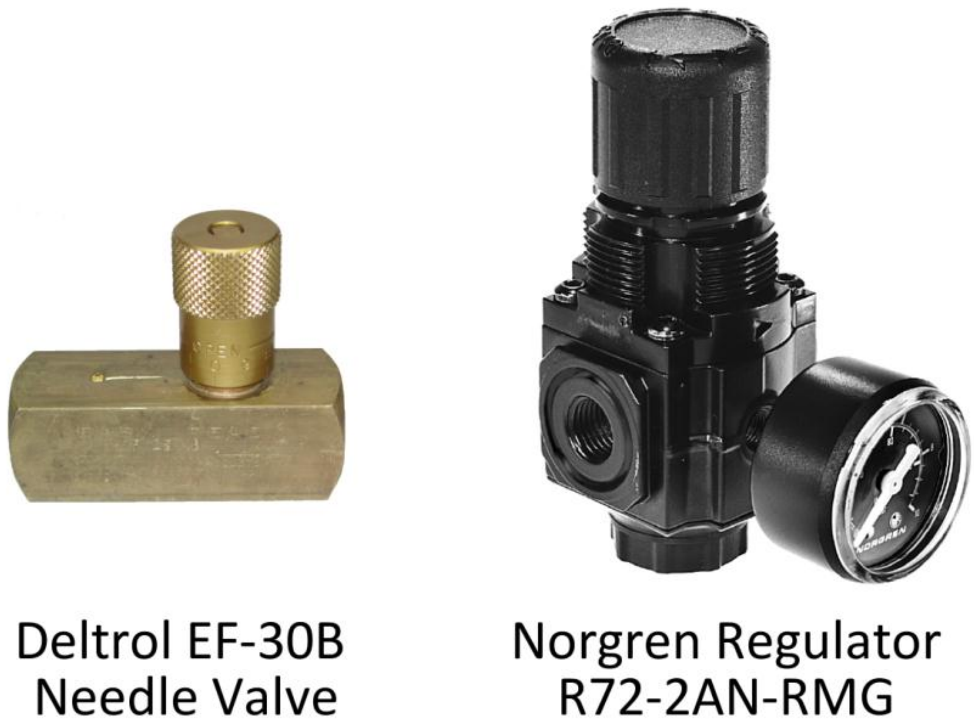

Figure 11: Deltrol needle flow-control valve and Norgren pressure regulator

Figure 12: Mac palm button that activates the Clippard Minimatic Actuator to lance the membrane.

Figure 13: Ingersoll Rand 2-way valve (model M212LS-G) and Arrow silencer (model 1008) for the pneumatic clamping system.

Figure 14: Steuby safety relief valve (model ASM250M) and Omega digital pressure gauge (model DPG 8000-200) mounted on shock tube pressure chamber

Figure 15: SPEEDAIRE air cylinder (model 6D886) and Wilkerson regulator (model R12-02-F000) for pneumatic clamping system

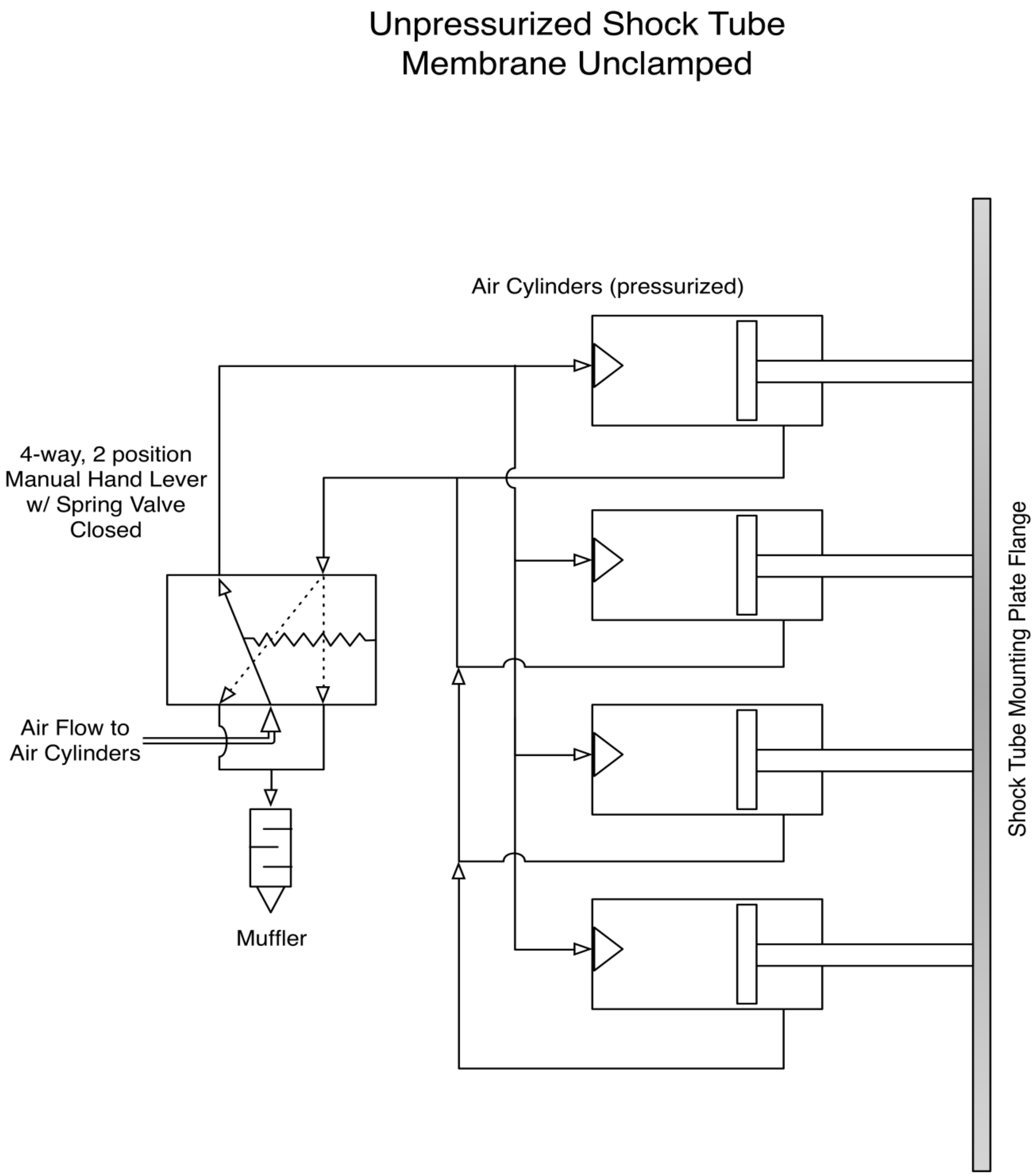

Figure 16: Airflow diagram illustrating the unpressurized shock tube and unclamped membrane

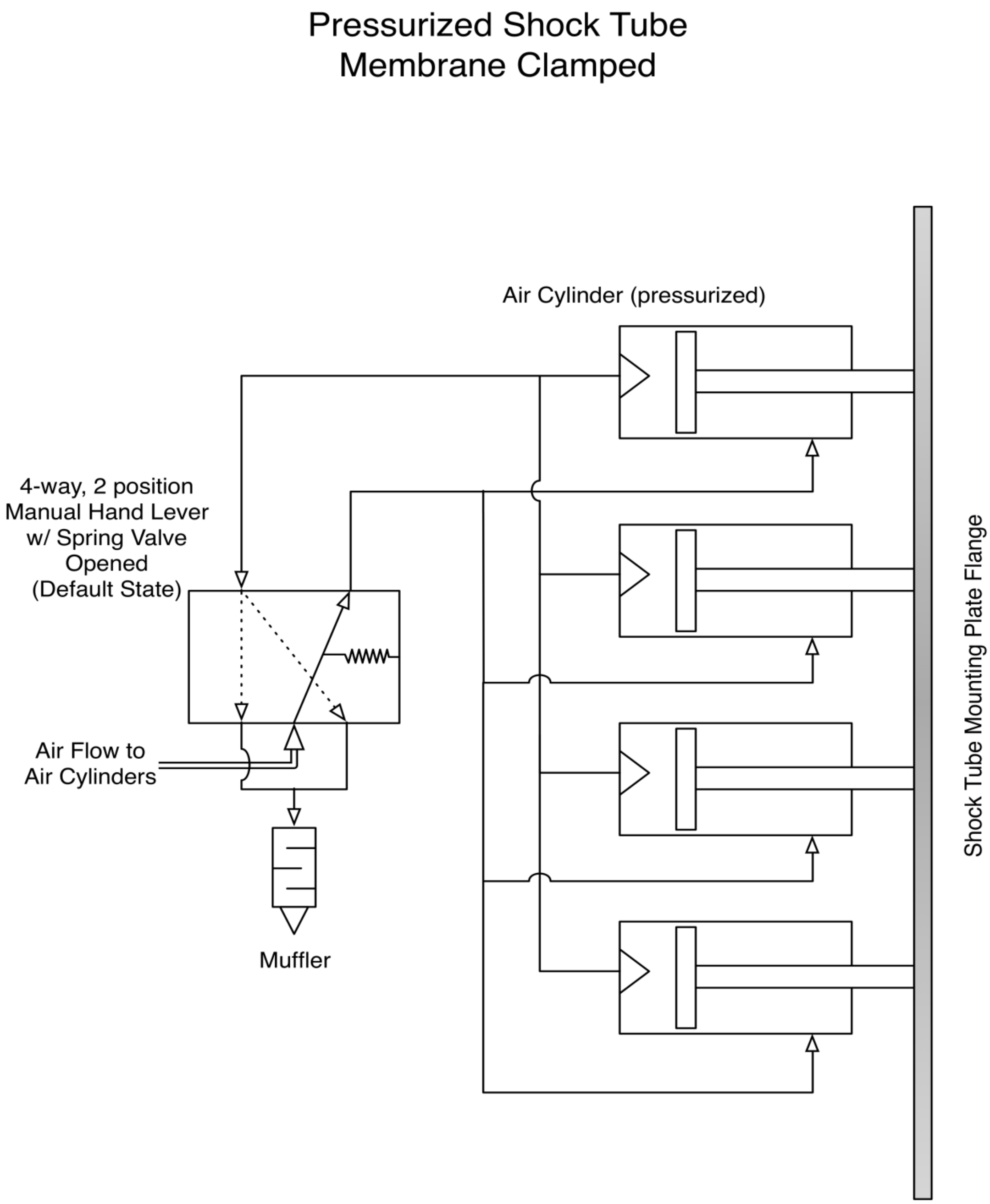

Figure 17: Airflow diagram illustrating the pressurized shock tube and clamped membrane

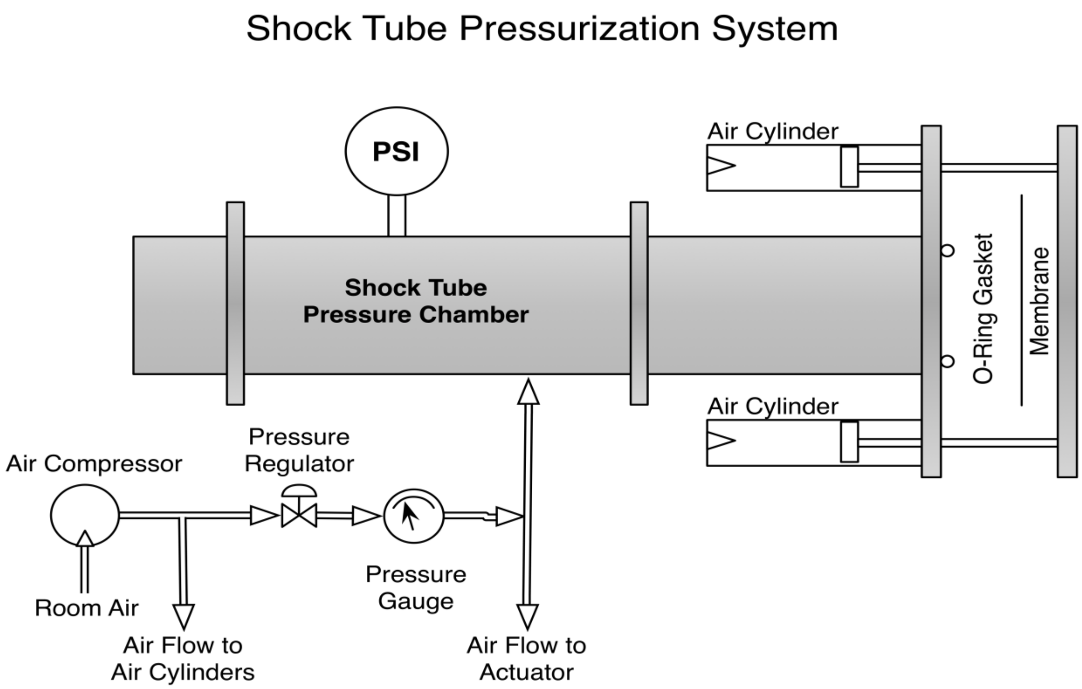

Figure 18: Shock tube pressurization system

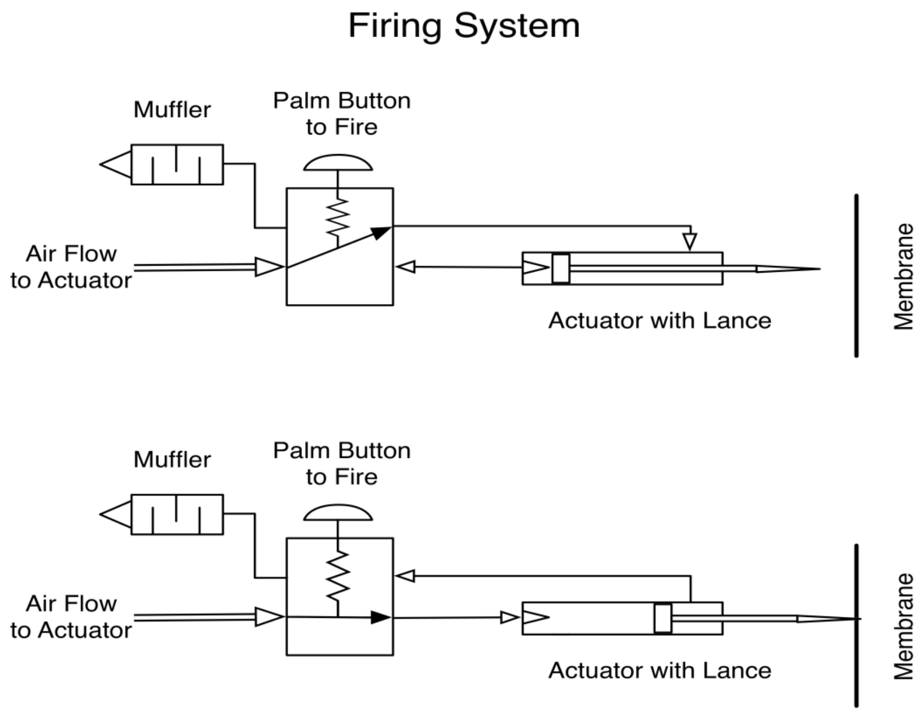

Figure 19: Pneumatic lance system for puncturing the membrane

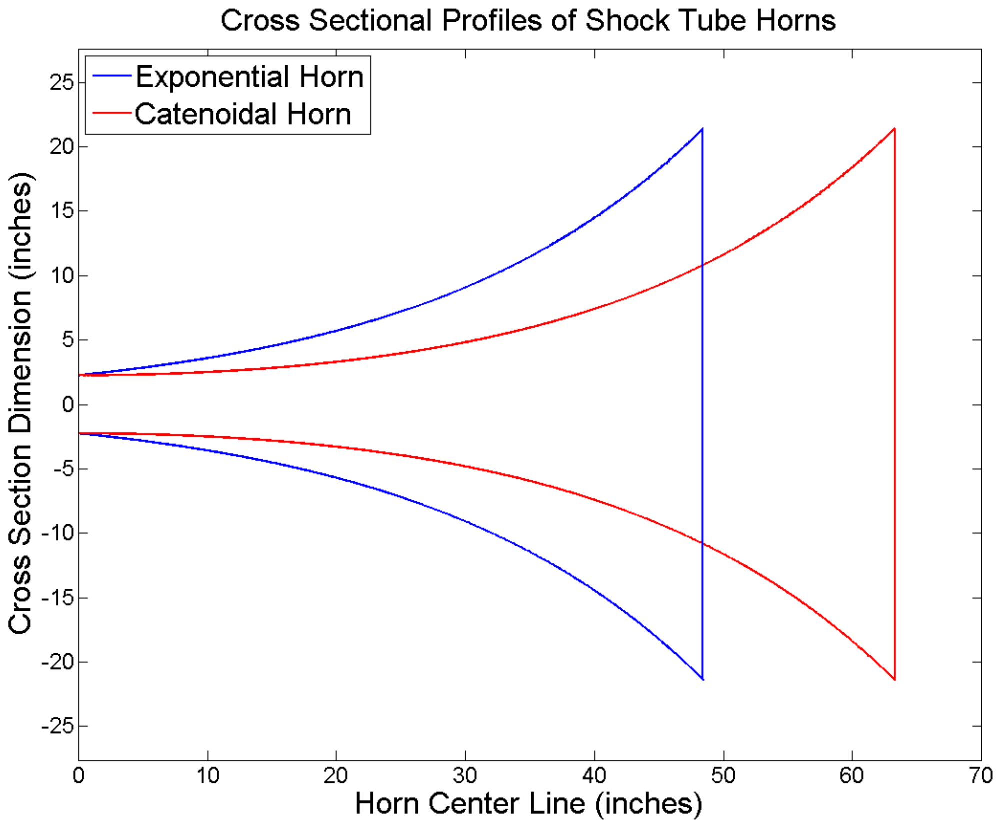

Figure 20: Catenoidal and exponential center-line cross-section profile of the horn

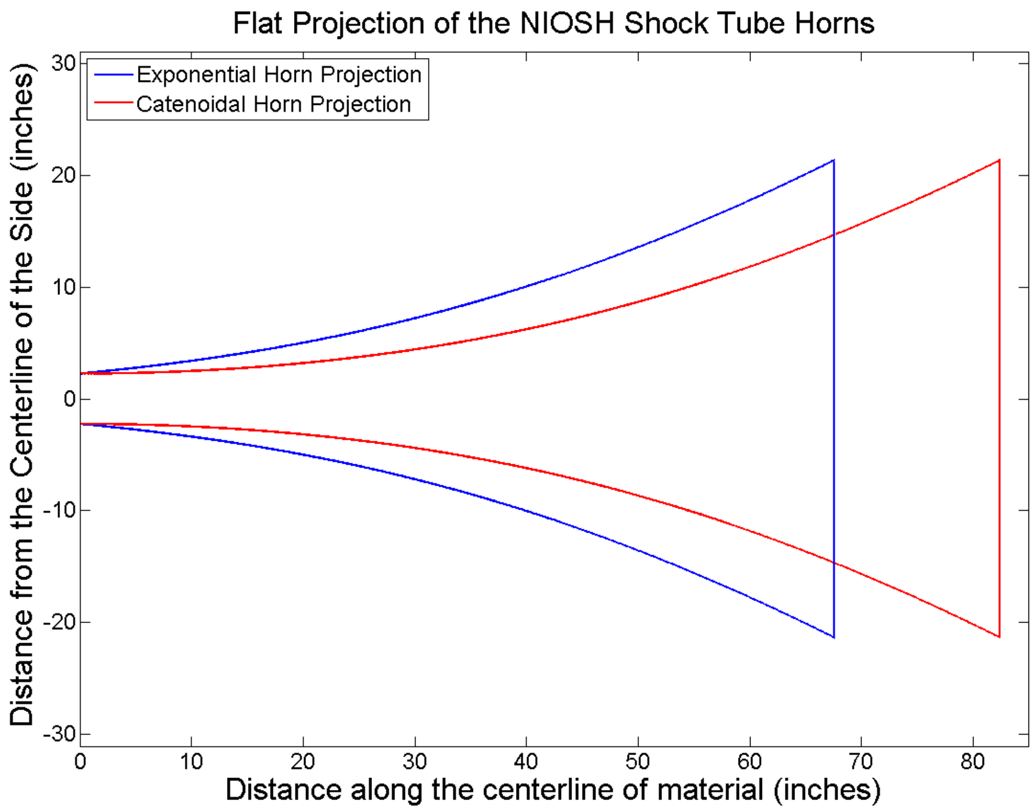

Figure 21: Catenoidal and exponential sides of the horn projected onto a flat surface

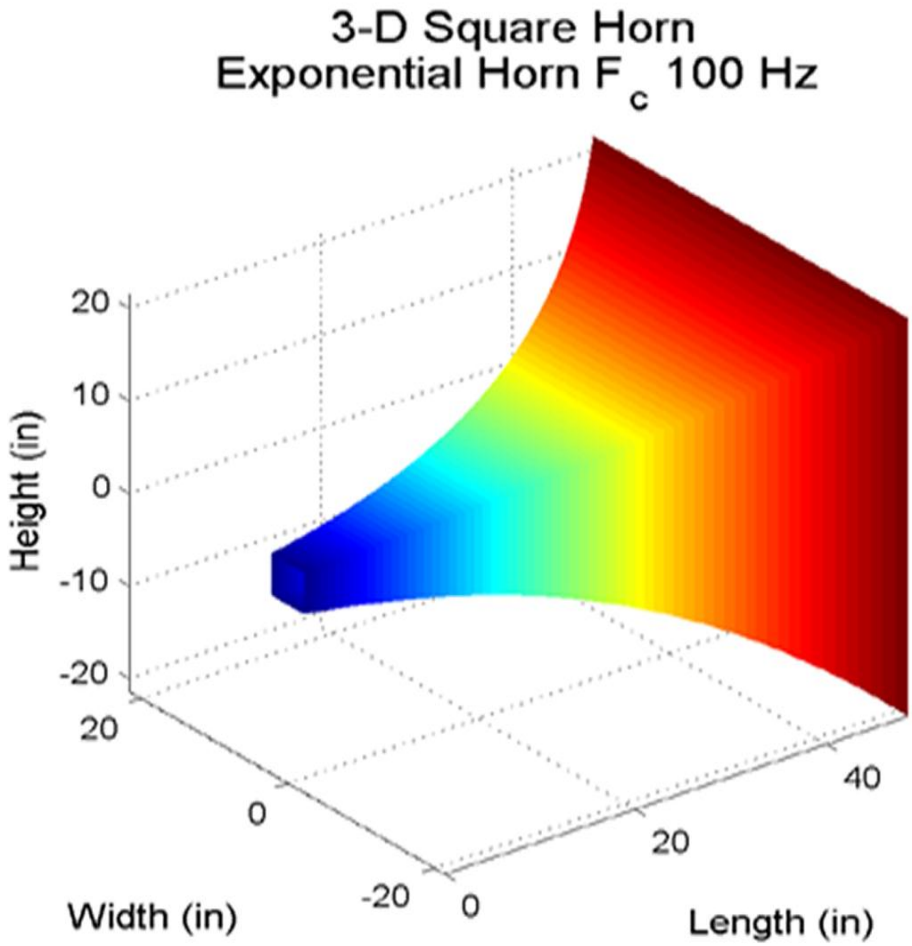

Figure 22: Three-dimensional rendering of the exponential horn

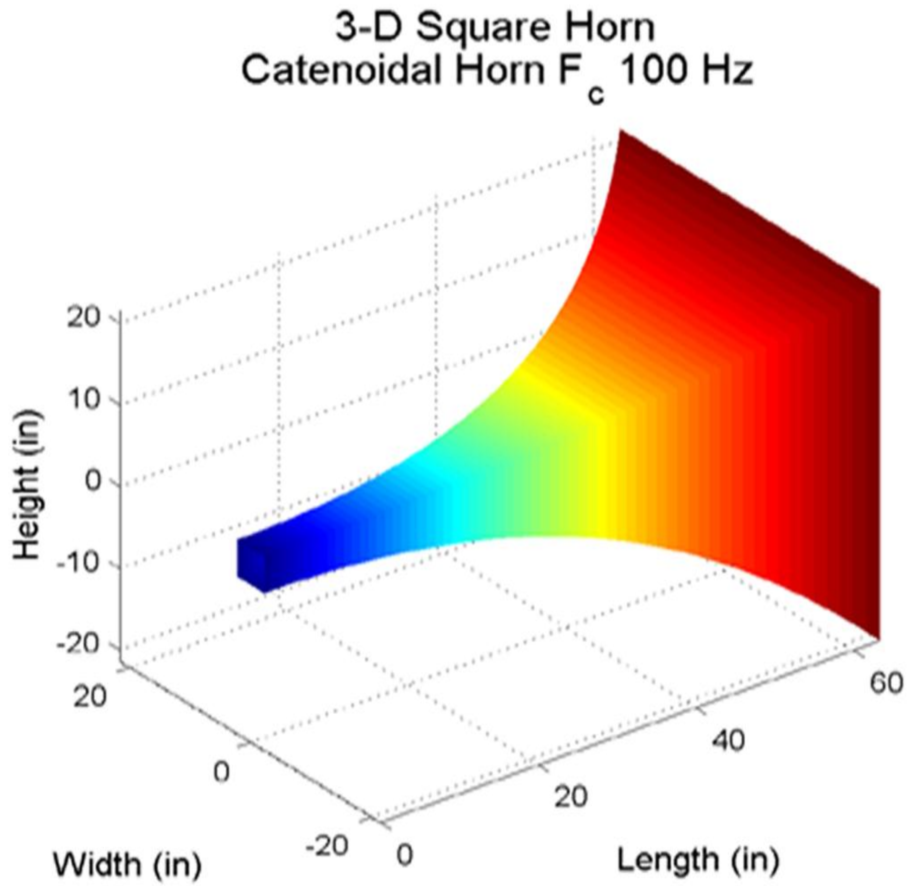

Figure 23: Three-dimensional rendering of the catenoidal horn