Horns as particle velocity amplifiers

Dimitri M. Donskoy[a)]
Stevens Institute of Technology, Hoboken, New Jersey 07030
ddonskoy@stevens.edu

Benjamin A. Cray
Naval Undersea Warfare Center, Newport, Rhode Island 02841-1708
benjamin.cray@navy.mil

Abstract: Preliminary measurements and numerical predictions reveal that simple, and relatively small, horns generate remarkable amplification of acoustic particle velocity. For example, below 2 kHz, a 2.5 cm conical horn has a uniform velocity amplification ratio (throat-to-mouth) factor of approximately 3, or, in terms of a decibel level, 9.5 dB. It is shown that the velocity amplification factor depends on the horn's mouth-to-throat ratio as well as, though to a lesser degree, the horn's flare rate. A double horn configuration provides limited additional gain, approximately an increase of up to 25%.

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1. Introduction

Acoustic pressure receiving horns, commonly used during the first half of the last century (for example, in telephony and for the detection of war planes) were swiftly phased-out and eliminated, primarily due to the development of radar and progress in microphone design. Recently, advances in acoustic particle velocity sensing, both in air[1,2] and water,[3] have created an incentive to revisit passive means for particle velocity amplification. Particle velocity sensors typically are less sensitive and have higher electronic noise floors (especially at low frequencies), than pressure sensors (microphones and hydrophones). Hence, vector sensors may uniquely benefit from additional signal amplification provided by horns.

In terms of pressure, and at low frequencies, the size of an acoustic horn must be quite large (comparable to, or even greater than, the acoustic wavelength) to create any significant amplification. A conventional receiving horn is terminated at the throat with high load impedance, $Z_L \rightarrow \infty$ (which represents the receiving microphone or hydrophone). Here, a conventional "Acoustic Pressure Horn" (APH) will be distinguished from an "Acoustic Velocity Horn" (AVH), where the purpose is to amplify oscillatory particle velocity, rather than pressure, of an incident acoustic wave. Unlike an APH, a AVH must be opened at the throat, as shown in Fig. 1, which of course minimizes the acoustic impedance at the throat. In essence, an AVH works as a funnel, increasing particle velocity within the narrow throat, compared to the velocity at the wider mouth (conservation of mass). Given this, even a relatively small AVH (having a size much smaller than a wavelength) can provide useful velocity amplification.

2. Numerical analysis of acoustic particle velocity horns

Developed in 1919,[4] "Webster's Horn Equation" remains the established approach to horn analysis. However, Webster's formulation utilizes a number of simplifications and assumptions, notably in simplifying the three-dimensional wave equation to a one-

[a)]Author to whom correspondence should be addressed.

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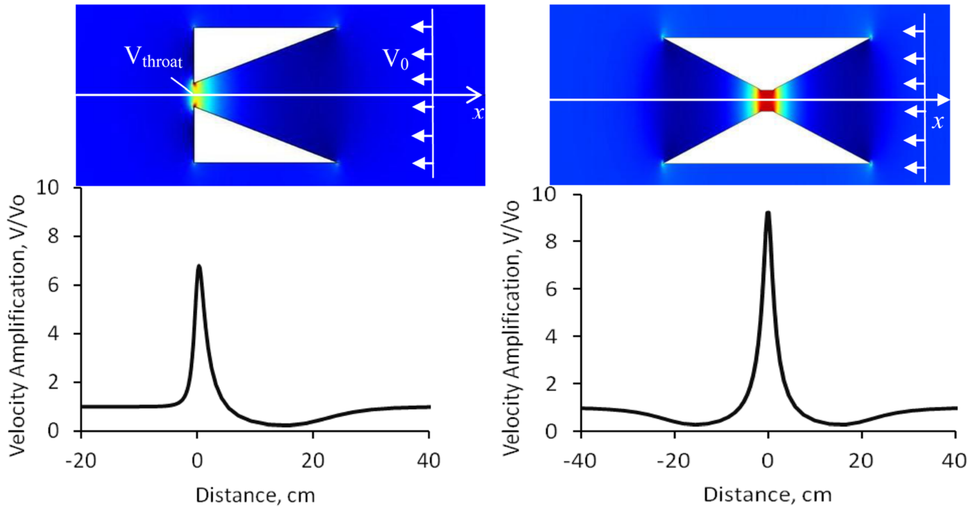

Fig. 1. (Color online) Particle velocity field (upper plots, color on-line) and its dependence on axial coordinate x (lower plots) for axisymmetrical conical horns. In this illustrative example the frequency is 1 Hz, with a single horn length 20 cm, a throat radius of 1 cm and a mouth radius of 5.7 cm. The medium is water.

dimensional problem via a plane wave assumption: the sound energy is uniformly distributed over a plane wavefront perpendicular to horn's axis and that the wave travels only along the axial direction. The formulation serves quite well for many practical evaluations of pressure horns.

With open throat configurations, though, employing Webster's approach is questionable, since the incident wave enters through the mouth and, the same wave, delayed and diffracted over the outer horn surface, also enters through the throat. The distortion of the acoustic field due to diffraction may be significant; not only distorting the amplitude of the wavefront, but also the phase between pressure and particle velocity within the throat. Therefore, in the following analysis, direct numerical solution was utilized using the COMSOL_4.1 aeroacoustics module. Unlike COMSOL's acoustic module, which solves for pressure, the aeroacoustics module solves the wave equation for the velocity potential, ϕ:

$$-\frac{\rho}{c_0^2}\frac{\partial^2\phi}{\partial t^2}+\nabla(\rho\nabla\phi)=0, \tag{1}$$

there ρ and c_0 are fluid density and speed of sound, respectively, and t is the time. Acoustic particle velocity, $\mathbf{v}$, and pressure, p, as a function of distance, $\mathbf{r}$, are determined in the usual manner by

$$\mathbf{v}(\mathbf{r},t)=\nabla\phi, \quad p(\mathbf{r},t)=-\rho_0\frac{\partial\phi}{\partial t}, \tag{2}$$

assuming a fluid with uniform ambient density, $\rho=\rho_0=$constant. For all the horn configurations, COMSOL 2D axisymmetrical geometry was assumed along with rigid boundaries for all horn surfaces.

Figure 1 illustrates the single and double axisymmetrical conical horn geometry and the axial velocity fields due to an incident wave (traveling with velocity amplitude V_0) toward horn's mouth. The amplification effect at the horn's throat is clearly evident.

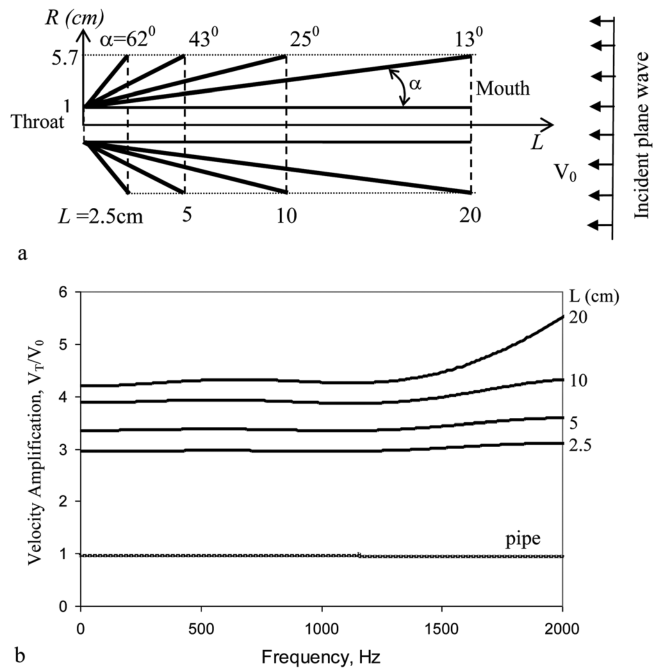

Fig. 2. (a) Varying horn geometry, and (b) respective velocity amplification frequency responses.

An attractive characteristic of an AVH is the apparent uniform gain over a very broad range of frequencies below the horn's first resonance. The amplification responses, measured at the AVH throat, for various horn geometries [as shown in Fig. 2(a)] are provided in Fig. 2(b). In this analysis, the horn's length varied from 2.5 cm to 20 cm, while the mouth-to-throat radii ratio, K, was fixed at 5.7. In all cases, the throat velocity, V_T, was normalized to velocity amplitude, V_0, of the incident wave, thus, the ratio V_T/V_0, has been denoted as the horn's velocity amplification factor. (Note, in these figures, the amplification factor is given on a linear scale.) For reference, the response of a pipe, having the same radius as the throat, is also shown in

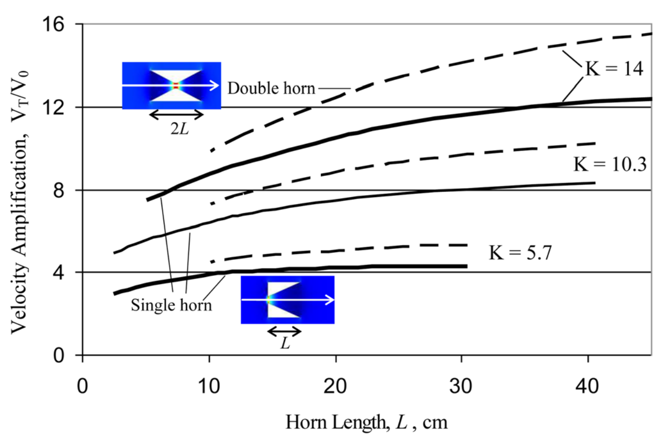

Fig. 3. (Color online) Horn amplification vs length, L, for various mouth-to-throat radii ratios, K, for both single (solid) and double (dashed) conical horns. The throat radius is fixed at 1 cm.

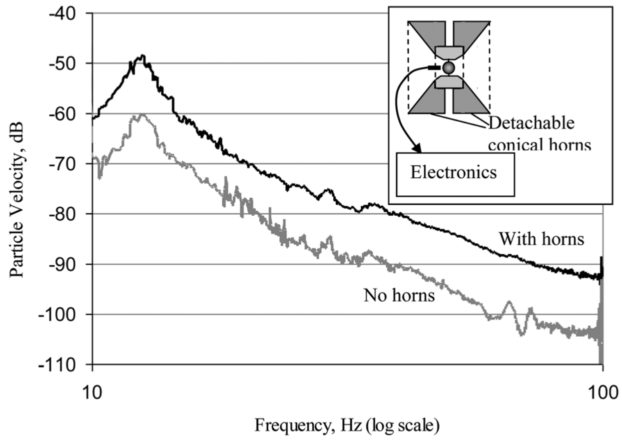

Fig. 4. Cross-section diagram of the velocity sensor with detachable axisymmetrical horns (upper right corner) and its frequency responses in air with no horns (lower curve) and with horns (upper curve).

Fig. 2(b). As expected, the pipe response is unity within this frequency range; that is, a straight pipe provides no amplification below its first resonance.

As shown, an AVH provides appreciable amplification, even the smallest (2.5 cm) horn achieves an amplification factor of approximately 10 dB. Greater amplification is achieved for horns with increasing mouth-to-throat radii ratio, K, as shown in Fig. 3. Unexpectedly, a double horn does not double the amplification factor. Indeed, the amplification increase is marginal, only up to 25%, as compared to a single horn having half the length. Also, notice that for the fixed K, increasing the horn's length yields only a marginal increase in amplification once the cone angle decrease to approximately 20°–25°, as indicated in Fig. 3.

3. Experimental verification of the amplification effect

Experimental verification was conducted in-air in an anechoic chamber at the Naval Undersea Warfare Center (NUWC) Division, Newport, RI, using a non-inertial particle velocity sensor.[5] Although the sensor was designed for underwater measurements, it is sensitive enough for measurements in-air. The sensor consists of a hollow aluminum sphere of 1.9 cm diameter, suspended, with two strings, in a plastic housing. The acoustic induced motion of the sphere is measured with an extremely sensitive eddy-current displacement sensor. The sensor is equipped with a pair of removable conical horns (see inset in Fig. 4), creating a symmetrical double-horn configuration.

The throat radius of the horns was, $R_T = 3.2$ cm, and the mouth radius was, $R_M = 12.7$ cm; which yielded a mouth-to-throat ratio of $K = 4$. The length of each horn was 12.7 cm.

The measured frequency responses of the sensor, with and without horns, are shown in Fig. 4. The obvious resonance, near 12 Hz, is due to the suspension of the sphere. These measurements, which verify a broadband velocity amplification of 10–11 dB, are in good agreement with the numerical predictions of 11.3 dB.

4. Conclusion

Numerical modeling revealed that horns provide excellent particle velocity amplification, with a uniform frequency response over a broad frequency range, below horn's first resonance frequency. The particle velocity amplification factor depends on the horn's mouth-to-throat radii ratio and, to a lesser degree, the horn flare rate. For conical horns, the amplification gains saturate as cone angle decreases to about 20°–25°. A double-horn symmetrical configuration does provide additional, but limited, amplification of approximately 25%. The numerical findings were experimentally verified, in-air, using a particle velocity sensor, configured with a pair of detachable horns.

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