Research on the Design of Sound Horn Based on Optimizing the Transmission of Human Voice

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Abstract. Trumpet is very common in daily life and plays an important role. With the development of science and technology, the research on the physical characteristics and performance of the horn has reached a new level. For a long time, the research on electrical loudspeaker and other electronic products is more popular, while the design of horn which can optimize the human voice transmission is less involved. Aiming at this research direction, this paper introduces in detail the influence of horn parameters on the sound output of human voice frequency. Based on the theoretical calculation results, the sound horn with good performance is manufactured by using 3D printing technology, and relevant experiments are designed. Combined with the theoretical and simulation results, the performance of the horn with different parameters is explored to optimize the voice transmission to distant listeners, which are helpful to further understand the performance of the horn, are applied in various fields.

Keywords: Optimize voice transmission, sound power distribution, frequency characteristics, directivity, inauthenticity

1. Introduction

As we all know, we put the palm shaped horn on the mouth, which can make the sound spread further. This is the simplest application of the horn. With the development of history, the sound horn is also in continuous development. At present, the widely used sound horn is a driving unit connected with a (or a group of) horns to radiate sound waves in one direction. In human society, the horn plays a very important role.

For the nature and function of the horn, many scholars have carried out a lot of research on it, and many theories have been born. Among them, the research by Du Gonghuan of Nanjing University is more recognized in China. In his book "Fundamentals of acoustics", the author analyzes the characteristics of the sound field inside the horn, points out the reasons why the horn can transmit sound, and deduces the basic equation of the sound field [1]. In the foreign research, foreign scholars mentioned the characteristics of the horn sound field more carefully, and put forward that sound power, frequency characteristics, directivity and fidelity are the four criteria to measure the performance of the horn [2, 3].

Through the research on the published literature and books about the characteristics and performance of the horn, it is found that all the relevant research is carried out around the working principle and characteristics of the electrical loudspeaker, while there is no specific research on the change of the internal sound field of the horn and the design of the best performance horn when the
voice or voice frequency band is input [4]. Through the combination of theory, simulation calculation and experimental analysis, this paper summarizes the acoustic environment of the horn, deduces the velocity potential of air particles in the horn, introduces the experimental equipment and experimental environment, and points out the parameters of the study and the parameters to measure the performance of the horn. Considering the sound power, frequency characteristics, directivity and distortion of the four aspects of the performance of the horn to the human voice transmission, this paper focuses on the analysis of the effect of the output of the voice through the horn, and compares the amplification effect of the horn with different parameters, and finally determines the design parameters of the horn which can optimize the human voice transmission.

2. Sound Field of the Trumpet

In this study, understanding the sound field of the horn is the prerequisite for the study of the horn. Inside the horn, the sound propagates in the form of plane wave. The sound intensity  \( I = \frac{p^2}{2\rho c} \) does not decay with distance. However, outside the horn is a free sound field, sound propagates in the form of spherical wave without reflected wave. The sound intensity \( I = \frac{A}{2\rho c r^2} \) attenuates in inverse square law [5].

Inside the horn, the sound passes through the throat and produces a plane wave with the wave front perpendicular to the axis. If the displacement of the air particle at \( x \) is \( u \) and the sectional area of the horn is \( S \), then the volume change is

\[
\delta V = S \frac{\partial u}{\partial x} \delta x + u \frac{\partial S}{\partial x} \delta x
\]

(1)

The pressure change is

\[
p = -\gamma P_0 \frac{\delta V}{V}
\]

(2)

where \( \gamma \) is specific heat ratio, \( P_0 \) is atmospheric pressure. Using momentum theorem

\[
p = \rho_0 \frac{\partial \phi}{\partial t}
\]

(3)

Where, \( \rho_0 \) is the air density, \( \phi \) is velocity potential. For the simultaneous formula (1) (2) (3), the partial derivative of T is obtained

\[
\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial \ln S}{\partial x} \frac{\partial \phi}{\partial x} = \frac{\rho_0}{\gamma \rho_0} \frac{\partial^2 \phi}{\partial t^2}
\]

(4)

For the exponential horn with winding index \( m \), its cross-sectional area is a function of \( x \):

\[
S(x) = S_0 e^{mx}
\]

(5)

Therefore, the velocity potential is:

\[
\phi = A e^{-\frac{m}{2}x - j \sqrt{k^2 - \frac{m^2}{4}}} + B e^{-\frac{m}{2}x + j \sqrt{k^2 - \frac{m^2}{4}}}
\]

(6)

For conical horns, the radius of the smaller diameter is \( r_0 \) and the cross-sectional area is also a function of \( x \):

\[
S(x) = \pi (nx + r_0)^2
\]

(7)

Therefore, the velocity potential is:

\[
\phi = \frac{\sin \left[ \sqrt{k} \left( x + \frac{r_0}{\pi} \right) \right]}{\sqrt{k} \left( x + \frac{r_0}{\pi} \right)}
\]

(8)

where \( k \) is the wave number.
3. Theoretical Analysis of Horn Performance

3.1. Sound Power

In the process of sound transmission, the vibration velocity of sound is

\[ v = -\frac{d\phi}{dx} \]  \hspace{1cm} (9)

The sound pressure is

\[ p = j\omega\rho_0\phi \]  \hspace{1cm} (10)

The acoustic impedance is

\[ z = \frac{pS}{v} = R + jX \]  \hspace{1cm} (11)

Thus, it is deduced that the radiated sound power is

\[ W = Rv^2 \]  \hspace{1cm} (12)

According to this formula, it can be seen that the sound power is related to the opening size of the horn. The larger the opening area is, the greater the sound resistance is, and the greater the radiated sound power is.

Using the sound pressure level distribution map of COMSOL simulation horn, the sound source frequency is set at 1 kHz. As shown in figure 1, figure 1 (a) represents that the sound pressure level decreases rapidly with the increase of distance in the environment with only sound source and no horn. Figure 1 (b) and figure 1 (c) show the distribution of sound pressure level under the condition of having a horn. It can be seen that the strong sound pressure level extends outward obviously, and with the increase of the length of the horn, the opening area expands, and the strong sound pressure level can extend to further places, thus verifying the conclusion of formula (12).
3.2. Frequency Characteristic

The shape of the horn affects the cut-off frequency of sound. The sound wave below the cut-off frequency will be attenuated in the horn. The cut-off frequency is related to the meandering index $m$:

$$f_c = \frac{mc}{4\pi}$$ (13)

Therefore, the winding index $m$ should be selected reasonably in the design process to obtain a better amplification effect of low frequency sound.
For hyperbolic horn, the expression of sectional area curve cluster is as follows:

\[ S = S_0 (\cosh mx + T \sinh mx) \]  

(14)

where \( T \) is the parameter of the shape of the horn, and the value of \( T \) can be from zero to infinity. when \( T = 1 \), it is an exponential horn, and when \( T \to \infty \), it is a conical horn.

when \( Q = \frac{2k}{m} \) is taken as the variable, the acoustic impedance per unit area of hyperbolic horn is

\[ z_{0+} = \rho_0 c \left[ \frac{\sqrt{Q^2 - 1}}{a^2 - (1 - T^2)} + j \frac{aT}{a^2 - (1 - T^2)} \right] \]  

(15)

The horn is equivalent to a simple circuit. As shown in figure 2, the output of the horn is equivalent to the output of the resistance \( R_{\text{external}} \) (i.e. load resistance), and the impedance of the horn is equivalent to the resistance \( R_{\text{horn}} \) (i.e. internal resistance). When the resistance values of the two resistors are the same, the output power reaches the maximum and reaches the impedance matching state. For different \( T \) values, the impedance versus frequency curve is plotted, as shown in figure 3.

In figure 3, three trumpets with different shapes of \( T = 1, 0.6 \) and 0.5 are drawn. For human voice, the closer the ratio is to 1, the better the corresponding output effect is. Therefore, the hyperbolic tube with \( T = 0.6 \) has the best sound resistance matching degree and the best low-frequency characteristics, which is better than the exponential type tube.

\[ R_{\text{horn}} \]

\[ p \sim \Omega = 2k/m \]

\[ R_{\text{external}} \]

**Figure 2.** Equivalent circuit.

**Figure 3.** Matching curve.

### 3.3. Directivity of Frequency Characteristics

The mouth of the horn is equivalent to a circular piston vibration plate with radius \( a \) and the directivity of the circular piston is

\[ D = \left| \frac{\theta(y)}{\theta(0)} \right| = \left| \frac{2J_1(k\sin y)}{k\sin y} \right| \]  

(16)
where $\gamma$ is the direction angle, $J_1$ is the first order Bessel function of the first kind.

The working range of horn is when $D$ is 0.5, that is, when the sound pressure is 6 dB lower than that on the axis. At this point,

$$\gamma_{0.5} = \arcsin\left(\frac{2.216}{ka}\right)$$

(17)

The far-field working range of hyperbolic and exponential horns is plotted by COMSOL, as shown in figure 4 and figure 5.

![Figure 4. Operating range of hyperbolic horn.](image)

![Figure 5. Operating range of exponential horn.](image)

It can be seen from figure 4 and figure 5 that the working range of the exponential horn is wider.

3.4. Distortion
Distortion characteristic is one of the most important physical characteristics of sound reproduction system. Due to the nonlinearity of horn system, all harmonics are produced, which leads to harmonic
distortion and intermodulation distortion, which changes the spectrum and leads to the change of timbre.

For harmonic distortion, the equation of passive linear sound field can be written as follows

$$\frac{\partial^2 \psi_1}{\partial t^2} - c_0^2 \frac{\partial^2 \psi_1}{\partial x^2} = 0$$  \hspace{1cm} (18)

For the quadratic nonlinear active sound field, the equation is as follows:

$$\frac{\partial^2 \psi_2}{\partial t^2} - c_0^2 \frac{\partial^2 \psi_2}{\partial x^2} = \frac{\partial}{\partial t} \left[ \left( \frac{\partial \psi_1}{\partial x} \right)^2 + \frac{\gamma - 1}{2c_0^2} \left( \frac{\partial \psi_1}{\partial t} \right)^2 \right]$$  \hspace{1cm} (19)

If $\psi_1 = A \cos \left( \omega \left( t - \frac{x}{c_0} \right) \right)$,

$$\psi_2 = -\frac{\beta \omega^2 A^2}{4c_0^3} x \cos \left( 2 \omega \left( t - \frac{x}{c_0} \right) \right)$$  \hspace{1cm} (20)

where $\beta = 1.2$ is nonlinear coefficient of air.

In the nonlinear medium, the fundamental frequency excites the second harmonic frequency, and the nonlinear effect gradually accumulates with the increase of the length of the horn.

Next, the distortion degree of the second harmonic of the horn is calculated, and the curve relationship between the second harmonic sound pressure level and the length of the two horns (as shown in figure 6) and the curve relationship between the fundamental wave, second harmonic and the length of the exponential horn are drawn (as shown in figure 7).

![Figure 6. Degree of second harmonic distortion.](image-url)
Figure 7. Nonlinear distortion of exponential horn.

It can be seen from figure 8 that with the increase of the length of the horn, the faster the cross-section changes, the greater the amplitude of the second harmonic. Combined with figure 8, in order to ensure that the sound pressure level of the second harmonic is lower than 20dB, the length of the horn should not be greater than 0.4m.

Figure 8. Distortion of the horn.

For intermodulation distortion, substitute

$$\phi_1 = A_1 \cos \left( \omega_1 \left( t - \frac{x}{c_0} \right) \right) + A_2 \cos \left( \omega_2 \left( t - \frac{x}{c_0} \right) \right)$$

(21)

into equation (20):
\[
\Phi_2 = -\frac{\beta \omega_1^2 A_1^2}{4c_0^3} \times \cos \left(2\omega_1 \left(t - \frac{x}{c_0}\right)\right) - \frac{\beta \omega_1^2 A_1^2}{4c_0^3} \times \cos \left(2\omega_2 \left(t - \frac{x}{c_0}\right)\right) + \frac{\beta \omega_1 \omega_2 A_1 A_2}{2c_0^3} \times \cos \left((\omega_1 - \omega_2) \left(t - \frac{x}{c_0}\right)\right)
\]

In intermodulation distortion, two different frequencies of sound waves in nonlinear media do not meet the principle of linear superposition, which will produce double frequency, sum frequency and difference frequency distortion. The degree of such distortion is also positively related to the length and cross-section area of the horn.

4. Experimental Analysis of Horn Performance

In the process of the experiment, in order to maximize the simulation of this free sound field, the experiment is carried out in the anechoic recording studio. The wall of the anechoic recording studio is of wedge structure and covered with porous sound absorption materials, which can minimize the interference of reflected sound and approximately meet the conditions of free sound field. In addition, in order to ensure that the inner part of the horn is a plane wave, a mini sound with the same caliber as the horn is selected to ensure that all the sound waves are input into the inner part of the horn and are approximately plane waves. For the receiving device, choose the U87 microphone. This microphone is heart-shaped, which is conducive to receiving direct sound. Moreover, the frequency bandwidth, flat response and high fidelity can reduce the system error of experimental data [6].

For a horn, its parameters include shape, size and material. The type and parameters of the cross-section curve of the horn determine the shape of the horn, including straight-line type, exponential type and hyperbolic type. The bending degree of the horn is represented by the winding index \( m \), which affects the cut-off frequency of the sound; the throat diameter and axial length determine the size of the horn, thus determining the opening sectional area and directivity of the horn. For the material of the horn, 3D printing technology is used in the experiment to print the horn made of resin and paper materials.

Before measuring the amplification effect of the horn, it is necessary to set the control group, that is, to keep the same level of the speaker, and not to place the horn to measure the sound intensity (level) at a specific distance, so as to measure the output effect of the horn. In the experiment, set up the experimental group, control the distance, frequency, angle three variables. In the variable of distance, first measure the amplification effect of the near-field of the horn (0.5m away from the horn, about the length of a horn), and then measure the amplification effect of the far-field of the horn (3m away from the horn, about the length of eight horns). In the frequency variables, four single frequency sounds (110Hz, 440Hz, 1000Hz, 3000Hz) in the vocal frequency band are selected to represent the bass and treble of the human voice respectively. In addition, in order to simulate the most real human voice state, the human voice is recorded in the experiment to measure the amplification ability of the horn to the multi band sound. In the variable of angle, change the direction of the horn from 0° to 30° and 60° to measure the directivity of the horn.

In the following experiments, sound power, frequency characteristics, directivity and distortion are used to measure the optimization effect of horn on human voice.

4.1. Sound Power

In the process of experiment, the effect of horn material on its amplification effect is mainly explored. The conical horn made of A4 paper and resin is used for amplification experiment. The parameters of the horn are shown in table 1.

The experimental results are shown in table 2. According to the experimental data, the amplification effect of A4 paper horn and resin horn is basically the same, but because the paper is relatively soft sound field boundary, small deformation will occur in the process of sound propagation in the A4 paper horn, which will disturb the sound field inside the horn, and there is sound absorption and transmission. The amplification effect of A4 paper horn is slightly weaker than that of resin horn.
4.2. Frequency Characteristic

First, the influence of the shape of the trumpet on the amplification effect is studied. The conical and exponential horn of resin are used for the experiment. The experimental parameters are shown in table 3. The experimental results are shown in table 4.

It can be seen from table 4 that the amplification effect is better than that of conical horn because the cross-section area of the opening of exponential horn is larger. In addition, in the third group, the winding index of the exponential horn is 4, and the sound source frequency is close to the cutoff frequency, so its sound amplification capacity is weaker than that of the tube with winding index of 2.

In order to verify the response of horn with different shapes to frequency characteristics, experiments were carried out on hyperbolic type and exponential type tube with different input frequencies. The experimental parameters are shown in table 5. The experimental results are shown in table 6.

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### Table 1. Experimental parameters

| Throat diameter /cm | Length /cm | Sound source frequency /hz | Distance between receiving device and sound source /m |
|-------------------|-----------|---------------------------|-----------------------------------------------------|
| 3                 | 15        | 440                       | 0.5                                                 |

### Table 2. The parameters of horn.

| Material quality | Electrical level /dB |
|------------------|-----------------------|
| A4 paper horn    | +6.31                 |
| Resin horn       | +6.66                 |

### Table 3. Experimental parameters.

| Order number | Shape               | Winding index | Length/m | Sound source frequency /Hz | Distance between receiving device and sound source /m |
|--------------|---------------------|---------------|----------|---------------------------|-----------------------------------------------------|
| 1            | Conical horn        | \             | 0.15     | 440                       | 0.5                                                 |
| 2            | Exponential horn    | 2             | 0.15     | 440                       | 0.5                                                 |
| 3            | Exponential horn    | 4             | 0.15     | 440                       | 0.5                                                 |

### Table 4. The experimental results.

| Order number | Shape               | Winding index | Magnified value /dB |
|--------------|---------------------|---------------|---------------------|
| 1            | Conical horn        | \             | +6.66               |
| 2            | Exponential horn    | 2             | +7.26               |
| 3            | Exponential horn    | 4             | +4.71               |

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### Table 5. Experimental parameters.

| Shape               | Exponential type | Hyperbolic type |
|---------------------|------------------|-----------------|
| Winding index       | 2                | \               |
| Distance from sound source /m | 0.5             | 0.5             |
| Length/m            | 0.4              | 0.4             |
Table 6. The experimental results.

| Frequency /Hz | 110  | 440  | 1000 |
|---------------|------|------|------|
| Exponential type | +2.64 | +14.99 | +8.78 |
| Hyperbolic type | +7.15 | +14.89 | +8.59 |

According to the experimental results, near the cut-off frequency, the sound reinforcement effect of hyperbolic type tube is obviously better than that of exponential type tube, while in the high frequency band, the sound reinforcement effect of the two types of horn is basically the same, which is in good agreement with the previous conclusion.

4.3. Directivity of Frequency Characteristics

The loudness of different angles is measured by hyperbolic and exponential horns. The input frequency is 1kHz. The experimental results are shown in table 7.

Table 7. The experimental results.

| Angle / degrees | 0    | 30   | 60   |
|----------------|------|------|------|
| Exponential type | +31.22 | +18.55 | +14.17 |
| Hyperbolic type | +21.01 | +10.46 | +9.96 |

According to the experimental results, because the opening section of the exponential horn is larger and the acoustic radiation is more concentrated, the far-field sound amplification effect is better, which is consistent with the theoretical results.

Using the same experimental conditions, the input frequency is 3kHz. The experimental results are shown in table 8.

Combined with the directivity function, it can be seen that the working range of the two kinds of horns is no more than 30 degrees.

Table 8. The experimental results.

| Angle / degrees | 0    | 30   | 60   |
|----------------|------|------|------|
| Exponential type | +22.38 | +14.53 | +13.51 |
| Hyperbolic type | +20.28 | +14.48 | +11.97 |

4.4. Distortion

Finally, the harmonic distortion is further measured by experiments.

According to the experimental data in table 9, combined with the human ear discrimination threshold of 0.2dB, it can be seen that the horn harmonic distortion is small and has little impact on the sound amplification effect.

When the input frequency is 220hz and 550hz, the nonlinearity of air will lead to the generation of sum frequency (770hz) and difference frequency (330hz).

Table 9. Harmonic distortion.

| Shape              | degree of distortion /dB |
|--------------------|---------------------------|
| Exponential type   | 0.35                      |
| Hyperbolic type    | 0.22                      |

Combined with figure 6 and figure 8, it is found that the distortion of hyperbolic horn is smaller under the same length, and the distortion of trombone is larger under the same curve parameters. It is consistent with the experimental results.
5. Conclusion and Work Summary

5.1. Conclusion

Through all the above analysis results, considering the influence of the material, shape and size of the horn on the performance of the sound horn, it is finally determined that the two kinds of horns can optimize the voice output to the distance. The optimal horn parameters and application are shown in table 10.

5.2. Work Summary

This paper focuses on the influence of various parameters of horn on human voice output. The paper discusses the characteristics of the horn, such as the quality of the horn, the theoretical analysis of the distortion of the horn, the theoretical analysis and the experimental results. Finally, the two kinds of horn can optimize the voice output to the distance.

| Shape          | Length/m | Section curve equation | Advantage               | Purpose                               |
|----------------|----------|------------------------|-------------------------|---------------------------------------|
| Exponential type | 0.4      | $y = 0.015e^{2x}$      | Good directivity and high sound power | Suitable for outdoor long distance sound transmission |
| Hyperbolic type | 0.4      | $y = 0.015(ch2x + 0.6sh2x)$ | Uniform direction, good low frequency characteristics | Suitable for sound reinforcement in larger rooms |

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