ON THE DESIGN AND ANALYSIS OF ACOUSTIC HORNS FOR ULTRASONIC WELDING

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ABSTRACT

The acoustic horn plays a very vital part in high energy ultrasonic machining, and its design is critical to the quality and the efficiency of machining. This paper performs the analysis and design of acoustic horns for ultrasonic machining by employing ANSYS finite element software. The results indicate that not only the natural frequencies of horns designed by theoretical models are more close to the vibration frequencies of ultrasonic generators, but also their amplitudes are superior to commercially available horns.

Keywords: ultrasonic, acoustic horns, finite element analysis.

CONCEPTION ET ANALYSE DE PAVILLON ACOUSTIQUE POUR SOUDAGE PAR ULTRASONS

RÉSUMÉ

Le pavillon acoustique joue un rôle essentiel dans l'usinage par ultrasons de forte puissance, et sa conception est fondamentale pour la qualité et l'efficacité de l'usinage. Dans cette étude, on effectue l'analyse et la conception de pavillon acoustique pour usinage par ultrasons à l'aide du logiciel d'élément finis ANSYS. Les résultats indiquent que non seulement les fréquences naturelles des pavillons conçus selon les méthodes théoriques sont plus près des fréquences des vibrations naturelles des fréquences de générateurs ultrasoniques, mais aussi que leur amplitude est supérieure aux pavillons commerciaux disponibles.

Mots-clés : ultrasonique ; pavillon acoustique ; analyse des éléments finis.

1. INTRODUCTION

The ultrasonic welding is extensively applied in industry due to its advantages its advantages of low cost, environmental protection, and energy efficiency. It can be classified by ultrasonic metal welding and ultrasonic plastic welding. Recently, the latter develops more and more rapidly. The design of acoustic horn is of prime importance to the quality and the efficiency of machining. The function of the acoustic horn is to magnify the amplitude of mechanical vibration, or accumulate the energy on the smaller cross section. In general, the amplitude generated by an ultrasonic vibrator is 4–10 μm, however, the amplitude required for effective ultrasonic machining has to be more than 10–100 μm [1]. Therefore, the amplitude of a vibrator has to be magnified by an acoustic horn. The amplifying principle of the acoustic horn is that the vibration energy through a cross section remains unchanged, therefore the smaller the cross section, the larger the energy density. The amplitude through the small section is magnified if the loss during energy transfer is neglected [2].

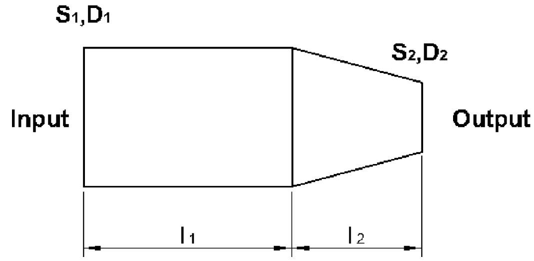
The traditional methods for the design of an acoustic horn are based on the equilibrium of an infinitesimal element under elastic action and inertia forces, and then integrates over the horn length to attain resonance [3]. One limitation of traditional design procedure is that it does not consider the tool attached to the horn. In practical design, a horn may require a hole for attaching it to the transducer or for suction of the slurry. The finite-element method (FEM) is one of the most flexible and powerful tools available for solving the horn design problems [4–6]. FEM can be applied to systems with any geometric configuration or boundary condition. A preliminary attempt of applying the FEM was by Coffignal [7], and it was assumed the acoustic horn and its tool as one body having a non-uniform counter in their analysis, the key point is how to tune a specific horn and its tool shape into a particular frequency.

The objective of this study is performs the analysis and design of acoustic horns for ultrasonic machining by employing ANSYS finite element (FEM) software. In industry, the shape and the length of a horn are obtained by experiments or rules of thumb; hence they consume much more materials and time. Moreover, the performance does not reach the maximum due to a poor design. Firstly, the modal analysis by using ANSYS software is performed to find the natural frequencies of various shapes of acoustic horns. Then, the amplitude magnification of the horns is obtained through the harmonic analysis. Finally, the resonance lengths are found and compared to commercial available horns.

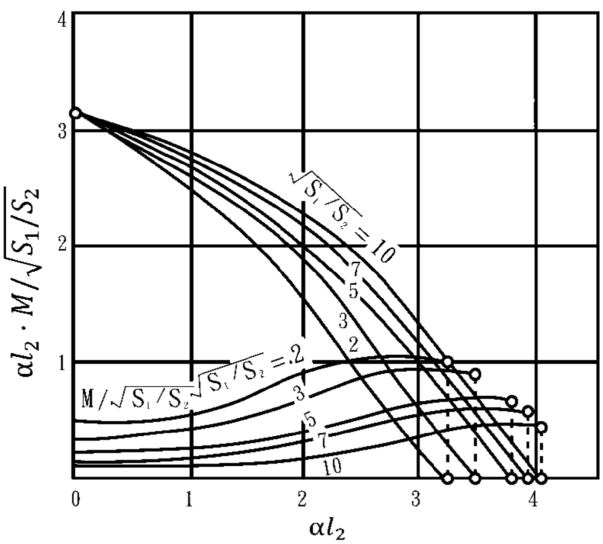
2. ACOUSTIC HORN DESIGN

There are many shapes of acoustic horn can be found in practice [8]. Under the condition of the same area ratio between its two ends cross sections, the amplitude magnifications of them in descending order are the stepped shape, the exponential shape, and the conical shape. If the cross sections are circular, then the amplitude magnification is equal to the ratio of diameter square, of its two end cross sections for a stepped horn, is equal to the diameter ratio for an exponential shape horn, and is proportional to the diameter ratio for a conical horn. A stepped horn will produce larger amplitude. Since it will have larger vibration stress (repeated alternating stress) inside the materials, it will cause the breakage of the material. Also larger internal energy loss will occur. If sorted in ascending order by the difficultness of manufacturing, they are the conical shape, the stepped shape, and the exponential shape, respectively. To preventing stress concentration due to the abrupt change of cross section, a fillet will be made for the stepped shape. How it reduce the efficiency of machining.

The design of an acoustic horn depends on the determination of the resonance length. The length must equal to the multiple of half wavelength of the system. The computation for an exponential shape horn is the easiest among three different shapes. Also, the horn of this shape has better amplitude than the others. However, it is seldomly applied, unless there are special demands, due to its difficulty in machining. Although the computation for a conical horn is the most difficult, it is not only easy in machining, but also



(a) Dimensions



(b) $\alpha l2$ vs. $m\sqrt{S_1/S_2}$

Fig. 1. Conical horn – the larger cross section connected by a cylinder [9].

has the same better amplitude as the exponential one. Therefore, the conical one has been extensively used in industry.

3. RESONANCE LENGTH OF ACOUSTIC HORN

The resonance length of an acoustic horn depends on the areas of input and output end, wavelength constant, etc. Therefore, its equation varies with different shapes of horns. In this section, the resonance equations and amplitude magnifications of conical horns, stepped horns, and stepped horn – two cylinders connected with an exponential curve are presented.

3.1. Conical Horn

3.1.1. Conical horn – The larger cross section connected by a cylinder

Figure 1a depicts the profile of a conical horn connected with a cylinder on its larger cross section. Its resonance length L is defined as the total length of the horn, i.e., $L = l_1 + l_2$, where l_1 and l_2 are the lengths of the cylinder section and the conical section, respectively. Figure 1b indicates the relationship between αl_2 and $M\sqrt{S_1/S_2}$ of the horn, where α $(= \omega/c)$ is the wavelength constant, ω is the resonance angular frequency, M is the amplitude magnification, and S_1 and S_2 are the cross section areas of the input end and output end, respectively. Obviously, $\sqrt{S_1/S_2} = D_1/D_2$, where D_1 and D_2 are the diameters of the input end

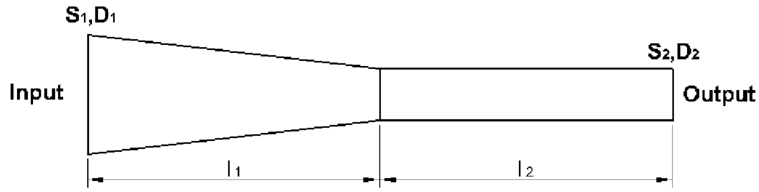


Fig. 2. Conical horn – the smaller cross section connected by a cylinder.

and the output end, respectively. If D_1/D_2 is specified, and $M\sqrt{S_1/S_2}$ reaches its maximum in the figure, then αl_2 can be found from Fig. 1b. If α is specified, then l_2 can be obtained.

Furthermore, l_1 can be obtained [9] by

$$\tan\alpha l_1 = \frac{\alpha l_2(\sqrt{S_1/S_2}-1)^2 - [\sqrt{S_1/S_2}(\alpha l_2)^2 + (\sqrt{S_1/S_2}-1)^2]\tan\alpha l_2}{\sqrt{S_1/S_2}\cdot\alpha l_2[\alpha l_2 + (\sqrt{S_1/S_2}-1)\tan\alpha l_2]} \tag{1}$$

Finally, the amplitude magnification M can be calculated by

$$M = \left|\sqrt{S_1/S_2}\cdot\frac{\cos\alpha l_1}{\cos\alpha l_2}\cdot\frac{\alpha l_2}{\alpha l_2 + (\sqrt{S_1/S_2})\tan\alpha l_2}\right| \tag{2}$$

3.1.2. Conical horn – The smaller cross section connected by a cylinder

Figure 2 indicates the profile of a conical horn connected with a cylinder on its smaller cross section. Its resonance length can be calculated by

$$\tan\alpha l_2 = \frac{\alpha l_1(\sqrt{S_1/S_1}-1)^2 - [\sqrt{S_1/S_2}(\alpha l_1)^2 + (\sqrt{S_1/S_2}-1)^2]\tan\alpha l_1}{\alpha l_1[\sqrt{S_1/S_2}\cdot\alpha l_1 - (\sqrt{S_1/S_2}-1)\tan\alpha l_1]} \tag{3}$$

and the amplitude magnification M is

$$M = \left|\frac{\sqrt{S_1/S_2}\cdot\alpha l_1}{(\sqrt{S_1/S_2}-1)\cos\alpha l_2\cdot\sin\alpha l_1 + \alpha l_1\cdot\cos(l_1+l_2)}\right| \tag{4}$$

3.2. Stepped Horn

A stepped horn is shown in Fig. 3, its resonance length is [10]:

$$L = k_1\left(\frac{c}{4f}\right) + k_2\left(\frac{c}{4f}\right) \tag{5}$$

To simplify computation, it is usually assumed that k_1 and k_2 are identical. Therefore, $L = c/2f$, and $l_1 = l_2 = L/2 = \lambda/4$ where λ is the ultrasonic wavelength of the horn material. Also, its amplitude magnification M is [9]:

$$M = \frac{S_1}{S_2} = \left(\frac{D_1}{D_2}\right)^2 \tag{6}$$

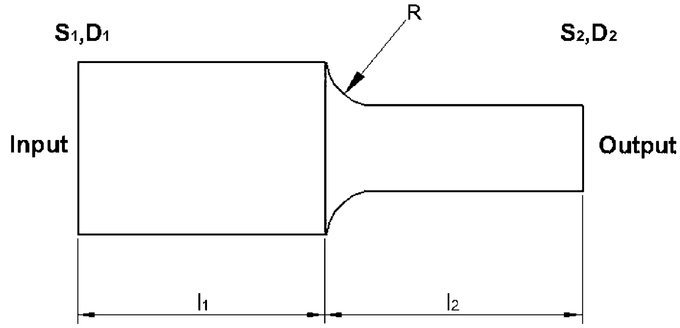


Fig. 3. Stepped horn.

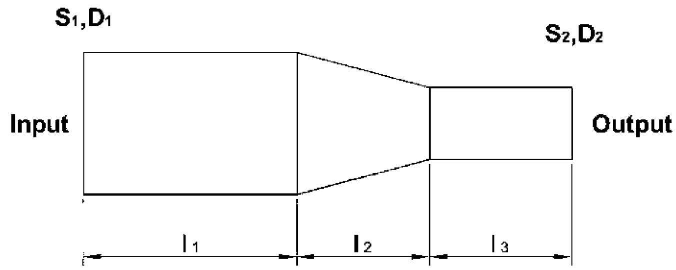


Fig. 4. Stepped horn – two cylinders connected with an exponential curve.

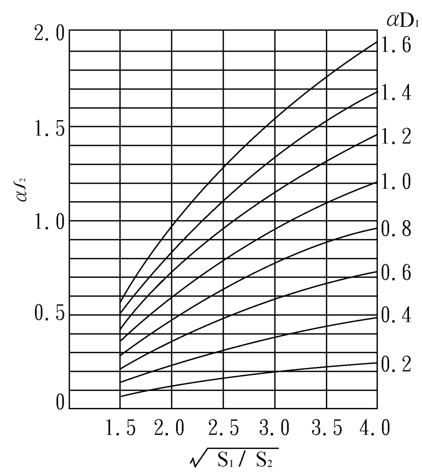


Fig. 5. Dimensions of l_2.

3.3. Stepped Horn – Two Cylinders Connected with an Exponential Curve

A stepped horn with two cylinders connected by an exponential curve is shown in Fig. 4. Let $l_1 = \lambda/4$, and let the profile be an exponential curve in the section l_2. If the length of l_2 is reduced, then the profile will approach a typical stepped horn. Contrarily, if the length of l_2 is increased and the length l_3 is shortened, then the profile will approach an exponential curve. After having calculated αD_1 and $\sqrt{S_1/S_2}$, then we can find the dimensions l_2 and l_3 from Figs. 5 and 6. The amplitude magnification M can be obtained from Fig. 7.

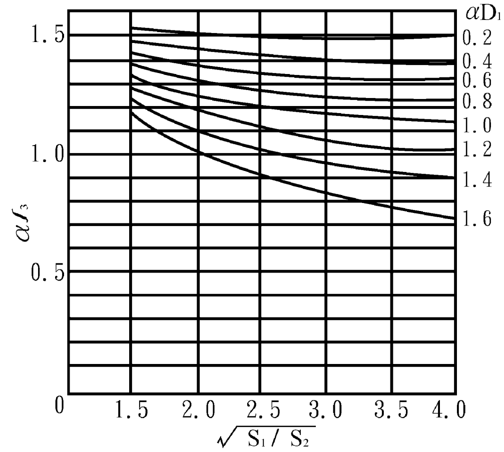


Fig. 6. Dimensions of l_3.

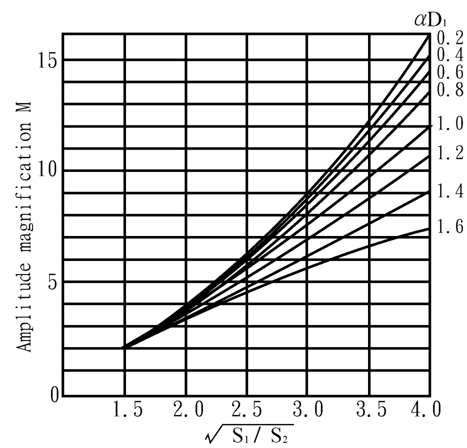


Fig. 7. Amplitude magnification of horn dimensions.

3.4. Finite Element Analysis

According to the requirement of finite element analysis approach, the horn has to be divided into simple, homogeneous, discontinuous finite nodes, shown in Fig. 8. Since the horn is symmetry vertically, only half of the nodes are necessary for FEM analysis, as shown in Fig. 8. The element of Solid95 is adopted in analysis, it is a cubic element with 20 nodes, and it has three degrees of freedom (x, y, and z). Without lowering the accuracy of computation, it allows irregular shapes of horns to be analyzed, and it also has superior compatibility of deformation. Moreover, it can also be applied on the curved boundary with plasticity, creeping, expansion, stress strengthening, large deformation, and even a body with failure [11].

By performing modal analysis, the natural frequency of the horn can be obtained. It represents the rigidity of the whole structure. The lower the natural frequency is, the smaller the rigidity is of the horn. By proper design, the horn can be resonating with the machine, and then the input energy can be greatly reduced. The structural response under the periodical loading can be work out by performing the harmonic analysis. For instance, the horn is excited by an ultrasonic wave at 15 kHz, the amplitude magnification can be found by calculating the displacement produced in the longitudinal direction [12].

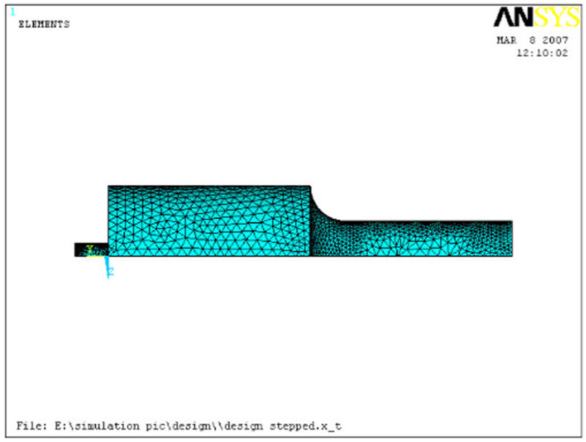


Fig. 8. Finite element model of the stepped horn.

3.4.1. Horn materials

Due to its high strength and stability in properties, the A7075-T651 aluminum alloy is used as the horn material for FEM analysis, its properties are elastic modulus $E = 71.7$ GPa, Poisson ratio $\mu = 0.33$, and mass density $\rho = 2810$ kg/m^3.

3.4.2. Boundary condition

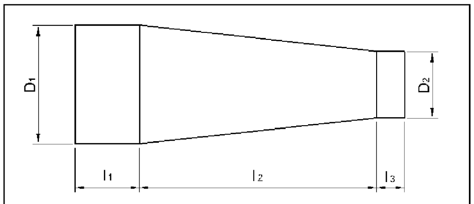
The work uses the fixed boundary in modal analysis. After the properties of the material are specified, then only the constraints are required, and the loading input is not necessary. That is, it constraints the connecting part between the horn and the vibrator in U_x, U_y, U_z, R_x, R_y, and R_z directions. In performing the harmonic analysis, after the connecting part has been constrained, then an excited displacement of 0.01 mm is given at the input end. Moreover, its range of frequency is set between 0–15 kHz. Finally, the amplitude magnification is found by the displacement of each cross section along the longitudinal direction from the fixed end to the free end.

4. RESULTS AND DISCUSSIONS

4.1. Analysis of Conical Horns

The commercial horn of conical shape is not a simple cone. Contrarily, both of its two ends are cylinders. Only a few studies on this type of horns can be found in the literature. This work computed the theoretical dimensions from Eqs. (1) and (3) according to the diameter ratios of commercial horns. Their dimensions are listed in Table 1. Also, their natural frequencies obtained by the modal analysis are shown in Table 2. It can be observed that the natural frequency of the horns designed by the equation is more close to the operating frequency of the machine. Since they can be operated at the resonance frequency with the machine, the horns will be more energy effective than commercial horns. In addition, their rigidities are higher than those of commercial horns. Amplitude magnifications, by the harmonic analysis, of two kinds of horns are shown in Table 3. It can be found that the amplitude magnifications by the equation are the closest to that by the FEM analysis. In addition, although its amplitude magnifications are only a little difference with a commercial horn, less volume of material will be used.

Table 1. Dimensions of conical horns.



Dimensions (mm)	Commercial	Equation
D1	60	60
D2	30	30
L1	45	17.3
L2	133	162.2
L3	15	4

Table 2. Natural frequencies of conical horns.

Horn / Mode	Commercial(Hz)	Equation(Hz)
1st modes	234.75	254.58
2nd modes	4098.8	4244.4
3rd modes	4617.1	4859.6
4th modes	8607	9122
5th modes	13575	14183

Table 3. Amplitude magnification of conical horns.

Horn / Properties	Commercial			Equation		
D_1/D_2	2 : 1			2 : 1		
Total lengrh(mm)	193			183.5		
Operating frequency(kH_z)	15			15		
Amplitude magnification M	Analysis method					
	ANSYS	Calculation	Error	ANSYS	Calculation	Error
	2.23	2.58	13.5%	2.03	2.01	0.99%

If both the l_3 sections of the commercial and the design horns (the Larger Cross Section Connected by a Cylinder) are cut off, their natural frequencies can be found by FEM analysis, and shown in Table 4. The natural frequencies of the horn computed by equation are much higher and closer to the operating frequency (15 kHz) than those of commercial horns. The reason may be attributed to that the commercial horn is not an integrated design by the equation. It causes the significant difference between two frequencies. Therefore, the performance of a commercial horn has to be tuned to the maximum by adjusting the length of l_3. Furthermore, having performed the harmonic analysis, the comparison of their amplitude magnifications is shown in Table 5. It can be found that the amplitude magnification of the horn computed by equation is less than the original horn by about 0.06. However, the error of the amplitude magnification for the commercial horn is relatively large. It may be caused by the extraordinary magnification of the amplitude

Table 4. Natural frequencies of conical horns- neglecting output cylinder l_3.

Horn / Mode	Commercial(Hz)	Equation(Hz)
1st modes	251.72	258.55
2nd modes	4675.9	4366
3rd modes	4710.8	4885
4th modes	9532.2	9319.4
5th modes		14544

Table 5. Amplitude magnification of conical horns - neglecting output cylinder l_3.

Horn / Properties	Commercial			Equation		
D_1/D_2	2 : 1			2 : 1		
Total length（mm）	193			183.5		
Operating frequency（kHz）	15			15		
Amplitude magnification M	Analysis method					
	ANSYS	Calculation	Error	ANSYS	Calculation	Error
	2.23	2.58	13.5%	2.03	2.01	0.99%

Table 6. Natural frequencies of conical horns - neglecting output cylinder l_3 (0–16 kHz).

Horn / Mode	Commercial(Hz)	Equation(Hz)
1st modes	251.72	258.55
2nd modes	4675.9	4366
3rd modes	4710.8	4885
4th modes	9532.2	9319.4
5th modes	15289	14544

after l_3 is cut off, and can be avoided by setting the operating frequency to be 0–16 kHz. The corresponding natural frequencies and amplitude magnification of the change are shown in Tables 6 and 7, respectively. It can be observed that the natural frequencies of the commercial horn are larger than those of the horn computed by equation. However, under the conditions of closer to but less than the operation frequency 15 kHz, the horn computed by equation is a better design. Moreover, the error of amplitude magnification on the commercial horn in Table 7 is much less than that in Table 5, but it is still higher than that of the horn computed by equation.

Following the above studies on conical horns, the results indicate that the performance of the horn designed by equations is better than that of the commercial horn. Moreover, the amplitude magnifications with and without section are analyzed, their errors are about 1%. This result shows that the horn designed by Eqs. (1) and (3) use less material and has superior performance than a commercial horn.

4.2. Stepped Horn

The stepped horn is designated by Eq. (5) according to the diameter ratios of commercial horns, and both the lengths of and are set as one fourth of the wavelength. Then, their natural frequencies obtained by the modal analysis are shown in Table 8. It can be observed that the natural frequencies of the commercial horn

Table 7. Amplitude magnification of conical horns - neglecting output cylinder l_3 (0–16 kHz).

Properties \ Horn	Commercial			Equation		
D_1/D_2	2 : 1			2 : 1		
Total length (mm)	178			179.5		
Operating frequency (kHz)	15			15		
Amplitude magnification M	Analysis method					
	ANSYS	Calculation	Error	ANSYS	Calculation	Error
	17.3	2.58	-	1.97	2.01	1.99%

Table 8. Natural frequency of stepped horns.

Mode \ Horn	Commercial(Hz)	Equation(Hz)
1st modes	281.07	311.90
2nd modes	3074.4	3726.8
3rd modes	4957.9	5123.2
4th modes	8281.1	8794.2
5th modes	12778	14776

Table 9. Amplitude magnification of stepped horns.

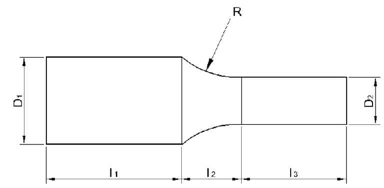
Properties \ Horn	Commercial			Equation		
D_1/D_2	2 : 1			2 : 1		
Total length (mm)	183			170		
Operating frequency (kHz)	15			15		
Amplitude magnification M	Analysis method					
	ANSYS	Calculation	Error	ANSYS	Calculation	Error
	3.79	4	5.25%	3.75	4	6.25%

are lower than those of the horn designed by equation, i.e., the natural frequency of the horn designed by equation is more close to the operating frequency of the machine. Since they can be operated more easily at the resonance frequency of the machine, the horn will be more energy effective than a commercial horn. In addition, its rigidity is higher than that of the commercial horn. The amplitude magnifications, by harmonic analysis, of two kinds of horns are shown in Table 9. If the error is defined as the difference between the values calculated from Eq. (6) and that by ANSYS analysis, then the errors of the amplitude magnification of the commercial horn and the horn calculated from Eq. (5) are about 5%, and the difference between their amplitude magnifications is about 0.04. Therefore, the performance of the horn by the equation is better than that of the commercial horn due to less volume of material required.

4.3. Stepped Horn – Two Cylinders Connected with an Exponential Curve

Firstly, the stepped horn is designed according to the diameter ratios ($\sqrt{S_1/S_2} = D_1/D_2$) of commercial horns. Let $l_1 = \lambda/4$, that is, the length of the cylinder at the input end is one fourth of the wavelength, then

Table 10. Dimensions of stepped horn – two cylinders connected with an exponential curve.



Dimensions（mm）	Commercial	Equation
D_1	55	55
D_2	30	30
L_1	86	85
L_2	28.17	28.10
L_3	66.83	68.60
R	38	37.83

Table 11. Natural frequencies of stepped horn – two cylinders connected with an exponential curve.

Horn / Mode	Commercial(Hz)	Equation(Hz)
1st modes	290.81	294.39
2nd modes	3528.7	3451.6
3rd modes	5211.7	5232.7
4th modes	8655.6	8633
5th modes	14210	14026

Table 12. Amplitude magnification. Stepped horn – two cylinders connected with an exponential curve.

Horn / Properties	Commercial			Equation		
D_1/D_2	11：6			11：6		
Total length（mm）	181			181.7		
Operating frequency（kHz）	15			15		
Amplitude magnification M	Analysis method					
	ANSYS	Calculation	Error	ANSYS	Calculation	Error
	3.10	3.25	4.62%	3.17	3.25	2.46%

the value of αD_1 can be obtained, the dimensions of l_2 and l_3 can be deduced from Figs. 5 and 6 using the values of αD_1 as well as $\sqrt{D_1/D_2}$, as shown in Table 10. Moreover, by performing the modal analysis, their natural frequencies can be found as shown in Table 11. It can be observed that both the natural frequencies and the rigidity of the commercial horn are higher than those of the horn designed by equation. Finally, conducting the harmonic analysis, the amplitude magnifications of the two horns are shown in Table 12. Both the errors between the values calculated by Eq. (6) and analyzed by ANSYS software are less than 5%, and the amplitude magnification of the horn designed by the equation is about 0.07 higher than that of the commercial horn. Therefore, the performance of the horn by the equation is better than the commercial horn due to less volume of material required.

5. CONCLUSIONS

In this paper, the modal and harmonic analyses for commercial horns and horns designed by equation have been carried out, and their results have been presented and discussed. From the results of the analyses, conclusions may be summarized as follows:

1. The natural frequency of the horn designed by equation is more close to the operating frequency of the machine. Since it can be operated more easily at the resonance frequency with the machine, the horns will be more energy effective than commercial horns.

2. The work provides a new approach for the conical horn design by adding a cylinder at its two ends. The horn designed by the proposed method will use less material and trial & error time. In addition, a higher amplitude magnification will be reached.

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