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# Experimental Design and Optimization of Conical Horn of Ultrasonic Amplitude

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***Abstract***— *Based on the basic principle of particles and the simple mechanical vibration system, then according to the wave equation and the traditional design theory of the amplitude transformer, we design an amplitude transformer commonly used in the equipment of Ultrasonic machining. Then, the structure is analyzed by the finite element analysis software ANSYS in the modal and harmonic response module and further optimized to obtain the design parameters of the amplitude transformer with good performances. Finally, the amplitude transformer is made according to optimized parameters and later it is analyzed by the impedance analyzer. And then the designed transformer is further modified to achieve better performance.*

***Keywords—Conical ultrasonic amplitude horn; Finite element analysis; Impedance analysis.***

## I. INTRODUCTION

The recent development of modern hi-tech industries has resulted in the creation of a range of new materials. These include steels and alloys of high strength, stainless and resistant to heat, titanium, ceramics, composites and other non-metallic materials. These materials may not be suitable for conventional machining processes due to scaling or fracturing of the surface layer or even the whole of the component and lead to poor quality of the product. Similarly, the creation of new materials often highlights some insoluble problems within a framework of traditional technologies. In some cases, these problems are caused by the construction of the object and the requirements peculiar to it. For example, in microelectronics, it is often necessary to connect certain components without heating them or to add intermediate layers. This prohibits the use of traditional methods such as welding or welding. Many of these and similar problems can be solved successfully using ultrasonic technologies [1].

The use of ultrasonic phenomena is increasingly used in many industries. Ultrasonic vibrations have been exploited with considerable advantages for a variety of applications such as ultrasonic cleaning, plastic welding etc. Has proven to offer benefits in a number of other applications . These applications include automotive industry, food preparation, medical assembly, textile and manufacturing industries. Significant increase in performance and qualitative improvements are obtained by using ultrasonic vibrations in the machining process. Applications of ultrasonic vibration energy in machining technologies are realized by two different approaches. The first approach, called ultrasonic machining, is based on the abrasive Principle of shrinking materials. The tool that is shaped in the exact configuration to Crushed in the piece and is attached to a vibrating horn . The second approach is based on conventional machining technologies [2-4].

In ultrasonic machining, ultrasonic vibrations are transmitted directly to the cutting tools or directly to a cutting process. These techniques are used for high-precision machining and for non-fragile materials and materials that are difficult to cut, such as hardened steels, nickel based alloys, titanium metal matrix composites and aluminum-SIC. The high repetitive frequency the vibro-impact mode brings unique properties and improvements in the metal cutting where the interaction between the work piece and the cutting tool is transformed into a micro-vibro-impact process. The application of ultrasonic vibration energy in the machining process offers many advantages and improvements in the cutting process[5].

The performance of ultrasonic machining equipment depends on the design of the sonotrode (Horn). The sonotrode is the only part of ultrasonic machining and unique system for each process. They are used in various shapes and sizes, depending on the application, but as other components should be resonant at the operating frequency. The sonotrode material used is a compromise between the needs of ultrasound and application - alloys of titanium, steel, stainless steel. The shape of ultrasonic horn depends on the technological process for which it will be used. The most frequently used forms of ultrasonic horns are: cylindrical, conical, exponential and climbed. To achieve optimum performance of the ultrasonic machining system, all relevant effects and parameters that affect the dynamics of the system must be taken into account. One of the most important elements of the sonotrode ultrasonic system must have the dynamic properties, which must be determined already in the design phase[6].

## II. TRADITIONAL METHOD OF HORN DESIGN

The traditional design method for acoustic horns is based on the differential wave equation of (1) (Fig. 1)

$$\frac{\partial(A\sigma)}{\partial x}dx = A\rho\frac{\partial^2\varepsilon}{\partial t^2}dx \qquad (1)$$

In the formula: **A** For the function of the cross section of the stem, $\mathbf{A = A(X)}$ σ Stress function, Particle displacement force function $\boldsymbol{\sigma = \sigma(x) = \frac{E\partial\xi}{\partial x}}$,$\boldsymbol{\xi = \xi(x)}$**.**

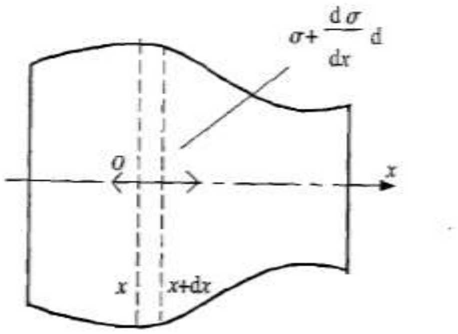


*Fig.1: Longitudinal vibration of the variable section stem*

In the case of a simple harmonic vibration, equation (1) can be written:

$$\frac{\partial^2\xi}{\partial x^2} + \frac{1}{A}\cdot\frac{\partial A}{\partial x}\cdot\frac{\partial\xi}{\partial x} + K^2\xi \qquad (2)$$

In the formula: **K** Round wave number, **K = ω / c; c** P-wave in the horn

The speed of propagation, **C = E / ρ**. The formula (2) is the wave equation of the longitudinal vibration of the variable section rod. According to the boundary conditions **[(ξ / x) x = 1 = 0, (ξ / x) x = 0** and **(u) x = 0** = initial amplitude, the resonance induced transformation can be calculated .The length of the band and amplitude amplitude change at this length. However, this formula can only be used to design horns whose section functions change according to certain rules, such as exponential, catenary, stepped and conical horns. For composite horns with complex section shapes, equation (2) cannot provide an analytical solution, which makes it difficult to design and use the horn.

## III. THEORETICAL DESIGN OF CONICAL HORN

### 3.1. Particle displacement and velocity EQUATION

It is assumed that the horn is uniform and isotropic, excluding mechanical losses, and that plane longitudinal waves propagate in the axial direction. The horn satisfies the wave equation in a one-dimensional condition.

$$\frac{\partial^2\xi}{\partial x^2} + \frac{1}{S}\frac{\partial S}{\partial x}\frac{\partial\xi}{\partial x} + k^2\xi = 0 \qquad (3)$$

In the formula: For the particle displacement function, S is the cross section, k = ω / c, k is the wave number, ω = 2π *f* is the circular frequency $c = \sqrt{E/\rho}$ is the velocity of propagation of the longitudinal wave, E is the modulus of elasticity of the material and ρ is the density of the material. The diameter at the origin of the coordinate is $X = 0$.

The diameter at the origin of the coordinate is $D_1$, $X = L$, where $D_2$, and its zone function is, where is, its zone function is

$$S = S_1(1-\alpha x)^2 \qquad (4)$$

$$D = D_1(1-\alpha x) \qquad (5)$$

$$\alpha = \frac{D_1 - D_2}{D_1 L} = \frac{N-1}{NL}, N = \frac{D_1}{D_2} \qquad (6)$$

The force and vibration acting on both ends of the horn

The velocities are $F_1, \dot{\xi}_1$ and $F_2, \dot{\xi}_2$ respectively, the sum and the boundary conditions Substituted in equation (1), the resulting solution is:

$$\xi = \frac{1}{x - \frac{1}{\alpha}}(A_1\cos kx + B_1\sin kx) \qquad (7)$$

After looking for the first derivative

$$\frac{\partial\xi}{\partial x} = \frac{1}{x-\frac{1}{\alpha}}(-A_1 k\sin kx + B_1 k\cos kx) - \frac{1}{(x-\frac{1}{\alpha})^2}(A_1\cos kx + B_1\sin kx) \qquad (8)$$

### 3.2 Frequency equation and resonance LENGTH

By boundary conditions $\left.\frac{\partial\xi}{\partial x}\right|_{x=0} = \left.\frac{\partial\xi}{\partial x}\right|_{x=l} = 0$

Substitution Equation (6) gives the frequency equation:

$$tg(kl) = \frac{kL}{1-(k/\alpha)^2(\alpha L - 1)} \qquad (9)$$

The length of the horn satisfies:

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$$L = \frac{\lambda}{2} \bullet \frac{(kL)}{\pi} \quad (10),$$ $\lambda$ (Wavelength for propagation of waves in the medium)

### 3.3 NODE OF DISPLACEMENT

The displacement node satisfies the equation:

$$tg(kx_0) = k/\alpha \quad (10)$$

### 3.4 MAGNIFICATION FACTOR

$$M_p = \left| N(\cos kL - \frac{N-1}{N} \sin kL) \right| \quad (11)$$

The horn is made of 45 # steel. The main parameters are: modulus of elasticity E = 209.2 GPa, Poisson's ratio γ = 0.28, density ρ = 7 850 kg / m3. The horn has two central hole diameters M18x1.5 and M12x1.7, end face diameters of 50 mm and 20 mm and a horn length of 136 mm. The designed horn is used in rotary ultrasonic machining equipment whose main parameters are: operating frequency range 20 to 50 kHz.

## IV. FINITE ELEMENT ANALYSIS OF THE HORN

### 4.1 MESH DIVISION

The quality of 45 # stainless steel is chosen as horn material with a working frequency of 20 kHz. Stainless steel offers good characteristics for the use of ultrasonic horns. They have high strength, stiffness, wear resistance and corrosion resistance. They can be used over a wide temperature range. In addition, due to the good machinability during manufacturing, the 45 # was chosen on other horn materials. The properties of stainless steel, 45 # are given in Table 1.

*Table.1: Properties of the material used for the horn*

| MATERIAL | 45# STEEL |
|---|---|
| Density $\rho$ /kg/m$^3$ | 7850 |
| Young's Modulus E/GPa | 209.2 |
| Sound speed C/m/s | 5162 |
| Poisson's ratio | 0.28 |

The allowable stress of the steel 45 is = 300MPa the finite element software ANSYS is used to establish the finite element model and the mesh. The number of nodes is 37880 and the number of units is 2574, as shown Figure 1:

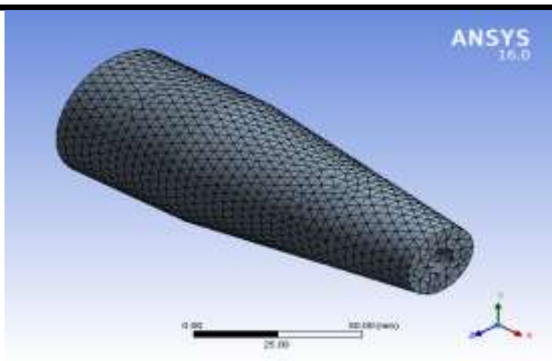


*Fig .1: Meshed geometry of the conical horn*

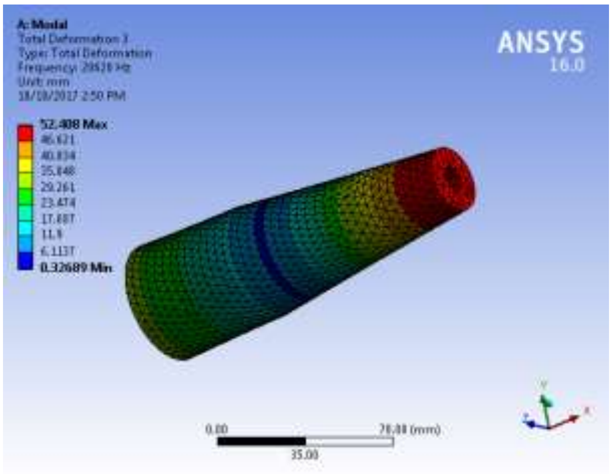


*Fig.2: Longitudinal displacement distribution cloud*

### 4.2 MODAL ANALYSIS

The modal analysis deals with the analysis of the free vibrations of a body / structure. The goal is to find the shapes and frequencies at which the structure will amplify the effect of a load. The method of the block lancets allows to perform a modal analysis on the model of the free horn at both ends, the search frequency is between 15 kHz and 30 kHz, the result is chosen in the solver and the natural frequency is 19 788 Hz. Near 20000Hz, for the results we need.

### 4.3 HARMONIC REPONSE

Harmonic analysis is used to determine the response of the load structure at a given frequency. It predicts the dynamic behavior of the structure by checking whether the structure is resistant to resonance, fatigue and other adverse effects. Case of our horn, the analysis of the harmonic response and apply in an axial displacement of 5μm to the large section of the horn. According to the amplification by the horn, the displacement is 15.1μm and the magnification is 2 , 4 times, the position of the knot is about the largest. The equivalent maximum stress is 38,556 MPa, which corresponds to the displacement curves and the equivalent stress distribution are illustrated

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in Figure 3 and Figure 4.

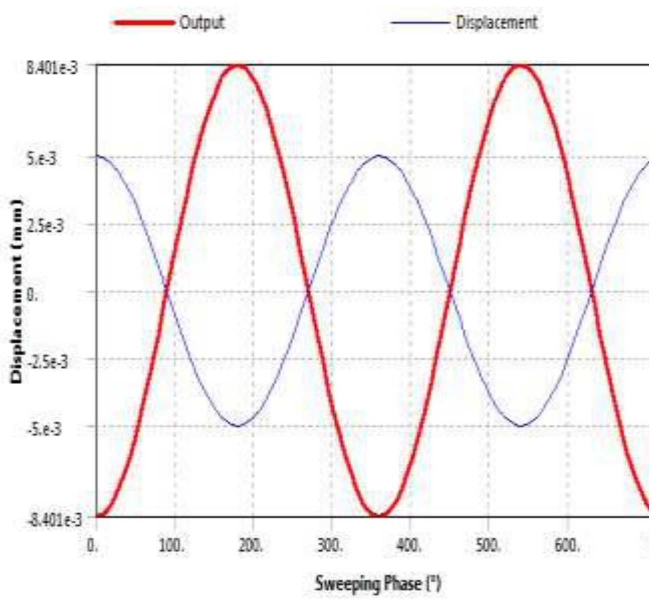


*Fig.3: longitudinal curve of vibration displacement*

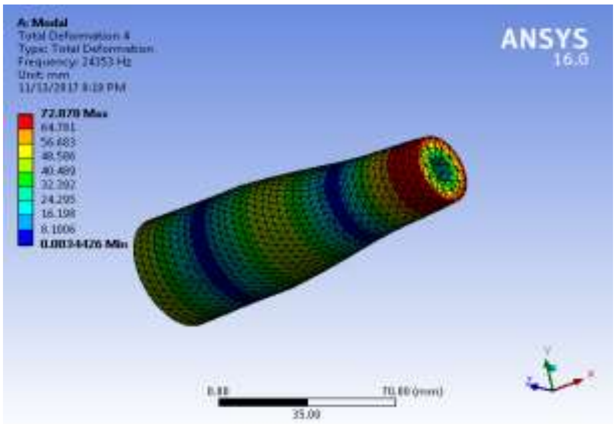


*Fig.4: Axial Equivalent Stress Distribution Cloud*

## V. IMPEDANCE ANALYSIS

The impedance analyzer can perform accurate measurements over a wide range of impedances and frequencies, It also adds low frequency current at different frequencies through the transducer, The natural frequency of the vibration system consisting of a transducer and of a horn is calculated by impedance.

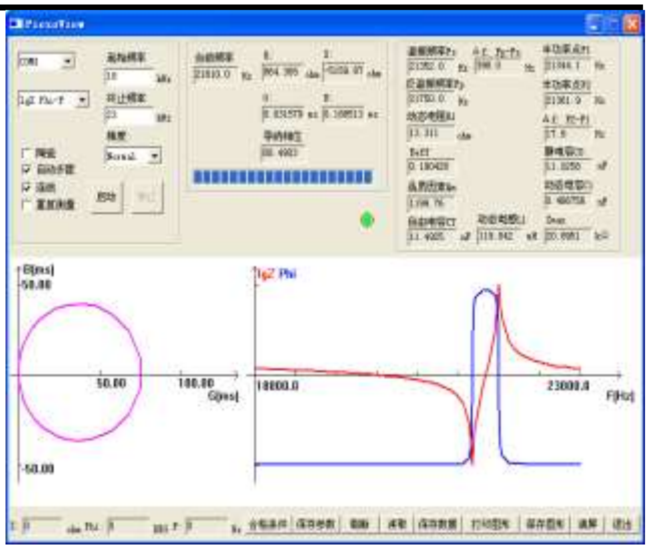

*Fig.5: Result of the horn impedance analysis*

After connecting the transducer and the horn, the ultrasonic vibration system was analyzed using a PV70A impedance analyzer manufactured by Beijing Commonwealth Electronic Technology Co., Ltd. The actual measured resonance frequency is 21352.0 Hz and the frequency error of the simulation results is less than 3%. Figure 5 shows that the circle of admittance is single circle and relatively regular, and the conductance curve has only a pair of maximum and minimum values, which shows that the design of the horn and the assembly with the transducer are relatively successful.

## VI. CONCLUSION

Based on wave theory, a conical ultrasonic horn was designed, ANSYS finite element analysis software was used to analyze horn dynamics, a horn was fabricated and an impedance analysis was performed with better performance. It shows that this method of analysis - the finite element method combined with the horn design method is efficient and allows to design more complex horns.

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