Modal Analysis of Horns used in Ultrasonic Vibration Assisted Drilling

Syam Narayana Addepalli
Assistant Professor
Department of Mechanical Engineering
K G Reddy College of Engineering and Technology, Hyderabad, Telangana.

Abstract: Horn or amplitude transformer is a key element in transferring the ultrasonic vibrations received at its input end from the transducer to the drill bit. So the design of horn has a huge impact on the amplitude of ultrasonic vibrations being imparted to the drill bit. The most important aspect of Sonotrode design is the determination of resonant frequency and resonant length of the horn. Hence, different horn shapes have been studied and analysis is performed to identify the desired shapes of the horn. Modal analysis was performed to calculate the mode shapes as well as natural frequencies of different shaped horns. Therefore the required analysis is performed using Ansys 15.0 workbench interface and the dimensions of the horn producing the resonant frequency within the range of 19500- 20500 is selected.

I. INTRODUCTION

Horns are made of materials which have a good combination of acoustical and mechanical properties. Titanium has the best acoustical properties and its high fatigue strength helps it to withstand high cycle rates at high amplitudes. It also possess high hardness when compared to other materials, which helps it to sustain wear conditions. Titanium 7-4 is often used to fabricate most of the horns, as this higher grade of titanium is approximately 15% stronger than the more common Titanium 6-4 grades. Apart from this one other main reason is that higher amplitudes can be achieved with horns made out of Titanium 7-4. Titanium horns can be carbide-coated for added wear resistance when working with abrasive materials containing glass or talc. Horns made up of titanium are typically more expensive than other materials due to the higher cost of the material and machining time. Aluminum heat-treated alloy has excellent acoustical properties and is used to make horns not requiring high amplitude, strength or hardness. Aluminum horns can be plated with chromium to prevent it from part marking. Horns made of alloy steel can be heat-treated for a wear-resistant surface, but the low acoustical efficiency of steel limits its use to horns for low amplitude applications such as insertion. Most important feature of horn design is the determination of resonant frequency and resonant length. The length must usually be in integral multiples of sonotrode wavelength.

The design of Horn is a complicated process and it involves the selection of correct material, production of the required amplitude and tuning it to a specific frequency. Incorrectly tuned horns can cause damage to the converter and power supply. Finite element analysis method is used to design and optimize horns for proper tuning, stress concentration and amplification factors. Horns are made in several basic styles and amplitudes to meet the requirements of various applications. For example, a small, high gain bar horn might be used for welding a small rectangular part while a large, slotted bar horn might be used for welding a large part requiring less displacement amplitude.

II. DIFFERENT SHAPED HORNS

Stepped horns consist of two different sections, each having a uniform cross-sectional area. They have the highest amplification factor of all horns due to the abrupt change in cross-sectional area at the nodal plane. Stress is maximum near the transition of the two sections. These horns can be used for any high gain application including welding, staking and swaging and cell disruption. Amplification factors of up to 4:1 can be attained by using stepped horns. Exponential horns have a cross-sectional area which follows an exponential equation. The gradual taper of exponential horns distributes internal stress over a greater length so that lower peak stress results. Consequently, these horns have desirable stress curves and are used mainly for applications requiring high force and low amplitude such as insertion. It is same as conical horn but produces more gain than conical horn. Conical horns have a cross-sectional area that changes conically with length. The gradual transition in conical horns distributes the stress over a greater length and thus, results in producing smaller stress concentrations than that are observed in stepped horns. They generally have lower gain factors so are used for applications requiring low forces and low amplitudes. Catenoidal horns combine the desirable gain of the stepped horn with the desirable stress distribution the exponential horn. They are most suitable for welding and staking small plastic parts.

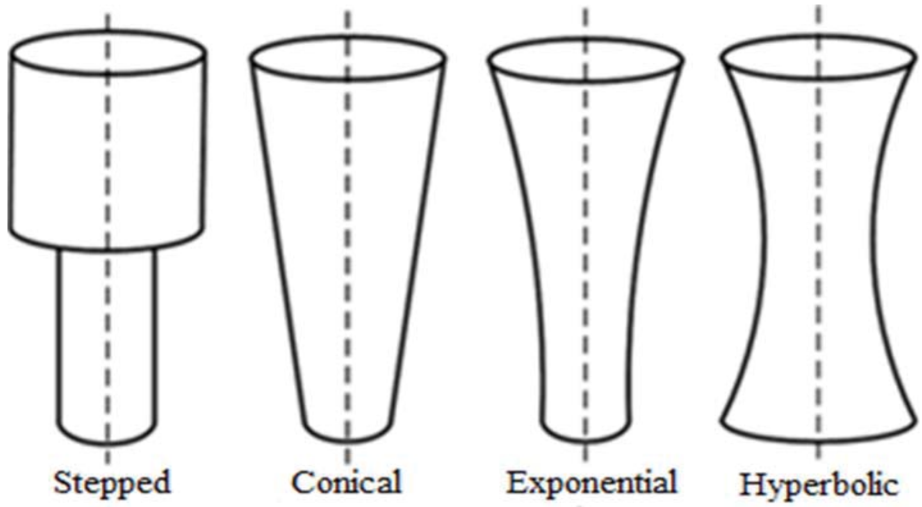

Fig: Depiction of different horn shapes

The main function of the horn is to amplify the vibrations imparted to it from the transducer to the desired level, based on the type of horn being used. Apart from this, it also acts as a means of transferring the vibrations from the transducer to the tool by staying in resonance with the generator and piezoceramic transducer. The designing as well as manufacturing of the ultrasonic horn must be done carefully because an inaccurately designed horn may cause reasonable damage to the ultrasonic transducer and generator.

III. PRINCIPLE OF MAGNIFICATION OF HORNS

The main purpose of the horn is to magnify the amplitude of vibrations. Usually, the amplitude produced by the piezo ceramic transducer is about 10-20 µm. But, the amplitude required for efficient machining is great than 50-100 µm. So horn is used at this point, to amplify the amplitude of vibrations to the desired level. The basic principle of magnification of horn is that the total vibrational energy through a particular cross sectional area remains constant, and as the cross sectional area decreases, the energy density increases. So as we are employing different shapes of horns, having less cross section at the output end when compared to the input end, different magnification factors are produced. There are multiple shapes of horn for different applications, out of which stepped, conical, exponential, cylindrical are the common ones.

IV. MODAL ANALYSIS

Modal analysis is performed to obtain the mode shapes and the natural frequencies of different shaped horns, for the given material. Analytical determination of mode shapes and natural frequencies for cylindrical structures are simple, whereas for others it is more complicated. So Finite element Analysis method is used to determine the natural frequencies of those materials. Modal analysis generally deals with the free vibration analysis of a body or structure. The purpose of this analysis is to find the mode shapes and frequencies at which the structure will amplify the effect of a load. In other words, it will generate the natural frequency of the structure for different mode shapes or modes of vibrations. Mode shape is nothing but the shape of the vibration corresponding to a vibration which the structure can absorb all the energy supplied by an excitation. For Ultrasonic Vibration assisted drilling, the horn should possess longitudinal mode. Based on the lengths of different shaped horns obtained during the mathematical modeling, the horns have been designed using and CATIA V5 R18 and analysis has been performed using ANSYS 15.0 workbench. The generator selected for our study is producing 20 kHz frequency. Hence the horns should be selected in such a way that they are possessing the same natural frequency.

4.1 Modal Analysis of Ultrasonic Horn with Varying Shapes

The different horn shapes considered here are stepped, cylindrical, conical and exponential. The generator selected for our study is having a resonant frequency of 20 KHz. So the Horn which is to be connected to it should also possess the same frequency, in order to be in resonance. Hence to exactly trace out the shape of the horn operating at the same frequency, modal analysis is performed on different shapes of horns. The material selected initially is Structural steel and the material properties has been assigned to observe the natural frequencies of different geometries.

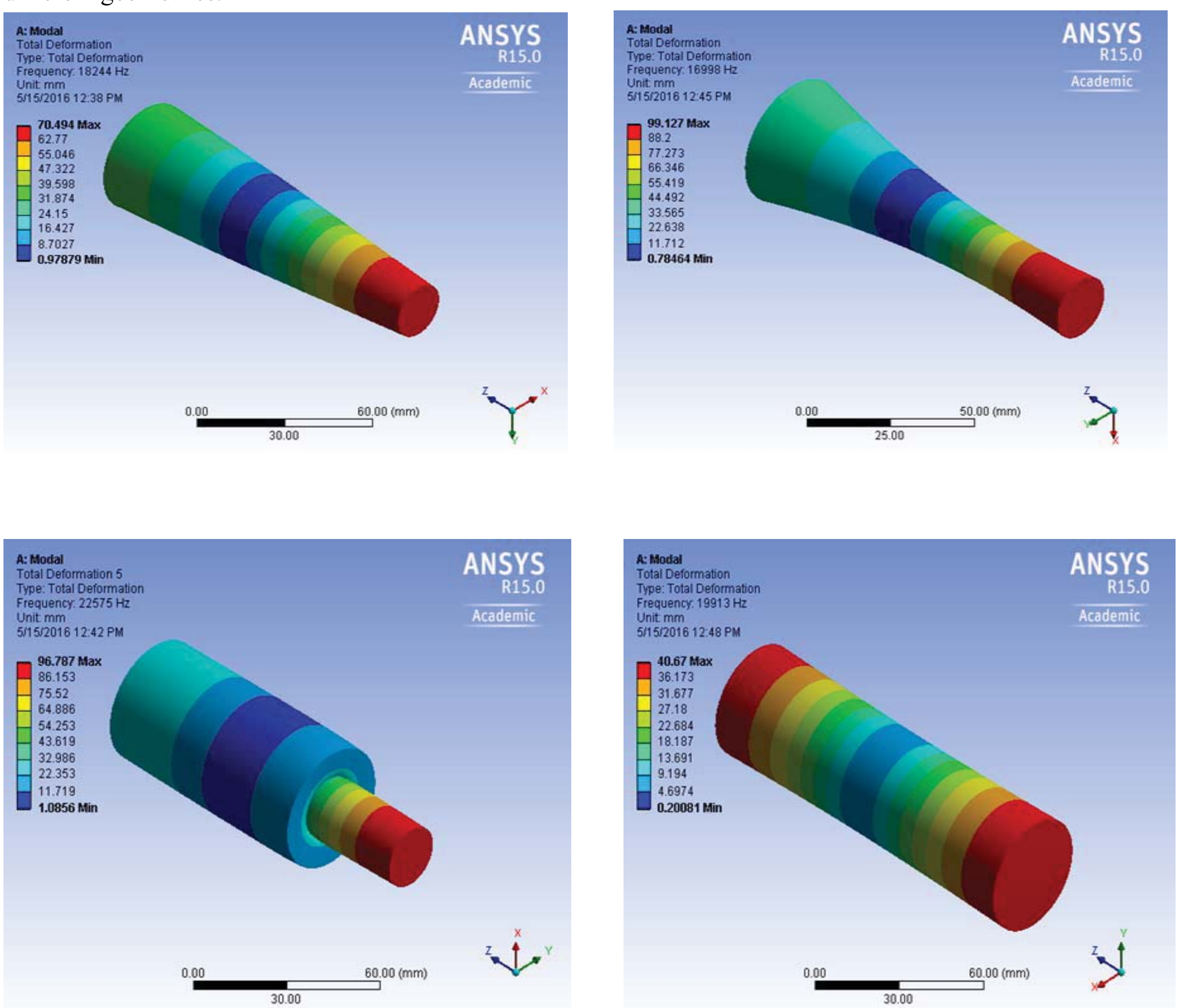

Figure 4.1: Natural frequencies of variable geometrical shapes of Horns

(a) Conical horn (b) Exponential horn (c) Stepped horn (d) Cylindrical horn

Mode	Frequencies observed for variable shapes of horn			
	Conical	Exponential	Stepped	Cylindrical
1	18244	16998	16115	19913
2	22498	21699	17495	20311
3	23862	21699	17495	20311
4	23862	23744	20204	24844
5	-	-	22575	-

4.2 Modal Analysis of Ultrasonic Horn with Varying Materials

The selection of the material used in the fabrication of the horn is done based on the results obtained by modal analysis. So Modal analysis is performed to calculate the mode shapes and the natural frequencies of different materials. Based on the results by performing the modal analysis of different shaped horns, stepped horn shape is selected, as it is possessing the longitudinal mode of vibration at a frequency close to that of the frequency of the generator. So to select the material for the stepped horn, again modal analysis is performed, to know the mode shapes and natural frequencies of different materials.

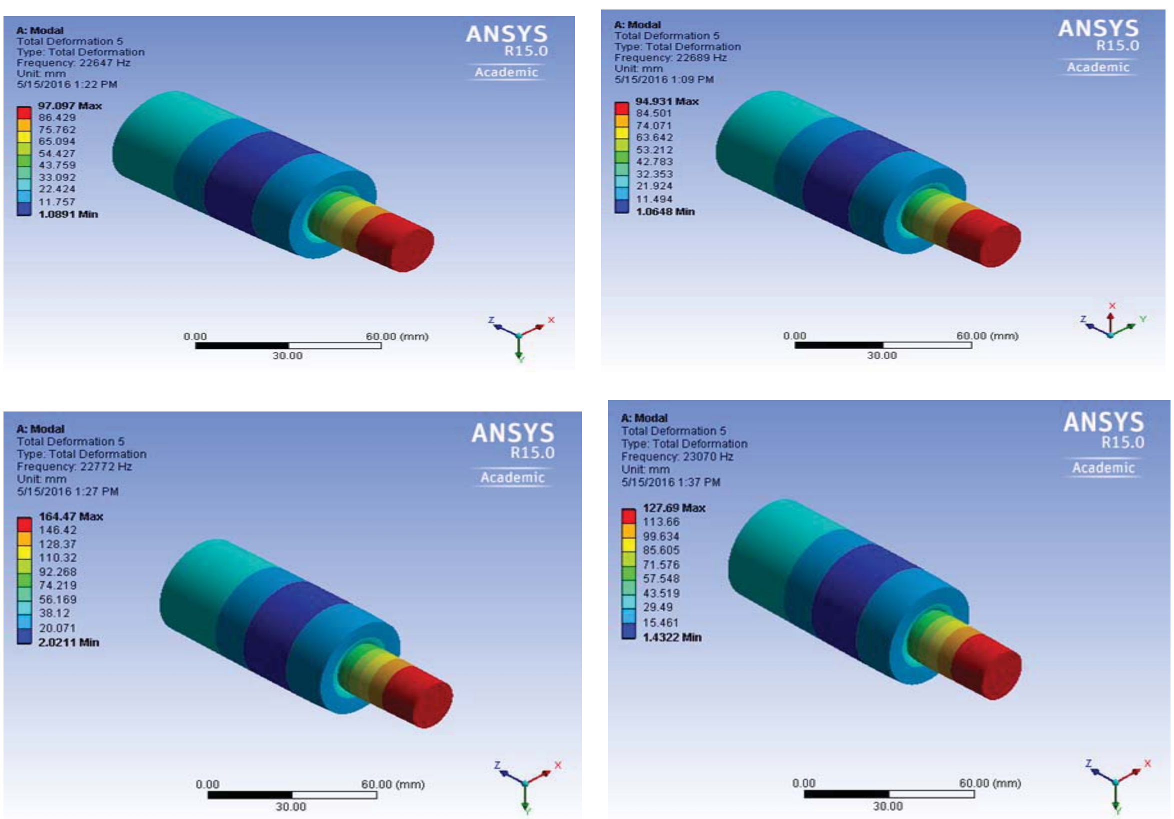

Figure: Depiction of Stepped horn mode shapes for different materials.
(a) Stainless steel (b) High speed steel (c) Aluminum (d) Titanium

V. RESULTS

Table: Frequencies of Stepped ultrasonic horn for variable materials.

Mode	Frequencies of Stepped Horn for Variable materials			
	HSS	Exponential	Stepped	Cylindrical
1	16166	16196	16072	16468
2	17551	17583	17622	17878
3	17551	17583	17623	17879
4	20269	20306	20150	20647
5	22647	22689	22722	23070

Table: Material Properties and Observed Frequencies for different materials

Material	Young's modulus (G Pa)	Density (kg/m^3)	Poisson's ratio	Theoretical Length (mm)	Frequency Observed at longitudinal mode (Hz)
Stainless steel	200	7800	0.3	127	22647
High speed steel	210	8160	0.28	128	22689
Aluminum	70	2700	0.33	126	22722
Titanium	120	4510	0.3	128	23070

VI. CONCLUSION

From the results, it is observed that different frequencies have been observed at different mode shapes and our desired frequency is the mode at which we are having longitudinal mode of vibration. So, the desired longitudinal mode of vibration is observed at 1st mode for conical horn, Exponential and cylindrical horn, and 5th mode for Stepped horn.

REFERENCES

[1] Mitrafanov A., Babitsky v. and Silberschmidt V. "Finite element simulations of ultrasonically assisted turning," Computational materials science, 28 (2003): pp. 645-653

[2] Mitrafanov A., Ahmed N., Babitsky V. and Silberschmidt V. "Analysis of forces in ultrasonically assisted turning," Journal of Sound and Vibration, 308(2007): pp. 845-854

[3] Babitsky V., Silberschmidt V. "Ultrasonically assisted turning of aviation materials: Simulations and experimental study," Ultrasonic, 42 (2004): pp. 81-86

[4] Seah K., Wong Y. and Lee L. "Design of tool holders for ultrasonic machining using FEM," Journal of Materials Processing Technology, 37 (1993): pp. 801-816