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Numerical Investigation of the Effect of Uniform Cutout on Performance of Ultrasonic Horn for Machining Nomex Honeycomb Core Material

Khurram Hameed Mughal* [a,b], Muhammad Asif Mahmood Qureshi [a], Asif Ali Qaiser [a], Fazal Ahmad Khalid [a], Syed Farhan Raza [a], Adnan Maqbool [a], Shehzad Ahmad [c] & Jianfu Zhang [d]

[a] *University of Engineering and Technology, Lahore 54890, Pakistan*
[b] *Department of Mechanical Engineering, Faculty of Engineering & Technology, The University of Lahore, Lahore54000, Pakistan*
[c] *Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Swabi 23640, Pakistan*
[d] *Beijing Key Laboratory of Precision/Ultra-Precision Manufacturing Equipment and Control, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China*

**Corresponding author: khurram.hameed@me.uol.edu.pk*

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ABSTRACT

Ultrasonic horn is utilized in order to enhance the amplitude of vibration transmitted by the transducer in an ultrasonic machining system. It plays a vital role in vibration amplification to a magnitude suitable for efficient machining of materials. Ultrasonic machining system has to operate at a frequency of at least . Therefore, horn may be subjected to high magnitude of stresses leading to failure. Mechanical horn is designed to get optimum vibration amplification while keeping stresses in acceptable limits. In this research an ultrasonic compound horn was designed with through cutout of uniform diameter. The performance of ultrasonic horn was observed by varying the cutout diameter by modelling horns of four different materials: titanium, aluminum, steel and stainless steel respectively. Modal analysis was performed for computing modal frequencies in the axial direction, whereas harmonic analysis was carried out in order to determine vibration amplitude, stresses and factor of safety. The effect of varying frequency ratio on vibration magnification, stresses, and factor of safety were also investigated. The axial modal frequency was observed to increase, whereas amplitude of vibration and stresses were observed to decrease by increasing the cutout size. Titanium was found to be the most suitable material for ultrasonic horns, because it provided up to 159.4 % more amplitude of vibration and 3 times higher safety factor thus operating life as compared to other materials.

Keywords: harmonic analysis; magnification; modal analysis; stresses; ultrasonic horn; uniform cutout

INTRODUCTION

Nomex honeycomb material is an advanced composite material consisting of phenolic resin reinforced by aramid fiber. It is used in aerospace sandwich structures due to its high compressive strength and ultra-lightweight (Li 1995; Foo et al. 2007; Karakoc & Freund 2012; Zhang et al. 2018; Mughal et al. 2021). Own to its soft and brittle nature, conventional machining such as drilling, milling and grinding may cause surface damage, surface roughness, burr formation, and poor machining quality. In order to cope with these problems, ultrasonic assisted machining is found to be more suitable solution for the machining of soft and brittle materials (Yong & Haiping 2012). The ultrasonic machining system (Fig. 1) consists of ultrasonic generator, transducer, mechanical horn and cutting tool. The ultrasonic generator converts low frequency (50-60 *Hz*) signal to high frequency (no less than 20 *kHz*)electrical signal. The high frequency electrical signal is then converted to high frequency mechanical vibrations by the transducer. The amplitude of these mechanical vibrations is usually extremely low (nearly 5 μm) which is not suitable for machining processes (Amin et al. 1995). Therefore, a mechanical horn is connected to transducer, in order to enhance the vibration amplitude. At the other end of horn, cutting tool is attached for particular machining operation. Good machining quality and reasonable reduction of forces have been achieved through ultrasonic machining systems (Singh & Khamba 2006; Li et al. 2006; Cong et al. 2014; Ning et al. 2016).

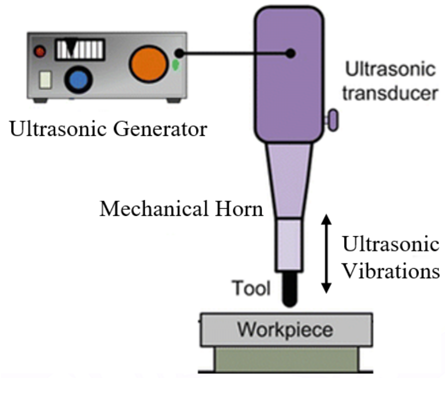


FIGURE 1. Schematic of Ultrasonic Assisted Cutting System (Cong & Pei 2015)

The design of ultrasonic horn is quite challenging. The main purpose of the ultrasonic horn is to magnify amplitude of vibrations transferred by transducer to a magnitude suitable for material cutting operations (Amza & Drimer 1976). There are various horn designs available in literature, like step horns, conical horns, Bezier horns, catenoidal horns and exponential horns (Coy & Tse 1974; Seah et al. 1993; Amin et al. 1995; Wang et al. 2011; Rai et al. 2020). Each design has its own merits and demerits. Step horn has the advantage of providing largest amplitude of vibrations but at the expense of greatest stresses which may reduce the operating life (Wang et al. 2011). Conical horn has resolved the issue of high stresses, but amplitude of vibration produced is quite low (Amin et al. 1995). Researchers have also designed and analyzed ultrasonic horns for various ultrasonic applications. Razavi et al. (2019) analyzed free and forced vibrations of five element horn for ultrasonic surface rolling. Yu et al. (2020) carried out Eigen frequency characterization and tuning of Ti-6Al-4V ultrasonic horn at high temperatures for glass molding. Cao et al. (2020) developed and analyzed the performance of a novel ultrasonic vibration plate horn for grinding. Pang et al. (2020) carried out frequency coupling design of ultrasonic horn with spiral slots longitudinal-torsional machining characteristics of hard materials. Yu et al. (2020) designed novel horn for mechanically enabled two-axis ultrasonic-assisted system for ultra-precision machining. Mughal et al. (2021) designed a novel ultrasonic horn to achieve high vibration amplification for machining advanced brittle composites. Other horn designs have been attempted to reduce stresses while keeping the amplitude of vibration in acceptable limits (Rosca et al. 2015; Mughal et al. 2021).

The main emphasis of this research work is to design a mechanical horn for the machining of Nomex honeycomb material. The idea is to make the design as simple as possible and use the benefits of both step and conical horn profiles, i.e. high-amplitude magnification and least stresses. For this purpose, a hollow compound horn which is the combination of step and conical profiles is designed, and the effect of varying the cutout diameter on the performance of horn has been studied. A lot of work has been done on horn design and various aspects has been studied by researchers, but the influence of cutout size on horn performance has not been fully explored yet. Therefore, an attempt was made to identify the effect of producing cutout in ultrasonic horn and changing the cutout size on the horn performance parameters such as natural frequency, amplitude of vibration, magnification, stresses induced and factor of safety. The influence of frequency ratio on magnification factor, stresses and factor of safety was also investigated. Vibration analysis of non-uniform horns is extremely difficult theoretically, and experimentations would involve lot of time and money, therefore an attempt has been made to investigate the effect of cutout size on the vibration characteristics of such complex horns through numerical computations. The results of this research effort can be implemented on any horn design and used by the designers and manufacturers of the ultrasonic machining system.

PROBLEM FORMULATION

Since the compound ultrasonic horn is a continuous system, and have infinite modes of vibrations, therefore determining vibration characteristics associated with first axial vibration mode is complex. In order to validate the results and understand the behavior of ultrasonic horns with simplicity, when a frequency of 20 *kHz* was provided by the generator, horn was modeled as a single degree of freedom undamped spring mass system as shown in Fig. 2. The mass m is lumped at the end and the stiffness k of uniform circular horn in the axial direction can be determined by (1) (Kelly 2011). Majority of the ultrasonic machining systems used for processing of composite materials has to operate at 20 *kHz* for smooth functioning, higher vibration amplification and sufficient quality (Seah et al. 1993; Pang et al. 2020; Mughal et al. 2021).

$$k = AE/L \tag{1}$$

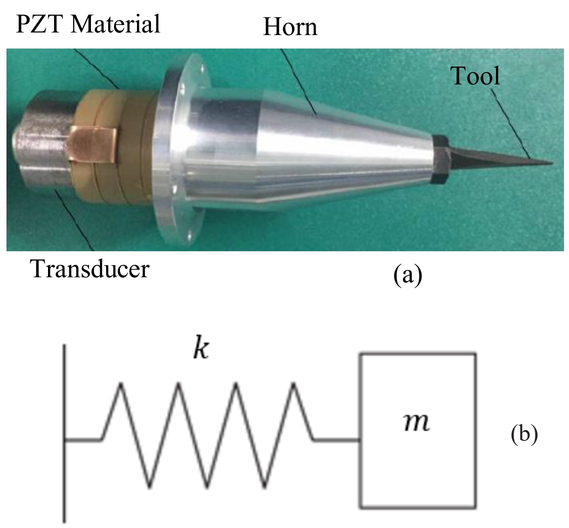


FIGURE 2. Schematic of a) Ultrasonic Assisted Cutting Tool and b) Equivalent Single Degree of Freedom Spring Mass System (Ke et al. 2019)

Ultrasonic horn mass having uniform circular cross sectional area A, length L, volume V and density ρ can be determined by $m = \rho V = \rho AL$ (Rao 2016).

The natural frequency ω_n of axial vibration for single degree of freedom system can be obtained through (2) (Kelly 2011; Rao 2016).

$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{AE/L}{\rho AL}} = \sqrt{\frac{E}{\rho L^2}} \tag{2}$$

The magnification factor M for single degree of freedom systems exhibiting undamped vibrations can be determined by using (3) (Kelly 2011).

$$M = \frac{1}{1-(\omega/\omega_n)^2} \quad (3)$$

METHODOLOGY

The main focus of this research effort was to investigate the effect of changing the cutout diameter of the ultrasonic horn that would be used in the machining of Nomex honeycomb structure. For this purpose, various geometric models of the ultrasonic compound horn were developed by using CAD software Solid Edge. The basic horn geometry considered for evaluating the influence of cutout diameter is shown in Fig. 3 (Ke et al. 2019). The horn materials considered in this research were aluminum (Al), steel (S), stainless steel (SS) and titanium (Ti), with properties presented in Table 1. The diameter of the cutout was varied in the range of 0 *mm* to 12 *mm* with increments of 1 *mm*. Cutout size of 0 *mm* meant completely solid horn. The size and shape of horn were taken exactly same for all materials, to have a fair comparison among performance parameters, like vibration amplitude, natural frequencies, stresses, and factor of safety.

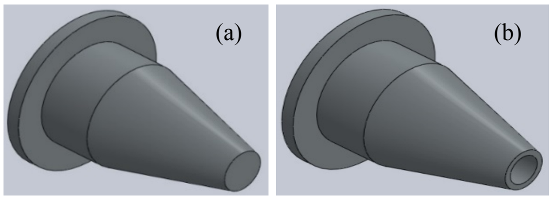


FIGURE 3. Ultrasonic Horn Models, (a) Solid Horn, (b) Hollow Horn

Three dimensional CAD models of horn were then imported to ANSYS in order to perform modal and harmonic analyses. Modal analysis was done for calculating natural frequency of horn vibrations, whereas harmonic analysis was carried out for determining amplitude of vibration, stresses (Amin et al. 1995; Wang et al. 2011; Mughal et al. 2021), factor of safety and magnification factor produced in ultrasonic horn when a 20 *kHz* continuous forcing frequency was provided by ultrasonic generator. The amplitude of mechanical vibrations transmitted by the transducer was taken to be 5 μm (Mughal et al. 2021). Therefore the harmonic displacement at the transducer end of the horn was taken to be 5 μm in axial direction, and displacement amplitude at tool end was computed numerically. Since horn is a continuous system, therefore there are infinite mode shapes and hence modal frequencies associated with it (Kelly 2011; Mughal et al. 2021). In ultrasonic cutting systems, tool vibrates in the axial direction, thus only axial modal frequency is important in stationary ultrasonic tools. While in rotary ultrasonic cutting systems, the tool rotates about its own axis as well as vibrates in the axial direction, therefore both axial mode of vibrations and tool angular velocity are important (Pang et al. 2020; Mughal et al. 2021). The simulation results for different cutout diameters and horn materials were later compared for making conclusion.

TABLE 1. Properties of standard ultrasonic horn materials.

Properties	Aluminum	Steel	Stainless Steel	Titanium
Density (kg/m^3)	2770	7850	7750	4620
Poisson's Ratio	0.33	0.3	0.31	0.36
Elastic Modulus (GPa)	71	200	193	96
Yield Strength (MPa)	280	250	215	830

RESULTS AND DISCUSSIONS

MODAL ANALYSIS

The modal analysis was performed in order to extract the natural frequencies of horn vibrations (Logan 2017; Mughal et al. 2021). Since whole ultrasonic cutting system vibrates in the axial direction, therefore among infinite modal frequencies, modal frequency in the axial direction is extremely important. The natural frequencies in the axial direction for solid horns for various materials are shown in Fig. 4. The modal frequencies of titanium, aluminum, steel and stainless steel horns were found to be 21162*Hz*, 23399*Hz*, 23236*Hz* and 23002*Hz*, respectively. Although the length, shape and other dimensions were identical for each horn, but the natural frequencies were observed to be different. This happened due to dissimilarity between material properties mainly modulus of elasticity E and density ρ, which influence the stiffness k and mass m of the horn respectively (Rao 2016). The axial modal frequency for aluminum horn was observed to be larger because it has relatively less stiffness but very low mass as compared to other horns used in this research. The horns made of steel and stainless steel have approximately same mass and stiffness respectively (both usually high), therefore the natural frequencies were found to be not so much different from one another. Titanium horn has relatively less stiffness but moderate mass, due to which its natural frequency was observed to be least among all ultrasonic horns considered in this work.

Similar numerical computations were performed for ultrasonic horns having through cutouts of different diameters. The modal frequencies for ultrasonic horns made of different materials were recorded and plotted as presented in Fig. 5. The modal frequency was observed to increase with increase in cutout diameter. This happened due to the fact that, with increase in cutout size, mass of ultrasonic horn was reduced, and the variation of stiffness was not very large as depicted in Fig. 6. Every horn model made of specific material was observed to be showing this behavior with similar pattern.

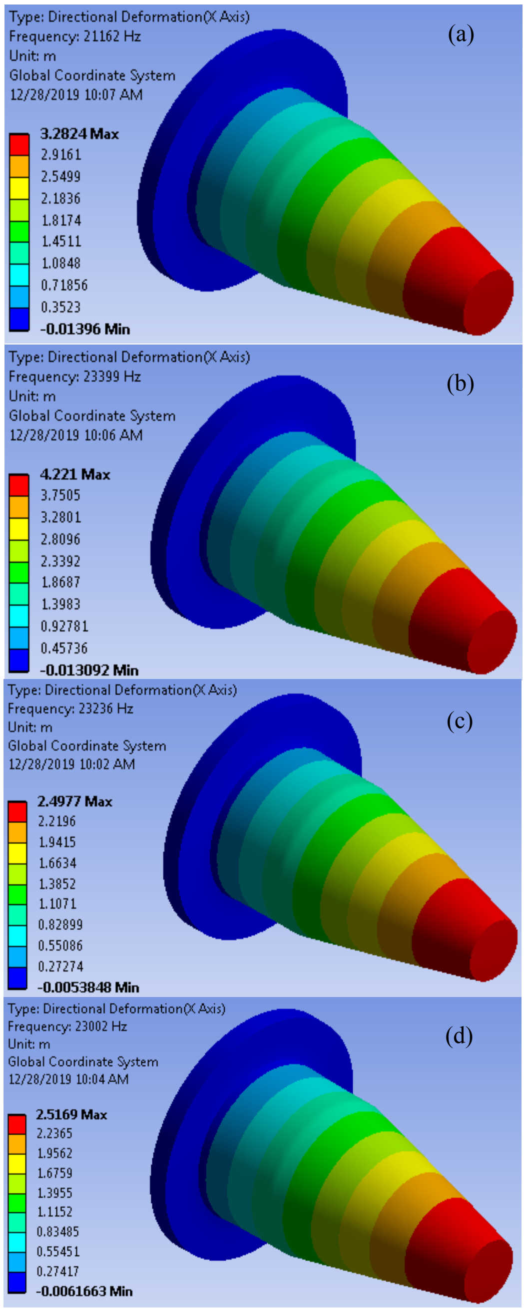


FIGURE 4. Modal Analysis Simulation Results Indicating Natural Frequency and Displacement in Axial Direction for Solid Compound Horns for (a) Titanium, (b) Aluminum, (c) Steel, (d) Stainless Steel.

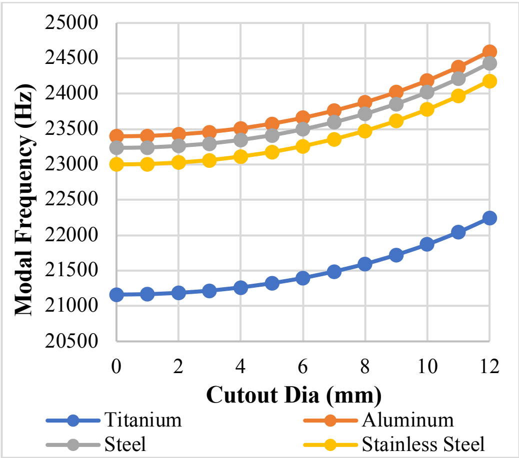


FIGURE 5. Variation of Modal Frequency With Cutout Diameter for Ultrasonic Horns of Various Materials

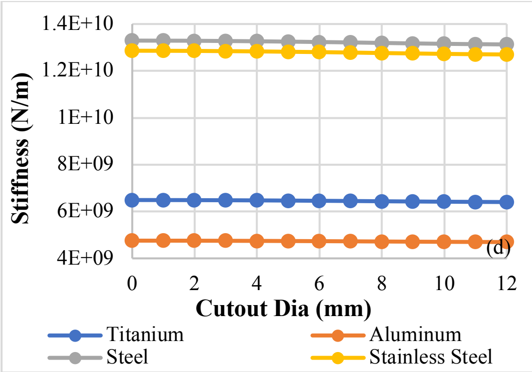


FIGURE 6. Variation of Stiffness with Cutout Diameter for Ultrasonic Horns

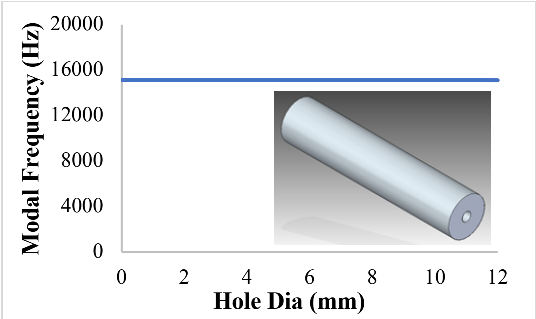
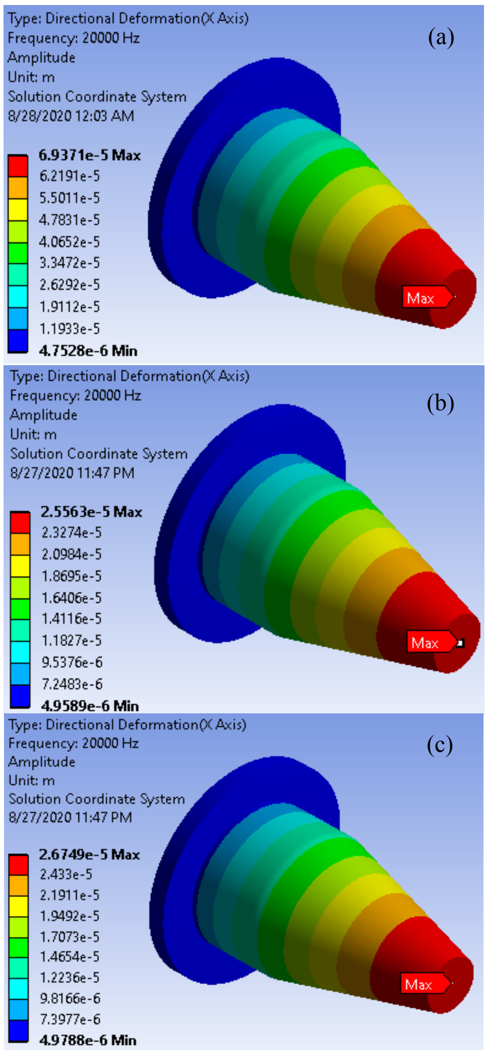


FIGURE 7. Variation of Modal Frequency with Cutout Diameter for Prismatic Ultrasonic Horn

It is very important to note that when the cutout is produced in prismatic cylindrical horn then it makes theoretically no effect on the natural frequency in the axial direction (Fig. 7), and thus the effect on vibration amplitude can be considered negligible (Rao 2016). This is due to the fact that cutout in uniform cylindrical horn (considered as single degree of freedom system in the axial direction) decreases the mass but reduces the stiffness as well by the same amount. Therefore, their ratio remains unchanged, and there is no effect of generating cutout on the modal frequency in the axial direction in case of cylindrical horns. Since the ultrasonic horn considered in this research were compound horns having non uniform cross section, therefor producing cutout would not reduce the mass and stiffness in the same pattern.

HARMONIC ANALYSIS



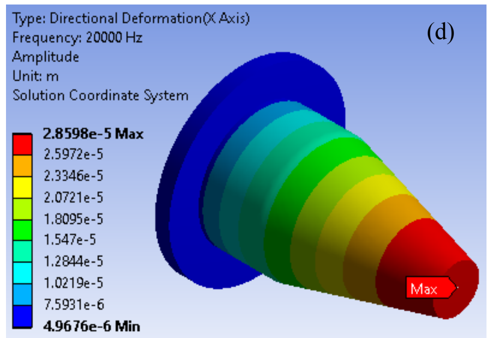


FIGURE 8. Contour Plots of Displacement Amplitude for Solid Compound Horns for (a) Titanium, (b) Aluminum, (c) Steel, (d) Stainless Steel.

After performing modal analysis, harmonic analysis of ultrasonic horn was carried out, and the amplitude of vibrations, magnification factor and stresses were computed numerically (Logan 2017). Since the horn materials considered in this research are all ductile in nature at given operating conditions, therefore only Von Mises st resses were evaluated (Hibbeler 2016). The amplitudes of vibration were found to be 69.39μm, 25.567μm, 26.751μm and 28.602 μm for solid horns made of titanium, aluminum, steel and stainless steel respectively as shown in Fig. 8. The amplitude of vibration achieved at horn end depends on the frequency ratio ω/ω_n (i.e. ratio of forcing frequency ω and natural frequency ω_n). Since the forcing frequency provided by the generator was 20kHz and the natural frequency of axial vibrations for each horn material was different, therefore the vibration amplitude obtained for each horn was observed to be different. The largest amplitude of vibration was achieved by Titanium horn because the forcing frequency provided by the generator was closer to the natural frequency of horn. The amplitude of vibration is maximum at resonance i.e., when the forcing frequency transmitted by transducer matches with the natural frequency of the horn ($\omega = \omega_n$) (Kelly 2011).

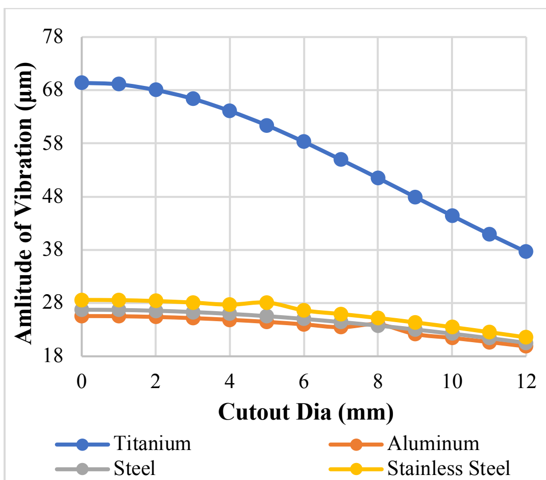


FIGURE 9. Variation of Amplitude of Vibration with Cutout Diameter for Ultrasonic Horns

The harmonic analysis of the ultrasonic horns indicated that the amplitude of vibration decreased with increase of cutout diameter as shown in Fig. 9. The drop in vibration amplitude for aluminum, steel and stainless steel horns were observed to be quite less, whereas there was a significant reduction in case of titanium horns. This happened because the modal frequencies for steel, aluminum and stainless steel horns were already quite different from 20*kHz* transmitted by transducer. However increasing cutout size enhanced the natural frequency of titanium horns to a magnitude much larger than 20*kHz* e.g. 22.242*kHz* for cutout diameter of 12*mm*, therefore amplitude of vibration dropped to 37.625*μm* from 69.39*μm* (for solid horn) indicating 45.78% reduction. In other words the magnification factor reduced by increasing the cutout size as presented in Fig. 10. The magnification factor dropped 22.23% from 5.35 to 4.11 for steel, 24.62% from 5.72 to 4.21 for stainless steel, 22.32% from 5.11 to 3.97 for aluminum, when cutouts of 12*mm* dia were produced in solid horns.

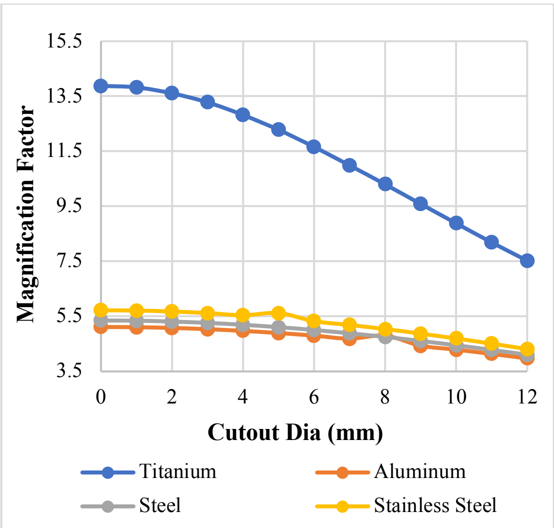


FIGURE 10. Variation of Horn Magnification Factor with Cutout Diameter

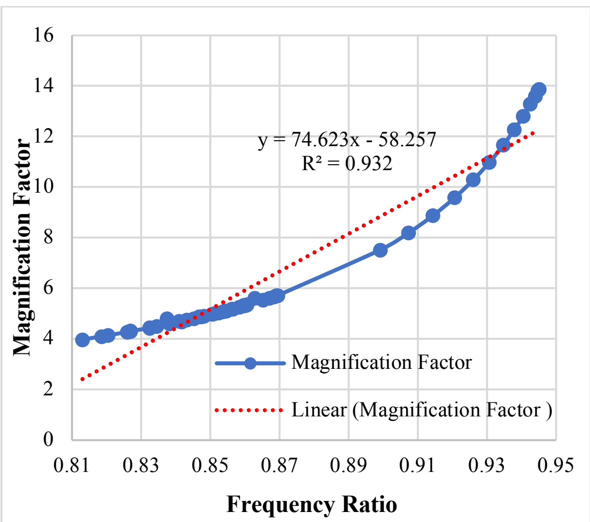


FIGURE 11. Variation of Magnification Factor with Frequency Ratio for Ultrasonic Horns

The reduction of vibration amplitude could be explained conveniently by observing variation of magnification factor with frequency ratio as plotted in Fig. 11. In this plot, all ultrasonic horn models were considered, and the magnification factor was computed numerically against the frequency ratio. It was observed that the magnification factor increased by enhancing the frequency ratio till the resonance condition (where frequency ratio is 1). After resonance occurs further increase in frequency ratio would decrease the magnification Factor (Kelly 2011). The regression analysis of the variation of magnification factor with frequency ratio indicated a very strong relationship having correlation coefficient R^2 = 0.932. This meant that majority of the variation of magnification factor was indeed due to frequency ratio.

STRESS ANALYSIS

The stresses produced in ultrasonic horns for different materials and cutout sizes were then computed numerically when vibration frequency of 20 *kHz* was applied at the transducer end of horn (Logan 2017). The stresses were observed to be reduced with increasing cutout size as indicated in Fig. 12. The stresses were computed to be 186.65 *MPa*, 46.994 *MPa*, 140.23 *MPa* and 145.86 *MPa* for solid compound horns made of titanium, aluminum, steel and stainless steel respectively, as shown in Fig. 13. Very large stresses were produced in titanium horn with maximum stress of 189 *MPa* for 3 *mm* diameter cutout. Stresses were observed to be reduced to 101 *MPa* for titanium horn having 12 *mm* diameter cutout. For steel and stainless steel horns, maximum stress of 145.9 *MPa* and 151.5 *MPa* were observed respectively with cutout size of 3 *mm*. Again least stresses were observed at cutout diameter of 12 *mm* with magnitudes 106.29 *MPa* and 108.77 *MPa* respectively. Among all horns, extremely low stresses were developed in aluminum horns with largest stress of 48.9 *MPa* for 3 *mm* cutout size and least stress equal to 36.1 *MPa* for cutout diameter of 12 *mm*.

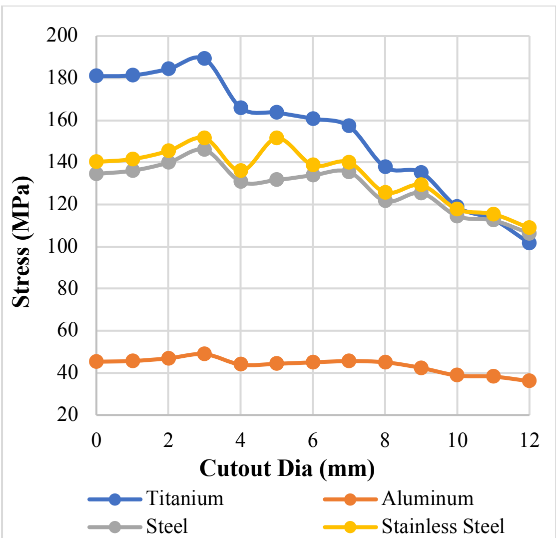
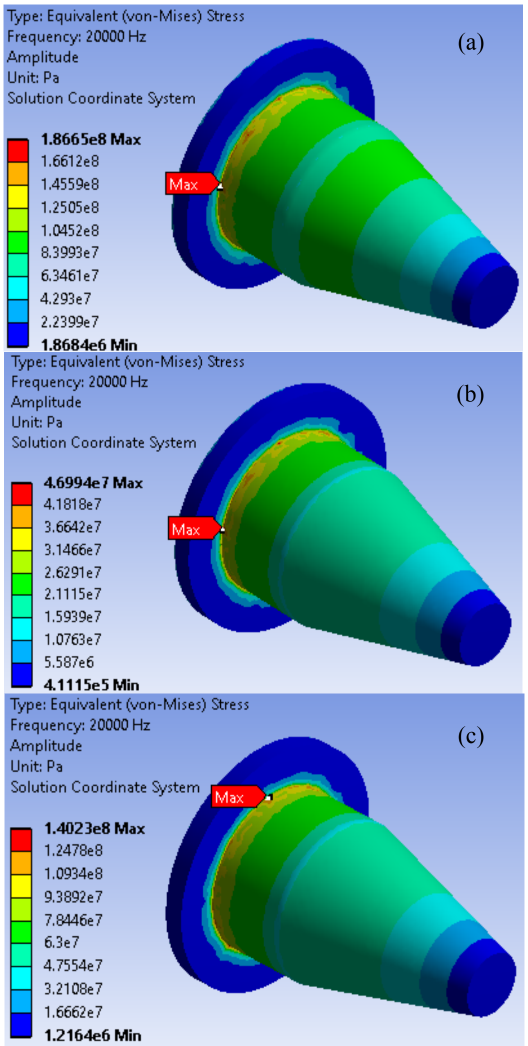


FIGURE 12. Variation of Stress with Cutout Diameter for Ultrasonic Horns

The low stress magnitudes in ultrasonic horns made of Aluminum did not mean that it would be more suitable material for horn design and would have more operating life. Similarly, large stresses in titanium horns would not limit its use in ultrasonic systems. In ultrasonic machines, stresses are usually greatest at resonance ($\omega/\omega_n = 1$). Since titanium horns used in this research have natural frequencies close to operating frequency of the generator, therefore the stresses produced in these horns have relatively higher magnitudes. Furthermore, these stresses are dynamic stresses in nature, therefore they do not depend only on the frequency ratio. The overall scatter plot of stresses versus frequency ratio for all horn geometries and materials is shown in Fig. 14. The regression analysis provided a good insight into the dependence of stresses on frequency ratio. It was observed form the plot and value of correlation coefficient $R^2 = 0.42$ that the variation of stresses could not be explained by frequency ratio alone. There are other horn parameters such as mass, acceleration, dynamic forces and geometry as well which influence the stresses developed.



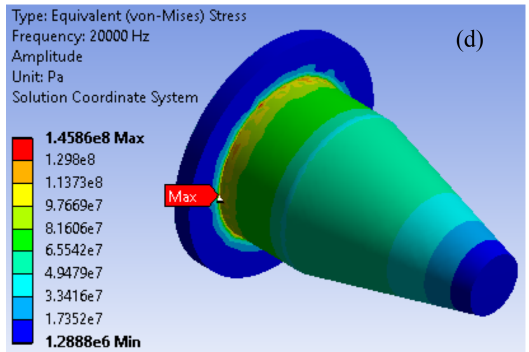


FIGURE 13. Contour Plots of Von Misses Stresses for Solid Compound Horns for (a) Titanium, (b) Aluminum, (c) Steel, (d) Stainless Steel.

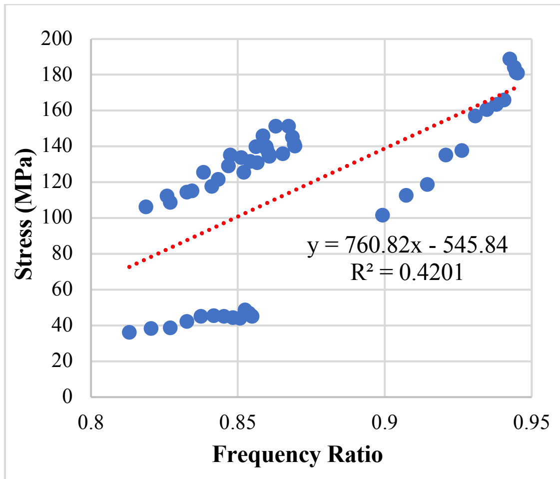


FIGURE 14. Scatter Plot of Von Misses Stress Against Frequency Ratio for Ultrasonic Horns

As four materials for modelling ultrasonic horns were considered in this research, and each horn material has different yield strengths from one another, therefore only stresses could not indicate the operating life of the horn. The factor of safety for each horn geometry was computed by using the maximum stress and yield strength of the material, and plotted as shown in Fig. 15. The horns made of steel and stainless steel were observed to have lesser factor of safety up to 2.35 indicating lower operating life, despite of the fact that they were operated at a frequency far away from their natural frequencies. When they would be designed in a manner to keep their natural frequencies close to 20 *kHz* and resonant condition, then the stresses induced would become more and factor of safety (hence operating life) would further reduce. On the other side, for aluminum horns with cutouts, the factor of safety was observed to be in the range of 5.72 and 7.76, where as the factor of safety was found in between 4.39 and 8.17 for titanium horns with cutout, forecasting more operating life. For given materials and range of parameters, the factor of safety, thus operating life were observed to increase, in general, with the increase of hole diameter.

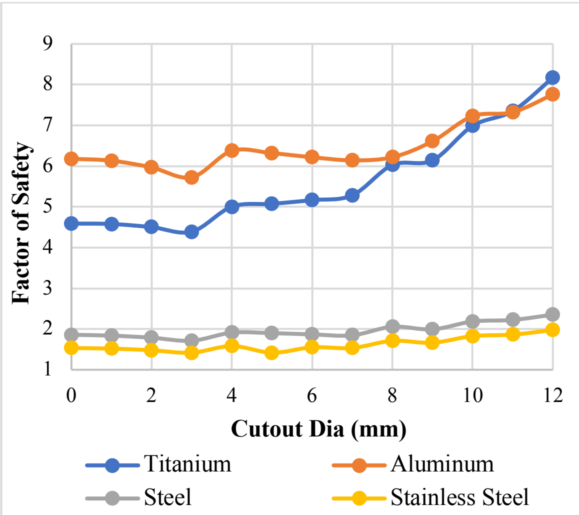


FIGURE 15. Variation of Factor of Safety with Cutout Diameter for Ultrasonic Horns

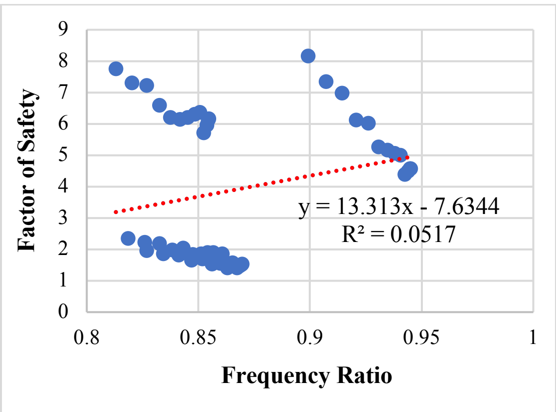


FIGURE 16. Scatter Plot of Factor of Safety Against Frequency Ratio for Ultrasonic Horns

Aluminum horns were designed to have natural frequencies in the axial direction distinct from operating frequency of 20 *kHz*, therefore stresses developed were less and factor of safety was higher. When they would be designed with natural frequency close to 20 *kHz* to operate at resonant condition, their stresses would become large and factor of safety along with operating life would become less. Titanium horns were designed to operate at frequencies closer to operating frequency, the factor of safety and operating life were observed to be still higher. The factor of safety and operating life were observed to be greater for titanium horn having 12 *mm* diameter cutout. When ultrasonic horns would be designed and developed with natural frequencies far away from operating frequency produced by ultrasonic generator, then they would perform even much better, with least stresses and much greater factor of safety and operating life. Fig. 16 shows the scatter plot of factor of safety versus frequency ratio for all horn models.

The regression analysis and low correlation coefficient R^2 = 0.0517 indicated that the variation of safety factor could not be explained by taking into consideration the frequency ratio alone. Factor of safety for ultrasonic horn depend on other parameters such as mass, dynamic forces, acceleration, geometry and material properties as well.

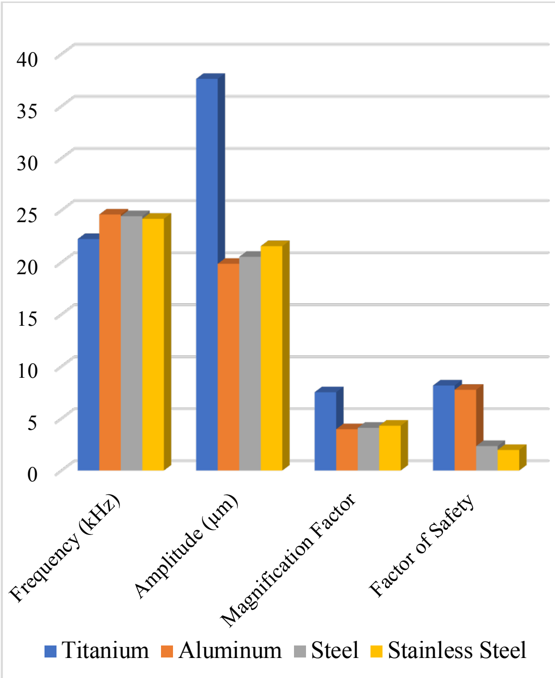


FIGURE 17. Comparison of Horn Performance at Cutout Diameter of 12 mm for Different Materials

The comparison of the performance of hollow ultrasonic horn at uniform cutout size of 12 mm is shown in Fig. 17. The titanium horn was observed to have greatest amplitude of vibration, magnification and factor of safety among other horns of different materials. The comparison of solid horn with hollow horn (Fig. 18) indicated that magnification factor hence amplitude of vibration significantly reduced, whereas factor of safety hence operating life enhanced by producing cutouts of constant diameter. The numerical computations of the ultrasonic horn were validated by comparing the simulation results with the theoretical expectations by considering the simplified model of the ultrasonic horn. The comparison of simulated values of magnification factor with that of theoretical values is presented in Fig. 19 for solid horn and hollow horn with 12 mm diameter. A close agreement was observed between the simulation results and theoretical expectations; however, the difference was obvious due to the simplification of the horn geometry. To summarize the results, the overall effect of varying the cutout diameter on the performance parameters of ultrasonic horn, such as modal frequency, vibration amplitude, magnification and stresses, is presented in Table 2.

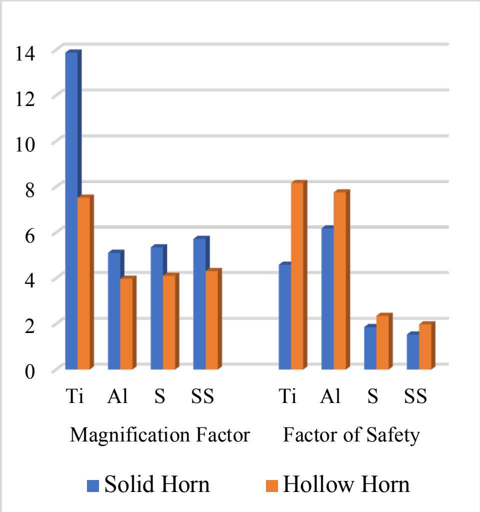


FIGURE 18. Comparison of Solid Horn and Hollow Horn with 12 mm Diameter

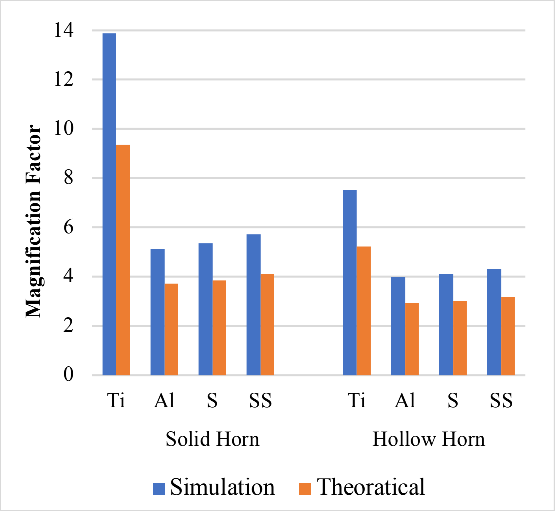


FIGURE 19. Comparison of Simulated Magnification Factor with Theoretical Expectation for Solid Horn and Hollow Horn with 12 mm Diameter

TABLE 2. Summarized Details of Effect of Increasing Cutout Size on Ultrasonic Horn Performance Parameters

Performance Parameter	Aluminum	Steel	Stainless Steel	Titanium
Horn Mass	↓	↓	↓	↓
Modal Frequency	↑	↑	↑	↑
Axial Stiffness	↓	↓	↓	↓
Amplitude of Vibration	↓	↓	↓	↓
Magnification Factor	↓	↓	↓	↓
Stress	↓	↓	↓	↓
Factor of Safety	↑	↑	↑	↑

CONCLUSION

This research effort was focused on the numerical investigations of the effect of varying cutout size on the performance of ultrasonic horn used for the machining of Nomex honeycomb core material. For this purpose, compound horn was designed including both step and conical profiles, and cutout was produced with maximum size upto 12 mm. The investigations were carried out by performing vibration analysis on ultrasonic horn using four isotropic materials titanium, aluminum, steel and stainless steel respectively. The simulation results showed good agreement of modal and harmonic analysis with the theoretical expectations. After intensive numerical computations, the following conclusions were made regarding the design performance of ultrasonic horn.

1. The natural frequency generally enhances by increasing the cutout size for all materials.
2. The stiffness of ultrasonic horn drops slightly with increase in cutout size.
3. The amplitude of vibration and hence magnification factor decreases by increasing the cutout diameter for $\omega < \omega_n$. This means that for operating frequency of ultrasonic system smaller than horn natural frequency, the amplitude of vibration can be decreased by enlarging the cutout size.
4. The magnification factor and vibration amplitude achieved by the horn enhances by increasing the frequency ratio for $0 < \omega / \omega_n < 1$.
5. The stresses normally reduce and factor of safety enhances with increase in cutout size when the ultrasonic system is operated at a frequency less than the natural frequency of the horn.
6. The largest magnification and amplitude of vibration is achieved by titanium horns, whereas the stresses are observed to be least in aluminum horns (due to their light weight). But the yield strength of titanium is much larger as compared to aluminum and steel materials, guarantying more safety factor and operating life. Therefore, titanium is found to be the ultimate choice for the design of high performance and efficient ultrasonic horns.

7. Due to high cost of titanium, aluminum may be chosen as the alternative material for horns due to light weight, reasonably good magnification and operating life, and least stresses as compared to steel horns.
8. The optimum performance with high magnification factor and reasonable factor of safety was observed for ultrasonic solid horn.
9. The outcomes of the present research would be highly useful for researchers, designers and manufacturers of ultrasonic machining system for soft and brittle composites to achieve better machining quality, efficiency and high material removal rate.

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DECLARATION OF COMPETING INTEREST

None

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