Jurnal Kejuruteraan 36(1) 2024: 49-62
https://doi.org/10.17576/jkukm-2024-36(1)-06

Harmonic Excitation Response of Standard Ultrasonic Horn Designs for Machining Nomex Honeycomb Core Composite

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Received 16 November 2022, Received in revised form 15 May 2023
Accepted 15 June 2023, Available online 30 January 2024

ABSTRACT

Ultrasonic horn plays a vital role in achieving vibration amplitude at tool end (VATE) by enhancing output displacement of piezoelectric ultrasonic transducer suitable for efficient machining of advanced composites. Higher vibration amplitude enhances ultrasonic machining quality, surface integrity and dimensional accuracy of Nomex honeycomb composite (NHC) while reducing cutting forces. Furthermore, low stress concentrations allow ultrasonic tool to have more safety factor and longevity. Ultrasonic horn is designed to enhance displacement amplitude of piezoelectric ultrasonic transducer and get optimum VATE while keeping stresses in acceptable limits to avoid failure at very high operating frequency of ultrasonic machining system. In this research, variety of standard ultrasonic horns (SUH) were designed with same length and end diameters; and were tested under similar operating conditions, using finite element method. The ultrasonic actuation of the horn exploits the first axial mode of horn vibration. Harmonic response analysis was carried out to determine axial modal frequencies (AMF), VATE, stresses, and factor of safety for performance evaluation. VATE attained by step horn was found to be greatest among all other SUHs for frequency ratio greater than one, but may be prone to early failure due to high stress concentrations. VATE achieved by third order Bezier, Gaussian, exponential, catenoidal, conical and second order Bezier horns were found less than that of step horn by 11.7 %, 16.6 %, 16.7 %, 17 %, 16.73 % and 18 % respectively. However, 44.2 %, 43.43 %, 42.5 %, 43.5 %, 42.8 % and 37.67 % reduction of stresses was achieved by Gaussian, exponential, catenoidal, conical, second and third order Bezier horns respectively. Outcomes of present work would be beneficial for designers, researchers, scientists, and manufacturers of ultrasonic machine tool to select appropriate SUH designs according to requirements.

Keywords: Finite Element Analysis (FEA); Nomex Honeycomb Composite (NHC); stresses; Standard Ultrasonic Horn (SUH); Vibration Amplitude at Tool End (VATE).

INTRODUCTION

Nomex honeycomb composite (NHC) is an advanced brittle and soft material, consisting of phenolic resin reinforced by aramid fiber. It has astonishing thermal and mechanical characteristics for instance better thermal insulation, good flame retardation, ultra-lightweight and high compressive strength etc., ensuring its popularity in automotive, aerospace and defence applications as sandwich structures (Mughal et al. 2022). Traditional machining including drilling, orthogonal cutting, milling and grinding may cause poor machining quality, delamination, surface damage, tearing of walls, burr formation and surface roughness due to its soft and brittle characteristics. To tackle such problems, ultrasonic assisted machining is determined more appropriate for processing of soft and brittle composites, as discussed by Ahmad et al. (2020) in their comprehensive review of processing technologies for NHC. Figure 1 shows schematic of ultrasonic vibration assisted machining system, which comprises, piezoelectric transducer, ultrasonic horn, harmonic excitation unit / generator, and straight knife cutter. Ultrasonic generator converts low frequency (50 to $60\ Hz$) electrical signal to high frequency (minimum $20\ kHz$) signal, that is converted to mechanical vibrations via piezoelectric transducer. Transducer's displacement amplitude is typically extremely low and not sufficient for ultrasonic machining of target material. For that reason, ultrasonic horn is essential between cutting tool and transducer to enhance displacement amplitude. According to Kang et al. (2019) and Mughal et al., (2023), considerable cutting force reduction and better machining quality have been realized via ultrasonic machining technology.

Ultrasonic horn design to enhance vibration amplitude of piezoelectric ultrasonic transducer with longevity and low stress concentrations for specific processing application is challenging. Horn geometric parameters, profile and material are generally decided based on required VATE appropriate for ultrasonic processing of target material (Mughal et al., 2021; Mughal et al., 2022; Mughal et al., 2023; Munir et al., 2023). For this purpose, several horn profiles have been designed and analyzed by researchers.

Wang et al. (2011) developed third order Bezier horn profile for ultrasonic welding. VATE attained by proposed horn was found larger than that of catenoidal horn, however, 33.12 % lower than that of step horn. Albeit, stresses developed were found significantly lower than those of catenoidal and step designs. Jung et al. (2013) optimized step type horn having a slot and rectangular cross section for ultrasonic micro pattern replication. Nguyen et al. (2014) designed non-uniform rational B-spline horn to be used in ultrasonic welding application. The proposed non rational B spline (NURBS) horn was optimized using genetic algorithm for high VATE comparable to step horn. However, this specific horn did not offer substantial stress reduction and amplification improvement as compared to those of step horn. Furthermore, NURBS horn was found to have limited applications in ultrasonic machining and has not been considered in the present work.

Rani et al. (2013) examined Gaussian, catenoidal, Bezier, cylindrical and step horns used in plastic welding. They observed VATE attained by Bezier horn to be closer to step horn and greater than that of cylindrical, Gaussian and catenoidal horns. Albeit, the stress concentrations were found to be closer to step horn and much larger than those of other horn designs. Roy et al. (2016) used finite element analysis for hollow exponential horn. VATE attained by proposed horn was observed to be marginally higher than that of exponential and conical designs; albeit, 77.88% lower than that of step design. Naseri et al. (2016) used multi-step horn design with support position having zero displacement node to be incorporated in ultrasonic vibration assisted angular pressing.

Jagadish et al. (2017) analyzed exponential horn by replacing circular section with rectangular one and observed the slight enhancement in VATE as compared to exponential and conical horns. However, it was observed to be 71 % lower than that of step design. Wang et al. (2018) examined step horn for better arc acoustic interaction in ultrasonic vibration aided welding. Kumar et al. (2018) analyzed complex horn by connecting front portion, bearing pair, nut and bolt. Lin et al. (2018) suggested actively adjustable horn comprising piezoelectric element and step profile, linked to amendable electric impedance. Influence of electric impedance and piezoelectric material location on horn's resonance frequency and VATE was investigated. VATE and resonance frequency were observed larger for piezoelectric element location near transducer end. Razavi et al. (2019) analyzed five element horn based on cylindrical and conical sections through FEA. Rai et al. (2020) compared second and third order Bezier horns for rotary ultrasonic machining and found third order Bezier horn performance better than second order in terms of high VATE and less stress.

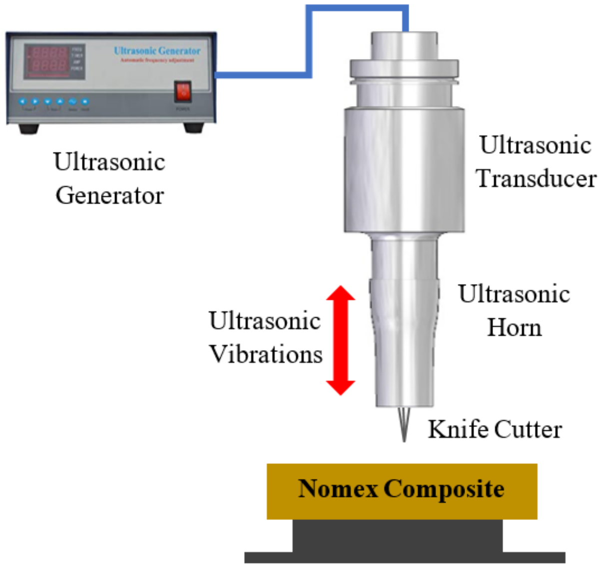


FIGURE 1. Ultrasonic Assisted Machining System

Pang et al. (2020) analyzed influence of step and diagonal spiral slot location with 52° spiral angle on modal frequency and VATE. They achieved improvement in surface quality and reduction in cutting forces through coupling of longitudinal and torsional vibration modes. Mughal et al. (2021) designed and analyzed a novel third order polynomial horn profile for ultrasonic machining of hard materials. Their proposed design was found to achieve greatest VATE among all standard horns for longitudinal natural frequency closer to but higher than ultrasonic tool's operating frequency. Mughal et al. (2022) investigated the effect of uniform cutout on the performance of ultrasonic horn suitable for the machining of Nomex honeycomb composite. They varied cutout diameter in non-uniform horn geometry to investigate influence on resonant frequency, VATE, stresses, magnification factor (MF) and factor of safety (FOS). They found increase of axial stiffness, modal frequency and FOS, while drop of magnification factor and amplitude of vibration at tool end by increasing cutout diameter. Ouyang et al. (2022) designed and optimized step ultrasonic horn having 3rd order B-spline profile at step location using orthogonal technique for micro-injection molding application. Munir et al. (2023) designed and analyzed novel longitudinally-torsionally coupled Bezier horns for ultrasonic machining of hard and brittle materials. Although a lot of work has been done on horn design for various operating conditions. Performance evaluation of standard ultrasonic horn (SUH) profiles to enhance vibration amplitude of transducer, having same end diameters and length, under same operating conditions, is extremely required, which has not been investigated yet in the past research.

Aim of present research work is to evaluate novel USH designs to enhance vibration amplitude of ultrasonic transducer for machining brittle and soft composites e.g. NHC. In past research, various horn designs have been proposed, but dimensions and sizes were found different from each other. Moreover, performance of suggested designs was compared only with few SUHs. Thus, there is a dire need to have a comprehensive performance comparison of SUH designs with similar sizes under comparable operating conditions. Present work fills this gap through analysis and evaluation of SUH designs for frequency ratio greater than one i.e., harmonic excitation frequency larger than horn's axial modal frequency (AMF). Harmonic excitation response analysis of SUHs is challenging analytically, while experiments would be time consuming and costly. Thus numerical computations were attempted to evaluate performance characteristics of SUHs. Outcomes of present research would be valuable for manufacturers, scientists, designers and researchers of ultrasonic machining technology to select better SUH designs to enhance vibration amplitude of ultrasonic transducer for specific material and application as per requirement.

GOVERNING EQUATIONS

Acoustic axial waves propagation in SUH is expressed by Webster's equation Mughal et al. (2021); Mughal et al. (2023).

$$\frac{\partial^2 u(x,t)}{\partial x^2} + \frac{\partial^2 u(x,t)}{\partial x^2}\frac{\partial}{\partial x}\ln A(x) = \frac{1}{c^2}\frac{\partial^2 u(x,t)}{\partial t^2} \quad (1)$$

Here $c = \sqrt{E/\rho}$ is longitudinal wave propagation speed through SUH. For simple harmonic motion (SHM), equation (1) takes the form;

$$\frac{\partial^2 u(x,t)}{\partial x^2} + \frac{\partial^2 u(x,t)}{\partial x^2}\frac{\partial}{\partial x}\ln A(x) = \frac{\omega^2}{c^2}u(x,t) = {k_1}^2 u(x,t) \quad (2)$$

$k_1 = \omega/c$ is circular wave number. SUH displacement at desired time and position is obtained by solving (2).

$$u(x,t) = (C_1 \sin K_1 x + C_2 \cos K_1 x)/\sqrt{A(x)} \quad (3) \quad (3)$$

$u(x,t)$ is displacement as a function of time t and axial position x, $A(x)$ is cross-sectional area, C_1 & C_2 are parameters dependent on system's initial conditions and K_1 is a factor dependent on k, A and x. Von Mises (VM) stress can be computed from (4) in terms of principal stresses σ_1, σ_2 and σ_3.

$$\sigma_{VM} = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \quad (4)$$

Factor of safety (FOS) for SUH is determined by (5) in terms of maximum VM stress σ_{VM} and material's yield stress σ_Y

$$FOS = \sigma_{VM}/\sigma_Y \quad (5)$$

Magnification factor M of SUH is determined by (6) in terms of displacement amplitude at transducer end $DATE$ and amplitude of vibration at tool end $VATE$.

$$M = VATE/DATE \quad (6)$$

PROBLEM FORMULATION

Standard ultrasonic horn (SUH) has indefinite vibration modes being a continuous system. Determination of SUH performance characteristics associated with desired vibration mode is complex. For validation of numerical results and realizing SUH performance characteristics at harmonic excitation frequency of $20\ kHz$ provided by ultrasonic generator, SUH was modeled as a single degree of freedom (SDOF) un-damped mass-spring system with lumped mass m and axial stiffness k as shown in Figure 2. Its axial stiffness can be calculated using (7) (Mughal et al., 2022). Ultrasonic vibration assisted machining (UVAM) system typically used for composite processing operates at $20\ kHz$ excitation frequency for smooth working with sufficient quality and vibration amplification (Mughal et al. 2021; Mughal et al., 2023).

$$k_{th} = AE/L \quad (7)$$

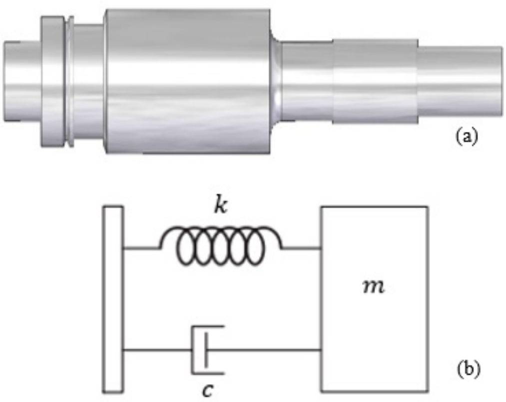


FIGURE 2. a) Ultrasonic Tool with Step Horn and b) Equivalent SDOF Mass Spring System

Mass of vibrating body with uniform cross-sectional area A, volume V, density ρ and length L is determined by $m = \rho V = \rho AL$. Axial modal frequency ω_n of SDOF system is determined by (8).

$$\omega_{n_{th}} = \sqrt{\frac{k}{m}} = \sqrt{\frac{AE/L}{\rho AL}} = \sqrt{\frac{E}{\rho L^2}} \quad (8)$$

Analytical magnification factor M_{th} of undamped SDOF system is determined by (9) (Rao, 2016).

$$M_{th} = \sqrt{\frac{1 + \left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2}} \quad (9)$$

METHODOLOGY

Primary purpose of present research was to evaluate SUH designs critically in terms of vibration amplitude at tool end (VATE), longevity, and stresses. For this purpose, standard horns were redesigned and integrated with piezoelectric transducer for assessment under axial vibrations. Horn material, length and end diameters were set identical for all SUH designs to get fair evaluation of performance parameters such as AMF, VATE, stresses, and FOS under similar working conditions. The length of horn was taken to be $L = 114\ mm$, whereas the tool end and transducer side diameters were set equal to $D = 41\ mm$ and $d = 33\ mm$ respectively, based on the commercially available ultrasonic transducer (Figure 2). SUH material taken in present research was mild steel (S) with properties listed in Table 1 along with PZT transducer properties. Another purpose of this work was identification of SUH for brittle and soft composites to attain reduced stresses and enhanced operating life without compromising VATE.

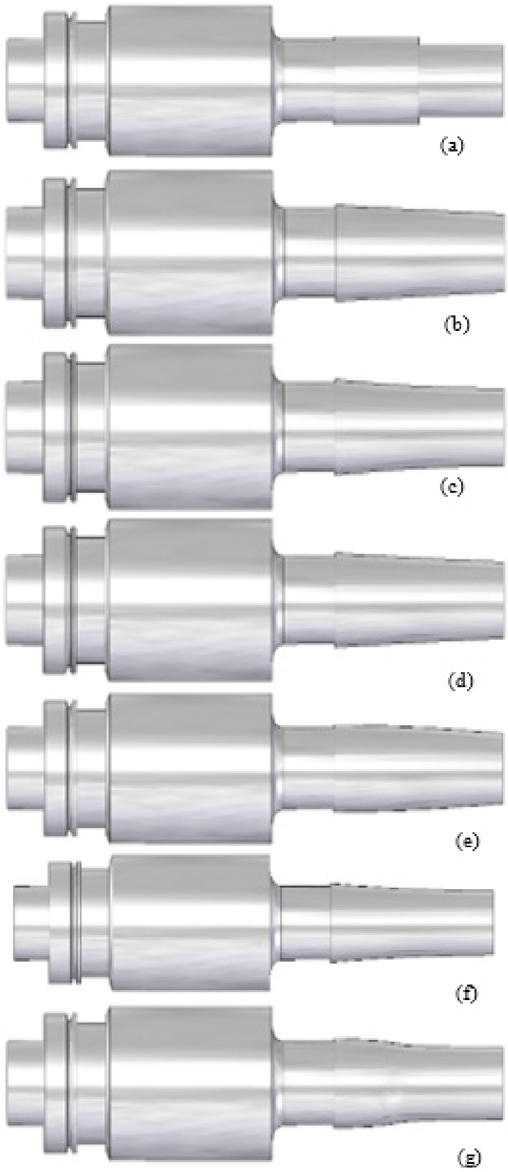


FIGURE 3. Ultrasonic Transducers integrated with (a) Step, (b) Conical, (c) Catenoidal, (d) Exponential, (e) Gaussian, (f) 2nd order Bezier, (g) 3rd order Bezier Horns

Three-dimensional CAD models of ultrasonic horns integrated with piezoelectric transducer were developed (Figure 3) for modal and harmonic analyses. Solid Edge was utilized to develop three-dimensional models of ultrasonic tool, whereas ANSYS was used to conduct FEA. Eigenfrequency characterization was done for determining resonant frequencies, mode shapes, axial stiffness, stresses, FOS and VATE numerically for $20\ kHz$ harmonic excitation frequency. Mesh independence analysis was performed to attain accurate simulation results related to resonant frequency, VATE and stresses (Mughal et al., 2020; Mughal et al, 2021; Mughal et al., 2022; Mughal et al., 2023). Figure 4 presents the meshed model of ultrasonic horn integrated with transducer. Genetic algorithm based optimization procedure is typically used for second and third order Bezier horns. Being continuous system, indefinite modal frequencies and mode shapes are associated to ultrasonic tool. In ultrasonic machining systems, tool vibrates axially, thus only AMF is important (Mughal et al., 2021; Mughal et al., 2023). Simulation results for SUH designs were compared later to draw conclusion.

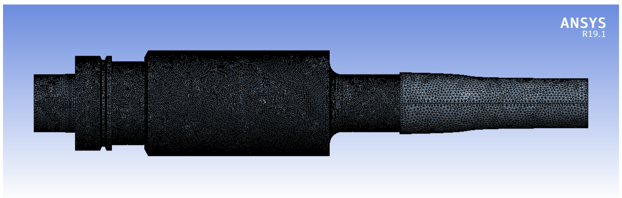


FIGURE 4. Meshed Model of Ultrasonic Tool

TABLE 1. Material properties of ultrasonic piezoelectric transducer and horn.

Ultrasonic Horn		Ultrasonic PZT Transducer		
Properties	Magnitude	Relative dielectric permittivity $[\varepsilon_r^S]$	Piezoelectric stress $[e]\ (C/m^2)$	Stiffness matrix $10^{12}\ N/m^2$
Density (ρ)	$7850\ kg/m^3$	$\begin{bmatrix} 730 & 0 & 0 \\ 0 & 635 & 0 \\ 0 & 0 & 730 \end{bmatrix}$	$\begin{bmatrix} 0 & -5.2 & 0 \\ 0 & 15.1 & 0 \\ 0 & -5.2 & 0 \\ 12.7 & 0 & 0 \\ 0 & 0 & 12.7 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 12.06 & -5.10 & -3.98 & 0 & 0 & 0 \\ -5.10 & 18.11 & -5.10 & 0 & 0 & 0 \\ -3.98 & -5.10 & 12.06 & 0 & 0 & 0 \\ 0 & 0 & 0 & 21.72 & 0 & 0 \\ 0 & 0 & 0 & 0 & 21.72 & 0 \\ 0 & 0 & 0 & 0 & 0 & 32.07 \end{bmatrix}$
Elastic Modulus (E)	$200\ GPa$			
Poisson's Ratio (υ)	0.3			
Yield Strength (σ_Y)	$250\ MPa$			
Speed of Sound (c)	$5048\ m/s$			
Damping Factor (ζ)	0.013			

RESULTS AND DISCUSSION

MODAL ANALYSIS

Modal analysis was performed for determining horn mode shapes and modal frequencies numerically. Various modes of ultrasonic tool vibrations closer to transducer frequency are exhibited in Figure 5(a-c). Among unlimited modal frequencies, AMF was desirable due to system's axial vibrations. Modal frequencies of third order Bezier and step horns were found much higher than those of other standard SUHs including catenoidal, conical, exponential, Gaussian and second order Bezier as shown in Figure 6. Ceteris paribus, modal frequencies were found dissimilar due to distinction of USHs geometries, that effected mass

and and axial stiffness, as presented in Figure 7 (a & b). Axial resonant frequencies of step and third order Bezier horns were found higher owing to less mass and larger stiffness, respectively. Gaussian horn was found to have larger mass along with stiffness causing moderate AMF.

(a)
(b)
(c)

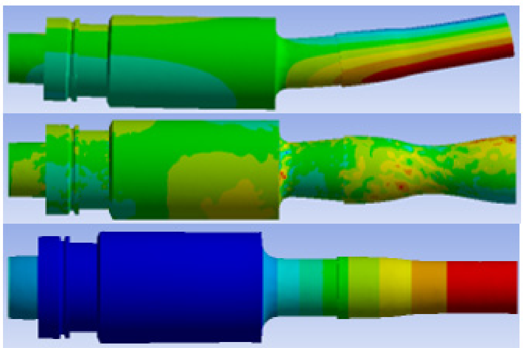


FIGURE 5. Various modes of ultrasonic tool vibrations, a) bending. b) torsional, c) axial

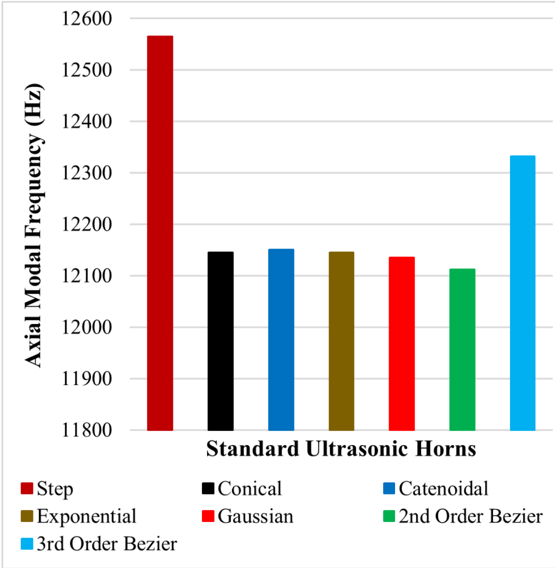


FIGURE 6. Comparison of AMF for SUH Designs

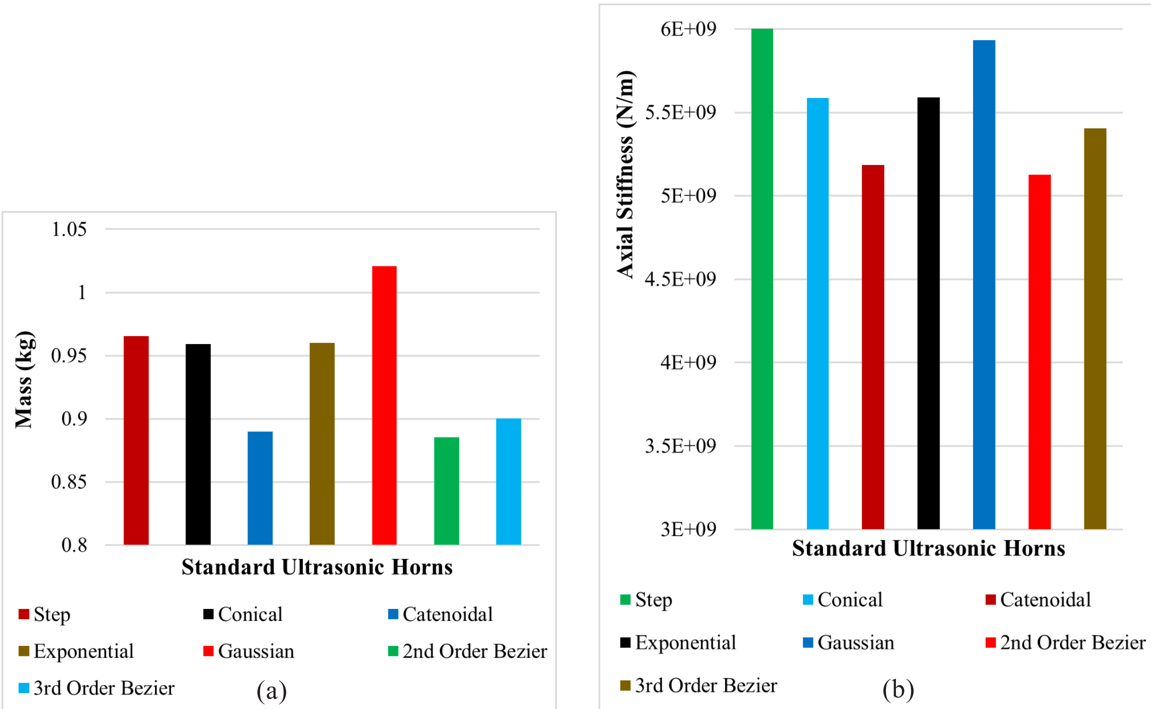


FIGURE 7. Comparison of a) mass and b) axial stiffness for SUH Designs

HARMONIC ANALYSIS

Harmonic response analysis of SUH designs was conducted for determining vibration amplitude at tool end (VATE) and stresses. Material for all SUHs evaluated in present research is steel which is ductile under specified working conditions, thus only Von Mises (VM) / equivalent stresses were examined. The comparison of VATE achieved through standard USH designs, as well as, variation of axial displacement magnitude along horn length are presented in Figure 8 & 9, respectively. Maximum axial displacement was attained by SUHs at tool end justifying the effectiveness of SUH designs and FEM used. VATE achieved by third order Bezier, Gaussian, exponential, catenoidal, conical and second order Bezier horns were found less than that of step horn by 11.7 %, 16.6 %, 16.7 %, 17 %, 16.73 %

and 18 % respectively. Among SUH designs considered in present work, VATE of step design was found highest due to closeness of its AML to harmonic excitation frequency. VATE attained by step USH was computed analytically as 1.55 for current horn dimensions through $M_{step} = (D/d)^2$, indicating reliability and effectiveness of FEM used. VATE attained by 3rd order Bezier horn was observed to be larger than that of exponential, catenoidal, conical, Gaussian and second order Bezier horns, however 11.74 % less than that of step horn indicating a room to enhance VATE further. Usually, VATE is greatest at resonant condition i.e., when excitation frequency coincides with horn's AMF $(\omega = \omega_n)$.

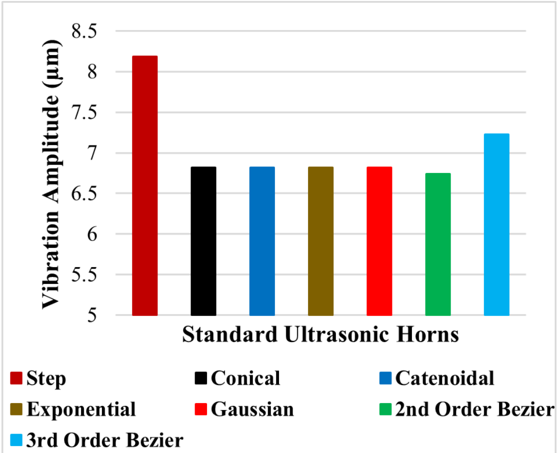


FIGURE 8. Comparison of VATE for SUH Designs

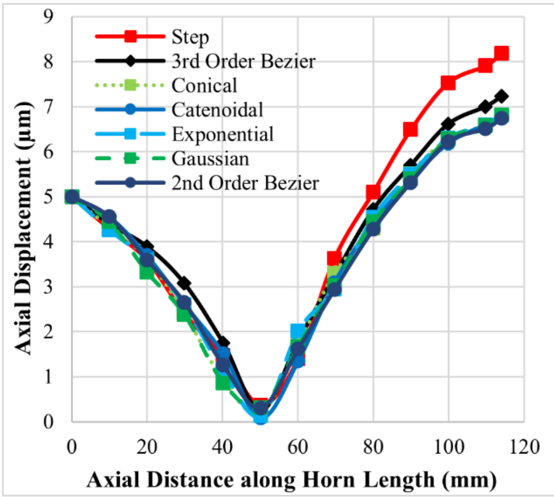


FIGURE 9. Variation of displacement along length of SUHs

STRESS ANALYSIS

Aim of current work was to assess SUH designs in terms of stresses, VATE and operating life. Idea was to identify SUH designs with high VATE, low VM stresses, and good operating life. For that reason, SUH profiles were used for integration with piezoelectric transducer based on commercial ultrasonic vibration assisted machining system. For assessing stresses and operating life, VM stresses generated in SUH designs having same end diameters and length, were then calculated numerically when $20\ kHz$ harmonic excitation frequency was provided at horn's transducer side. The stresses produced in SUHs were observed considerably higher in axial direction than tangential, radial and other directions as a result of axial vibrations transmitted by transducer. Since, SUH material used in present work was ductile, so axial stresses cannot predict its failure. VM stresses were numerically computed through either principal stresses, or axial, radial and tangential stresses for that purpose. Additionally, stresses are dynamic in nature and depend upon SUH geometry, frequency ratio (ratio of excitation frequency to AMF), VATE, cross section area, acceleration, mass and transducer output, thus they were seen different in various SUH designs.

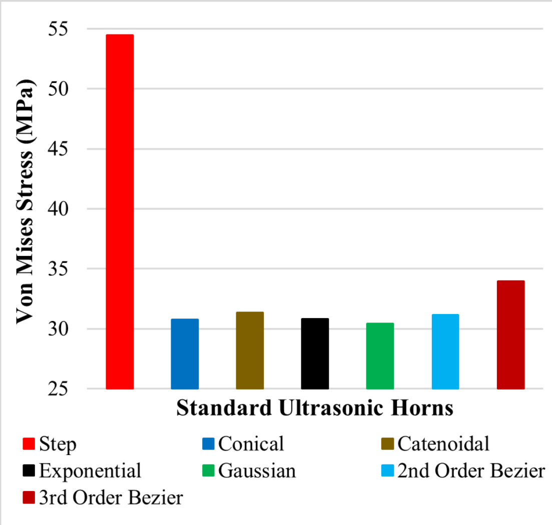


FIGURE 10. Comparison of VM stresses for SUH Designs

Comparison of maximum VM stresses developed in SUH designs, as well as, variation of stresses along horn length are presented in Figure 10 & 11, respectively. 44.2 %, 43.43 %, 42.5 %, 43.5 %, 42.8 % and 37.67 % reduction of stresses was achieved by Gaussian, exponential, catenoidal, conical, second and third order Bezier horns respectively. Stresses were found to be greatest in step horn due to sudden variation in cross section resulting in greater stress magnitudes. Stresses were found to reduce considerably in exponential, 3rd and 2nd order Bezier, Gaussian, catenoidal and conical horns due to uniform cross-sectional variation. Stresses produced in Gaussian horn were found to be least with magnitude 44.17 % lower than those of step design. VM stresses in 3rd order Bezier horn were found 37.67 % less than those of step horn, whereas 8.95% and 11.64 greater than those of 2nd order Bezier and Gaussian horns, respectively. It demonstrated suitability of third order Bezier horn for high VATE, low stresses and longevity in ultrasonic applications.

For larger FOS, thus operating life, VM stresses produced in SUHs must be as low as possible as compared to material's yield strength. For identifying most suitable SUH design for machining soft and brittle composites e.g. NHC, the FOS for each horn design was calculated using maximum VM stress and material's yield strength and presented in Figure 12. Actual FOS would be less than simulated values due to possible yield strength reduction caused by certain factors dependant on operating conditions. These factors may comprise of stress concentration, temperature, reliability, size and other factors (Mughal et al., 2021).

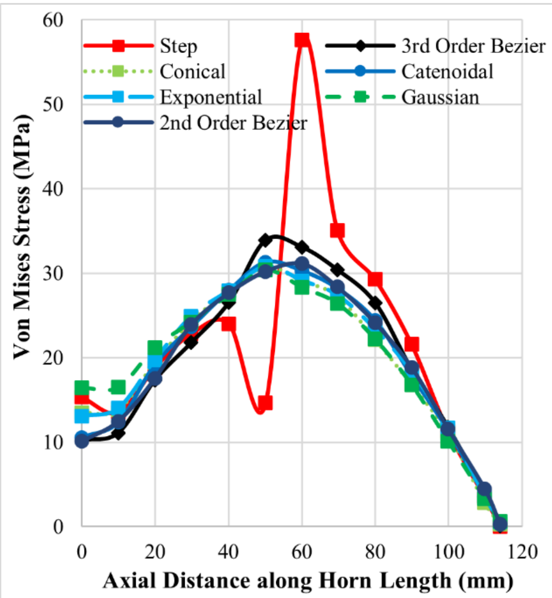


FIGURE 11. Variation of VM Stresses along length of SUHs

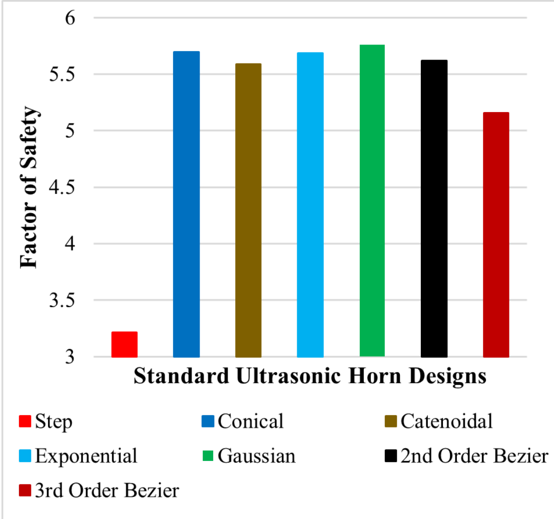
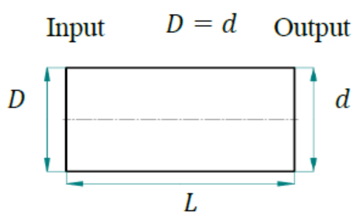
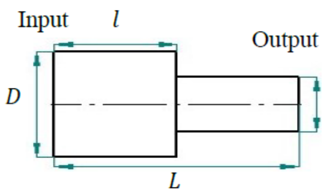


FIGURE 12. Comparison of FOS for SUH Designs

SUH designs, evaluated in present research work, were designed with AMLs distinct from $20\ kHz$ operating frequency, therefore stress magnitudes were lower and FOS was higher. When they would be designed with AML close to $20\ kHz$ to work at resonance, the stresses would be greater and FOS, hence operating life, would reduce. The comparison of SUH designs for machining Nomex honeycomb composite along with advantages, disadvantages and mathematical models is presented in Tables 2. Ranking of SUH designs in terms of various performance parameters is presented in Table 3.

TABLE 2. Mathematical models, profiles, advantages and disadvantages of SUHs for $\omega/\omega_n > 1$

Ultrasonic Horn	Advantages and Limitations
Cylindrical Horn (Mughal et al., 2022)  $y(x) = \frac{D}{2} = \frac{d}{2}$	**Advantages** • Simplest design and easy to manufacture • Most basic form of ultrasonic tool • Commonly used in ultrasonic machining, welding, cleaning, and other industrial applications as a subcomponent of modern USHs • Low stresses • Uniform stress distribution and energy transfer • Analytical solutions available for performance analysis **Limitations** • Lowest AMF and VATE
Step Horn (Lin et al., 2018; Pang et al., 2020)  $y\{x \in \langle 0; l\rangle\} = D/2$, $y\{x \in \langle l; L\rangle\} = d/2$	**Advantages** • Most commonly used horn type in ultrasonic applications • Largest VATE which can be calculated by $(D/d)^2$. • Simple design and fabrication • Analytical solutions available for performance analysis • Stress concentration slightly reduced by incorporating fillet at step location **Limitations** • Large stress intensity and subject to failure at transition section • Greatest acoustic energy losses

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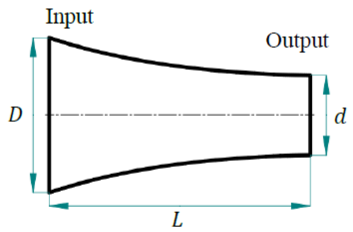
2nd Order Bezier Horn (Rai et al., 2020)

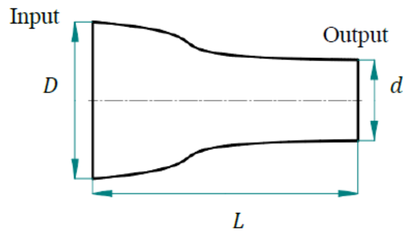


$$0 \leq t \leq 1$$
$$x(t) = (1-t)^2 x_0 + 2t(1-t)x_1 + t^2 x_2$$
$$y(t) = (1-t)^2 y_0 + 2t(1-t)y_1 + t^2 y_2$$

Advantages
- Low to moderate MF
- Low stresses due to smooth profile

Limitations
- Complex design
- Design through numerical methods

3rd Order Bezier Horn (Wang et al., 20111: Rai et al., 2020)

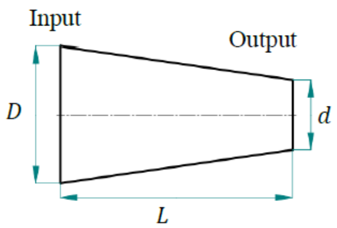


$$0 \leq t \leq 1$$
$$x(t) = (1-t)^3 x_0 + 3t(1-t)^2 x_1 + 3t^2(1-t)x_2 + t^3 x_3$$
$$y(t) = (1-t)^3 r_0 + 3t(1-t)^2 r_1 + 3t^2(1-t)r_2 + t^3 r_3$$

Advantages
- Most versatile USH
- Moderate to higher VATE
- Low to moderate stress concentrations
- Right choice for higher VATE and force transmission.

Limitations
- Complicated design
- Require optimization due to unlimited options of horn profile development
- Need finite element analysis for effective design

Conical Horn (Mughal et al., 2021)

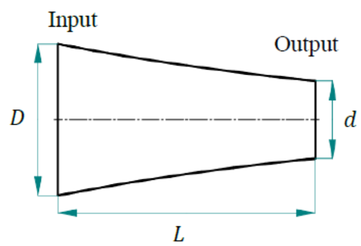


$$y(x) = -\left(\frac{D-d}{2L}\right)x + \frac{D}{2}$$

Advantages
- Easy to design and construct
- Low stresses
- Low acoustic losses as compared to step horn
- Analytical solutions available for performance analysis
- Used in ultrasonic welding, cleaning, machining, and other industrial applications as a subcomponent of modern USHs
- Good for moderate VATE, high operating life, and large force transmission.

Limitations
- Lowest VATE

Exponential Horn (Roy et al., 2017)



$$y(x) = (D/2)e^{-\left(\frac{1}{L}\ln\left|\frac{D}{d}\right|\right)x}$$

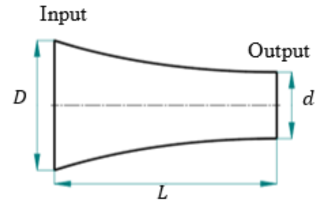
Advantages
- Low stress intensity due to smooth area reduction
- Good efficiency and less energy losses
- Suitable for low VATE, high operating life, and transmission of large forces.
- Used as a subcomponent of some modern USHs

Limitations
- Low VATE, but higher than that of cylindrical horn

continue ...

... cont.

Catenoidal Horn (Wang et al. 2011; Rani et al., 2013)

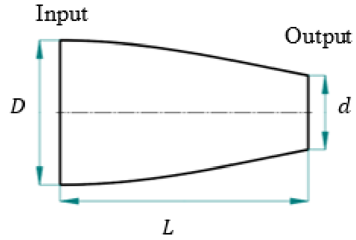


$y(x) = d \cosh a(x - L)$

Advantages
- Low stress due to smooth profile
- Suitable for moderate VATE, high operating life and transmission of large forces.

Limitations
- Low to moderate MF
- Complex mathematical model and design
- Need finite element analysis for effective design

Gaussian Horn (Mughal et al., 2021)



$y(x) = (D/2)\sqrt{e^{-\frac{2}{L^2}\mathrm{Ln}\left|\frac{D}{d}\right|x^2}}$

Advantages
- Low stresses due to smooth profile
- Suitable for moderate VATE, high operating life and large force transmission.

Limitations
- Low to moderate VATE, albeit higher than that of exponential and catenoidal horns
- Complex mathematical model and design
- Need finite element analysis for effective design

TABLE 3. Ranking of SUH designs in terms of various performance parameters for $\omega/\omega_n > 1$

Ultrasonic Horn	VATE	Stress	FOS	Axial Stiffness
Step	1	7	7	1
Conical	5	2	2	4
Catenoidal	6	5	5	6
Exponential	4	3	3	3
Gaussian	3	1	1	2
Second Order Bezier	7	4	4	7
Third Order Bezier	2	6	6	5

SUH designs considered in present research work met the design requirements of least vibration amplitude (6 µm) at tool end required for machining Nomex honeycomb composite within safe working stress. The SUH designs with high vibration amplification were found suitable for application in ultrasonic machining system for advanced brittle composites, because researchers have shown through experimentations that higher VATE improves the material removal rate and machining quality, which would help in minimizing wastes and achieving clean and energy efficient sustainable environment. Finally, low stresses in ultrasonic machine tool would cause high factor of safety, thus longevity, that makes USH designs with high VATE and less stresses a cost effective design product.

CONCLUSION

Present research was aimed at harmonic excitation response analysis of standard ultrasonic horn (SUH) designs to attain higher vibration amplitude at tool end (VATE) and minimum stress concentrations for ultrasonic assisted processing of Nomex honeycomb composite (NHC). For this purpose, SUHs were designed having same operating conditions, length and end diameters and. Investigations were performed through vibration analysis on SUHs in terms of axial resonant frequency, stresses, and VATE. Simulations indicated good agreement of harmonic and modal analyses' results with previous research and theoretical expectations. According to numerical investigations, performance of third order Bezier horn design was observed to be extremely well in terms of high VATE, FOS and operating life. After numerical computations, following conclusions were made regarding performance of SUH designs to enhance piezoelectric transducer amplitude for frequency ratio greater than one ($\omega/\omega_n > 1$).

1. VATE attained by ultrasonic step horn was observed larger than all other SUH designs followed by third order Bezier, Gaussian, exponential, conical, catenoidal and second order Bezier horns.
2. Axial stiffness of ultrasonic step horn was observed superior than all other SUH designs followed by Gaussian, exponential, conical, third order Bezier, catenoidal and second order Bezier horns.
3. Third order Bezier ultrasonic horn design performance was seen better than second order Bezier profile in terms of VATE. Although, VM stresses were found higher.
4. Step horn performance was observed inferior than all other SUHs in terms of stresses and longevity. Largest stresses were produced in step horn followed by third order Bezier, catenoidal, second order Bezier, exponential, conical and Gaussian horns.

Design of ultrasonic horn to attain high VATE without undergoing failure is vital to improve machining quality and efficiency of advanced soft and brittle composites. Good potential of future research is present regarding design of novel ultrasonic horn with VATE closer to step horn but with low stress concentrations.

ACKNOWLEDGMENT

The authors gratefully acknowledge financial support for this research from Pakistan Science Foundation (Project No. PSF/NSFC-II/Eng/P-UET (01)).

DECLARATION OF COMPETING INTEREST

None

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