Design and Simulation of Ultrasonic Metal Welding Horn

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Abstract

Ultrasonic metal welding (USMW) has become an efficient technique covers a wide range of applications of metals. Because of recent light weight of the parts, an efficient technique like (USMW) has become more applicable, because it considers more accurate, more minimised welding method than before. Welding horn must be designed on satisfying many criteria: vibrate longitudinally at operating frequency, isolated the axial mode from other nearest vibration frequencies, uniformity of vibration amplitude at the working surface and high amplitude of the operating mode. This research presents an approach to the design and simulate of the horn configuration which satisfies these criteria. The simulation and vibration mode shape characterisation of the horn is discussed and the analysis is accomplished using FE-package (ABAQUS), whilst the vibration modes are classified using experimental data from 3D laser Doppler vibrometer measurements. Modal and harmonic analysis are completed successfully to examine the frequency for the welding tuned horn.

Keywords: **Ultrasonic metal welding, Horn, Modal analysis, Harmonic analysis, resonant frequency**

تصميم ومحاكاة أداة لحام المعادن بالموجات فوق الصوتية

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الخلاصة

اللحام بالموجات فوق صوتية أصبحت تقنية فعالة تغطي مجموعة واسعة من التطبيقات لكلا المعادن. بسبب الحجم الصغير للأجزاء المصنعة، لذا فان استخدام هذه التقنية في الوقت الحاضر أصبح أكثر تطبيقاً، لدقتها العالية وصغر أجزائها مقارنة بطرق اللحام. أداة اللحام المستخدمة في تقنية اللحام بالموجات فوق الصوتية تدعى (Horn). للحصول على لحام فوق صوتي، ينبغي إن تصمم أداة اللحام بناءا على معايير معينة ، مثلا يجب أن تهتز الأداة بشكل طولي بتردد ما، إمكانية العزل للتردد الطولي عن باقي الترددات الأخرى ، توحيد سعة الاهتزاز على سطح العمل والسعة العالية لوضعية التشغيل. هذا البحث يقدم تصميم ومحاكاة تركيب أداة اللحام (Horn) المستخدمة في لحام الموجات فوق الصوتية والتي تتطابق في تصميمها مع هذه المعايير. محاكاة أداة اللحام ووصف أنماط الاهتزازات لها أنجز من خلال توظيف برنامج (ABAQUS)، في حين إن تصنيف أنماط الاهتزازات قد تم بالاعتماد على استخدام مقياس الاهتزازات (3D laser Doppler vibrometer). التحليلات التصميمية وكذلك التحليلات التوافقية أظهرت تطابقا في قياس التردد الطبيعي لأداة اللحام المهتزة بفعل الترددات العالية.

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Introduction

Nowadays ultrasonic welding has become a well established technique which is applied in many different fields and industries. While ultrasonic technique have been applied extensively to join metals and polymers, for many types of the electronic products of mechanics and other industrial assemblies which are attributed for lighter in weight, stronger, smaller and high precision, make the technique versatile and becoming more important than before [1]. beside that, the production of the electronic parts is accomplished by using solder in the welding, is constrained by the new green process, while ultrasonic metal welding is a possible method even with a cold condition, and the method does not need to use solder or any other filler so it is environment-friendly and economic [2].
Generally, ultrasonic welding systems consist of four or five components; power supply, transducer (convertor), booster, horn and anvil with other parts relevant to the support tooling, Figure 1.

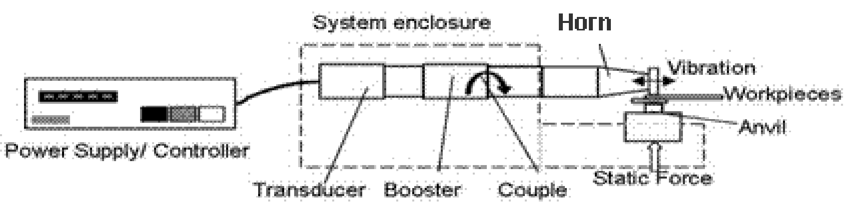


Figure 1 Mechanism of Ultrasonic metal welding [3]

The high frequency vibrations are combined with pressure to join two materials together rapidly and strongly, without using significant amount of heating or melting to the bonded areas, therefore for the ultrasonic welding of sheet or plate metals, normal and shear force act on the two parts to be welded and the weld interface. These forces are produced from the movement of the vibration welding stack (horn tip) which is effectively pressed upon the parts to be bonded.

Equation of longitudinal vibration in bar

The governing equation of the bar will be derived and the basic propagation characteristics considered. Therefore, a straight bar with length (L) and a cross-section coordinate (x), have a longitudinal displacement of the section by u(x, t). We presume that the bar under a tensile force F(x, t), so that adjacent sections are subjected to varying forces, as described below Figure 2 [4].

Applying Newton-Euler equation with the condition of the equilibrium of force on bar through longitudinal direction (x), the equation of motion becomes:-

$$\sum F = m\ddot{x} \qquad \text{Where} \quad \ddot{x} = \frac{d^2u}{dt^2} \tag{1}$$

$$F = \sigma A = EA.\frac{\partial u}{\partial x}(x,t) \qquad E = \frac{\sigma}{\varepsilon} \rightarrow \sigma = E\varepsilon \qquad \varepsilon = \frac{\partial u}{\partial x} \tag{2}$$

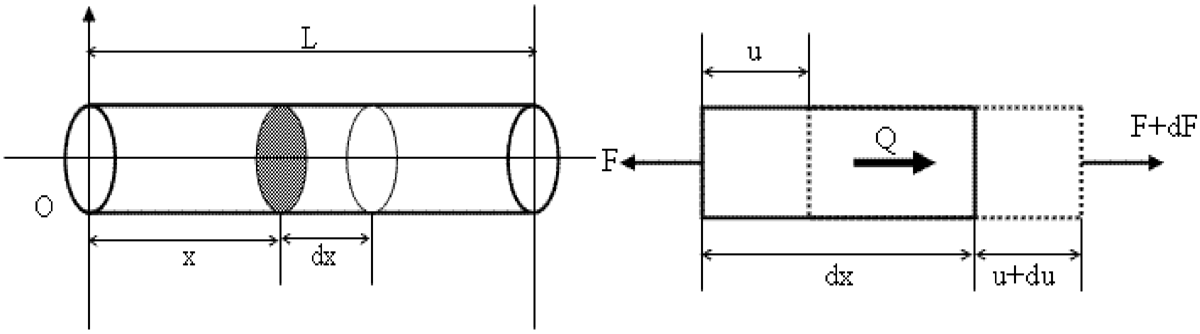


Figure 2 Model of the bar

$$-\sigma A + (\sigma + \frac{\partial \sigma}{\partial x}dx)A + QAdx = \rho Adx\frac{\partial^2 u}{\partial t^2} \qquad (3)$$

We now presume that the material behaves elastically and follows the simple Hooke's law as mentioned above (2), so the equation of motion can be re-written as:-

$$\frac{\partial}{\partial x}(E\frac{\partial u}{\partial x}) + Q = \rho\frac{\partial^2 u}{\partial t^2} \qquad (4)$$

On the assumption that the rod is homogeneous so the young modulus of elasticity does not vary with (x), then the equation is reduced to:-

$$E(\frac{\partial^2 u}{\partial x^2}) + Q = \rho\frac{\partial^2 u}{\partial t^2} \qquad (5)$$

Continuing, with the absence of body forces (Q), the equation may be re-written as follow:-

$$E\frac{\partial^2 u}{\partial x^2} = \rho\frac{\partial^2 u}{\partial t^2} \quad \text{Or} \quad C^2\frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 u}{\partial t^2}\ , \quad \rightarrow C = \sqrt{\left(\frac{E}{\rho}\right)} \qquad (6)$$

Where:

$C \rightarrow Sound\ Velocity$

$\rho \rightarrow Density$

$E \rightarrow Modulus\ of\ Elasticity$

$$\frac{d^2U}{dx^2} + YU = 0 \qquad Y = \frac{\omega}{C} = \frac{1}{\lambda} \qquad (7)$$

Where: $Y = wavenumber,\ \lambda = Wavelength$

$$\therefore \ \omega_n = \frac{Y\pi}{L}\sqrt{\left(\frac{E}{\rho}\right)} \quad , \ f_n = \frac{Y}{2L}\sqrt{\left(\frac{E}{\rho}\right)} \tag{8}$$

The wave length (λ) is like below formula [5].

$$\lambda = \frac{C}{f_n} \tag{9}$$

Design of welding horn

One of the main important parts of the ultrasonic welding stack is known as horn, some times called (sonotrode); these are tuned longitudinally at a low ultrasonic operating frequency (20 kHz). So for consistent operation of the horn, it is important to segregate the longitudinal mode frequency from any other nearest vibration modes, in order to prevent the sharing in frequency response and to concentrate a fully ultrasonic power that is matching the weld zone.

The model is designed according to ultrasonic spot welding, so the shape of the horn makes a resonance to transmit ultrasonic energy efficiently by expanding and contracting longitudinally along its length (i.e. expands and contract at the frequency of vibration). In general, the most common shapes of the horn are exponential, catenoidal, and stepped horn. Therefore, in this study the horn chosen has a catenoidal shape, because it offer high gains with low stress concentrations Figure 3 [6].

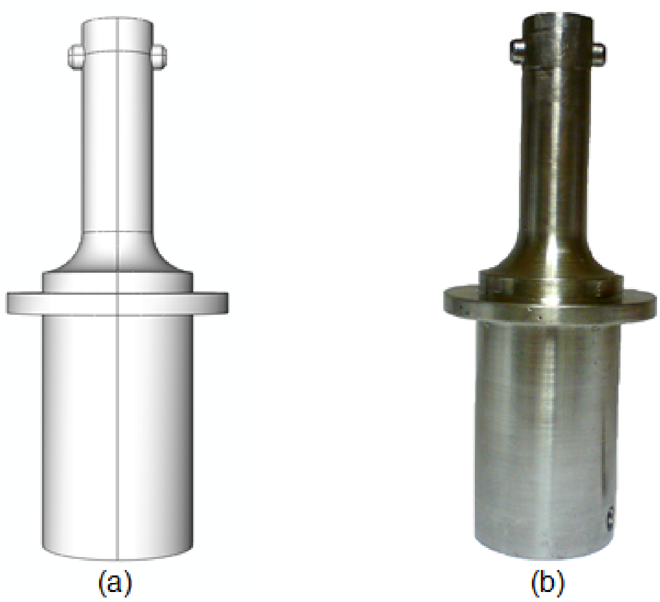


Figure 3 The spot welding horn (a) Modelled horn (b) Fabricated horn

Horn materials are usually made from aluminium, titanium, or steel [7]. So, the selection of material type will depend on the welding application. Because poor surface hardness and fatigue properties of aluminium, as well as the difficulty in machining and high cost of titanium, the horn material was selected from steel. However, steel horn can only be used for low fatigue strength through high response requirement. It is perfectly perform for severe wear application. The properties of material are tabulated in Table 1.

Table 1 Material properties of the designed Horn

Properties	
Density	7850 Kg/m^3
Young's Modulus of Elasticity	210 GN/m^2
Poisson's Ratio	0.33

The length of the horn is selected according to the half wavelength (λ) and it 128.4 mm, of applying the formula (9) of the longitudinal vibration. Other dimensions of the horn were measured according to the ideal horn design to make the natural frequency close to the resonant frequency, and many attempts was successfully done by using simulation model in order to vibrate a horn at a resonant value (20 kHz). Therefore, the final dimensions of the tuned horn according the model simulation are indicating that (input dia. 34 mm and output dia. 16 mm).

At end of the horn working diameter, weld tip protrusion was designed which is effectively represented as the working surface for ultrasonic welding spot and therefore, ultrasonic energy and static force are transferred across it to the parts being welded, Figure 4.

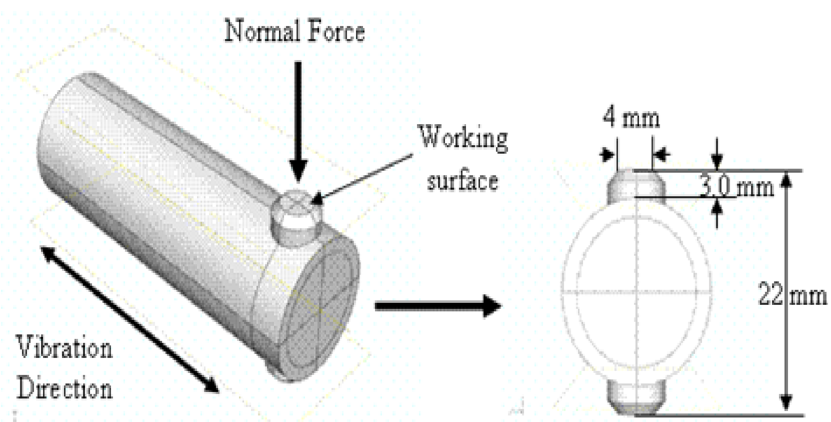


Figure 4 Weld tip drawing

A weld tip is an economical part commonly known as either a replaceable (interchangeable) device or integrated part that is tightened onto another component such as a horn. In most cases, the use of detachable tips becomes more reliable to allow expedient of variable tools in ultrasonic welding especially in the industrial fields. However, this may lead to initiate a non-acceptable stress concentration in the joining of the tip with the horn shaft; and may drop of the vibration amplitude due to insufficient horn contact. Generally, most of the tips in ultrasonic welding horns are made from titanium or hardened steel to perform a specific function such as: stacking or spot welding. In order to ensure a high amount of power that approached to the welded parts without undesirable effects, the use of the welding tip are machined as an integrated part of a solid horn, and it is made from the same material (steel) of the welding horn, Figure 5.

Figure 5 Weld tip design

According to the part thickness in spot welding, the radius R of the welding tip may be in the range (50-100) relative to the thickness of the upper part[8]. Typically, the tip surface has machined flat or knurl pattern of grooves and lands, or may be designed with a slight convex curvature in order to change the contact stresses [9]. In this research, the shape of the welding tip was evaluated as a flat tip and has a diameter 4 mm (Figure 4), which represents the area of the actual weld.

Amplitude and stress distribution of welding horn

In ultrasonic metal welding, the amplitude can be defined as the peak-to-peak displacement of the welding horn at its working face and expressed in micron or inches[10]. It is very important to simulate a proper design for a horn to ensure a best sufficient amount of the ultrasonic power that transmitted to the welding zone. If any of the welding stack parts like converter (Transducer), booster and welding tool (horn) isn't proper design then the vibration energy doesn't fully matched to the welding tip and in turn affected on weld quality. The amplification of the ultrasonic vibration approaches an optimum value when the distance between the input/output of the horn is equal to the half of the sound wave. Or by another way, it is required to the size of the welding tool to achieve suitable amplitude. Therefore, the maximum amplitude of the horn tip can be obtained at anti-nodal point of oscillation.
Moreover, it should take more consideration at the point of zero displacement to avoid any damage in nodal region that may lead to fatigue in metal and failure. Many attempts were done due to modification of the horn in order to close the variation distance between the nodal point and the high stress value. Figure 6 show the variation of both normalised stress and displacement along the axial mode of the tuned horn at operating frequency (20 kHz), predicted successfully and accomplished by using FE-model.

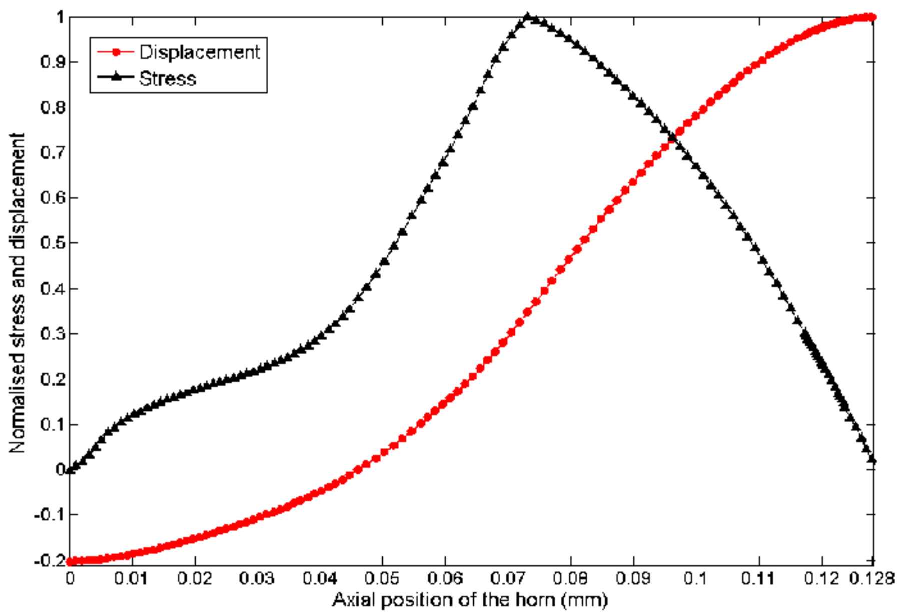


Figure 6 Normalised stress and displacement along the wave length (λ/2)

As expected there is a shift in the highest value for the stress according to the nodal point, because due to catenoidal shape of the horn which has a gradual transition radius through the nodal point. However, the horn offers high gains with low stress concentrations. The flange coupling was attached to the welding horn. Therefore, more care should be taken while designing a clamped flange in order to ensure that is positioned at a minimum value of displacement and to prevent any losses in the vibration energy transferred from the transducer to the welding tip. Also, the amount of amplification may be affected during in correcting the location of the flange coupling through out the damping effects. Any change in the flange dimension in concern with the horn design, may lead to convergence in the modes of vibration. And this in fact affects the weld quality, besides reduction of vibration amplitude. A good estimation of the flange dimension was done due applying FE-analysis for the flanged horn. According to ultrasonic metal welding, the isolation should be at least (1 kHz) from the longitudinal mode vibration, which from measurements and previous data, was deemed to give a sufficient remove the problems of modal coupling [11]. Therefore, the model give a good estimation for the frequency separation (1779 Hz) from the close flexural mode and (1037 Hz) from the axial mode, and higher from other modes.

The quality of the joining surface parts is intensively demanded in all industrial fields. So, through using ultrasonic technique it is significant to test the weld quality. The proper design of the horn and accurate control of the parameters during rapid operation can give a good surface uniformity. The uniformity defined as the relation in response between the minimum and maximum amplitude of the horn working surface [12]. According to the calculation of simulated horn, the uniformity gives an excellent estimation value (99 %). The reason is the narrow surface area of the horn tip. However, as the horn surface area increased the control of the uniformity becomes difficult [13].

Interpretation results of the horn model

In order to achieve a good result for the nearest value of the mode vibration to the transducer resonance frequency (20 kHz), a modal analysis is performed for various shapes of horns according to the change of the R values with no change of the other dimensions. The results are listed in the Table 2 and Figure 7.

Table 2 Nature frequency of simulated horns

R (mm)	f (Hz)	R (mm)	f (Hz)
8.5	20524	12.0	20989
9.0	20647	12.5	21018
9.5	20739	13.0	21044
10.0	20811	13.5	21066
10.5	20868	14.0	21086
11.0	20916	14.5	21103
11.5	20956	15.0	21119

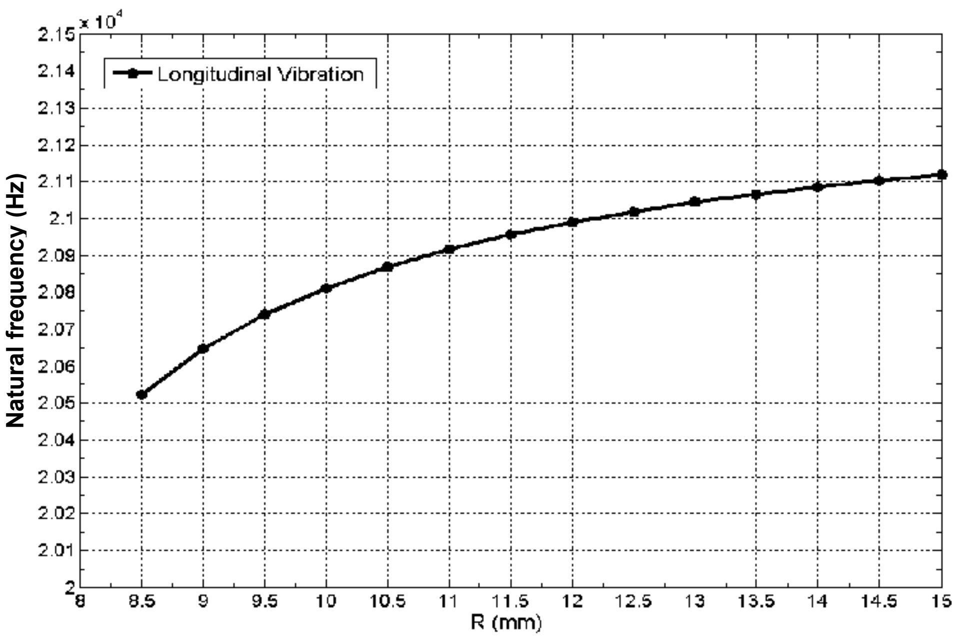


Figure 7 Natural frequency of the welding horn

It can be seen clearly after analyses that the increasing of the R values leads to increase the values of the modes vibrations table 2. And according to these results it was noticed that when R values go up, the natural frequency became hgier as illustrated in Figure 7. Because the welding horn was designed according to the excitation frequency of the transducer (20 kHz), then it is decided to choose the R value equal to (10 mm), as seen in Figure 8. The reason for choosing this value is to obtain a good separation (mentioned before) of the axial mode and to isolate it from the other nearest vibration modes by at least 1 kHz, besides reducing stress concentration of the horn.

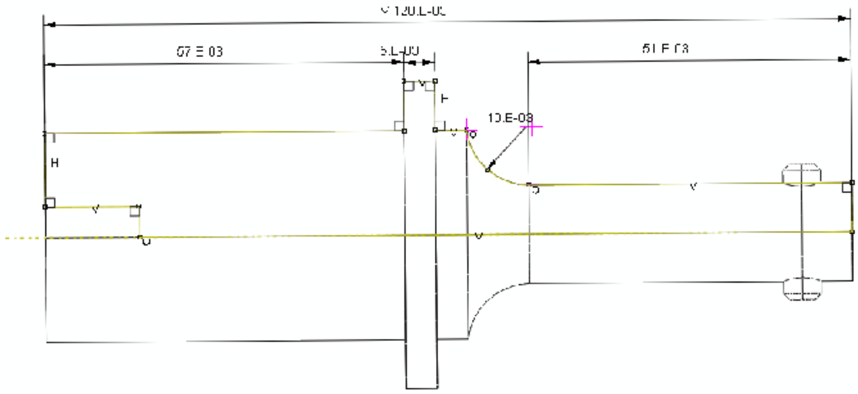


Figure 8 Drawing of the welding horn

However, the prediction of mode sensitivities along the variation of R values gave stable behaviour of the natural frequencies, Fig. 9.

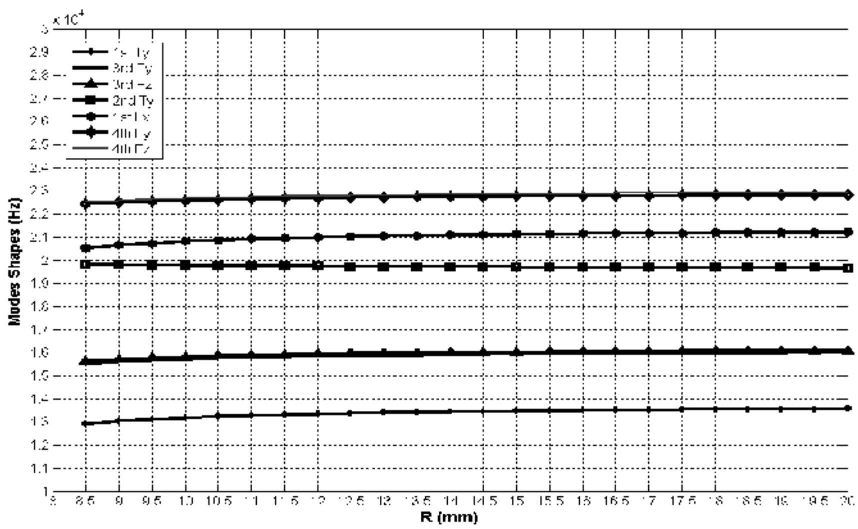


Figure 9 Effects of R value on natural frequencies

Verification of the horn design for ultrasonic spot welding

The Welding horn was designed using (FE) analysis and the modal frequencies and associated mode shapes were confirmed using experimental modal analysis (EMA). This was successfully done by aiding use (3D-Laser Doppler Vibrometer) measurements, as in Figure 10.

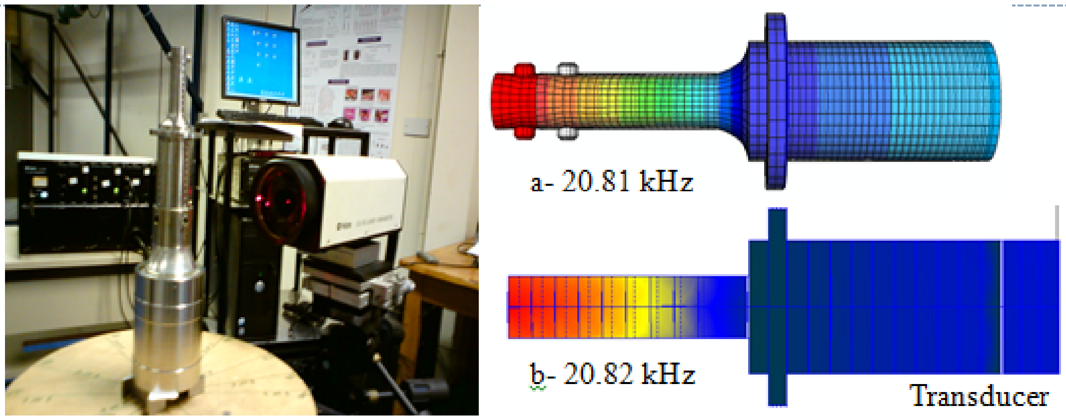


Figure 10 Comparison of (a) FE predicted and (b) EMA measured longitudinal mode and modal frequency

The variation between the FE- simulation and EMA, shows good compatibility of the longitudinal mode, which is intensively affected the ultrasonic vibration matching the welding zone, also to ensure a high rate of the vibration amplitude that concentrated at the welding tip. According to the modal analysis and harmonic analysis, the natural frequencies of each mode were examined through a vibration range (10-40 kHz) as tabulated in the Table 3.

Table 3 comparison between FEA and EMA for the horn

No.	Type of Modes	FEA	EMA
1	1Ty	13190	13690
2	3Fy	15731	-
3	3Fz	15821	15740
4	2Tz	19774	-
5	1Lx	20811	20820
6	4Fy	22590	23450
7	4Fz	22680	24410
8	2Lx	33642	34550
9	5Fy	33973	32630

Figure 11 shows the change in the vibration modes of modal analyzed horn, the frequency range between (10-40 kHz) as mentioned before and the tuned frequency of the 5th mode was 20811 Hz longitudinal vibration mode.

The corresponding experimental modal analysis (EMA) of the fabricated horn is shown in Figure 12. The measurements were carried out by connecting horn with a transducer, where it is latter excited with a random signal over a bandwidth of frequency range (0-40 KHz). The harmonic analysis also was done for measuring the horn vibration response in order to ensure a highest value of the amplitude matching at the horn tip.

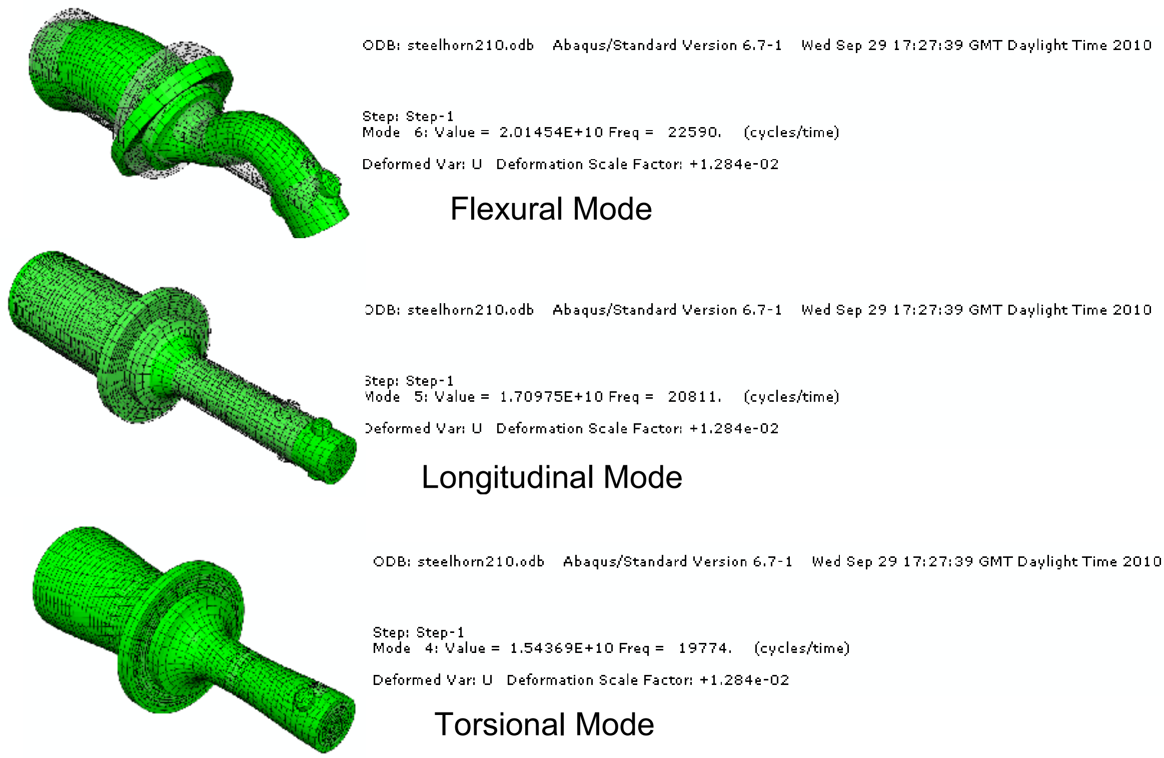


Figure 11 Modal analysis of the spot welding horn

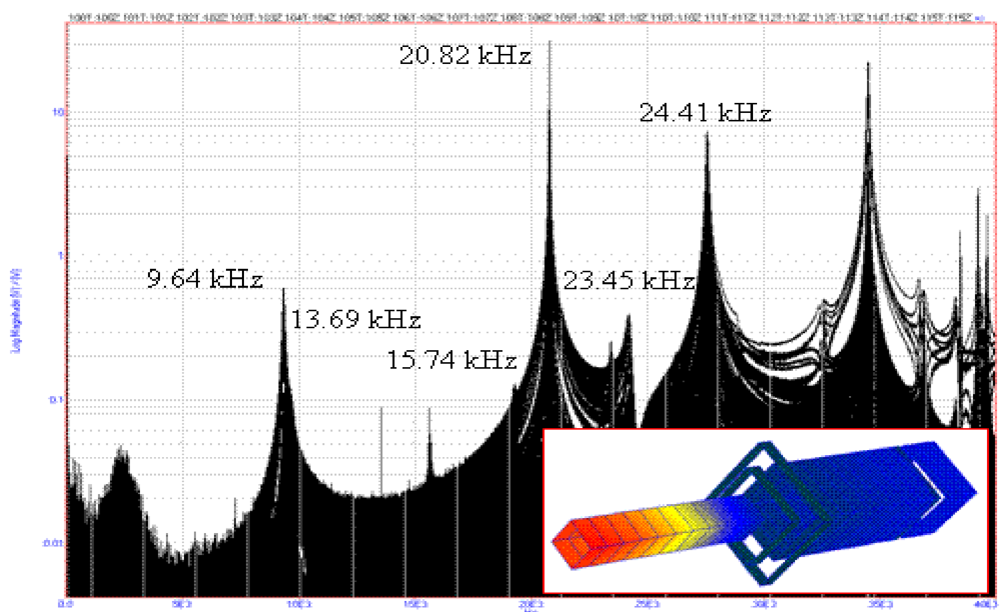
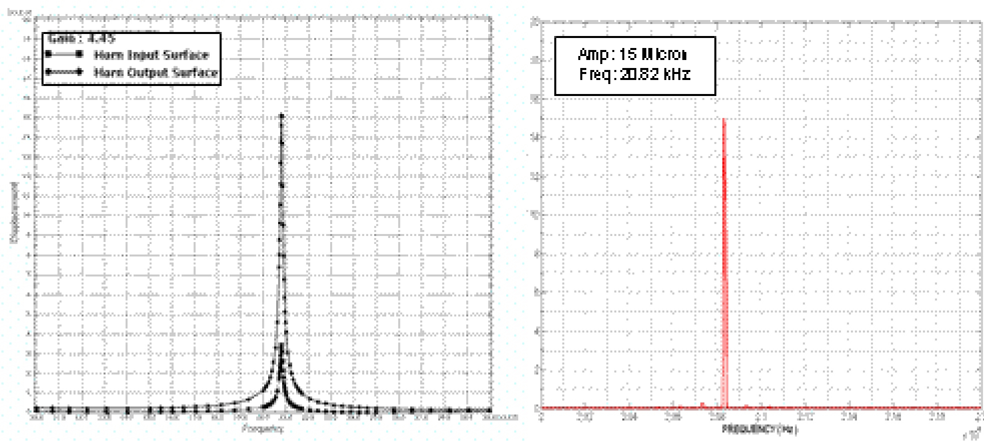


Figure 12 Modal analysis spectrum and vibration mode of welding horn

It is clear to notice that the spectrum analysis of the horn shows a good separation of the vibration modes. Where as the optimal value of the longitudinal mode are similar to that value obtained from the simulation model. Others modes shows an acceptable values in comparison with those predicted from the finite modal analysis. It is expected by applying the ultrasonic energy to the weld; the value of the vibration amplitude was effectively tied. Based on many references, “typical values of output amplitude, origin to peak, are approximately (20 kHz =

10 microns, 30 kHz = 7-8 microns, 35 kHz = 6.5 microns, and 40 kHz = 3-4 microns)"[5]. Amplitude values are mostly affected by electronic regulation with some type of the generator interface, i.e., running at 80 percent amplitude reduces the excursion by 20 percent. The (FEA) and (EMA) submits perfect indication of the frequency response over a wide range of natural frequencies (0-40 kHz), and the displacement was concentrated on the welding tip, Figure 13.



(a) (b)

Figure 13 vibration amplitude of the ultrasonic spot welding horn:
(a) Modal analysis and (b) Harmonic analysis

The gain is defined as the ratio of the output to input amplitude of the vibration horn [11]. However, when the resonant frequency of the designed horn are too closed to another neighbour frequencies, this may leads to a coupling at the working frequency, and therefore, could distort the motion of the horn and reduce the uniformity of the surface as well as decreasing the gain value, This in turn has an affect on weld quality.

Conclusion

In this research, a design and simulation of the ultrasonic welding horn have been successfully done, due to full configuration of both modal and harmonic analysis for vibration frequencies and modes shape. Optimal design for ultrasonic spot welding was carried out to ensure matching of the vibration energy to the parts being welded. A 20 kHz, resonant frequency is transferred correctly from the excited transducer passing to the welding tip. Many criteria are intensively affected on the tuning horn, such as ensuring a fully ultrasonic energy of the tuned horn (20 kHz) longitudinally, isolated the axial mode from other vibration frequencies, uniformity amplitude at working surface and increasing the displacement on the welding tip at a resonant frequency. The results show a significant improvement in experimental validation of the welding horn using 3D laser Doppler vibrometer measurements. Optimum value of the vibration response is concentrated at the welding tip, this value was confirmed by the modal analysis of the simulated horn, as well as examining of both natural frequency and modes vibration. By this research, we understood the vibration characteristics of the welding horn used in ultrasonic metal welding through applying simple methods for analysis of natural frequencies and modes shape.

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The work was carried out at the college of Engineering. University of Mosul