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**Article** *in* International Journal of Advanced Manufacturing Technology · September 2016

DOI: 10.1007/s00170-016-9517-0




Reza Naseri
Ferdowsi University Of Mashhad



Kamal Koohkan
Iran University of Science and Technology



Mahmoud Ebrahimi
University of Maragheh



F. Djavanroodi
Prince Mohammad University

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**R. Naseri, K. Koohkan, M. Ebrahimi, F. Djavanroodi & H. Ahmadian**

**The International Journal of Advanced Manufacturing Technology**

ISSN 0268-3768

Int J Adv Manuf Technol
DOI 10.1007/s00170-016-9517-0

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ORIGINAL ARTICLE

# Horn design for ultrasonic vibration-aided equal channel angular pressing

R. Naseri [1] · K. Koohkan [2] · M. Ebrahimi [3] · F. Djavanroodi [4] · H. Ahmadian [2]

Received: 16 April 2016 / Accepted: 21 September 2016


**Abstract** This work focuses on the resonance frequency determination of a horn as a main part of ultrasonic vibrated equal channel angular pressing using experimental and simulated modal analyses. A stepped shape hot-work tool steel horn was successfully designed and manufactured to promote maximum punch force reduction. The resonance frequency of the system which includes the horn with an initial length of 220 mm was obtained by simulated modal analysis. Experimental work using Audio-Technica microphone on five different horn lengths at the free condition was developed to verify the simulated modal analysis. Also, the changes in frequency with the horn length were obtained experimentally. By considering both the system resonance frequency of 18,760 Hz for the horn length of 220 mm and 90 Hz change of longitudinal frequency for 1 mm of horn length, the final horn length was obtained to be 206 mm. Moreover, it was shown that the billet length has no considerable effect on the resonance frequency of the system. Finally, 9 % reduction at the required punch load was achieved by employment of ultrasonic vibration as compared to the conventional equal channel angular pressing process.

**Keywords** Equal channel angular pressing · Ultrasonic vibration · Horn design · Modal analysis

## 1 Introduction

Attention to the production and application of the ultrafine grain (UFG) and nanostructure (NS) metals and alloys using various severe plastic deformation (SPD) techniques has been considerably increased during the last two decades [1, 2]. The unique feature of all SPD methods is imposing intense plastic strain without any significant change in the overall dimensions of the deformed specimen. This leads to the fabrication of material with the exceptional grain refinement and thus, superior properties and characteristics like mechanical, fatigue, superplasticity, corrosion, and wear behavior [1–3]. Equal channel angular pressing (ECAP) is one of the most developed and famous severe plastic deformation processes among numerous SPD methods such as high pressure torsion (HPT) [4], equal channel forward extrusion (ECFE) [5], accumulative back extrusion (ABE) [6], multi axial forging (MAF) [7], constrained groove pressing (CGP) [8], and elliptical cross-section spiral equal-channel extrusion (ECSEE) [9]. ECAP fame is attributed to its fairly large sample fabrication, low costs, relatively simple procedure and performance, and reasonable homogenous structure. Additionally, it has the potential to utilize as a commercial metal forming process. The principle of the ECAP process is that a billet with the cross section of the circle or square is pressed through a die in which two equal cross-sectional channels meet at a die channel (Φ) and outer corner (Ψ) angles as shown in Fig. 1. This process can be repeated several times to attain the desired properties because of no alteration at the dimensions of the sample during the process [3, 10, 11].

✉ M. Ebrahimi
ebrahimi@maragheh.ac.ir

[1] Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran

[2] Department of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

[3] Department of Mechanical Engineering, University of Maragheh, Maragheh, Iran

[4] Department of Mechanical Engineering, Prince Mohammad Bin Fahd University, Al Khobar, Kingdom of Saudi Arabia

Published online: 30 September 2016

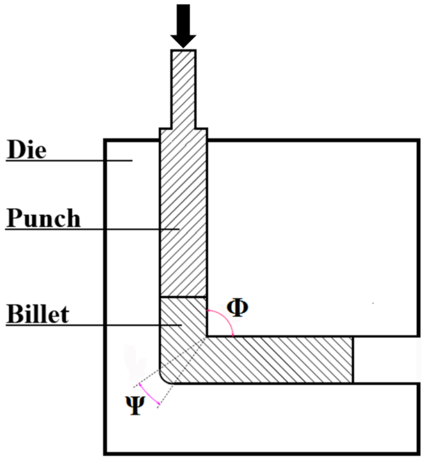


**Fig. 1** The schematic representation of equal channel angular pressing (ECAP) process

On the other hand, ECAP method can be considered as a friction sensitive process because friction plays a major role in the required pressing load. Thus, decreasing the sliding friction between the sample and the die surfaces especially in the entrance channel at the high pass numbers is beneficial to the process. Hence, it has been proposed to reduce the sliding friction by imposing the ultrasonic vibration (UV) on the ECAP process [12]. The application of UV on the variety of well-known metal forming processes such as compression [13], wire drawing [14], deep drawing [15], extrusion [16], and forging [17] has created new challenges for scientists and experts in the material science field. The previous researches revealed some advantages of the UV application on the different processes [18–20]. Flow stress reduction, lower required compressive load, and finer grain structure are achieved during an ultrasonic assisted compression test at the room and elevated temperatures [13, 21]. In addition, significant diminution at the extruded force and flow stress, better

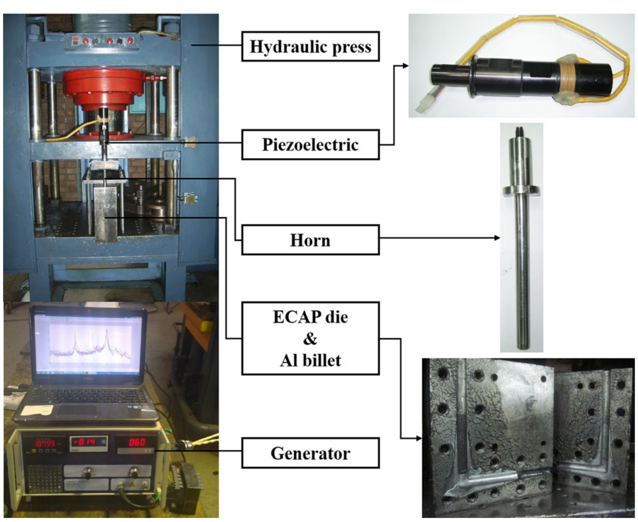


**Fig. 2** The representation of ultrasonic vibrated equal channel angular pressing facilities

final surface quality, and the possibility for the difficulty to lubricate materials are attained during the application of UV in the extrusion process [16, 22]. Furthermore, diminution of friction between the interface of the sample and die, higher formability and lower cracks, better sheet deformation operation, improvement of surface quality, enhancement of drawing resistance, rise at the material temperature during the process, the spring-back reduction, reduction of wire breakage, decrease of forming force, and material flow stress can be considered as merits of the UV imposing during both the wire and deep drawing processes [14, 15, 23, 24].

Although there are mentioned advantages of the UV employment on the various metal forming processes, this technology has not been developed yet on the severe plastic deformation methods, hence, there are few studies in this field [12]. The investigation by Djavanroodi et al. on the effect of ultrasonic energy during the ECAP process revealed that the required pressing force is reduced by the use of the vibration amplitude and frequency. Also, the influence of vibration amplitude on the force reduction is more profound than that of the frequency [25, 26]. The numerical study by Ahmadi and Farzin on the application of UV technique during the ECAP process indicated that the lower required pressing load is related to the vibration amplitude and the die velocity [27]. The superimposing ultrasonic vibration during the tubular channel angular pressing (TCAP) by Faraji et al. showed that the radial ultrasonic is a more significant factor than that of the axial one from the strain behavior and punch force points of view. Additionally, the results showed that the die vibration is more sizeable than either the mandrel or punch [28].

Suitable acoustic horn design as a main part of the UV set-up is necessary for the efficient application of the ultrasonic energy during the various metal forming processes. Previously, the acoustic horn design was made on the basis of having the force equation imposed to an element and integration over the whole horn length [29]. In the recent years, finite element method (FEM) have been utilized to design the horn (the horn geometry and dimensions) for the various geometries and boundary conditions in the variety of scientific and industrial applications [30, 31]. Additionally, experimental techniques were employed to validate the FEM results [32].

In the recent years, this criterion (the horn proper form and dimension) has been usually studied using the finite element method for the various geometries and boundary conditions in the variety of scientific and industrial applications [30, 31]. Additionally, some experimental techniques for measuring the resonance frequency and, thus, optimized horn features have been carried out to validate the FEM results [32].

The purpose of this investigation is to design a horn suitable for the application of UV on the ECAP process. To achieve maximum required load reduction, the whole system

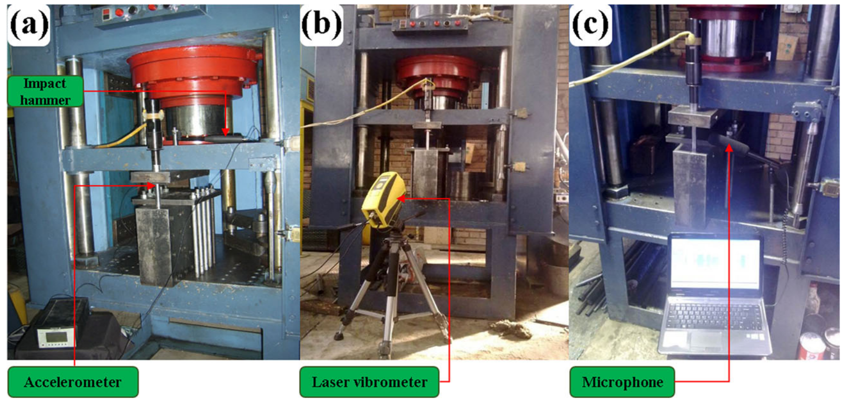


**Fig. 3** The experimental modal analyses via **a** accelerometer and **b** laser vibrometer **c** microphone during ultrasonic vibrated equal channel angular pressing system

must be vibrated in one of the natural frequencies. Therefore, the natural frequency of the horn as the main part of the vibration set-up has been numerically and experimentally obtained using the modal analysis.

## 2 Horn design

To achieve high amplitude in the vibration system and to avoid generator overload, the ultrasonic assisted ECAP process system should excite in one of its natural frequencies. In this research, all parameters including the ECAP die geometry and vibration equipment have been assumed to be constant. Therefore, the only part that can change the vibrational characteristics of the process is the horn, by altering its dimension, material, and geometry (shape). The major functions of the horn are the following:

- To achieve the intended resonance frequency
- To transmit the load from the hydraulic press to the specimen
- To increase the vibration amplitude via cross-sectional reduction
- To make the necessary support for housing the vibration parts and also imposing load

There are a number of different geometries of the acoustic horns. Previous investigations indicated that the stepped, exponential, conical, and Bezier shape horns have respectively maximum amplitude magnification if the cross-sectional ratio between the head and tail is the same. On the other hand,

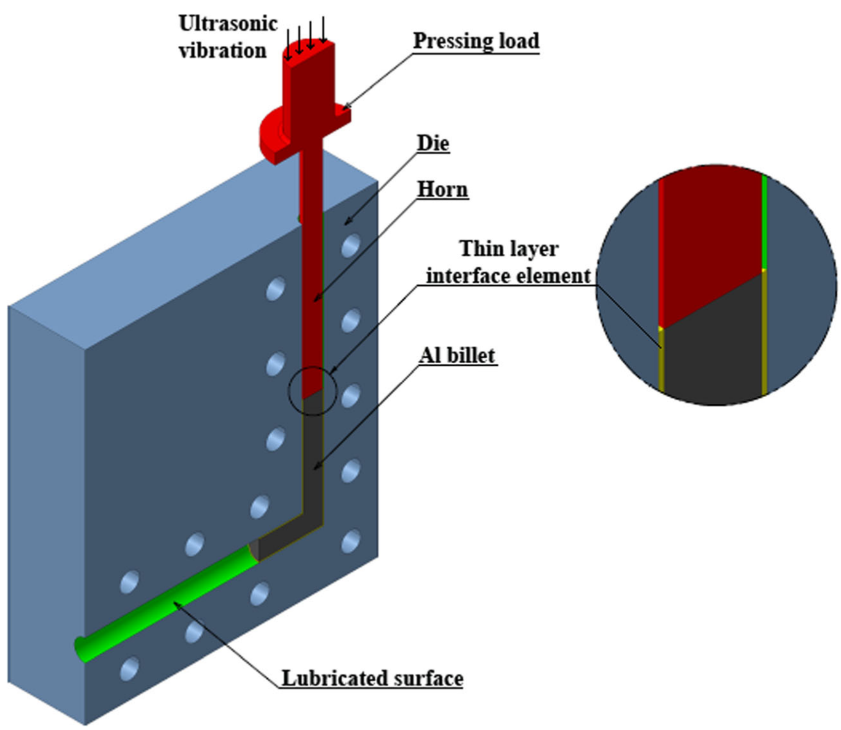


**Fig. 4** The simulated modal analysis of the ultrasonic vibrated equal channel angular pressing process

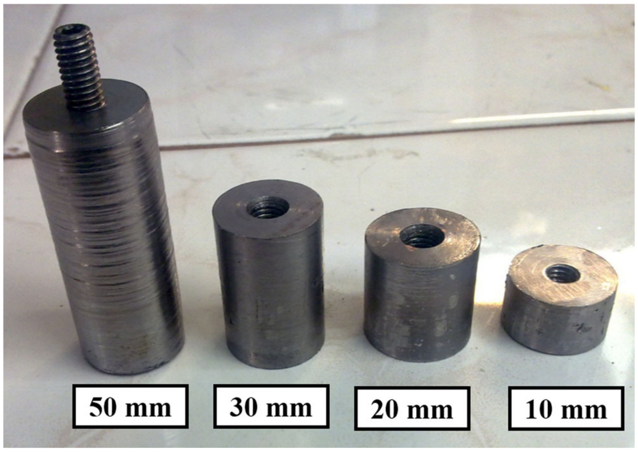


**Fig. 5** The four different length cylindrical pieces fastened and connected to the horn tail

although the amplitude magnification of the stepped shape horn is more than the others, the stress on the horn and the energy loss is high [29, 33]. For this study, stepped shape horn has been chosen due to the limitations of the ECAP die set-up.

Generally, aluminum alloy, titanium alloy, and hot-work tool steel are used for the fabrication of horns [34]. Since the horn used in this research must have enough strength to bear the high stress, it avoid buckling effect, transmit the vibration, and act as a punch for the load transmitter; hot-work tool steel (ANSI H13) has been chosen as the horn material. Additionally, the contact surface between the horn and the press ram has been assumed the vibrated node type with zero amplitude in order to minimize the energy loss and transmit the vibration between them. Figure 2 represents the ultrasonic assisted ECAP process facilities. The ultrasonic vibrated set-up includes the ultrasonic generator, ultrasonic transducer or piezoelectric converter, and the horn. This ultrasonic set-up imposes ultrasonic vibration to the aluminum billet during the deformation process.

## 3 Modal analysis

Although several methods can be utilized in order to find the dynamic properties and the adjustment of the ultrasonic vibration set-up in the metal forming processes, modal analysis is the most well-known way to achieve the natural frequency of the system in the case of non-automatic tunable generator [35]. The three usual methods of experimental modal analysis (EMA) to attain the dynamic properties of a system are accelerometer, laser vibrometer, and microphone. The three EMA methods used during the UV-ECAP process are shown in Fig. 3.

Three dimensional (3D) finite element modeling was performed using ABAQUS 6.10 for the modal analysis of the ultrasonic vibrated ECAP process to obtain the required length of the horn. As mentioned above, the hot-work tool steel stepped shape horn was opted for this simulation. The diameters of the head and tail sides were equal to the piezoelectric and ECAP die channel diameters (31 and 20 mm), respectively. The first item which should be considered about the horn design is the selection of the mode that must be excited and, also, the separation of this mode from the others. Afterwards, various frequencies were investigated to make sure that the intended frequency matches the excited one. It must be pointed out that the system would vibrate in one of the longitudinal modes because the longitudinal vibration is intended, and, also, the excited vibration is applied axially. The excitation is in the axial direction at the frequency of 20 kHz. The natural frequency mode of the system which is the third longitudinal

**Fig. 6** The responded frequencies of the different length horns in the free condition recorded by the Audio-Technica microphone

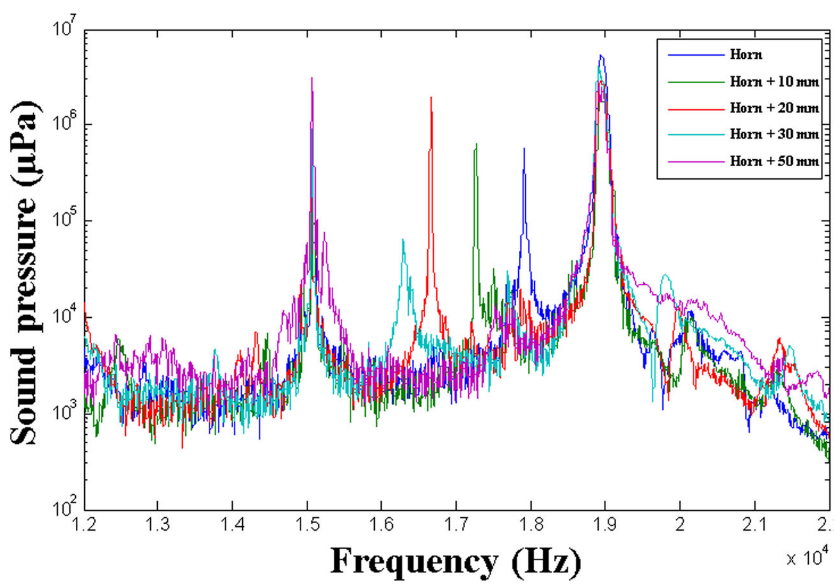

**Table 1** The horn natural frequency at the free condition resulted from the experimental and numerical modal analyses via microphone method

| Natural frequency (Hz) | Horn length (mm) | | | | |
|---|---|---|---|---|---|
| | 220 | 230 | 240 | 250 | 270 |
| Experiment | 17,910 | 17,260 | 16,660 | 16,280 | 15,140 |
| Simulation | 17,782 | 17,196 | 16,561 | 15,970 | 14,911 |
| Discrepancy (%) | 0.7 | 0.4 | 0.6 | 1.9 | 1.5 |

mode can be designed based on the alteration of material, geometry, and dimension of the parts. By considering the available set-up, the only parameter that can be altered is the horn length. Figure 4 represents the simulated modal analysis (SMA) of the UV-ECAP process.

To obtain the magnitude of the horn length, all parts were flexibly modeled according to their materials and geometries same as the experimental procedure. ECAP die with the channel angle of 90°, outer corner angle of 15°, and the channel diameter of 20 mm was modeled and meshed by the C3D8R. Additionally, three dimensional hexahedral elements (C3D8R) with the feature of the linear and reduced integration were assigned to both, the commercial pure aluminum (CP-Al) billet and the hot-work tool steel stepped shape horn. The billet diameter and length are 20 and 130 mm, respectively. Also, the horn head and tail diameters are 31 and 20 mm, respectively. The optimum element numbers of the horn, die, and billet were attained using the mesh sensitivity diagram which is respectively equal to 38,428, 79,130, and 9600. The automatic remeshing was applied due to large elements distortion during the deformation. The ram speed was equal to 2 mm/s, and all SMAs were carried out at the ambient temperatures. Moreover, the contact surface between the horn and piezoelectric was fully constrained except in the axial direction. Also, the degree of freedom in the ECAP die was assumed to be zero. A virtual isotropic hypothesis based material with the defined properties as a thin layer interface element (Fig. 4) was utilized at the interface material between the ECAP die and the Al billet [35, 36]. Elastic modulus and density of the interface material can be calculated with the acceptable precision by adopting the Hertz contact and Fractal theories and also by considering the contact surfaces' pressure as well as the elastic modulus, Poisson's ratio, density, surface roughness, yield strength and hardness of both the die and billet [37, 38]. To obtain the yield strength and the hardness magnitude of the CP-Al billet, tensile and hardness measurements were carried out according to the ASTM B557M and ASTM E384, respectively. The thickness of the interface virtual material was obtained to be equal to 1.3 mm.

## 4 Results and discussion

According to the SMA result, an initial horn length of 220 mm achieves a frequency of 18 kHz. Hence, a H13 steel stepped shape horn with the length of 220 mm at the tail section has

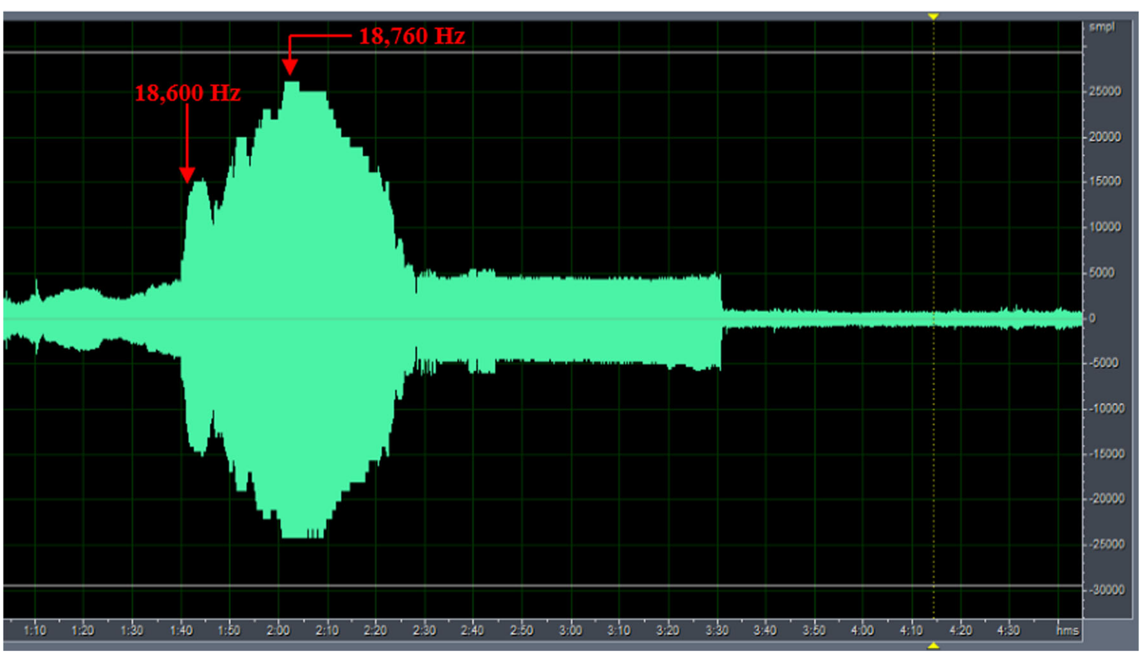


**Fig. 7** The recorded sounds by the Audio-Technica microphone for various frequencies during ultrasonic vibrated ECAP process

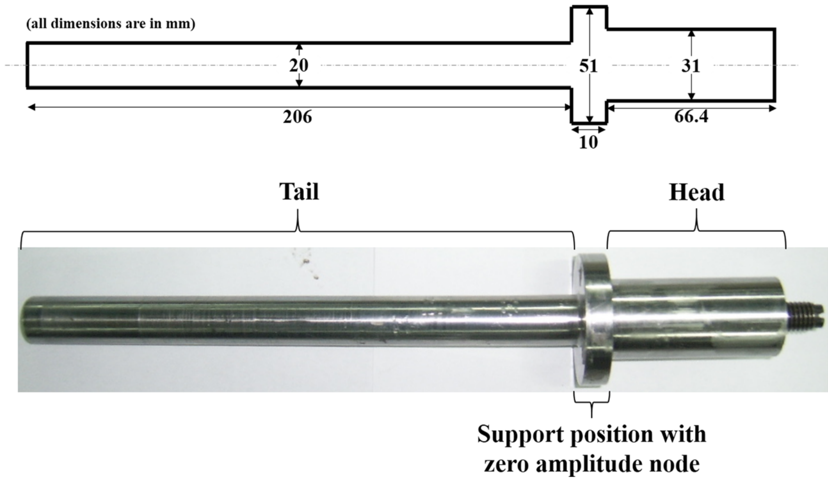


**Fig. 8** The final hot-work tool steel stepped shape horn dimensions

been designed and manufactured. The reason for adopting the primary frequency to be lower than 20 kHz is that the intended frequency of 20 kHz can be accomplished experimentally by altering the horn length. Reduction of the horn length leads to the increment of the intended frequency. As previously mentioned, after attaining the natural frequency of the system, the excitation would be carried out in this frequency to obtain the maximum reduction of the required punch load magnitude.

To apply the ultrasonic vibrated on the ECAP process, the horn is fastened to the upper ram of the hydraulic press and act as a punch on the billet at the entrance channel of the ECAP die. The ECAP material is commercially pure aluminum. Also, the contact surface of the die and the billet is properly lubricated with $MoS_2$ [10]. Ultrasonic excitation is implemented by a 20 kHz piezoelectric and ultrasonic generator with the maximum capacity of 2 kW. Additionally, modal analyses tests are performed using an accelerometer, laser vibrometer, and microphone as shown in Fig. 3. The natural frequency of the system is achieved using the excitement of the piezoelectric. The receiving responses are recorded via accelerometer, laser vibrometer, and microphone. Also, further tests have been performed to assess the validity of microphone method. In these tests, the horn is freely hung and excited by the piezoelectric. The horn responses after the excitation are recorded using two different kinds of microphone and the laser vibrometer. The equipments used are the following:

- Brüel & Kjær (B & K) seven-channel microphone, 4190 model
- Audio-Technica microphone, 6550 model, directly connected to the PC
- OMETRON laser vibrometer, VH-1000-D model

**Table 2** Resonance frequency changes versus the billet length alteration via Audio-Technica microphone method

| Billet length at the die entrance channel (mm) | 130 | 100 | 70 | 40 |
|---|---|---|---|---|
| Resonance frequency (Hz) | 19,930 | 19,950 | 19,940 | 19,970 |

In spite of all, responses from the three above methods are approximately the same, the B & K microphone and laser vibrometer exhibit less noise in comparison with the Audio-Technica microphone at the free condition. On the other hand, although the above methods (accelerometer, laser vibrometer, and two types of microphones) show reliable results for the horn excitation at the free condition, there is no suitable location for installing the 20 kHz accelerator and the laser vibrometer at the ECAP set-up. Thus, the outputs of accelerometer and laser vibrometer methods exhibit a large amount of noise. Hence, the microphone method was used to find the set-up natural resonance. Other advantages of the Audio-Technica microphone are its efficiency and simplicity.

After the microphone type selection, the responses are investigated by changing the horn length in the free condition to verify the SMA work. For this aim, four cylinders with the lengths of 10, 20, 30 and 50 mm as shown in Fig. 5 are connected to the horn tail, and the responses are experimentally recorded and compared with the simulated results. Figure 6 represents the obtained responses from this experiment. In this figure, the frequencies of 15,080 and 18,700 Hz are related to the excitations of the piezoelectric. Furthermore, one definite peak is observed for each response which shows the frequency of the second longitudinal vibrated mode of the horn. Table 1 also lists the magnitudes of the horn natural frequency for the various lengths by the use of both the experimental and numerical approaches in the free condition. From these results, it is clear that the natural frequency of the horn is reduced by increasing its length. For example, about 15 % reduction has been obtained at the horn natural frequency by changing the horn length from 220 to 270 mm. In addition, the discrepancy magnitudes between the experimental and simulated results indicate that there is a satisfactory agreement between the results; therefore, the FEM outputs can be considered reliable.

Following the above procedure, it is concluded that the Audio-Technica microphone can be used to record the system response during the modal analysis on the ultrasonic assisted ECAP process. The KRF 300 ultrasonic generator and 2 kW power piezoelectric were employed for the experimentation. The highest sound intensity corresponds to the system resonance frequency. The generator can excite in frequencies between 6 and 31 kHz with the various amplitudes. Generator excited voltage is set on the 150 V and the frequency is continuously changed from 15 to 22 kHz. The sound recorded result via the Audio-Technica microphone and the Cool Edit Pro 2.1 software at the UV-ECAP process using 220 mm horn length is shown in Fig. 7. As can be observed, there is no significant alteration at the sound intensity recorded by the Audio-Technica microphone up to the frequency of 18,600 Hz. Then, up to the frequency of 18,760 Hz, the sound intensity increases continuously. Afterwards, it is gradually reduced. Hence, the frequency magnitude of 18,760 Hz is the system natural frequency for a horn tail sectional length of 220 mm. It should be noted that the frequency of 18,000 Hz at the above condition has been obtained using the UV-ECAP simulation which expresses approximately 4 % gap between the EMA and SMA.

In the simulated modal analysis of ultrasonic vibration equal channel angular pressing process, it is found that 1 mm alteration of the horn length corresponds to about 90 Hz change at the longitudinal vibrated natural frequency. Therefore, the frequency of 20 kHz can be achieved by reducing 14 mm of the horn length at the tail section. Consequently, the horn tail section is machined to the length of 206 mm. The experimentation is repeated with the new horn length, and the resonance frequency of 19,930 kHz is obtained. This frequency is acceptable for carrying out the ultrasonic vibrated ECAP process. The final dimension of the H13 tool steel stepped shape horn has been depicted in Fig. 8. Moreover, the resonance frequency change during the UV-ECAP process is obtained by the use of the Audio-Technica microphone for 130, 100, 70, and 40 mm of the Al billet length at the die entrance channel, and the results are listed in Table 2. It can be seen that the billet length alteration has a low effect on the horn resonance frequency and, hence, this frequency does not vary significantly during the process. There is only 0.2 % change at the resonance frequency of the system by varying the billet length from 130 to 40 mm. Accordingly, the billet length influence on the resonance frequency determination of the UV-ECAP process can be ignored.

The required punch forces at the first pass ECAP process are approximately 162.5 and 147.7 kN for the conventional and ultrasonic vibrated assisted ECAP, respectively. This corresponds to about 9 % reduction in the pressing force. The principal cause of this behavior can be attributed mainly to the frictional force diminution because of reduction at the actual contact surface area between the ECAP die and the CP-Al billet and the acoustic softening which occurs during application of ultrasonic vibration to the ECAP process [18, 25–28].

## 5 Conclusion

This work dealt with the design and manufacture of a horn as a main part of the ultrasonic assisted ECAP process to reduce required forming load by the numerical and experimental modal analyses. The following conclusions were drawn:

- The natural frequency of the system and its adjustment for imposing the ultrasonic vibration via horn to the equal channel angular pressing process was successfully simulated and implemented. The numerical results indicated that the initial tail length of the horn was 220 mm for the frequency of 18 kHz. This was also verified with modal analysis experimental work.
- Three different methods for recording the responses namely accelerometer, laser vibrometer, and microphone were experimented. It was shown that all three methods give reliable results for the horn excitation at the free condition. Accordingly, an Audio-Technica microphone was utilized in order to determine the horn resonance frequency due to its ease of installation and simplicity.
- It is shown that the billet length has no considerable effect on the resonance frequency of the system.
- Finally, all these findings resulted in about 9 % reduction in the required punch load for the ultrasonic vibration ECAP process in comparison with the conventional ECAP method.

**Acknowledgments** The authors would like to thank the Iran Nanotechnology Initiative Council (INIC) for the financial support of this research.

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