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Vibration Analysis of an Ultrasonic-Assisted Joining System

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Abstract

In the field of lightweight construction, the bonding of multi-material components is an emerging topic. Strong bonds of different materials and material combinations are necessary and in the focus of research [1,2,3]. Within the German federal cluster of excellence MERGE (Merge Technologies for Multifunctional Lightweight Structures), ultrasonic-assisted joining of lightweight materials such as polymers, light metals and fibre composites is investigated. By support of mechanical pressure, strong bonds can be achieved by ultrasonic-assisted joining, being a suitable technology for adhesive bonding of various materials and material combinations. For these investigations, a modular ultrasonic-assisted joining system was designed which allows different arrangements concerning force and vibration directions.

One of the main components of the system is the sonotrode which is the part for coupling energy into the work pieces. The shape of the contact zone between sonotrode and material is crucial for joining, because it defines size and shape of the joining area. The sonotrode geometry is modified to match the joining requirements, but this shifts the resonance frequency and changes the vibration mode. In this work, the influence of different sonotrode geometries onto resonance frequencies and vibration modes was evaluated. By FEM (finite element method) simulations various vibration analyses were conducted and compared to the damped natural frequencies of selected geometries which were measured by single-point laser vibrometer.

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Keywords: ultrasonic-assisted joining; finite element method

1. Introduction

Ultrasonic-assisted systems are often used in bonding processes for joining multi-material systems due to their very short process times and high energy efficiency [9]. Multifunctional lightweight structures have a high potential for resource-efficient mass production of lightweight structures with high performance and functional density.

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By combination of different materials such as textiles, plastics and metals and their manufacturing processes, complex structures can be produced with a wide range of use. Such lightweight structures have the potential for efficient use of resources and energy.

Next to saving energy and material consumption of valuable resources, the emission of the greenhouse gas carbon dioxide is reduced. Within the Federal Cluster of Excellence MERGE, ultrasonic welding is the favoured method for joining different composite materials and several material combinations. Therefore, preliminary investigations are conducted and presented in this paper.

A special type of vibration is sound. It is a spatially spreading vibration, which is coupled to a medium as a carrier. In gases and liquids, sound waves propagate, due to the lack of elasticity of shape, in the form of longitudinal waves. In solid media, however, they appear as longitudinal, transverse, bending, stretching or torsion modes. It is divided into different sound frequency ranges (see Table 1). Ultrasound is an acoustic wave with a frequency above 20 kHz. Ultrasonic oscillations can be generated by various methods. The applied methods use two physical effects, the magnetostrictive and piezoelectric effect. The magnetostrictive effect, also known as Joule Effect, is based on the fact that a magnetic material can be deformed under an applied magnetic field. Under the influence of an external magnetic field, dipoles (so-called Weiss domains) are aligning within the material. Consequently, a change of the shape at constant volume takes place. The strain is proportional to the magnetic field strength. For alloys with iron, nickel or cobalt, an elongation of 10-30 µm/m can be achieved, with high magnetostrictive materials up to 2000 µm/m [7]. The second physical effect is the piezoelectric effect. Certain materials (e.g. lead zirconium titanate) react to mechanical stress with a change in the electrical polarization. Piezoelectric materials have a very high electromechanical efficiency. Depending on their type, they allow high frequencies [8]. This is detected as an electrical charge and is referred to as the direct piezoelectric effect. Additionally, piezoelectric materials respond to an applied external electric field with an alignment of the piezo domains along the field which leads to a change in length at the same volume (inverse piezoelectric effect). The frequency of the change in length is directly proportional to the applied voltage frequency. Thus, the desired frequency for the particular application can be easily adjusted by changing the AC voltage. For this study, a commercial ultrasound system (Hielscher Ultrasonic) was used, consisting of a transducer with an output of 23.9 kHz and a cylindrical horn with an amplitude of 5 µm (peak to peak).

Table 1. Classification of sound ranges [5].

Frequency range	Description
< 20 Hz	Infrasound
20 Hz – 20 kHz	Audible sound
20 kHz – 1 GHz	Ultrasonic sound
1 GHz – 10 THz	Hypersound

Subject of this research is the sonotrode. It is originally designed to have a high amplitude and to resonate near the frequency delivered by the piezoelectric transducer. Due to the subsequent use of the sonotrode for ultrasonic-assisted joining there was the necessity to adjust the geometry to the requirements of these processes. For this reason, one or more planar joining surfaces are to be created at the tip or in the central region. Since, however, accompanied by any change in the shape of a sonotrode is a change of the natural frequency, the magnitude of this influence should be explored. Typical construction materials are titanium alloys, hardened steel or aluminium alloys. For this study, a sonotrode made of the titanium alloy TiAl6V4 was used. The material properties of TiAl6V4 are given in Table 2. The unprocessed cylindrical sonotrode has a diameter of 30 mm, a total length of 106 mm and a bore of 7 mm at the receiving end. A mounting hole (4 mm in diameter) is placed radially (see Fig. 1). In solids, usually several natural frequencies can be excited. These frequencies depend on the sound velocity in transverse and longitudinal direction in the medium and the length of the sonotrode. The sound velocities resulting from equation 1 and depend on material constants such as density and modulus of elasticity respectively the shear modulus. The possible resonant frequencies result from the velocity of sound in the material (equation l and 2) and the length of the sonotrode (equation 3). For resonance, the length of the horn must be n-fold the wavelength (λ) of the sound. Typical length of sonotrodes is half the wavelength of the operation frequency.

Longitudinal velocity of sound: $$c_l = \sqrt{\frac{E}{\rho}} \quad (1)$$

Transversal velocity of sound: $$c_t = \sqrt{\frac{G}{\rho}} \quad (2)$$

Possible resonant frequencies: $$f = \frac{c}{l} \quad (3)$$

2. Experimental setup

For the setting of a modular ultrasonic-assisted joining system, the shape of a sonotrode has to be changed to provide a plain contact area. Hence, this influences the resonance frequency. The influence of material removal, combined with different geometrical shapes, onto the resonance frequency was simulated using finite element method (FEM) with COMSOL Multiphysics software. The horn is the key component for ultrasonic welding systems to couple energy into the welding area. Sonotrodes are made of materials with a high creep resistance and a high resistance against mechanical stresses. As carrier of the vibrational energy to the joint surface, the sonotrode is of very high importance. Their design and manufacturing has a significant impact on the quality of the joint [4]. Incorrectly manufactured horns may lead to the destruction of the vibration system and the generator.

Table 2. Properties of titanium alloy TiAl6V4.

Property	Value
Density (ρ)	4.43×10^3 kg/m³
Yield strength (R_e)	880 MPa
Tensile strength (R_M)	950 MPa
Modulus of elasticity (E)	113.8 GPa
Shear modulus (G)	44 GPa
Poisson ratio (ν)	0.342
Longitudinal velocity of sound (c_l)	5068.4 m/s
Transversal velocity of sound (c_t)	3151.6 m/s

If the user wants to alter the natural frequencies according to his requirements, various factors need to be considered [4]:

- Increasing the mass of a component, resulting in a reduction of the natural frequencies, a reduction of the mass results in an increase.
- A change of mass at nodes has no effect on the natural frequency.
- A change of mass at antinodes alters the natural frequency strongly.
- Additional bonds increase the natural frequencies.
- Shortening of rods or beams leads to a strong increase in natural frequencies.
- By increasing mass while reducing the slope stiffness, the natural frequencies can be changed deliberately.

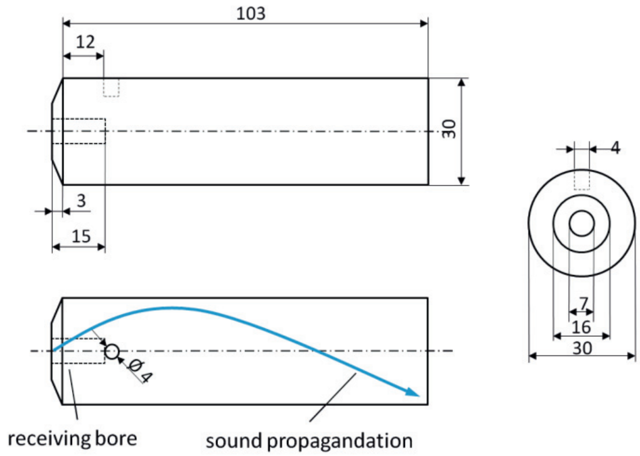
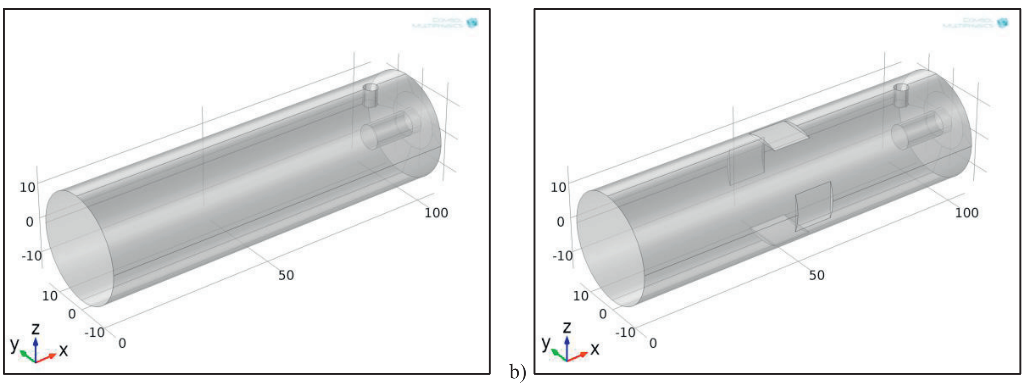


Fig. 1. Dimensions (in mm) of the sonotrode.

2.1. Computational model

To evaluate the effect of a geometrical shape change by material removal on the natural frequency response of a horn, a 3D solid mechanics model was created by using COMSOL Multiphysics software. The geometry of the specimen is depicted in Fig. 3. Based on this model, different geometries were created, as shown exemplarily in Fig. 4. The material is a titanium-alloy (TiAl6Ni4), the properties are given in Table 2.

For the simulation of natural frequencies the geometry was changed by placing planar arrays with an area of 10 x10 mm² at different positions along the surface. The number and location of these regions is varied along the y- and the z-axis (see Fig. 2a and 2b). The number of areas varies between 1, 2 and 4; positions are located at the top and in the middle, respectively. The restraint bore (x = 106 mm) was defined as a fixed point, the remaining areas as free. After setting up the model, it was spanned by a network of free tetrahedral elements. For analysing modal displacements in the actual horn, a mode extraction is carried out in the frequency range 16-80 kHz. In this range more than 40 natural frequencies were identified. For further considerations, the ninth natural frequency of 23.415 kHz (see Fig. 3) is considered more detailed. The reason for this is that the horn is designed, according to the manufacturer, for an operating frequency of 23.9 kHz corresponding to the transducer output. Then, the respective planar areas are modeled on the sonotrode, and the displacement of the resonant frequency is determined. After the operating frequency was set to 23.415 kHz, the simulation of each flat area was performed (Fig. 4). Thereupon, the frequency shift to the original natural frequency is to be compared. The results of this comparison are shown in Table 3.



a) b)

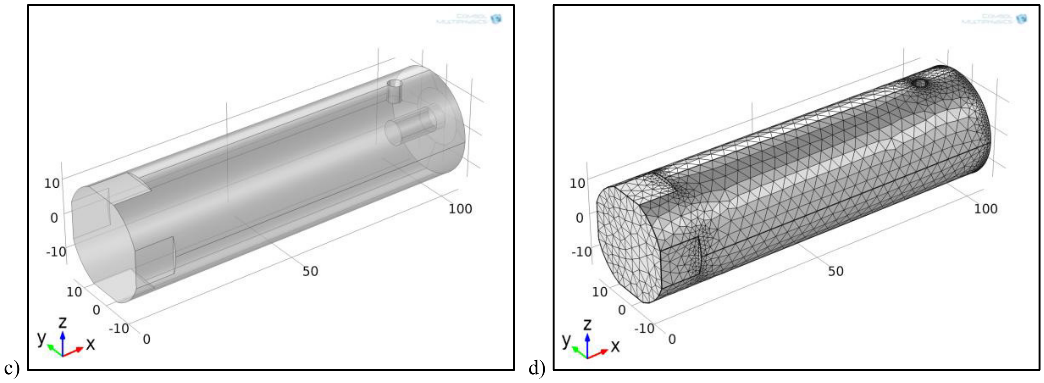


Fig. 2. Geometry model of sonotrode: a) original shape, b) four flattened areas in the middle, c) four flattened areas at the top and d) tetrahedral mesh.

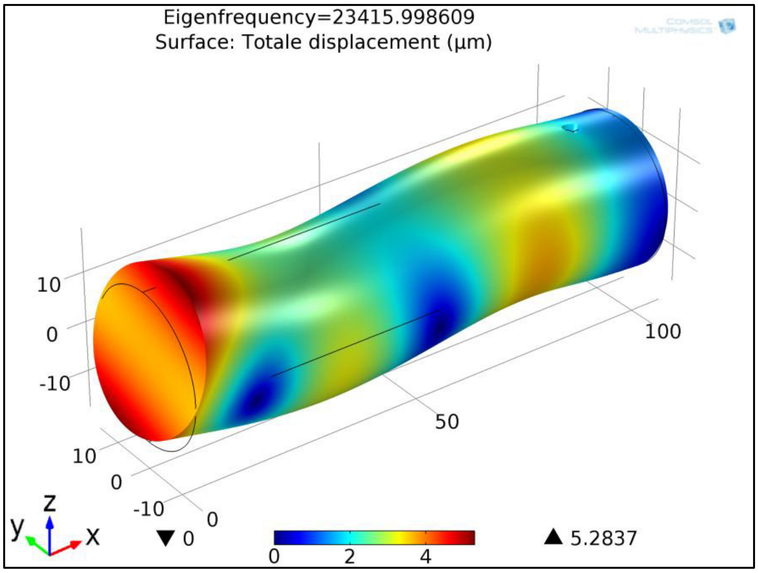


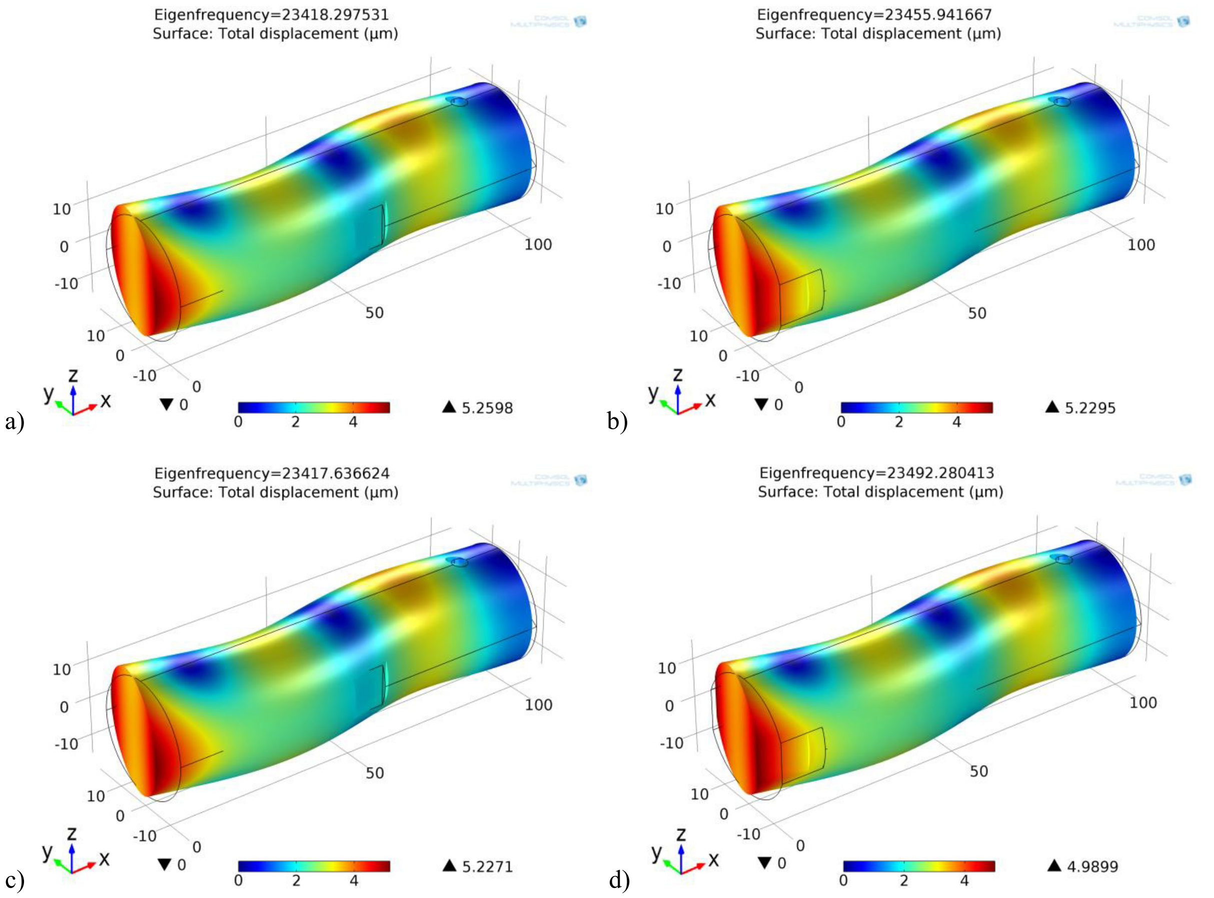
Fig. 3. Determined ninth natural frequency.

2.2. Experimental studies

To determine the frequency shift on a real system, comparative measurements were carried out using a laser vibrometer. For this purpose, the raw horn was firstly measured and afterwards the modified horn with two faces in the y-axis. The measurement system consists of a laser vibrometer OFV-505 from Polytec, a clamping device and an impulse hammer. When the horn is excited by the impulse hammer, the free damped oscillation can be determined. With a sampling rate of 100 kHz, a range of 0-50 kHz can be measured. By transferring the measurement results from the time to the frequency domain using Fast Fourier transform (FFT), the individual frequency components are represented. The natural frequency for the original sonotrode was measured to be at 23.924 kHz, this corresponds to the manufacturer's instructions. For the altered geometry a shift of the natural frequency to 23.956 kHz was detected. This corresponds to a deviation of about 0.15% ($\Delta f = 32$ Hz).

3. Results and discussion

In the course of this investigation it could be shown by using COMSOL Multiphysics software that a small change in the geometry of a horn has no great influence on the natural frequency. Clearly visible is a difference in the individual positions of the inserted flat areas. Very small deviations from the natural frequency of the original horn can be seen for the middle range of the horn, while a change in the geometry at the tip of the horn leads to a greater change. The reason for this is that in the middle range of the horn, a vibration node forms while it is at the tip to form an antinode. This is consistent with the identified factors on the self-oscillating behavior. The comparison of the simulation with a real measurement sonotrode gave a natural frequency of 23.924 kHz before processing the planar areas. This represents a deviation of 2.2% from the simulated value which is at 23.415 kHz for the original horn. So the simulated value corresponds very well with the real one. Two surfaces in the z-direction resulted in a frequency shift of Δf = 32 Hz = 0.13 % and the measured natural frequency of 23.956 kHz (see Fig. 5). This corresponds to the magnitude of the simulated frequency shift for two planar areas in z-direction at the top of the sonotrode (Δf = 76 Hz = 0.3%). The simulations show that not only the natural frequency of the sonotrode can be influenced by changing geometry, but also the spatial orientation of the amplitude is changed. As can be seen in Figure 3, the original sonotrode oscillates in the z-axis perpendicular to the propagation direction. By attaching small planar surfaces on the y-axis, the direction of oscillation is shifted also in the y-plane (see Fig. 4a,b). Thus, the direction of vibration of a horn can be adjusted by selectively introduced planar surfaces. Furthermore, it was shown that by a small change in the shape of the sonotrode the natural frequency is hardly affected. The maximum deviation from the original natural frequency was placed on the order of 0.4% (see Table 3).



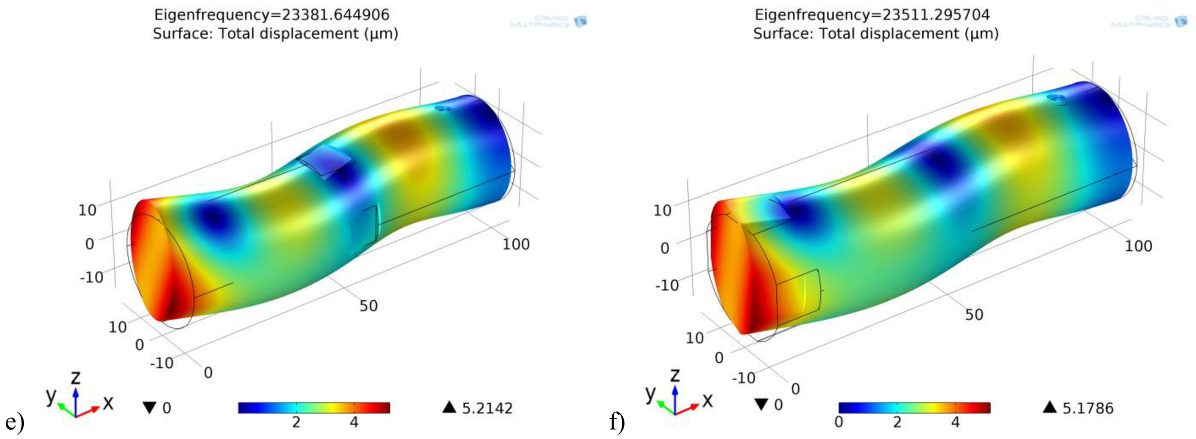


Fig. 4. Results of modelling: a) one area y-axis middle, b) one area y-axis top, c) two areas z-axis middle, d) two areas z-axis top, e) four areas middle and f) four areas top.

Table 3. Simulated frequencies for different positions of flattened areas.

Position	f [Hz]	Δf [Hz]	Δf [%]
Middle negative y-axis	23418.297	2.299	0.009
Middle positive z-axis	23417.397	1.399	0.006
Middle 2 areas y-axis	23417.636	1.638	0.007
Middle 2 areas z-axis	23419.853	3.855	0.017
Middle 4 areas y-z-axis	23381.644	-34.354	-0.1
Top negative y-axis	23455.941	39.943	0.2
Top positive z-axis	23452.837	36.839	0.1
Top 2 areas y-axis	23492.280	76.282	0.3
Top 2 areas z-axis	23490.394	74.396	0.3
Top 4 areas y-z-axis	23511.295	95.297	0.4

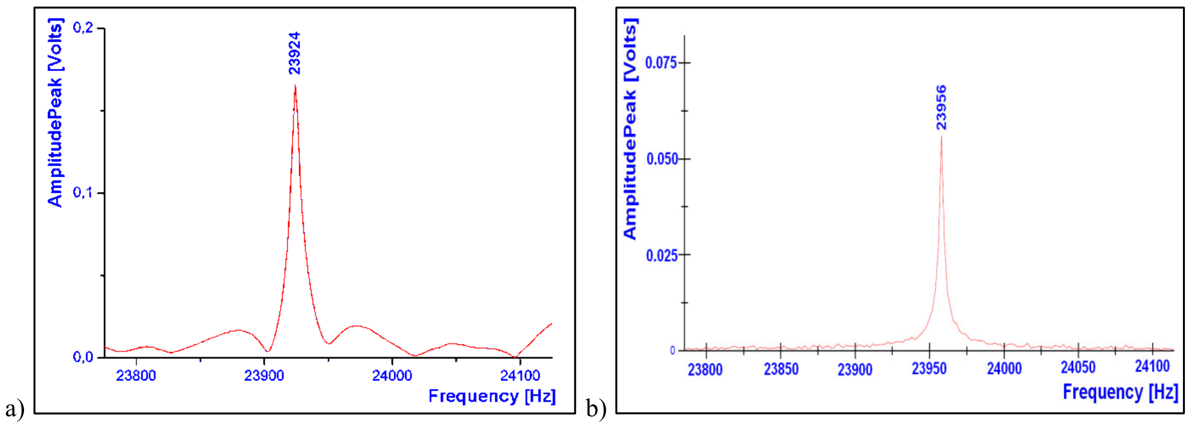


Fig. 5. Frequency measurements of: a) original sonotrode (after FFT) and b) sonotrode with changed shape (after FFT).

4. Conclusion

The influence of a change in the geometry of a sonotrode for ultrasonic-assisted welding was investigated by using COMSOL Multiphysics. A simulation model was set up and the effects of introduced planar surfaces at the horn to the natural frequency were determined. The frequency shifts were determined and compared to the original natural frequency. Following the simulation, the natural frequency behavior of a real sonotrode was measured and compared to the simulations.

The introduction of planar layers of a joint surface on solid cylindrical horns leads to no significant deviation of the natural frequency of the sonotrode. It was shown by simulation that the maximum deviation between original and machined sonotrode is very small at 0.4%. Also it was found that with the introduction of the joining surfaces an influence to the vibration in the direction of the sonotrode can be taken. The frequency shift of a comparative sample of a horn made of titanium alloy showed an even smaller variation in the order of 0.13%. The change in the geometry of a horn may represent an adequate mean to sonotrodes without much change in frequency for ultrasonic-assisted joining processes. COMSOL Multiphysics is an accurate and easy to use simulation software that simulates well the actual conditions and the deviation of the results to the real measurements are very small.

As a result of these investigations, a sonotrode with two flattened areas (figure 4d) was produced. With this tool an experimental rig for ultrasonic-assisted welding of multimaterial composites like fibre-reinforced-plastics or metalized polymer-films will be set up. It will include a universal clamping device for the ultrasonic transducer to ensure the possibility for fast changing of joining partners on the one hand and the sonotrode on the other hand.

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