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# Design of Ultrasonic Probes for use in Food and Chemical Industries

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**ABSTRACT**

In recent years, the food industries experts have drawn their attention toward using high frequency ultrasound waves in producing processes. The main part of these equipments is the ultrasonic probe which called sonotrode. The performance of ultrasonic equipments depends on properly design of sonotrode shape. In this study, four methods were used to design the ultrasonic probes for use in food and chemical industries. Two types of probes, namely, step type and cylindrical type were considered and the related calculations for the both types of probes were performed based on the four design methods. For both of the cylindrical and step type probes, the length of the designed probe was equal to half of the ultrasonic wavelength. Modal analysis of the models were determined by the numerical simulation using finite element method (FEM) design procedures. The results showed that although the probe material does not affect vibration amplitude, it can affect stress distribution along the probe. In the cylindrical type probe, the maximum stress raised in the middle part of probe, whilst in the step type probe, regardless of design probe, the maximum stress was occurred in the surface variation location. Based on the results, to design a probe, it should be noted that the maximum created stress in the probe must not exceed the yield stress of the selected material.



## Introduction

Ultrasound is divided into three categories: power ultrasound (20-100 kHz), high frequency ultrasound (100 kHz-1MHz), and diagnostic ultrasound 1MHz-10MHz). In recent years, the food industries experts have drawn their attention toward using high frequency ultrasound waves in producing process. The physical, mechanical, and chemical attributes of ultrasonic waves are able to alter the attributes of materials (i.e. disorder in the physical integration, accelerating a number of determined chemical reactions) through running high pressure, cutting, and temperature gradient of the material in which they propagate (Neis and Bume, 2003). One of the industrial applications of high frequency ultrasonic waves is cleaning operation and it is so efficient in this field. Surface cleaning is the widest application of this technology. There are some advantages of using ultrasonic waves including chemical materials in cleaning (Clarck, 2008):

1) Decrease in the use of chemical materials
2) Decrease in the direct contact of the worker with the perilous cleaning chemical materials and composition
3) Increase in the speed of cleaning, consistency in cleaning (the ultrasonic wave is able to penetrate in all complex surface areas for running integrated cleaning operation)
4) Automatic controlling which helps saving energy expense, worker, and space.

Among the notable applications of this method, other progressions in essence extraction, purifying, blending, homogenizing, and giving rise to the speed of powder materials transforming under high pressure circumstances, food productions drying, removing microorganisms and separating powders that bring about problems in the production process (for example in materials fermentation) have been developed (Clarck. 2010, Alvarez-Lo´pez et al, 2003, Canumir et al. 2002, Cheeke and David. 2002, Kuldiloke and Eshtiaghi. 2008, Rawson et al. 2011, Valero et al. 2007, Vecret et al, 2002, Peshkovsky and Peshkovsky 2007).

The ultrasonic generator initially converts the voltage (50 Hz or 60 Hz frequency) to the electrical energy having high frequency in the ultrasonic waves production system. Then, the intermittent voltage is yield to the ceramic piezo-electric crystals being disc-formed which coerces them to expand and constrict with each polarity changing (Nad, 2010). Hence, these linear vibrations are strengthened by the probe (sonotrode) and then are transported to the probe environment. It is necessary to delicately design the probe because it (the probe) plays an indispensable role in improving the efficiency of ultrasonic waves influence on the environment.

The principal function of the sonotrode is to amplify the amplitude of ultrasonic vibrations of the tool to the level required for the effective machining. It transmits the vibration energy from the transducer towards to the tool interacting with workpiece. It is in resonance state with the transducer. The design and manufacture of the sonotrode requires special attention. Incorrectly manufactured sonotrode will impair machining performance and can lead to the destruction of the vibration system and cause considerable damage to the generator. Generally, the sonotrodes are made of metals that have high fatigue strengths and low acoustic losses. The most important aspect of sonotrode design is a sonotrode resonant frequency and the determination of the correct sonotrode resonant wavelength. The resonant frequency of sonotrode, which has simple geometrical shape, can be determined analytically (cylindrical shape). For complicated geometrical shape, the resonant frequency is usually determined numerically using finite element method (Nad, 2010).

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In this study, four methods are used to design ultrasonic probes for use in food and chemical industries. First, the design procedures of probes are discussed separately in the following sections. Then, the four methods will be compared and analyzed to validate the results.

## 2. Determination of ultrasonic probe vibration relation

In order to design the probe and obtain the governing relation on probe vibration, first, the relation between the forces, stress and strain should be written as follows (Mcculloch, 2008):

$$P = \sigma . S = E . S . \frac{\partial u}{\partial x} \qquad (1)$$

where, $\sigma$ is axial stress, $E$ is the Young's modulus, $u$ is axial deformation, $\partial u/\partial x$ is axial strain. If $f(x,t)$ is assumed as external force incoming to the unit of length, through summation of forces in x-axis direction we have (Fig. 1):

$$(P + dP) + f dx - P = \rho . S . dx . \frac{\partial^2 x}{\partial t^2} \qquad (2)$$

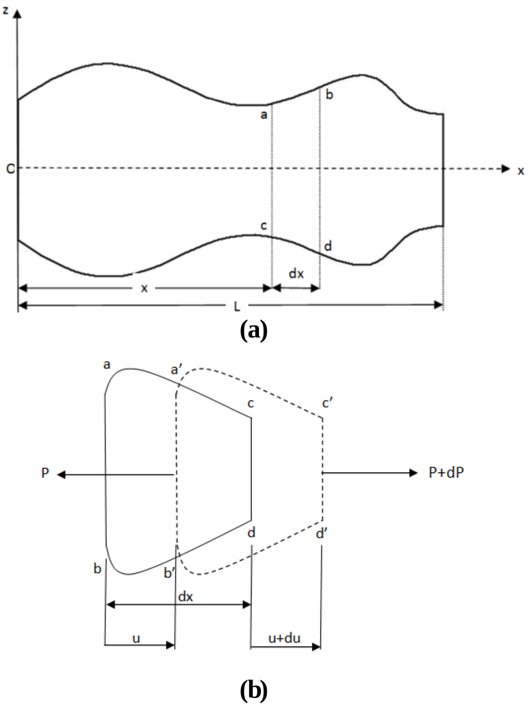


**Fig. 1. Schematic view of probe with variable section (a); Deformation along a part of probe (b)**

where, $\rho$ is the probe density. Using $dP = \left(\frac{dP}{dX}\right)$ and Eq. (2), we have:

$$\frac{\partial}{\partial x}\left[E . S(x) . \frac{\partial u(x,t)}{\partial x}\right] + f(x,t) = \rho(x) . S(x) . \frac{\partial^2 x}{\partial t^2} \qquad (3)$$

Eq. (3) is defined as instigated longitudinal vibration of a non-uniform rod. By replacing f=0 in Eq. (3), the free vibration equation of non-uniform rod can be written in the form of Eq. (4):

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

Considering $C = \sqrt{\frac{E}{\rho}}$ and Eq. (4), we have:

$$c^2 . \left[\frac{\frac{\partial S}{\partial x}}{S(x)} . \frac{\partial u(x,t)}{\partial x} + \frac{\partial^2 u(x,t)}{\partial x^2}\right] = \frac{\partial^2 u(x,t)}{\partial t^2} \qquad (5)$$

Eq. (5) shows the overall form of vibration in the probe. Considering the boundary conditions, the longitudinal deformation in the probe during vibration can be obtained.

### 2.1. Design of cylindrical type probe

The cylindrical probe is the simplest type of probes. In such type of probes, because the area along the probe length is constant, we have:

$$\frac{\partial S}{\partial x} = 0 \qquad (6)$$

According to Eq. (5) and (6):

$$c^2 . \frac{\partial^2 u(x,t)}{\partial x^2} = \frac{\partial^2 u(x,t)}{\partial t^2} \qquad (7)$$

To solve the above partial differential equation, the variable separable method can be used. By replacing $u(x,t) = g(x) . h(t)$, Eq. (7) is converted to two ordinary differential equations as follows:

$$\frac{\partial^2 g(x)}{\partial x^2} + \frac{\omega^2}{c^2} . g(x) = 0 \qquad (8)$$

$$\frac{\partial^2 h(x)}{\partial t^2} + \omega^2 . h(t) = 0 \qquad (9)$$

In the above equations, $\omega$ is the angular frequency of vibration. Solving the Eq. (8) and (9), the below equation is obtained:

$$u(x,t) = \left(A \cos\frac{\omega x}{c} + B \sin\frac{\omega x}{c}\right)(C \cos \omega t + D \sin \omega t) \qquad (10)$$

Eq. (10) is solved in steady state and boundary equation as follows:

$$\left\{\begin{array}{ll} a) & \frac{\partial u(x)}{\partial x} = 0, x = 0 \\ b) & \frac{\partial u(x)}{\partial x} = 0, x = l \\ c) & u(0) = u_{in} \end{array}\right\} \qquad (11)$$

where, $l$ is the length of probe and $u_{in}$ is the amplitude of transmitted motion from the transducer to the probe. Using Eq. (11a) and (11c), the overall equation of amplitude is obtained:

$$u = u_{in} . \cos\frac{\omega x}{c} \qquad (12)$$

The length of probe can also be calculated from Eq. (11b):

$$u'(l) = 0 \rightarrow -u_{in} . \frac{\omega l}{c} . \sin\frac{\omega l}{c} = 0 \rightarrow \frac{\omega l}{c} = n\pi$$

$$\frac{2 . \pi . f . l}{c} = n\pi \rightarrow l = \frac{c}{2 . f} \rightarrow l = \frac{\lambda}{2} \qquad (13)$$

where, $f$ is vibration frequency of the probe. By use of $\sigma = E . \varepsilon$ and Eq. (12), the variations in the stress along the probe can be calculated:

$$\sigma = -E . u_{in} . \frac{\omega}{c} . \sin\frac{\omega . x}{c} \qquad (14)$$

In order to obtain the maximum axial stress, the derivative of Eq. (14) must be set to zero. So:

$$\sigma' = -E . u_{in} . \frac{\omega^2}{c^2} . \cos\frac{\omega . x}{c} = 0 \rightarrow \frac{\omega . x}{c} = n\pi + \frac{\pi}{2} \xrightarrow{n=0} x = \frac{\lambda}{4}$$

$$\sigma_{max} = \pi . E . \frac{u_{in}}{l} \qquad (15)$$

In Fig. 2 the variation trend of stress and vibration amplitude along the probe is shown which has been resulted from Eq. (12) and (14).

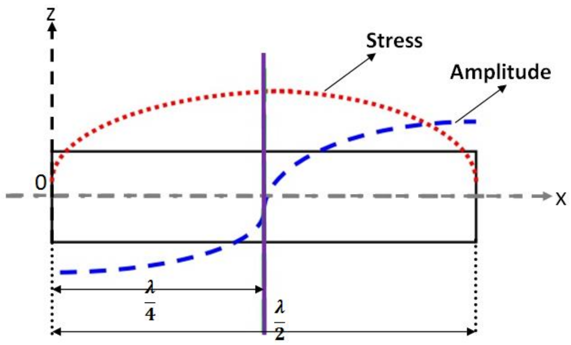


**Fig. 2. Variation trend of stress and vibration amplitude along the cylindrical probe**

### *2.2. Design of step type probe*

Step type probe, as shown in Fig. 3, is one of the most common probes used for ultrasonic machining technologies (Nad, 2010). The method of solution of deformation equations along the step type probe is similar to cylindrical probe with a difference in boundary conditions. For obtaining the governing equations on deformation along the step type probe in steady state condition, Eq. (5) is used. In solution of the mentioned differential equation, the answers are divided into two subsets and each of the answers is obtained considering the boundary condition.

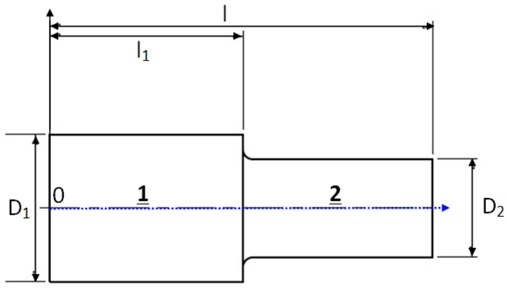


**Fig. 3. Schematic of step type probe**

From Eq. (5), we have:

(16)
$$\text{a)}\ u_1 = A\cos\frac{\omega x}{c} + B\sin\frac{\omega x}{c}, \qquad 0 \le x \le l_1$$
$$\text{b)}\ u_2 = C\cos(\omega x/c) + D\sin(\omega x/c), \qquad l_1 < x \le l$$

The boundary conditions for Eq. (16) are written as follows:

$$\left\{\begin{array}{ll} \text{a)}\ u_1(0) = u_{in}, & u'_1(0) = 0 \\ \text{b)}\ u_2(l) = u_{out}, & u'_2(l) = 0 \\ \varepsilon_1 = \left(\frac{D_2}{D_1}\right)^2 . \varepsilon_2 & \end{array}\right\} \qquad (17)$$

Eq. (17-c) is obtained from the below relationships:

$$\varepsilon = \frac{P}{E.S} \rightarrow S.\varepsilon = \frac{P}{E}$$
$$S_1.\varepsilon_1 = S_2.\varepsilon_2 = \frac{P}{E}$$
$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{S_2}{S_1} = \left(\frac{D_2}{D_1}\right)^2 \qquad (18)$$

Using Eq. (17), the constants of Eq. (16) is obtained as follows:

$$\xrightarrow{(17\text{-a})} u_1 = u_{in}.\cos\frac{\omega x}{c}, \qquad 0 \le x \le l_1 \qquad (19)$$

$\omega l_1$

$\omega l_1$

One of the most important parts in probe design is preventing of stress concentration in locations in which area changes. To prevent this problem, the displacement in this section must be equal to zero (Nanu et al., 2011). Consequently:

$$u_1(l_1) = 0 \rightarrow u_{in}.\cos\frac{\omega l_1}{c} = 0 \rightarrow l_1 = \frac{\lambda}{4}$$

For obtaining the probe length, the displacement equation and the $l_1$ parameter are used:

$\{$a) $u_1(0) = u_{in}$, $u'_1(0) = 0$ b) $u_2(l) = u_{out}$, $u'_2(l) = 0$

$$u_2(x) = \left(\frac{D_2}{D_1}\right)^2 .u_{in}.\cos\frac{\omega x}{c}, \qquad l_1 < x \le l \qquad (22)$$

From Eq. (19) and (22) the variation of stress along the probe can be obtained:

$$\sigma_1 = -E.u_{in}.\frac{\omega}{c}.\sin\frac{\omega.x}{c}, \qquad 0 \le x \le l_1 \qquad (23)$$

$$\sigma_2 = \left(\frac{D_2}{D_1}\right)^2 .u_{in}.\frac{\omega}{c}.\sin\frac{\omega.x}{c}, \qquad l_1 < x \le l \qquad (24)$$

In order to determine the maximum axial stress in step type probe, Eq. (23) and (24) are derived and set equal to zero. Therefore, the maximum stress will be equal to:

$$\sigma_{max} = \pi.E.\left(\frac{D_2}{D_1}\right)^2 .\frac{u_{in}}{l} \qquad (25)$$

In Fig. 4 the variation trend of stress and vibration amplitude along the cylindrical type probe is shown which has benn obtaied from Eq. (19), (22) to (24).

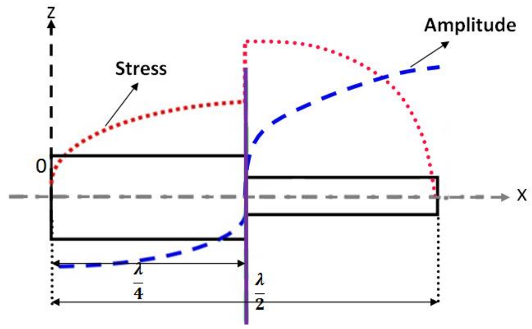


**Fig. 4. Variation of stress and vibration amplitude along the step type probe**

### 3. Design of ultrasonic probe using Finite Element Method (FEM)

In the recent works, the selection of a suitable shape and corresponding dimensions of sonotrode are usually determined by numerical simulations using finite element method (Seah et al., 1993, Amini et al., 1995, Sherrit et al., 2004, Amini et al., 2008, Wang, et al., 2009). In order to determine the modal properties for various shapes of sonotrode and assessment of the effect of relevant geometrical parameters on the modal properties, the finite element method is used. The governing equation of motion to describe of sonotrode free vibration of is expressed in following form (Nad, 2010):

$$M\ddot{u} + B\dot{u} + Ku = 0 \qquad (26)$$

where $M$, $B$ and $K$ are mass, damping, stiffness matrix respectively, $\ddot{u}$, $\dot{u}$, $u$ are vector of nodes acceleration, velocity and displacement, respectively. Since it can be supposed that the sonotrode materials have a low damping capacity (from dynamical aspect), the damping in equation of motion can be neglected. The equation of motion (Eq. 26) can be for B = 0 rewritten into the form (Nad, 2010):

$$M\ddot{u} + Ku = 0 \qquad (27)$$

The modal properties of sonotrode are determined by the solution of eigenvalue problem (Nad, 2010)

$$\left[[K]-\omega^2[M]\right]\vec{Q}=\vec{0} \qquad (28)$$

In Eq. (28), the mass and stiffness matrix for an element is defined as below:

$$[K]=\frac{AE}{L}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix} \qquad (29)$$

$$[M]=\frac{\rho Al}{6}\begin{bmatrix}2 & 1\\ 1 & 2\end{bmatrix} \qquad (30)$$

The effective parameters on probe design using FEM are obtained by replacing Eq. (29) and (30) in Eq. (28):

$$\left[\frac{AE}{L}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}-\frac{\omega^2\rho Al}{6}\begin{bmatrix}2 & 1\\ 1 & 2\end{bmatrix}\right]\begin{bmatrix}u_{in}\\ u_{out}\end{bmatrix}=\begin{bmatrix}0\\ 0\end{bmatrix} \qquad (31)$$

In Eq. (31), according to known values of $E$, $A$, $\rho$, $\omega$ and $u_{in}$, the length of the probe ($l$) and the amount of displacement at the end of the probe ($u_{out}$) can be obtained. It should be noted that in solving Eq. (31) it is assumed that the probe is to be designed for a transducer with certain vibration frequency. If the dimensions of the probe are known and the goal is to determine the mode shape, the length of the probe is known and ω is unbeknown. Also, using Eq. (28) to (30), the elements in the form of Fig. 5 can be used for designing the step type probe:

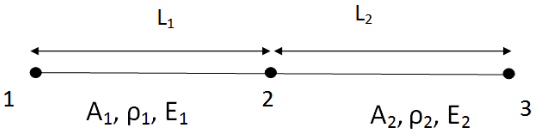


**Fig. 5. Relative elements to step type probe in FEM**

$$[K^{(1)}]=\frac{A^{(1)}E^{(1)}}{L^{(1)}}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix} \qquad (32)$$

$$[K^{(1)}]=\frac{A^{(1)}E^{(1)}}{L^{(1)}}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix} \qquad (33)$$

$$[M^{(1)}]=\frac{\rho^{(1)}A^{(1)}l^{(1)}}{6}\begin{bmatrix}2 & 1\\ 1 & 2\end{bmatrix} \qquad (34)$$

$$[M^{(2)}]=\frac{\rho^{(2)}A^{(2)}l^{(2)}}{6}\begin{bmatrix}2 & 1\\ 1 & 2\end{bmatrix} \qquad (35)$$

Using Eq. (32) to (35) and forming the mass and stiffness matrix for the probe and by replacing in Eq. (28), we have:

$$\frac{A^{(1)}E^{(1)}}{L^{(1)}}\&-\frac{A^{(1)}E^{(1)}}{L^{(1)}}\&0@-\frac{A^{(1)}E^{(1)}}{L^{(1)}}\&\frac{A^{(1)}E^{(1)}}{L^{(1)}}+\frac{A^{(2)}E^{(2)}}{L^{(2)}}\&-\frac{A^{(2)}E^{(2)}}{L^{(2)}}$$

$$\begin{bmatrix}u_1\\ u_2\\ u_3\end{bmatrix}=\begin{bmatrix}0\\ 0\\ 0\end{bmatrix} \qquad (36)$$

In the above equations, indexes (1) and (2) are elements number and $u_1$, $u_2$ and $u_3$ are displacement of nodes 1, 2 and 3, respectively. By solving the above equations, the desired parameters for designing the step type probe are obtained.

**4. Design of probes using other methods**

There are other procedures which can be used to determine the length of probes (Fig. 6). In one method, first the surface of the probe is selected according to diameter of transducer and desired magnification. Then, the length of each part of the probe can be determined considering the values of selected surfaces and the material probe and intersecting the related curves in Fig. 6 (Anonymous. 2008).

$$\beta=\frac{A_1}{A_2}=\left(\frac{D_1}{D_2}\right)^2 \qquad (37)$$

where, $\beta$ is magnification of vibration transmission.

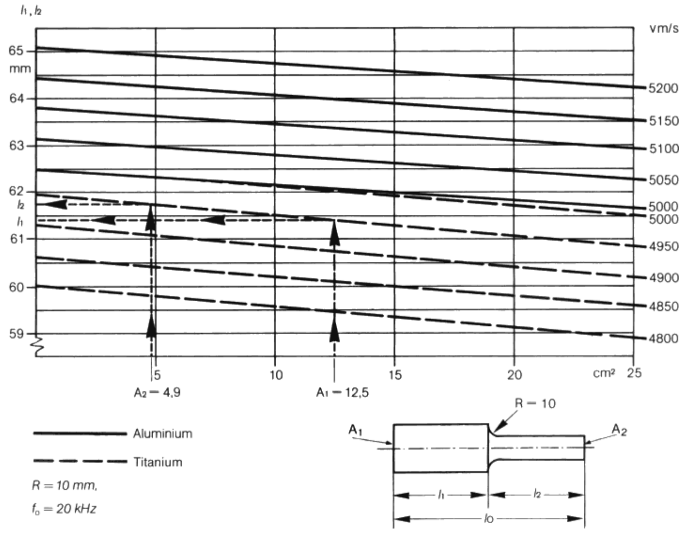


**Fig. 6. Curve to estimate the length of the step type probe considering the surface and material of probe at the frequency of 20 kHz (Anonymous. 2008)**

In the other method, the length of probe is calculated by the following formulas (Nanu et al., 2011):

$$l_1=\frac{1.5c}{2\pi f}, \qquad l_2=\frac{1.6c}{2\pi f} \qquad (38)$$

This method is a simple way to obtain the length of probe in which the effects of diameter and surface are neglected. However, for using this method, it is necessary to consider the amount of stress.

**5. Stress criterion for designing of ultrasonic probes**

For designing a probe, it has to be noted that the resulted stress should not exceed the yield stress. The stress distribution in the probe can be plotted using the von Mises criteria as shown in Eq (39) (Mcculloch. 2008):

$$\sigma_0=\sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \qquad (39)$$

where, $\sigma_1$, $\sigma_2$, $\sigma_3$ are the principal stresses and $\sigma_0$ is the yield stress.

Assuming the stress distribution lies in-plane along the cross–section of the probe where no traverse movement exist implies that there is only on principal stress, $\sigma_2$, acting in one direction always and no shear stress and using Eq. (40):

$$\sigma_0=\sqrt{\frac{(0-\sigma_2)^2+(\sigma_2-0)^2+(0-0)^2}{2}}$$

$$\sigma_0=\sigma_2 \qquad (40)$$

As shown in Eq. (40) the von Mises stress will be the same as the maximum principal stress in the longitudinal direction in the waveguides when excited in the longitudinal mode. The maximum allowable stress in an ultrasonic component can be considered to be the yield stress of the material divided by the safety factor (Mcculloch, 2008).

**6. Results and discussion**

As it can be seen from Eq. (14), (23) and (24), for designing a probe, although the material of probe has a direct effect on the amount of arisen stress along the probe, it has not a remarkable effect on the amplitude of vibration, according to Eq. (12), (19) and (22). One of the important parameters for selecting the material of a probe is its working environment. The different materials of probes show different erosion conditions when working in different environments. Also, the material of probe considering its density can affect the weight of probe which may influence the vibration of the probe caused by piezoelectric vibrative forces. Fig. 7 shows the effect of different materials on distribution of stress along the probe.

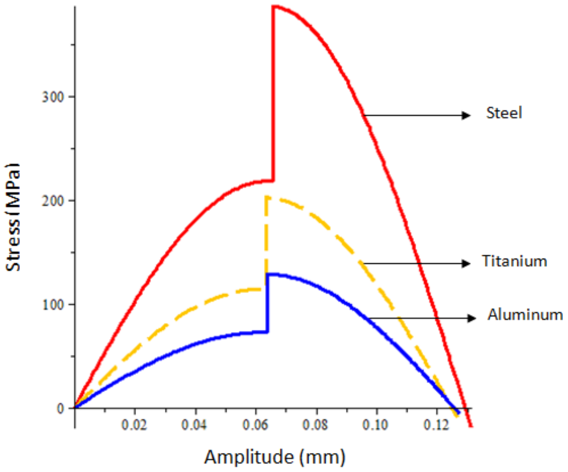


**Fig. 7. Effect of different materials of probe on stress distribution along the probe**

One of the most important factors to design a probe is the length of probe and Eq. (13) is used for designing it. According to this, the length of the probe is equal to half of the wavelength. Since the wavelength depends on the sound diffusion speed in the probe and the diffusion speed depends on the material of the probe, consequently, for designing a probe, the length of probe is determined after selecting the material of probe. In step type probes, determination of surface variation location is very important. Following the above discussion, the total length of probe is equal to half of the wavelength. But, for determining the length of each part of a step type probe, use of different mentioned methods results in different values. The length of each part of probe in the methods obtained through the governing equations on vibrative motion of probe and the finite element method is equal to 1/4 of the wavelength. If Eq. (38) is used to design the probe, the resulted difference as compared to the other methods is negligible. The reason for this result may be due to the fact that in this method the dynamic state of probe is considered, whilst in the other methods the equations have been solved under steady state conditions. Because the difference between the methods is very small, each of the methods can be used for designing the probe.

In order to assess and validate the mentioned results, the obtained dimensions for design a probe with aluminum material were analyzed by computer. The material properties for analyzing the probe by CAD-CAM software were defined as: $\rho$=2800 kg/m$^3$, E=74 GPa, C=5140 m/s.

According to the vibration frequency of the utilized transducer, the working frequency of the probe was equal to 20.3 kHz. By having the vibrative frequency and the speed of sound diffusion in aluminum and using Eq. (13), the length of the cylindrical probe is equal to 126.6 mm. Considering the diameter of transducer, the diameter of probe was selected equal to 40 mm.

As shown in Fig. 8, the highest amplitude of vibration was obtained in two end parts of the probe and displacement in the middle part of probe was zero. Similar to the discussed relationships, stress distribution in the middle part and the two end parts of the probe was maximum and zero, respectively (Fig. 9). The modal analysis indicated that for the designed probe, the natural frequency is equal to 19.98 kHz. The closeness of the probe natural frequency to the applied vibrative frequency shows the validity of design and the ability of the designed probe to work in the defined environment.

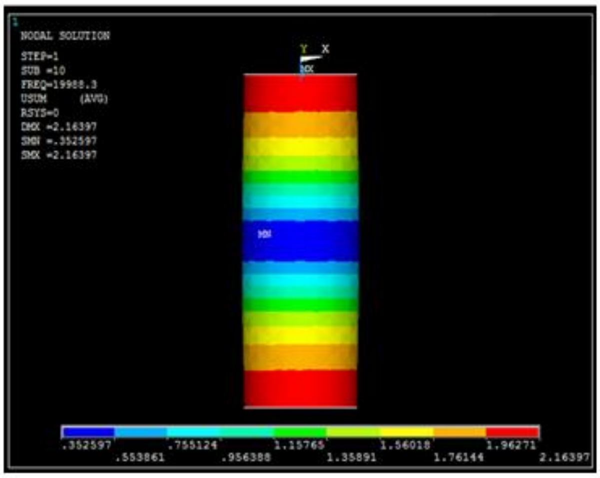


**Fig. 8. Determination of the displacement along the cylindrical probe by CAD-CAM software**

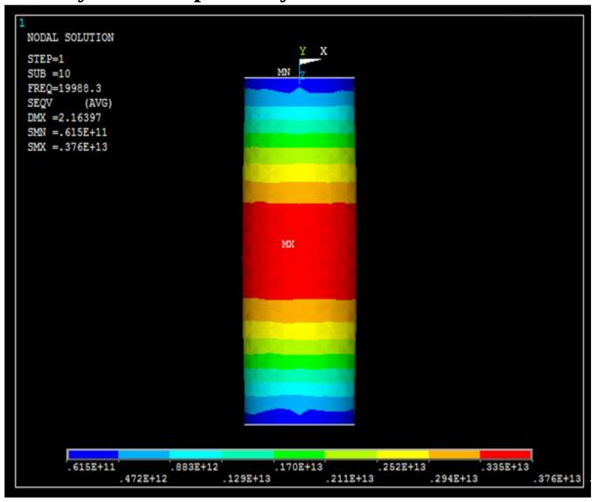


**Fig. 9. The von Mises stress along the cylindrical probe obtained by computer**

In order to assess the validity of step type probe calculations, the information obtained from aluminum probe design calculations were analyzed and evaluated in CAD-CAM software. The designed probe has a diameter of 40 mm and 30 mm at the inner and outer sections, respectively. According to the kind of probe and working frequency, the length of probe was determined as 126.6 mm. Considering Eq. (19), to prevent stress concentration, the length of each part of probe is equal to 63.3 mm. As illustrated in Fig. 10, the end section of each part has the highest displacement and the highest displacement is attributed to end part of the probe. Eq. (18) and (37) are used to calculate the increase in amplitude of motion at the end part of probe. According to values of selected diameters, the amplitude of motion is 1.78 fold. In solving the problem by the software, the magnification ratio is 2 that shows a 12% difference regarding to the calculated value.

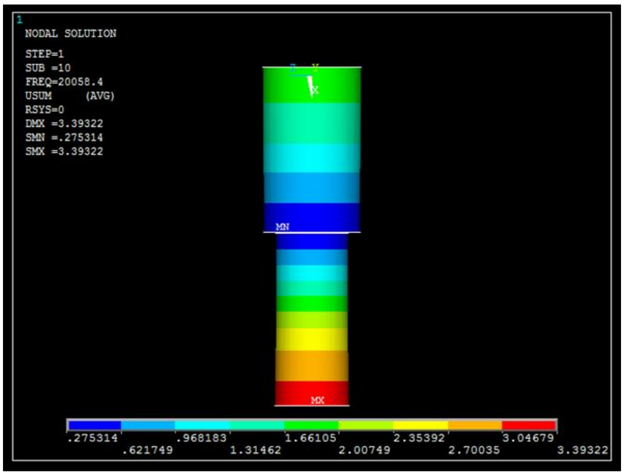


**Fig. 10. Determination of displacement along the step type probe by computer**

As shown in Fig. 11, the maximum value of stress is occurred at the surface variation location. The variation trend of stress along the probe indicates the compatibility of Fig. (7) with Fig. (11). It should be noted that Fig. (7) and Fig. (11) are obtained from calculations and computer software analysis, respectively. As a result of modal analysis, the natural frequency of the computer-designed probe was equal to 20.06 kHz which was close to the working frequency of the probe. This shows the compatibility of calculation method with computer solution method.

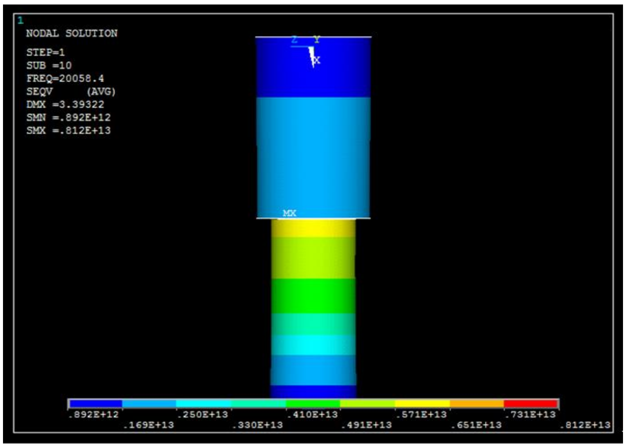


**Fig. 11- The von Mises stress along the step type probe obtained by computer**

## 9. Conclusion

- For both of the cylindrical and step type probes, the length of the designed probe is half of the ultrasonic wavelength.
- Although the probe material does not affect vibration amplitude, it can affect stress distribution along the probe.
- In the cylindrical type probe, the maximum stress was in the middle of the probe, whilst in the step type probe, it was in the surface variation location.
- To design a probe, the maximum created stress in the probe should not exceed the yield stress of the selected material.
- Probe density affects the weight of the probe which may influence the vibration of the probe caused by piezoelectric vibrative forces.
- The different methods used for designing ultrasonic probe had not significant difference.

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