Modeling of Ultrasonic Fatigue-Life Testing Machine

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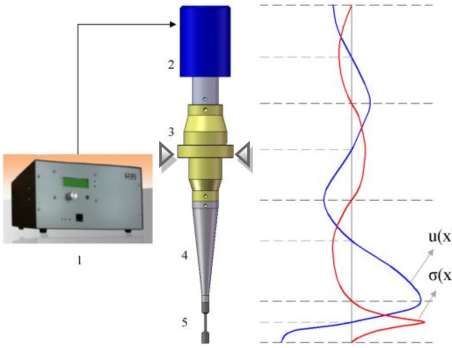
Abstract: Usually fatigue-life tests of materials are long, time-consuming and expensive. With the development of high power piezoceramic actuators nowadays it is possible to provide at very high cycles 10e10 fatigue tests (VHCF) for reasonable times, at high frequency. The ultrasonic fatigue machine consists of piezoceramic transducer, booster, horn and specimen made of tested material. System works in axial resonant regime. The most used working frequency is 20kHz due to some limitation of minimal specimen length. The response of ultrasonic system is modeled, using Structural Mechanic and Piezoelectric interfaces in the following sequence. First eigenfrequencies of the system are determined, second displacement amplitudes and stress distribution in frequency domain. Determined eigenfrequency is similar to the experimental, if a proper values (experimentally determined) of material constants is used.

Keywords: eigenfrequency, piezoceramic actuator, ultrasonic, VHCF.

1. Introduction

Usually fatigue-life tests of materials are time-consuming and expensive. The classic fatigue test equipment has some operational restrictions of frequency due to the technology used in the design of those machines. Due to this issue the number of testing cycles was generally limited to 10e6 or 10e7, called "endurance limit". With the development and improvement of high power piezoceramic actuators it is possible to provide fatigue tests at very high frequencies. Nowadays, ultrasonic fatigue testing machines with working frequency 20kHz are used to perform materials testing in the range of 10e7 to 10e10 fatigue cycles (the so called very high cycle fatigue VHCF)[1]. Scheme of typical ultrasonic fatigue machine is shown on **fig.1.**

The ultrasonic machine consists of a piezoceramic actuator (transducer), a booster for support, a horn (sonotrode) for amplifying the displacement amplitude and a specimen, made of the tested material.



1-generator, 2-piezoceramic actuator, 3-booster, 4-horn, 5-tested specimen

Figure 1. Ultrasonic fatigue testing machine

System works in axial mode resonant frequency. It is designed to produce high amplitude stresses in the middle point of the specimen (specimen is designed with stress concentrator). Stresses σ(x) are proportional to displacements u(x) (Equ.1).

(Equ.1) $$\varepsilon(x) = \frac{du}{dx} \quad , \quad \sigma(x) = E.\varepsilon(x)$$

,where $\varepsilon(x)$ is strain function, E is Young's modulus.

Displacement amplitudes are regulated by generator through controlling the voltage in the piezoceramic. The main purpose of this study is to model the relation between the actuator power, the displacement amplitudes and the stresses in the specimen.

2. Ultrasonic Machine

Commercially available for ultrasonic welding, a generator, an actuator and a booster, designed and produced by MPIntreconsulting – Switzerland, are used [2]. The generator is 1kW. The actuator is a high power (up to 3kW) sandwich type piezoceramic transducer, consisting of: 6 piezoceramic disks (PZT8) with 5mm thickness each, stacked mechanically in series, electrically in parallel; a backing mass (stainless steel 316L), a matching mass (Al 7075-T6); a central bolt (steel) for pre-stress. According to the producer the maximum displacement amplitude is 10µm. The booster (Ti-6Al-4V) is with an amplification factor 1:1.5 (gold), in and out diameters 50mm and 38mm.

The horn (sonotrode) is a unique element for each application. For this machine we designed Al 7075-T6 conical shape sonotrode with a length of 149.5mm and an amplification factor of about 3.37 (in diameter 38mm out diameter 10mm). The sonotrode was machined in our workshop.

The steel test specimen is designed without stress concentrator (cylindrical shape d=10mm, L=126mm).

The elements are connected by threaded studs (½'' 20UNF) between the transducer booster and the booster sonotrode. The specimen is machined with threaded end and screwed to the sonotrode.

3. COMSOL Multiphysics Model

For modal (eigenfrequency study) and harmonic frequency response (frequency domain study) analysis Comsol 4.2a Structural Mechanics Module was used. Piezoelectric Devices (pzd) physics, combining electrical and structural boundary conditions, was applied. [3]

Geometry was drawn in 2D-axisymmetric space due to the axial symmetry of the machine.

The material properties of the metal parts are given in **tabl.1**. For the piezoceramic discs material PZT8 build-in properties were used.

Table 1: Materials properties

Part	E, GPa	ρ, kg/m^3	ν
Back mass ss 316L	194	7962	0.29
Matching mass, Al 7075-T6	71.14	2720	0.33
Sonotrode Al 7075-T6	71	2811	0.33
Booster Ti-6Al-4V	110	4430	0.39
Bolt and studs Steel 1	205	7850	0.28
Test specimen Steel 2	204	7850	0.3

"Linear elastic material model" for metal parts and "Piezoelectric material model" for piezoceramic was applied [4]. Internal dumping was ignored for simplicity, although at resonance frequency the displacement amplitudes can be affected. Electrical boundary conditions, Electric potential and Ground were applied on each side of piesoceramic discs, **fig.2**. The construction was fixed, using Fixed constrain boundary condition at nodal point of the booster, **fig.2**. Default meshing was used.

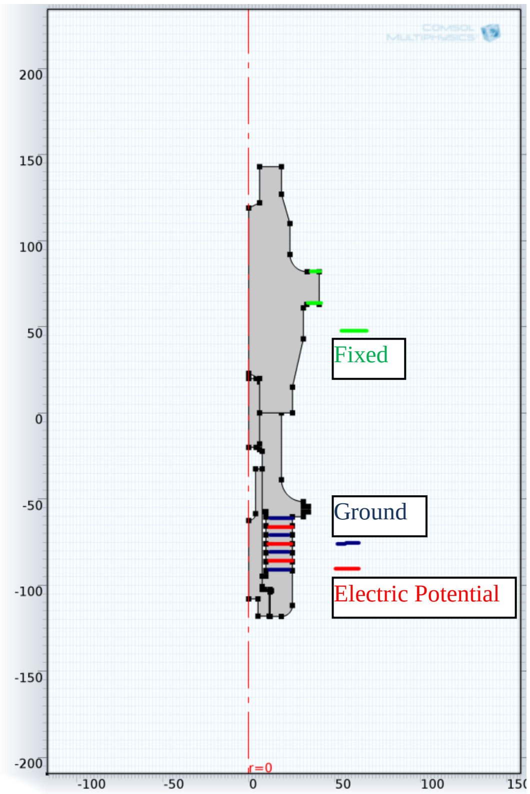


Figure 2. Geometry (transducer+booster) and boundary conditions

To monitor the displacement amplitudes 4 boundary probes were set - the first probe at the end surface of the transducer, the second one at the end surface of the booster, the third and the fourth ones at the end surfaces of the sonotrode and specimen respectively. The last probe is only for verification purpose since the specimen is a symmetrical element and the displacement amplitudes of its ends have to be equal, **fig.1**.

4. Results and Discussion

4.1 Eigenfrequency study

Eigenfrequences are dependent on the material properties (E, ρ, ν). Especially Young's modulus (E) which can vary ±5% for different pieces from one and the same material [5]. Since the transducer and the booster are delivered, we don't know the exact values of the material properties. So we slightly change these values to adjust the eigenfrequency of transducer+booster assembly to be similar to the experimental one. Young's modulus and density of sonotrode and specimen materials are determined experimentally. All material properties are given in **tabl.1.**

For this study the electric potential was set to zero (Vo=0). Determined by the model frequency of the axial vibration mode, is 20158Hz, slightly different from the experimental frequency (20180Hz). The mode shape is shown on **fig.3**. All nodal points are clearly visible.

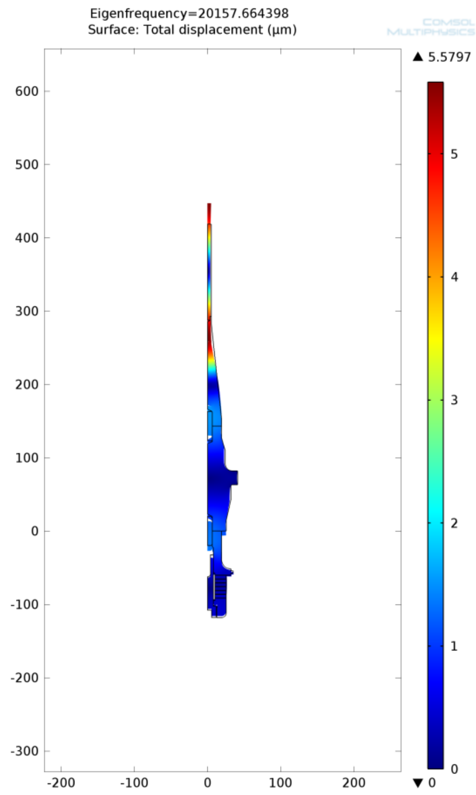


Figure 3. Axial mode shape at 20158Hz.

4.2 Frequency Domain Study

For this study a frequency range around eigenfrequency was set. The electric potential (Vo) varies in order to set the required displacement amplitude. Since the generator can control effectively the amplitude in the range 30 -70%, the electric potential was set by the trial and error method to produce displacement amplitude 3-7µm at the transducer (boundary probe 1). Displacement amplitudes in function of frequency at Vo=110V is shown on **fig.4**. Von Mises stresses at frequency 20158 and Vo=110V is shown on **fig.5** The electric potential and maximum stresses at 3 and 7µm displacement amplitude of the transducer are summarized in **tabl.2.**

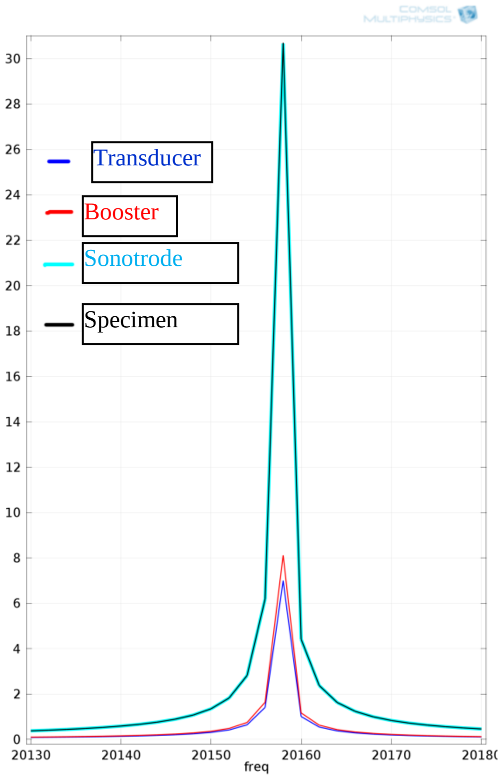


Figure 4. Displacement amplitude (z-direction) Vo=110V

As it is expected the displacement amplitudes at each end of the specimen are equal. Surprisingly, the booster is not giving the required amplification (1.5), and the sonotrode amplification factor is 31/8=3.88, which is higher than the projected value (3.37), **fig.4**.

The maximum stresses in each element are found as expected in the nodal points. For specimen maximum stress is 156MPa. For other elements safe maximum stresses are found – for sonotrode around 28MPa and around 10MPa for piezoceramic discs, **fig.5**.

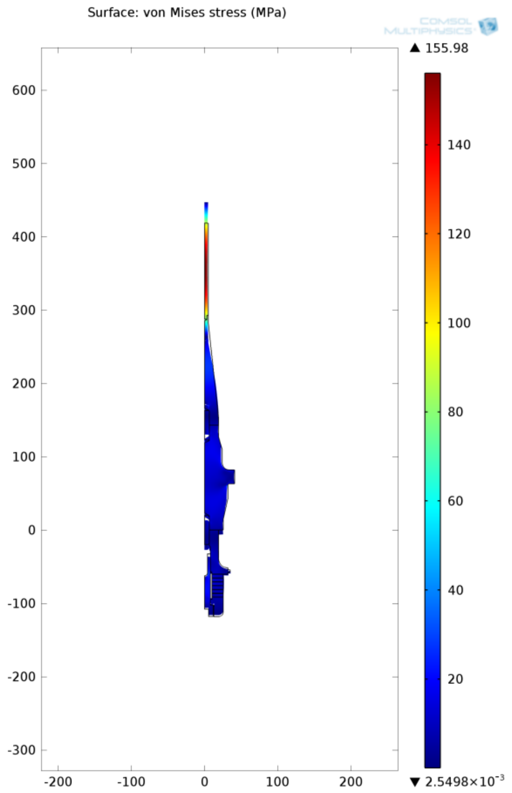


Figure 5. Von Mises stress distribution, Vo=110V , f=20158Hz

Table 2:, Actuating voltages and stress in specimen at min and max displacement amplitudes.

Displacement amplitude, µm			Vo, V	σ_{max} MPa
transducer	booster	sonotrode /specimen		
3	3.5	13.5	49	69.5
7	8	31	110	156

As it can be seen, **tabl.2**, stresses in the range of 69.5-156MPa can be effectively created. For most materials these stresses are not enough and a specimen with stress concentrator has to be used.

5. Conclusions

Eigenfrequency and frequency response of ultrasonic fatigue machine is modeled, using COMSOL Multiphysics – Piezoelectric Devices physics, which gives an opportunity to solve electrical and structural equations.

The determined eigenfrecuency shows good coupling with experimental results, but it has to be mentioned that the precise measurement of material constants (especially Young's modulus) is needed.

The harmonic frequency analysis gives the opportunity to predict displacement amplitudes and stresses in the tested specimen. Specimens from different materials with/without different stress concentrators can be designed and checked.

6. References

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Acknowledgements

The authors gratefully acknowledge financial support from Bulgarian Scientific Research Fund, through the project DMU03/98