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Effect of different standoff distance and driving current on transducer during ultrasonic cavitation peening☆

Fushi Bai*, Kai-Alexander Saalbach, Jens Twiefel, Jörg Wallaschek

Institute of Dynamics and Vibration Research, Leibniz Universität Hannover, Appelstr. 11, Hannover 30167, Germany

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ABSTRACT

Ultrasonic cavitation peening is a potential technique in the field of mechanical surface treatment. Owing to the collapses of cavitation bubbles, it generates high impacting pressures on peening surface whose reliability will be enhanced. However, the cavitation phenomena between horn tip and workpiece surface are highly nonlinear so that the piezoelectric transducer is subjected to tough operational condition. In this work, the influences of different standoff distances and vibration amplitudes on the transducer electrical impedance and resonance frequency are investigated both theoretically and experimentally. The results indicate that the changing of the resonance frequency is small at a standoff distance of ~1 mm. The electrical impedance of the transducer remains stable for high driving current.

1. Introduction

Manufacturing processes such as turning, milling, drilling, grinding and welding can cause detrimental effect to metal surface characteristics. Ultrasonic cavitation peeing innovated in the 1990s can effectively enhance the surface properties. Furthermore, it can be used for surface treatment of highly stressed components, e.g. axles of trains, gears, shafts of cars, aircrafts, etc., which suffer from cyclic loads [1].

Ultrasonic cavitation peening takes the advantage of the incubation period of material erosion. In general, the material erosion induced by cavitation bubbles follows four successive stages [2]: incubation period, acceleration period, deceleration period and steady-state period. During the first short incubation period, mass loss is negligible while much plastic deformation is generated. As the process time goes to the last three stages, the mass loss becomes significant, which is not desired. As a result, ultrasonic cavitation peening is only applied in the incubation period to achieve compressive residual stresses while no obvious mass loss occurs. This is beneficial to surface characteristics and fatigue properties. Although ultrasonic cavitation peening causes surface compressive residual stress in the same way as traditional shot peening, it enhances surface hardness without significantly increasing the surface roughness [3]. Ultrasonic cavitation peening is also a green process, as it does not require any use of shot, but only liquids.

In recent years, the ultrasonic cavitation peening technology has been studied by many researchers. Sriraman et al. [4] studied the residual stress variations in AISI 304 stainless steel samples caused by ultrasonic cavitation in water. It was found that residual stresses with appreciable values can be generated by ultrasonic cavitation peening under the investigated conditions. Nakagawa et al. [5] measured the residual stress distribution on the stainless steel workpiece surface treated by ultrasonic cavitation peening using a block type horn. Mathias et al. [6] explored the effects of ultrasonic cavitation on residual stress, texture, material loss, lattice distortion, and microhardness for AISI 4140 and AISI 1045 steels. Toh and Liu [7,8] have explored that ultrasonic cavitation peening induces compressive residual stresses on Stavax stainless steel for the purpose of decreasing/eliminating burr formation or debarring, where the peening induced residual stress has also been measured. Gao et al. [9,10] observed and measured the surface hardness, profile, and roughness for workpieces treated by ultrasonic cavitation peening with different horn vibration amplitudes. The workpiece surface morphology and the microhardness variation at different workpiece depths were studied as well. Furthermore, Gao et al. also developed a 2D model for focusing ultrasound propagation in water towards a solid target. Sasaki et al. [11] discussed the influence of cavitation peening on various factors related to the fatigue property of cold-rolled stainless-steel sheet with 0.1 mm thickness.

During ultrasonic cavitation peening the tip of the transducer is partly immersed in the fluid. The resonance frequency of a transducer is sensitive to the fluid density. And it was found that the resonance frequency becomes smaller as the fluid density increases

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* Corresponding author.
E-mail address: bai@ids.uni-hannover.de (F. Bai).

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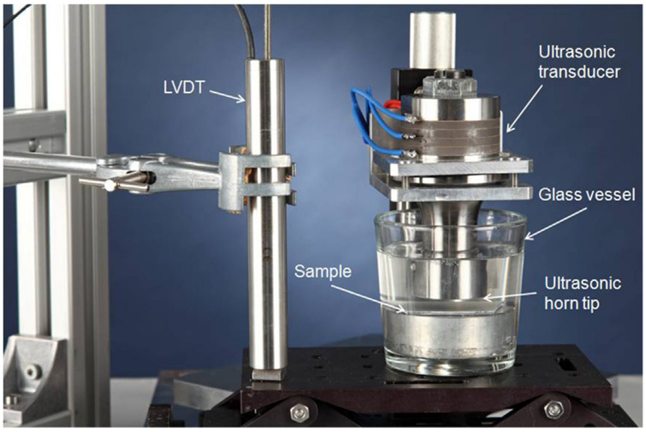

Fig. 1. Experimental setup.

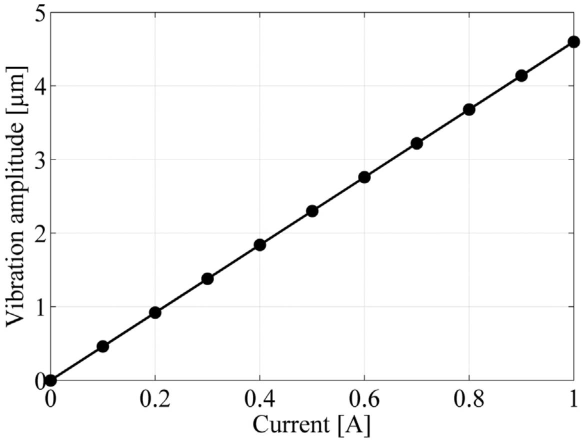

Fig. 2. Dependence of displacement amplitude at horn tip on transducer driving current (measurement).

[12]. The resonance frequency was also tested in the air and in liquid, respectively. Those experimental results showed that the resonance frequency in liquid is lower than that in the air [13,14]. After applying a complex load on a transducer, the transducer electrical impedance (the ratio of the driving voltage to the corresponding current) decreases when the complex load increases [15]. Regarding to transducer in cavitation liquid, D. Samah et al. reported that the transducer electrical impedance decreases with increasing cavitation activity [16]. Saalbach et al. [17] used a transducer with novel geometry to detect cavitation. They found that at a low driving current an increase in amplitude results in a drop in resonance frequency. For higher current values, however, the resonance frequency increases

Until now, little attention has been paid to the influence of driving current and standoff distance on electrical impedance and resonance frequency of a piezoelectric transducer in cavitation liquid. The standoff distance, which is a key parameter of ultrasonic cavitation peening, is defined as the gap width between the horn tip and the treated surface of workpiece. Cavitation is a complex and highly nonlinear process, which disturbs the operational condition of the transducer due to the changing of load conditions. Therefore the analysis of the changes of the ultrasound transducer electrical impedance and resonance frequency is beneficial for deep investigation of ultrasonic cavitation peening. In the following sections, the model of load impedance (the ratio of a loading force to the velocity) applied on the transducer and attenuation which are used to exploit the influence of cavitation bubbles in the case of ultrasonic caviation peening will first be described. Experiments will then be conducted to validate the theoretical models.

2. Experimental setup

Fig. 1 shows the experimental setup for investigating the relationship between standoff distance, resonance frequency and transducer electrical impedance. A glass vessel is put on a lifting table. The transducer used here is a classical sandwich transducer designed and manufactured at Institute of Dynamics and Vibration Research. It is composed of titanium alloy tail-mass, four PZT piezoelectric ceramics and a head mass in titanium alloy. A titanium screw is used to assemble and pre-stress the transducer. The transducer with a λ/2 mode which is free on the upper side is driven at its first longitudinal resonance frequency at 22.3 kHz. The diameter of the tip end is 28 mm. The transducer was driven in resonance by a self-developed digital phase control unit (IDS Digital-Phase Control 500/100k) [18] with a power amplifier QSC 4050. Both phase feedback and current feedback control are applied for the investigations. The ultrasonic horn is partly submerged in water. The distance between water surface and the tip end of the horn always keeps as 10 mm. The changes of standoff distances are measured by a linear variable differential transformer sensor. In Experiment, the detection of amplitude and phase information between the driving signals current and voltage is obtained using phase sensitive demodulation (PSD). This information is further used to retain the system in resonance all over the time by a PID-controller [19]. This hardware was also used to determine the steady state transducer electrical impedance which means the absolute ratio of voltage to current.

In resonance the displacement amplitude $\hat{X}$ is proportional to the current amplitude $\hat{\imath}$ [20]. For this measurement a relationship of approximately 4.6 µm/A could be determined which can be seen in Fig. 2. The vibration amplitudes at the center of the horn tip were measured in the center of the horn tip by a one point 3D vibrometer (Polytec CLV 3000). The curren loop control can keep the driving current steady with various loading. A current probe (Tektronix P6021) was used to get the current values.

During the experiments, the standoff distance was varied between 0.1 mm and 5 mm which is much less than the wave length in water with cavitation. The resonance frequency and the transducer electrical impedance were recorded for 30s. The initial temperature of the water used was 22 °C. Moreover, in order to minimize the influence of the temperature, the water in the glass vessel was replaced for each measurement.

3. Results and discussion

Because of the nonlinear characteristics of cavitation, the liquid load on the horn tip is various, which has significantly influences on the transducer electrical impedance and resonance frequency of the transducer. Hence, to avoid challenges of electrical control, it is necessary to find an optimal driving current and standoff distance for ultrasonic cavitation peening. Fig. 3 illustrates the equivalent circuit of a resonant driven transducer with loading. In the electrical part, C_p, U and i represent capacitance, driving voltage and current, respectively. In the mechanical part, d, c, m and V means modal damping, stiffness, mass and the velocity of the transducer tip, respectively. It is assumed that the liquid load impedance Z_L on the horn tip mainly consists of two parts: the normal impedance Z_N on the flat end of the horn and the tangential impedance Z_T surrounding the horn tip. Neglecting ageing phenomena, the transducer mechanical impedance, which is an intrinsic property of the transducer, is fixed once the transducer is assembled. When a transducer is driven exactly in its mechanical resonance frequency, the impedances resulting from c and m are offsetting each other. In