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Effects of driving frequency of longitudinal transducer on the vibration characteristics of a stepped plate

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ABSTRACT

The flexural vibration characteristics of a stepped plate, driven at its center by different frequency of longitudinal transducer with a certain area are investigated. The variation in the nodal circle, fundamental frequency and displacement distribution of the stepped plate are calculated by using finite element method (FEM) under different driving frequencies. The results show that the fundamental frequency and nodal circle of the flexural-vibration stepped plate (FVSP) increase with an increase in the driving frequency of the longitudinal vibration ultrasonic transducer (LVUT), before the second-order flexural vibration occurs. When the driving frequency is $f = 28$ kHz, the displacement amplitude of the stepped plate can achieve the maximum, and the nodal circle radius of the stepped plate is 2.61 cm which fits evenly the edge of stepped profile. Meanwhile, the directivity and radiation efficiency of the FVSP would be greatly improved in a special driving frequency. The conclusions agree with the experimental ones and are significant for both design and applications of the stepped plate.

Introduction

In general, the longitudinal–flexural vibration ultrasonic transducer system is basically constituted of an extensive flexural vibration radiator and a high-power longitudinal vibration ultrasonic transducer. This high-power longitudinal-flexural vibration ultrasonic transducer system is widely applied in many industries, such as atomization, washing, cleaning, plastic and metal welding [1–4]. In order to compensate the zones vibrating in counter phase properly and to control the acoustic radiation field effectively, a stepped profile is designed instead of the in-plane plate in practical application [5–7]. The height of the stepped profile is equal to the half-wavelength of the acoustic wave propagating in it. In such way, this longitudinal-flexural vibration ultrasonic transducer system has comprehensive characteristics with both high power efficiency of a longitudinal vibration ultrasonic transducer (LVUT) and large radiation area of a flexural vibration stepped plate (FVSP). The vibration system has been investigated based on the classical plate theory and improved Mindlin plate theory, in particular to the flexural vibration characteristics of a circular plate [8–10].

The relationship between the shape and dimension of radiator and the resonant frequency of ultrasonic transducer was analyzed by Feng et al. [11]. Ideally, to achieve the best working conditions of longitudinal-flexural vibration transducer system, the resonant frequency of the LVUT should be equal to that of the FVSP [2,5,6]. However, in high-power practical applications, some factors, such as temperature, stiffness, load, tool wear, parts of the installation and other variables, always may cause degradation of the nodal circle of the FVSP and drift of the natural frequency of the longitudinal-flexural vibration transducer system [12–14]. Once the LVUT and FVSP have a different resonant frequency, the efficiency of the longitudinal-flexural vibration transducer system would decrease. Besides, the frequency characteristics and acoustic radiation field of the FVSP would change accordingly, and also the equipment would be subjected to damage seriously [13,14]. Wang [15] improved various frequency tracking, such as maximum current, power, admittance and phase. A high power resonance tracking ultrasonics amplifier was described [16]. The geometry and size of the radiator plate and the performance of the LVUT have a great influence on the acoustic field distribution [17]. Moreover, they are critical to the development of the practical system.

In this paper, the design of stepped profile and the relationship between the vibration characteristics of the FVSP and the driving frequency of the LVUT are studied with interest. An extensive FVSP is driven at its center by a piezoelectric ceramics LVUT. The flexural vibration characteristics of the FVSP driven by the LVUT with a certain area and different operating frequencies are investigated by using finite element software ANSYS. Subsequently, the fundamental frequency, nodal circle and displacement distribution of the FVSP with different driving frequency of the LVUT are examined. A special driving frequency, in which the nodal circle of the FVSP

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is proper for best working conditions of the longitudinal-flexural vibration ultrasonic transducer system, is obtained successfully. Finally, the numerical results are verified by experiments.

1. Transducer structure system

1.1. Design of the flexural vibration stepped plate

The cross-section of the FVSP is designed and shown in Fig. 1. The vibration characteristic of the FVSP is governed by the small-deflections of the thin plate theory, omitting the effects of the rotary inertia and shear force. We mark the inner region ① by subscript 1 and the outer region ② by subscript 2. For regions ① and ② the governing equation is

$$\nabla^4 y_1 - k^4 y_1 + \alpha^4 y_1 = 0 \tag{1}$$

$$\nabla^4 y_2 - k^4 y_2 = 0 \tag{2}$$

here all lengths are normalized by r_1, $k^4 \equiv r_1^4 \omega^2 \rho / D$ is a parameter representing the frequency ω, and $\alpha^4 \equiv r_1^4 K/D$ represents the stiffness K of the plate. If $k > \alpha$, the general solutions [5,7] of the differential equation of FVSP are

$$y_1(r) = [A_1 J_0(k_1 r) + C_1 I_0(k_1 r)] \exp(j\omega t) \quad (0 \leqslant r \leqslant r_1) \tag{3}$$

$$y_2(r) = [A_2 J_0(k_2 r) + B_2 Y_0(k_2 r) + C_2 I_0(k_2 r) + F_2 K_0(k_2 r)] \exp(j\omega t) \quad (r_1 \leqslant r \leqslant a) \tag{4}$$

where, functions J_0, Y_0 indicate the zero-order Bessel functions of the first and second kind, I_0, K_0 indicate the zero-order modified Bessel functions of the first and second kind, and $\omega = 2\pi f$ is the angular frequency, h_1 represents the middle thickness of the FVSP (zone ①), h_2 represents the annular thickness of the FVSP (zone ②), $k_1 = \sqrt[4]{\omega^2 \frac{12\rho(1-\sigma^2)}{Eh_1^2}}$, $k_2 = \sqrt[4]{\omega^2 \frac{12\rho(1-\sigma^2)}{Eh_2^2}}$ are the wave number of the zone (①) and the zone (②), respectively, and here, D, ρ, E, σ are the flexural rigidity, density, Young's modulus and Poisson's ratio of the stepped plate, respectively (considering isotropic, homogeneous and perfectly elastic).

The coefficients A_1, C_1, and A_2, B_2, C_2, F_2 must be chosen to satisfy the continuity conditions and boundary conditions at $r = r_1$ and at $r = a$:

$$y_1(r_1) = y_2(r_1) \tag{5a}$$

$$\frac{dy_1(r_1)}{dr} = \frac{dy_2(r_1)}{dr} \tag{5b}$$

$$Q_1(r_1) = Q_2(r_1) \tag{5c}$$

$$M_{R_1}(r_1) = M_{R_2}(r_1) \tag{5d}$$

$$Q_2(a) = 0 \tag{6a}$$

$$M_{R_2}(a) = 0 \tag{6b}$$

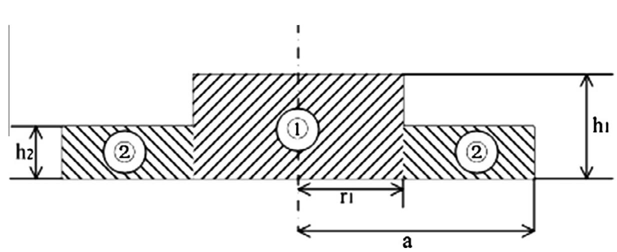

Fig. 1. Structural model of the stepped plate.

where shear force

$$Q = D\frac{d}{d\rho}\left(\frac{d^2y}{d\rho^2} + \frac{1}{\rho}\frac{dy}{d\rho}\right)$$

bending moment

$$M_R = -D\left(\frac{d^2y}{d\rho^2} + \frac{\sigma}{\rho}\frac{dy}{d\rho}\right)$$

If Eqs. (3)–(4) are introduced into the continuity boundary conditions Eqs. (5)–(6), a set of six homogeneous equations are obtained. For a non-trivial solution, the characteristic determinant of the equations must be zero. This condition leads to the frequency equation, which can be solved by using computer program.

In this study, the material of the FVSP is chosen for 45 steel, density $\rho = 7.8 \times 10^3$ kg/m^3, Young's modulus $E = 2.16 \times 10^{11}$ N/m^2, Poisson's ratio $\sigma = 0.28$, the eigenfrequency $f = 20$ kHz, the annular thickness $h_2 = 0.5$ cm. The parameters of the FVSP are obtained by programming, including the thickness $h_1 = 1.3$ cm, the stepped radius $r_1 = 2.61$ cm, and the radius of the FVSP $a = 3.82$ cm. The ratio of the thickness to surface size of the FVSP is $h_1/2a = 0.17 < 1/5$, which is available to the suitability range of the thin plate theory.

The stepped radius r_1 of stepped profile is designed to compensate the zones vibrating in counter phase and to control acoustic radiation field, and the stepped height $h_1 - h_2$ of stepped profile is equal to the half-wavelength of the acoustic wave propagating in it.

1.2. Longitudinal vibration transducer

FVSP is connected with the piezoelectric ceramic LVUT through a solid horn. An extensive FVSP is driven at its center by the LVUT, which has frequency range approximately from 10 kHz to 60 kHz. The structure configuration of the LVUT can be seen in the reference Ref. [18], where there is description in more detail.

2. Vibration characteristics of the stepped plate with driving frequency

The longitudinal-flexural vibration transducer system basically consists of the FVSP and LVUT. The FVSP and LVUT are modeled as a continuous structure. The finite element model of the longitudinal-flexural vibration transducer system is shown in Fig. 2. The vibration characteristics of the global structure are simulated numerically. The fundamental resonant frequency, nodal circle

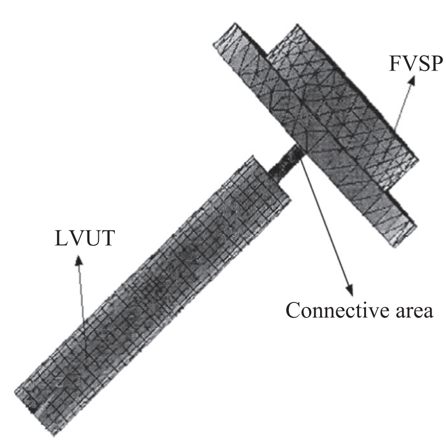

Fig. 2. The finite element model of the longitudinal-flexural vibration transducer system.