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Optimal working frequency of ultrasonic motors

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ABSTRACT

In this work, the existence of the optimal working frequency for ultrasonic motors (USMs) is theoretically and experimentally verified for the first time, at which working point the power dissipation of the motors arrives at its minimum value. The mathematical model of the mechanical quality factor is initially deduced to evaluate the loss level, because it shows an opposite tendency with losses. The derivative of the mechanical quality factor can be subsequently arrived at with the aid of the phenomenon model of the phase of the admittance. The theoretical derivation infers that the maximum value of the mechanical quality factor exists almost around the average value of the frequency of maximum conductance and the frequency of maximum resistance. Then the input power of the USM is measured under the constant velocity condition, which is supposed to counteract the loss; that is, the loss can be therefore evaluated experimentally. Measurements infer that the power dissipation of the motor reaches the minimum value around the calculated optimal working frequency. In other word, it is proven that the USM maintains an optimal working frequency from the loss reduction view point.

1. Introduction

Ultrasonic motors (USMs) usually pursue more stable performance, which is restricted by the heat generation due to losses in those devices [1]. The mechanical quality factor is then applied to evaluate loss level, because it has an opposite tendency with losses [2,3]; that is, the larger mechanical quality factor is, the smaller losses the USMs maintain. Traditional USMs used to be driven at the resonance frequency to easily obtain sufficient vibration amplitude because the motors approximately maintain the largest admittance at the resonance point [4–6]. A larger mechanical quality factor discovered at the antiresonance point therefore infers a superior working frequency to the resonance frequency from the loss reduction viewpoint [3]. Only mechanical quality factors at the resonance and the antiresonance frequencies, however, have been sufficiently studied by then [7,8]; a more competitive working frequency has been recently discovered due to new methods to determine the mechanical quality factor [9,10], at which point the mechanical quality factor arrives at the maximum value. The USMs theoretically benefit from applying the new working frequency, which will maintain less losses and subsequently more stable performance. The existence of the new working frequency has been fully verified by both theoretical derivations and experimental measurements [9,10], however, only based on piezoelectric materials.

In this work, the optimal working frequency of the USM will be theoretically and experimentally investigated. The analytical model of the mechanical quality factor of the motor will be initially built. The phenomenological model of the phase of the admittance will be subsequently applied to theoretically predict the ideal value of the new working frequency. Then the non-ideal factors influencing derivations of the optimal working frequency will be also analyzed, which include the parametric uncertainties of material properties and the errors of the modeling. The input power of an USM within the working bandwidth under the constant rotating speed condition will be subsequently measured to experimentally verify the existence and the superiority of the optimal working frequency.

2. Modeling of mechanical quality factor of USM

In this section, the analytical model of the mechanical quality factor of an USM, Q_m, will be deduced, whose derivation starts with the definition as follows [11]

$$Q_m = 2\pi \cdot \frac{\textit{Energy Stored}}{\textit{Energy dissipated per cycle}} = 2\pi \cdot \frac{W_U}{\int_V w_{loss} dV} = 2\pi \cdot \frac{W_T}{W_{EA}}. \quad (1)$$

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At a steady state, the maximum stored energy, W_U, and the maximum kinetic energy, W_T, reach equilibrium in an electrical cycle. As a result, $W_U = W_T$. Moreover, the active component of the electrical energy, W_{EA}, is supposed to compensate the dissipation, w_{loss}; that is, $W_{EA} = \frac{1}{2}\int_V ED \cdot \cos\varphi dV = \int_V w_{loss} dV$, is determined by the electrical field E, the charge density D, and the phase difference φ between the current and the input voltage ranging within $[-\frac{\pi}{2}, \frac{\pi}{2}]$, which is integrated in the volume of the piezoelectric materials, V. To analytically solve (1), W_T and W_{EA} should be explicitly described.

2.1. Derivations of W_T

In this paper, a rotary traveling-wave USM is taken as an example to verify the existence of the optimal working frequency of the USM. The quarter-phase input voltages have identical amplitudes and same driving frequencies; meanwhile, their phase difference is fixed as $\frac{\pi}{2}$. Locations of piezoelectric ceramics with different polarization directions inside the motor are carefully designed to efficiently force the stator to vibrate and subsequently the rotor to spin as sketched in Fig. 1 [12].

The total kinetic energy, W_T, therefore equals to the sum of the mechanical energy in the form of vibration of the stator and the rotor and the mechanical energy in the form of rotation of the rotor.

A point, O, on the neutral plane of the stator can be subsequently selected as the original point of the inertial coordinate system, Oxy, which leads to the selected shape functions $\mathbf{\Phi} = \begin{bmatrix} \phi_A \\ \phi_B \end{bmatrix} = \begin{bmatrix} \cos kx \\ \sin kx \end{bmatrix}$ [13]. The free variable x ranges within $[-\frac{n\pi}{k}, \frac{n\pi}{k}]$, where $k = \frac{2\pi}{\lambda} = \frac{n}{r}$, λ is the wave length of the traveling wave, n denotes the number of the vibrations mode, and r is the radius of the rotor. The Oxy can be then established as shown in Fig. 2, where the positive direction of Ox axis is the direction of the traveling wave movement meanwhile the positive direction of Oy axis points to the rotor. Moreover, a traveling point, O', on the Ox axis can be defined as the original point of the rotating coordinate system, $O'xy'$, which can make the distance from O to O' maintain ωt. The $O'y'$ axis is traveling with O', whose direction invariably points to the rotor. In the traveling coordinate system, the traveling wave is therefore fixed as a cosine shape explicitly independent of the time free variable as shown in Fig. 2. In Fig. 2, w_f denotes the vibration amplitude of the rotor in the Oy and Oy' direction. Meanwhile, the linear velocity of the rotor, V_R, equals to the production of the rotating speed, Ω_R, and the radius, r, which has the identical direction with the velocity of the point on the stator surface, V_S. The positive directions of V_S and V_R both point to the negative direction of Ox axis.

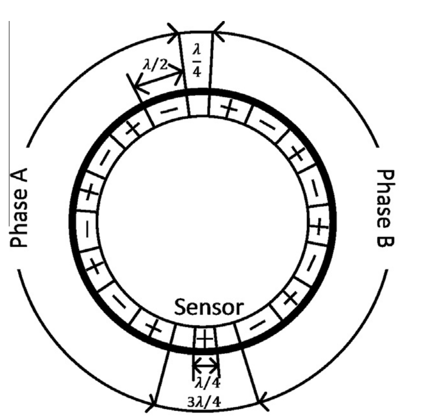

Fig. 1. Sketch of polarization directions of piezoelectric ceramics attached on stator.

In the $O'xy'$, the vibration amplitude and vibration velocity of the traveling wave on the stator can be simply described as

$$w(x) = W_0 \cos(kx), \tag{2}$$

$$V_s(x) = -\frac{h\omega W_0}{r}\cos(kx), \tag{3}$$

where the vibration amplitude of the stator, W_0, can be expressed by the mechanical modal amplitudes; that is, $W_0 = \sqrt{p_A^2 + p_B^2}$. Mechanical modal amplitudes [14] $\mathbf{p} = \begin{bmatrix} p_A \\ p_B \end{bmatrix} = \begin{bmatrix} W_0 \cos\omega t \\ W_0 \sin\omega t \end{bmatrix}$ are only related to the time free variable, where ω is the working angular frequency. h denotes the offset distance from the centerline.

The maximum value of the linear velocity of the rotor, V_{Rmax}, therefore equals to the velocity of the stator surface when $x = 0$; that is,

$$V_{Rmax} = V_s(0) = -\frac{h\omega W_0}{r} \tag{4}$$

where the linear velocity of the rotor can be subsequently described as

$$V_R = \gamma V_{Rmax} = -\gamma\frac{h\omega}{r} \cdot \sqrt{p_A^2 + p_B^2}, \tag{5}$$

where the velocity coefficient, γ, ranges within $[0, 1]$. The kinetic energy in the form of the rotation of the rotor can be then written as

$$W_{TJ} = \frac{1}{2}J\Omega_R^2 = \frac{1}{2}J \cdot \frac{\gamma^2 h^2 \omega^2}{r^4} \cdot (p_A^2 + p_B^2), \tag{6}$$

where Ω_R is the rotating speed of the rotor (the derivative of the angular displacement θ) and J denotes the rotational inertia. When reaching the steady state, γ will remain constant.

Meanwhile, the kinetic energy in the form of the vibration of the stator [14],

$$W_{TS} = \frac{1}{2}\int_V \rho \dot{u}^2 dV, \tag{7}$$

which is related to the vibration velocity of an arbitrary small volume element in the material $\dot{u}$ (the derivative of the displacement u) and the mass density ρ. Furthermore, the displacement u can be expressed by [9]

$$u = \mathbf{\Phi}_{mech}^T \cdot \mathbf{p} = \cos kx \cdot p_A + \sin kx \cdot p_B, \tag{8}$$

With the substitution of (8) into (7), W_{TS} can be rewritten as,

$$W_{TS} = \frac{n\pi M\omega^2 W_0^2}{2} = \frac{n\pi M\omega^2}{2}(p_A^2 + p_B^2), \tag{9}$$

where M is the modal mass of the stator of the USM [14], which can be calculated by $M = \int_{V_s} \mathbf{\Phi}^T \rho_s \mathbf{\Phi} dV_s + \int_{V_p} \mathbf{\Phi}^T \rho_p \mathbf{\Phi} dV_p$, V_s and V_p respectively denote the volume of substrate of the stator and the volume of the piezoelectric ceramics, ρ_s and ρ_p separately express the mass density of the substrate and the piezoelectric ceramics.

Then, the kinetic energy in the form of the vibration of the rotor can be expressed as,

$$W_{TR} = \frac{1}{2}M_R \dot{W}_R^2, \tag{10}$$

where M_R is the modal mass of the rotor, $\dot{W}_R$ is the vibration velocity of the rotor in the axial direction, which is the derivative of the vibration amplitude W_R. Further, W_{TR} is generated due to the kinetic energy in the form of the vibration of the stator. When the USM arrives at the steady state, W_{TR} can be therefore described as,