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Impact of the tribological characteristics on the dynamics of the ultrasonic piezoelectric motor

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1. Introduction

The ultrasonic motor (USM) characteristics driven by piezoelectric transducer strongly depend on the mechanical properties of the components stator, rotor and contact layer [1]. The methodology of contact zone parameters' control of USM is very important. The main tribological surface characteristics influencing the speed regularity of USM in steady regimen are macro- and micro-asperities and friction coefficient fluctuations between rotor surface and friction element. They are depend on contacting materials and its surface characteristics of the USM rotor [2]. The research show that the changes of rotor surface rigidity (in case if the contact between rotor surface and contacting element is not disturbed) and the fluctuations of diagonal impact recovering coefficient (when the contact between rotor surface and contacting element is regularly changing) have less influence on speed steadiness of USM [3, 4].

2. The synthesis of dynamic and tribological characteristics of piezoelectric motor

The research were performed at the prototype of the ultrasonic piezoelectric motor with the piezoelectric plate-shaped transducer (Fig.1a), in which the alternating strain is excited by an AC electrical field, preferably operating at the mechanical resonance frequency.

Fig. 1 presents the schemes of rotation and translation motion, which enables the diagnostics of tribological properties of USM contact zone. The diagnostic system signals correlating with tribological properties of contact zone are:

- macro- and micro-asperities of rotor surface and stochastic oscillation in contact zone arising because of friction coefficient fluctuation between rotor surface and contacting friction element which will generate electric charges in central electrode 9 because of direct piezo-effect;
- besides the electric charges in central electrode 9 (which value will correlate with the stochastic oscillation in contact zone) the longitudinal oscillation of piezoelectric plate at the oscillatory node (I form, δ_x = 0) will generate intensive electric charges of main frequency (with the lagging) which will be filtered at filter 12;
- oscillations of piezoelectric plate bending (II form) will not generate the electric charges in central measurement electrode (they will have opposite charge in bottom and upside of electrode 9 and the sum of their charges will be equal to zero).

The scheme of USM (Fig. 1, a) enables to get the interesting regimen of rotor's motion – continuous motion with rotation oscillations which is realised by the connecting electric voltages U_1 (t) and U_2 (t) to the electrodes *6, 8* and *5, 7*.

In order to excite specific rotational type oscillations within the rotor two harmonic signals (U_1 and U_2) of different frequency and amplitude are supplied to both groups of control electrodes. Signal expressions are presented in Eqs. (1) and (2) [3]:

$$U_1(t) = U_{01}\cos(\omega_1 t - \varphi_1), \quad (1)$$

$$U_2(t) = U_{02}\cos(\omega_2 t - \varphi_2), \quad (2)$$

where U_{01}, U_{02} are voltage amplitudes, ω_1, ω_2 are angular frequencies, t is time and φ_1, φ_2 are phases of harmonic signals. Here $\omega_2 > \omega_1$ and $\omega_2 - \omega_1 \ll \omega_1$.

In the presence of such conditions, the moving member (i.e. rotor) performs a periodic motion, which is defined by the following law [5]:

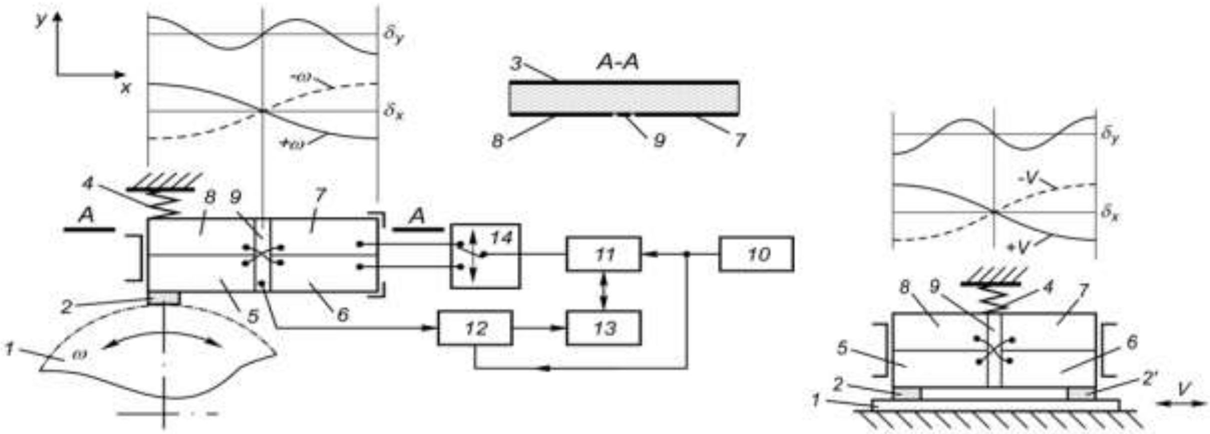
$$A = A_{max}\cos\left(\frac{\omega_2 - \omega_1}{2}t\right), \quad (3)$$

where A_{max} is the maximal amplitude and t is time of rotational type vibrations.

In this case harmonic oscillations are excited in frequency range from 0 Hz at $\omega_2 = \omega_1$, $A = A_{max}$.

The example of such rotor's rotational oscillations is displayed in Fig. 2 [5]. It presents the case when $U_1(t)$ = = $U_2(t)$, i.e. the average speed of rotor is equal to zero.

In order to determine the resonance frequency of the designed piezoelectric transducer, an impedance analyzer Wayne Kerr 6520 A (Fig. 3, a) is used to measure the impedance characteristics of the prototype, and the measurement plot of electric impedance within the measured frequencies is used (shown in Fig. 3, b).



a

b

Fig. 1 Schemes of rotation (*a*) and translation (*b*) motion, which enables the diagnostics of tribological properties of piezo-electric motors' contact zone: *1* – rotor (1b – slipper), *2* – frictional contact element, *3* – plate-form piezoelectric transducer, polarised according to the plate thickness, *4* – spring, *5, 6, 7, 8* – symmetric electrodes sectionalised by the transducer, *9* – central electrode for the measurement of electric charge, *10* – generator of harmonic signals, *11* – control unit, *12* – filter, *13* – detector/recorder

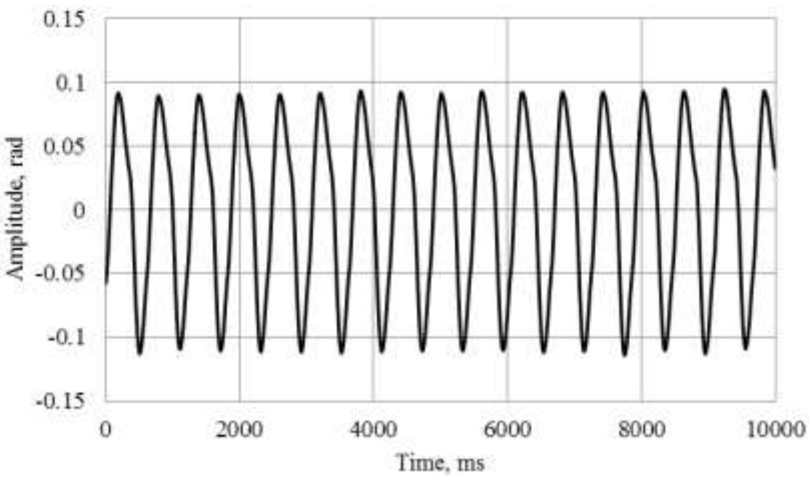
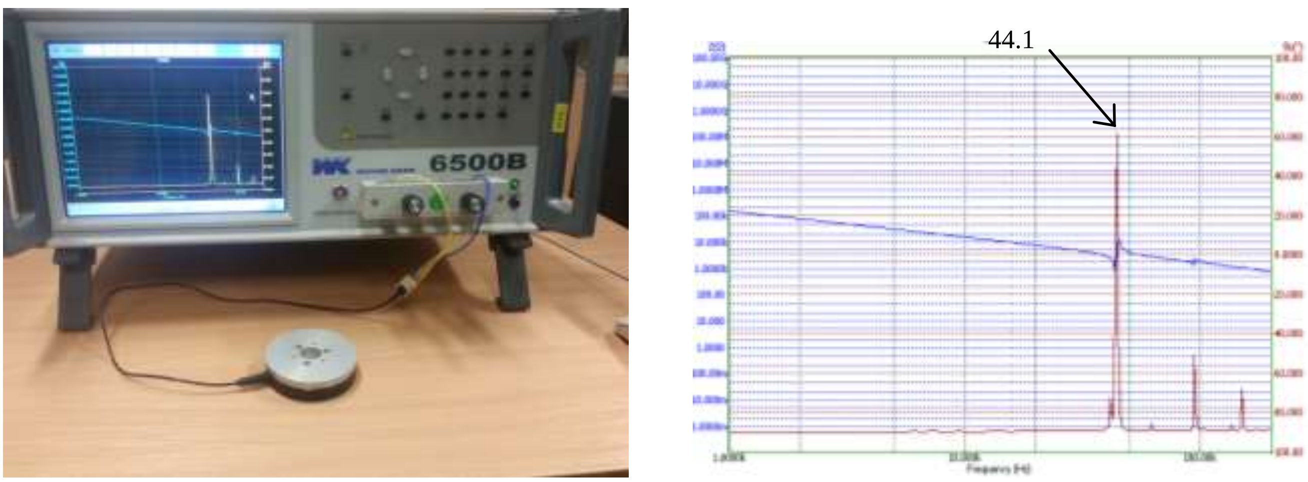


Fig. 2 Waveform of maximal oscillations of the rotor at the frequency of 2 Hz (f_1 = 44100 Hz, f^2 = 44102 Hz) and amplitude of harmonic signals voltage $U_1 = U_2 = 60$ V



a

b

Fig. 3 The measurement of the impedance (*Z*) and phase (*θ*) of the piezoelectric transducer vs. excitation frequency (operational (resonant) frequency – 44.1 kHz) with an analyser Wayne Kerr 6500B

By observing the measured impedance vs. frequency characteristic, shown in Fig. 3b, there are three resonant frequencies (around 44 kHz, 92 kHz and 132 kHz) when the impedance reaches a maximum. The operation frequency of the USM is 44.1 kHz and was determined experimentally.

The feedback synthesis between the parameters of diagnostic system and the oscillation parameters of USM transducer is realised by:

- controlling the oscillation amplitude of signals generator – it is the simplest way to regulate the rotor's speed in wide range. Fig. 4 presents the example of such control [6]. It is evident that the condition $\omega_{max}/\omega_{min}$ = 3...5; is realised easily, especially at lower loading of the rotor;
- controlling the frequency of harmonic signals which is in the operational resonance zone of USM transducer. Such example is presented in Fig. 5 [6]. This method is used less often, because the time quiescent of frequency change is usually higher than the amplitude change of the harmonic voltage;

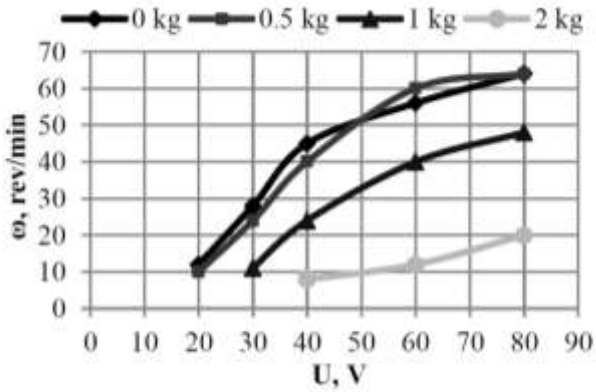


Fig. 4 Controlling of rotation speed of USM by the changing the supply voltage of harmonic signal and load of the rotor

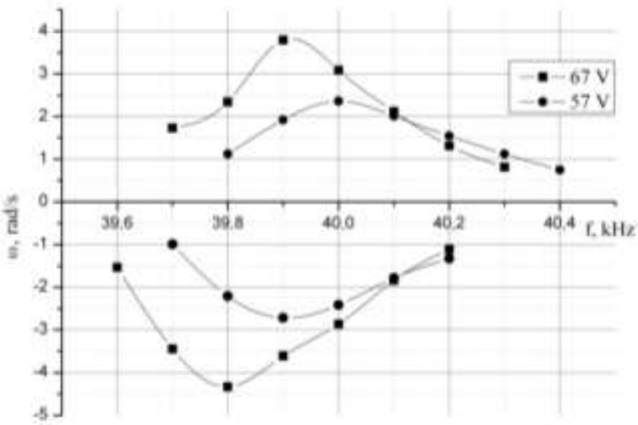
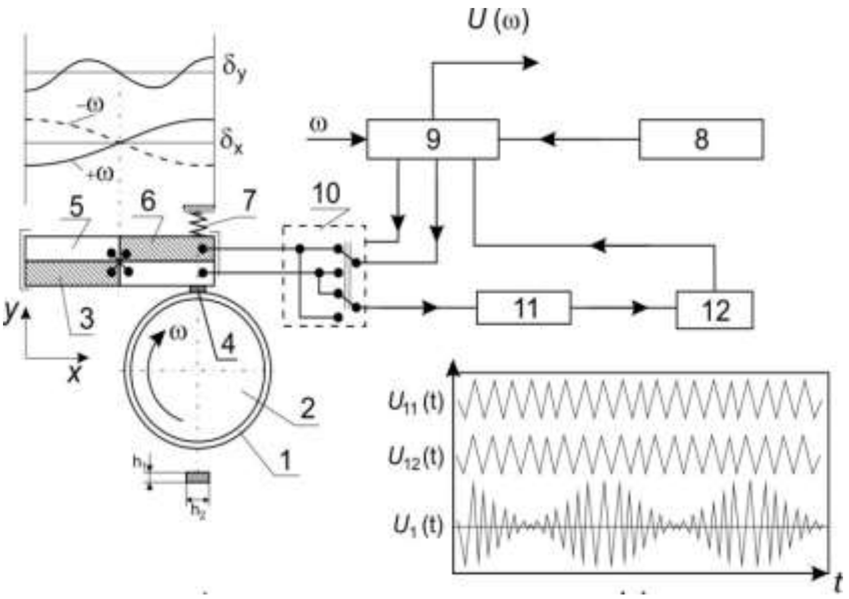


Fig. 5 Angular velocity vs. frequency feeding 57V and 67V amplitude signals

- there is the method used in piezoelectric step motors - controlling the filling coefficient of the supply impulses completed with the harmonic resonance signals;
- another method is the use of both signals of same resonance frequency $U_1(t)$ and $U_2(t)$, but changing the phase of second signal to zero. In that case (Fig. 1) only transducer's longitudinal oscillations are generated and the speed of USM is equal to zero.

3. Rotary speed stabilisation system of USM

The outside ring *1* of rotor (Fig. 6, a) should be made of the low acoustic resistance material (steel, ceramic etc.). It is mounted on internal part of rotor *2*, which is made from composite material with high acoustic resistance. Outside ring is contacting with the plate of piezoelectric transducer *3* (having the polarisation vector perpendicular to the plate) through the intermediate frictional element *4*. One electrode of piezoelectric transducer is earthed and other is divided in sectors *5* and *6*. Acoustic contact between transducer and rotor is made by the spring *7*.



a b

Fig. 6 Speed stabilisation system of piezoelectric motor (a) and superposition result $U_1(t)$ (b) of signals $U_{11}(t)$ and $U_{12}(t)$

The transducer's electrodes are connected to the electric signal generator *8* through the controller *9*. Generator's voltage $U\ cos2\pi\lambda t$ is connected to the electrodes' groups *5* and *6* through the switcher *10*, which is steered by the controller also connecting the free electrode to the and the filter of higher frequency harmonics *11*. Filtered signal pass to the detector *12*, which exit is connected to controller.

The measurements h_1 and h_2 of rotor's outside ring *1* (Fig. 6, a) should be significantly lower than the wavelength of excited oscillation (frequency λ) at the material of outside ring (for the reflection minimisation of diffusive waves).

The voltage of generator $Ucos2\pi\lambda t$ is exciting in piezo-transducer two types of oscillations because of the asymmetry of electrodes' groups: longitudinal first form oscillations (distribution of amplitudes in length δx of the plate is presented in scheme) and bending oscillations (second form, δy). There is not big difference between the resonance frequencies of both forms causing the elliptic oscillation trajectory of contact element *4* and consequently the rotor's revolution which direction decides the switcher *10*.

Complicated dynamic processes are taking place during the oscillations in contact zone (dependently on the oscillation amplitudes – from high frequency diagonal impacts to the sliding which is regularly changing friction force in contact zone) between rotor's outside ring *1* and intermediate frictional element *4*. It causes generation of harmonic oscillations of main frequency λ and higher frequencies. Because of direct piezo-effect the electric charges are excited in piezo-transducer, which are filtered in the filter *11* of λ and higher frequency harmonics.

Excited λ frequency oscillations pass also to outside ring *1* where they are channelized into two sides: clockwise and counter clockwise. When the direction of rotation speed ω is as in fig. 6a, counter clockwise in the rotating ring *1* diffused oscillations (*U11*) are reaching the contact zone with the delay and its frequency registered by the free electrodes is reduced (Doppler Effect):

$$\lambda_{11} = [V/(V + \omega R)]\ \lambda,$$

here V is sound speed in rotor's outside ring, $2R$ is diameter of outside ring.

When the oscillations are diffusing in outside ring clockwise (U_{12}) its frequency increase:

$$\lambda_{12} = [V/(V - \omega R)]\ \lambda.$$

The summary signal $U_1(t)$ after the filter *11* of λ and higher frequency harmonics is passing to detector *12* and controller *9* forms the signal $U(\omega)$, which is proportional to the rotation speed ω of frequency $f_m = |\lambda_{11} - \lambda_{12}|$. Dependently on the size of this signal, the controller *9* changes the amplitude of signal generator *8* stabilizing the rotation speed ω.

The acoustic measurement oscillations could be excited by the separate transducer enabling the extension of its frequency range and the increase of the preciseness of the measurement. Such scheme presented in Fig. 7 where the range of λ frequency could reach up to 5 MHz.

Thus using the feedback between the parameters of diagnostic system and the parameters of piezoelectric transducer oscillations there is possible to control the speed of USM at the impact of the external disturbances: temperature, wear, rheological changes of the surface etc.

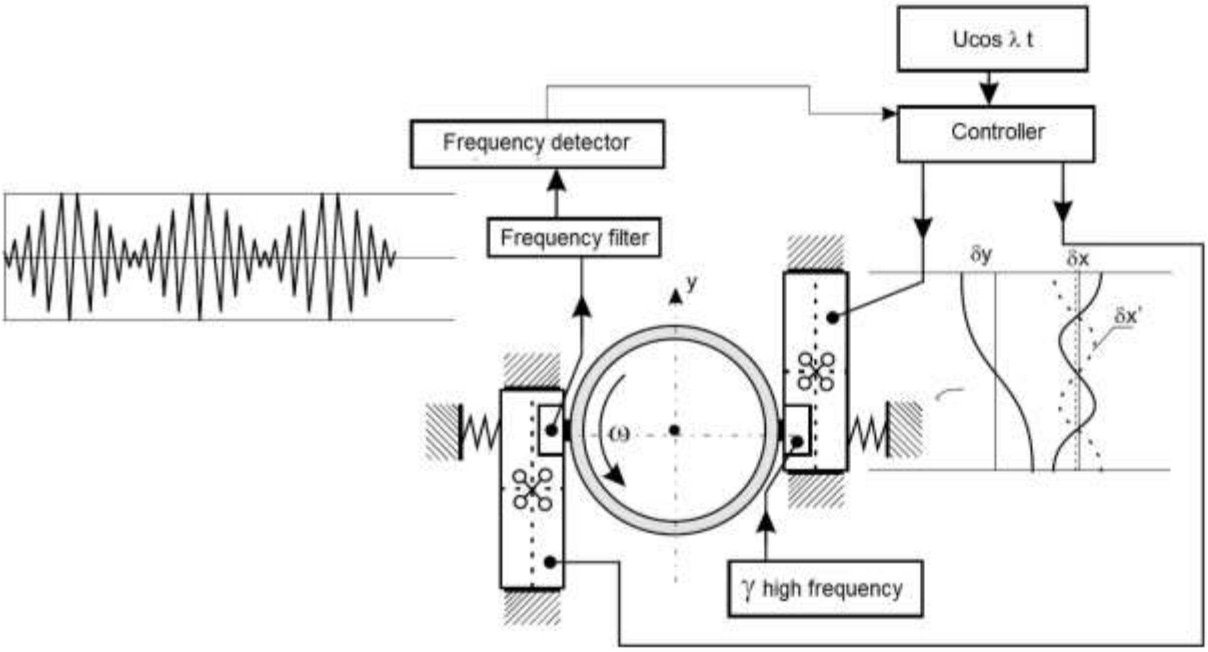


Fig.7 Modification of rotor speed stabilisation system with high frequency acoustic measurement oscillations γ .

4. Conclusions

The following conclusions on the influence of contact zone tribological parameters on the stabilisation of rotation speed of piezoelectric motors could be formed:

- created speed control schemes of rotation and translation motion piezoelectric motors allows to diagnose the tribological properties of USM contact zone;
- experimental results show the possibility to excite

the rotary low frequency oscillations at USM rotor when two ultrasonic frequency harmonic signals are supplied to the piezo-transducer;

- presented three USM schemes enable the regulation of speed control parameters of piezo-transducer: amplitude, frequency and phase;
- two rotor speed stabilisation schemes with the use of Doppler Effect were analysed.

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IMPACT OF THE TRYBOLOGYCAL CHARACTERISTICS ON THE DYNAMICS OF THE ULTRASONIC PIEZOELECTRIC MOTOR

S u m m a r y

The paper presents the methodology of tribological parameters control in the contact zone of ultrasonic piezoelectric motors. The main tribological surface characteristics influencing the speed regularity of USM in steady regimen (macro- and micro-asperities and friction coefficient fluctuations between rotor surface and friction element) were analysed. Presenting control schemes of piezoelectric motors can diagnose the tribological properties of the contact zone and stabilise the rotation speed of piezoelectric motor.

Keywords: tribology, friction, piezoelectric motor, resonant frequency, amplitude, vibrations.

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