Investigation of tribological properties in piezoelectric contact

J. Padgurskas[a], R. Bansevicius[b], A. Zunda[a], R. Rukuiza[a], A. Andriusis[a]

[a]Department of Mechanical Engineering, Aleksandras Stulginskis University
Studentu 15, Kauno raj., LT-53361, Lithuania, e-mail: juozas.padgurskas@asu.lt
[b]Mechatronics Centre for Research, Studies and Information, Kaunas University of Technology
Kęstučio g. 27, Kaunas, LT-44312, Lithuania, e-mail: ramutis.bansevicius@ktu.lt

The aim of the paper is to describe the ways to increase the reliability of the piezoelectric motors, related to tribological processes of the contact zones *piezoelectric transducer – rotor* or *slider*, in which both static forces and ultrasonic two dimensional vibrations are taking place. The problems of frictional wear are dealt with introducing and realizing the concept of adaptive tribological pair with optimal rheological parameters of components, enabling to effect self-diagnostics of the pair by exploiting direct piezoelectric effect of already existing piezoelectric transducers. This will allow for the forecast of durability and its significant increase when using new advanced materials (including nanoparticles). Some results of experiments are given, including correlation of diagnostic signals with the parameters of wear.

Keywords: ultrasonic motor, travelling wave, tribological properties, reliability of contact zone, piezoelectric transducer.

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INTRODUCTION

According to market research reports piezoelectric motors offer a high potential for miniaturization, produce no magnetic fields and through their specific advantages compared to conventional electromagnetic motors, fill a gap in certain actuator applications [1]. They are characterized by extremely high resolution and short response time. Unlike other actuators, commercialization of piezoelectric-operated actuators and motors is likely to proceed in those markets where the specific advantages of high torque, high precision and lack of magnetic interference are particularly useful. Ultrasonic motors have several unique properties such as: high output torque, large breaking torque due to the friction force without energy consumption, low leakage of magnetic flux [1–4].

Tribological aspects of piezoelectric motors are becoming more and important in their research. The investigations [5] show that stresses are generated by the elliptical motion of the material points of the stator or rotor surface and depend on frictional processes in the contact area. The contact mechanics of piezoelectric ultrasonic motors determines such operational characteristics as rotational speed and torque or transmitted mechanical power and efficiency. Wear properties and lifetime of piezoelectric ultrasonic motors are also determined by contact mechanics. The results of experimental and analytical modelling of a rotating-mode motor present the modelling based on an equivalent electric circuit. This is established by using geometrical and electromechanical parameters for the different parts of the motor. Advances in tribology of ultrasonic motors are introduced and reviewed synthetically from several main aspects [6–9]. Important problems of the functioning and wear of ultrasonic motors in vacuum and their modelling are investigated too [3]. The investigations on the wear mode control of ultrasonic motor drive tip evaluated the oscillation limit of operation voltage which bellow the surface roughness is not over 1 μm and wear intensity is about $2.5{\cdot}10^{-8}$ mm^3/Nm. Such voltage in the present research was in the range of 2–5 V [10]. The piezoelectric contact parameters at a higher voltage are still insufficiently investigated.

The efficiency and tribological reliability of piezoelectric motors depend on the material of friction surfaces. Different polymer materials (PTFE, PPS, PBT, PEEK, PPS), carbon-fibre reinforced plastics and others are used for piezoelectric contacts. Piezomotors can operate for 6000–8000 hours at the 0.5 mm thickness of such coats. The rotation of the permanent cycle actuator changes for less than 10% after 2000 hours operation at 250 rpm rotation and 0.5 kg/cm loading [11]. Tribological investigations confirmed the efficiency of polymeric materials used for piezoelectric contacts [12].

The aim of the present research was to find a way to increase the tribological reliability of ultrasonic motors at the contact zones of *piezoelectric transducer – rotor* or *slider*, in which both static forces and ultrasonic two-dimensional vibrations are taking place.

CONCEPT OF ADAPTIVE SMART BEARING WITH SELF-DIAGNOSTICS AND SELF-REPAIR FUNCTIONS

An Adaptive Smart Bearing (ASB) involves the development and detailed investigation of self-diagnostic smart bearing with adaptive self-repair

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functions, aimed at application in increased accuracy and precision rotor systems working in extreme conditions. The following functions will be realized in a smart bearing: (a) direct mission – support the rotor, ensuring the constant and alternating loads and speeds in a given range; (b) effecting self-diagnostics of smart bearings, supplying to control device the information on temperature, rheological parameters and thickness of the lubricant film, friction and wear parameters and unbalance of the rotor; (c) self-repair when a diagnostic signal informs on insubstantial lubrication or critical friction in the contact area.

Additional functions include small changes in rotor damping and values of resonant frequencies, realized by exploiting the direct piezo-effect of main active element - piezoelectric transducer, and introducing small changes of the position of the rotation centre by using inverse piezo-effect of a piezoelectric transducer. There is an additional function excited by rotor vibrations, which allows escaping the use of an external power supply for diagnostic system by periodically charging the capacitor with the help of energy harvested from the piezoelectric transducer.

An ASB will contain a piezoelectric transducer with specific topology of sectioned electrodes, capable to generate both standing and travelling waves of various forms and modes. Direct piezo-effect of the transducer will be exploited generating the diagnostic signals; self-restoring function will be realized by the generation of radial travelling waves and controlling additional lubricant film parameters.

GENERATING TRAVELLING AND STANDING WAVES IN PIEZOELECTRIC TRANSDUCERS

The concept of self-diagnostic ASB with the self-repair function is illustrated in Fig. 1. A piezoelectric transducer with special topology of electrodes, exploiting both direct and inverse piezo-effects, contains a special segment of electrode *5*, generating (due to the direct piezo-effect) a diagnostic signal: $U_{\mathrm{diag}} = U_1 \cos(\lambda t+\delta) + \xi(t)$, where U_1 and δ – amplitude and phase of signals, generated due to the direct piezo-effect; $\xi(t)$ – component of a diagnostic signal with a spectrum related to wear and tribological parameters of the contact zone.

In case of increased wear and the resulting change of speed, the diagnostic signal (amplified and filtered from the main frequency λ) controls the amplitude of the main signal with frequency λ keeping the angular velocity of rotation constant. In case of a sticking contact, the diagnostic signal affects both amplitude and frequency of signals. The application of non-harmonic signals (saw-tooth form) could also be effective. In this case the function of self-repair is affected. Thus both initial and current diagnostics of the contact zone by establishing the correlation between tribological parameters and characteristics of diagnostic signals can be realized.

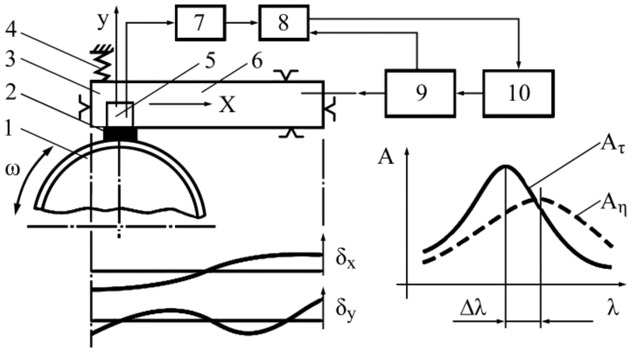


Fig. 1. Operation diagram of ultrasonic motor with standing waves: (a) scheme and oscillations' amplitudes distribution of ultrasonic motor: 1 – rotor with the layer of specific tribological properties; 2 – contacting element; 3 –piezoelectric plate with polar vector, perpendicular to the surface of the plate; 4 – spring; 5 – sectioned electrode for taking out the diagnostic signal; 6 – main electrode; 7 – amplifier; 8 – filter of main frequency of signal generator; 9 – signal generator; 10 – control device, regulating frequency and amplitude of signal generator; δ_x and δ_y – the distribution of amplitudes of longitudinal and bending oscillations in the direction of x and y axes; (b) – amplitude-frequency characteristics of longitudinal (Aτ) and flexural (Aη) oscillations: λ – frequency, Δλ – the gap between resonant frequencies of both types of oscillations, related to the form of trajectories in the contact area, ω – rotation velosity.

The range of possible cases of application of self-repair function could be extended by exploiting an to generate independent signals related only to longitudinal or flexural oscillations of the transducer (Fig. 2). In this case the optimal form of trajectory in a form of ellipsis could be generated.

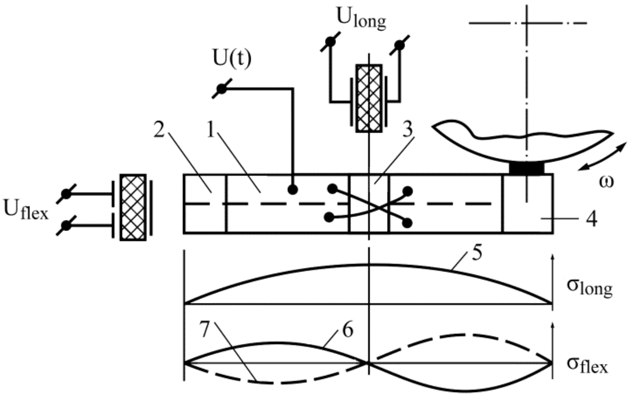
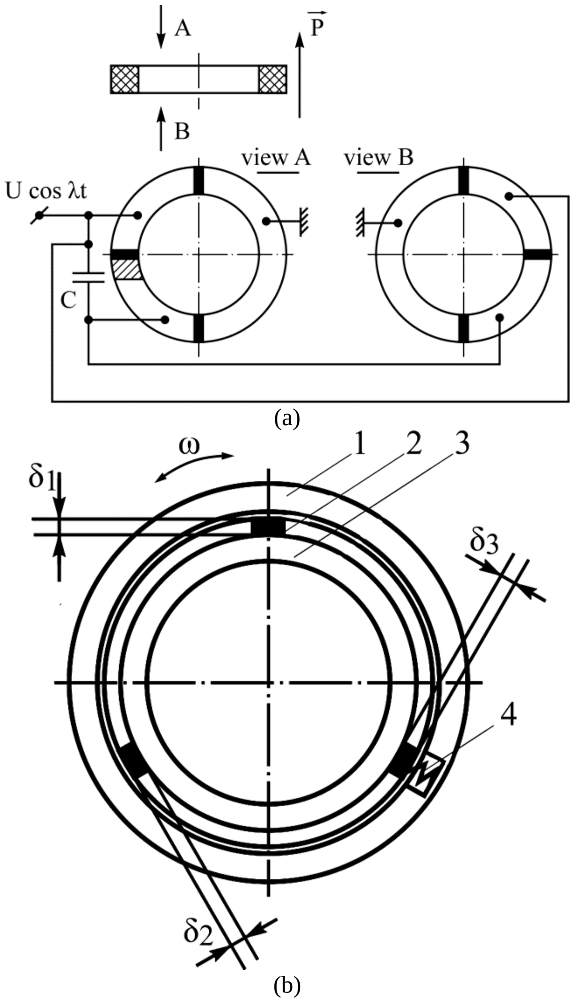


Fig. 2. Selection the place and form of sectioned electrode by the independently measuring the amplitudes of longitudinal and flexural oscillations: 1 – main electrode ($U(t)$ is applied); 2 – electrode, measuring the parameters of flexural oscillations (U_{flex}); 3 – electrode, measuring the parameters of longitudinal oscillations (U_{long}); 4 – electrode, measuring signals, related to wear of contact zone and geometry of rotor; 5 – distribution of electrical charges in case of longitudinal oscillations (in case of no electrode on the surface of transducer); 6 and 7 – distribution of electrical charges in case of flexural oscillations (in case of no electrode on the surface of transducer), when the reverse of motion is realized.

There are several ways to generate oscillations of the travelling wave type in regular structures. The simplest case is shown in Fig. 3, where the electrodes of a piezoceramic ring with polar vectors, coinciding with the axis of the ring, are sectioned in four parts (Fig. 3a). The capacitance *C* affects the phase shift of the signal $U\cos\lambda t$ by 90^0. As a result, four phases of the harmonic signal are applied: with 0^0, 90^0, 180^0 and 270^0 phase shifts, generating bending oscillations of the travelling wave type in the ring, which is contacting the rotor in three points (Fig. 3b). Contacting points are made from different materials, thus enabling the evaluation of the wear of materials with different rheological characteristics and hardness. The wear is evaluated by controlling the thickness of contacts δ_1, δ_2 and δ_3. To extend the range of practical applications of the device shown in Fig. 3b, two methods to realize different contact zones can be used:

(a) fixing two of the contacts (the third one is ensuring contact through the spring 4) to rotor *1*, realizing wear between contact *2* and the piezoelectric ring *3*;

(b) fixing two of the contacts to the piezoelectric ring *3*, realizing wear between contact *2* and rotor *1*.



(a)

(b)

Fig. 3. Generation of a travelling wave in a piezoelectric ring (a) and scheme of three contacts distribution (b): 1 – rotor with an external layer with specific tribological properties; 2 – contact; 3 – piezoelectric ring; 4 – spring.

RESEARCH EQUIPMENT AND METHODOLOGY

Tribological investigations were performed with a specially designed test rig. Two different schemes were used for the experiments with this stand. The first scheme (Fig. 4) with the plate of the piezoceramic element *3* was used when rotor *1* was driven by the piezoceramic element *3* through the friction element *2*. The radial force was applied to regulate the load in the contact zone of piezoelement-rotor surface. The rotation speed was measured with a special device – perforated disc with 180 rips and an optical sensor of a laser. Another device was applied to measure the torque. The axial load on the rotor was applied vertically through the load hub *7*. Different weights can be used for that. When the hub begins to rotate with the rotor, the lever (mounted in the hub) presses the tangential force sensor *9* and a special program converts the signal into torque parameters. All the data was collected on a PC.

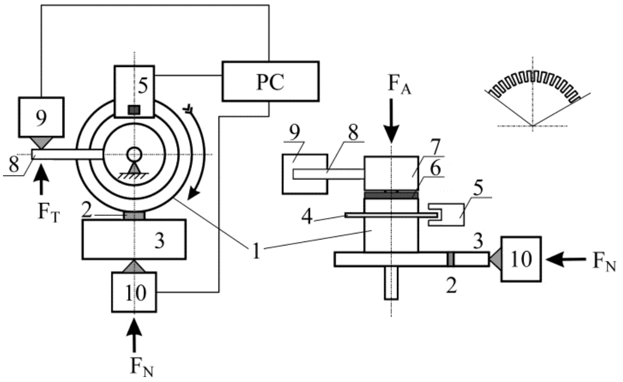
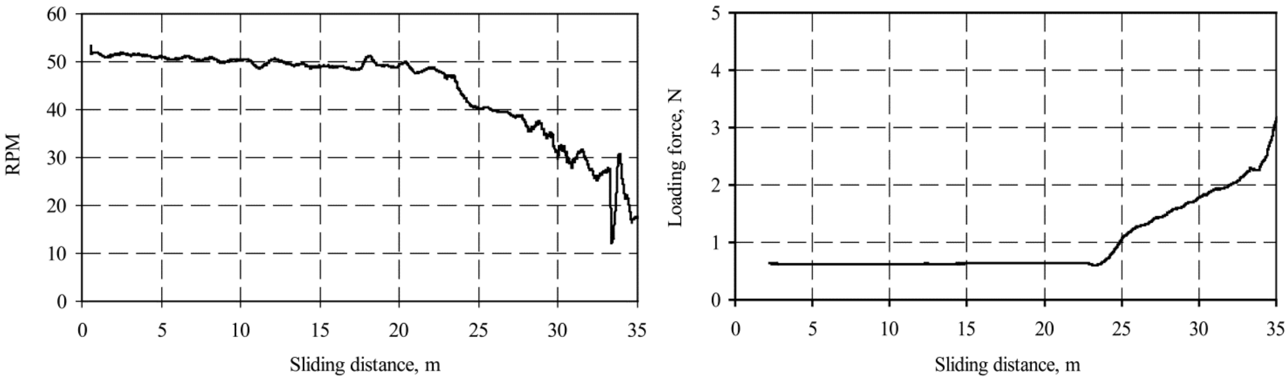


Fig. 4. Schematic diagram of tribological tests of piezoelectric ultrasonic motor (where: (a) top view; (b) side view; (c) perforated disc fragment): 1 – rotor; 2 and 6 – frictional material; 3 – piezoceramic element; 4 – perforated disc; 5 – laser sensor; 7 – load hub; 8 – tangential force lever; 9 – tangential force sensor; 10 – radial force sensor; F_A – axial force of motor loading; F_N – radial force of piezoelectric contact loading; F_T – tangential motor rotation force; PC – personal computer.

The experiments were performed with the plate of a friction element which was glued to a piezoceramic element. Two kinds of rotors were used: of steel and of bronze. The circle length of each rotor active surface was 0.144 m. The frequency of the supplied current was 116 kHz and voltage – 25 V.

Fig. 5. Picture of piezoelectric motor ring used in experiments.

Another test design was also used by applying a piezoceramic ring (Fig. 5) of 60×10×7 mm ($D\times d\times h$)



(a) (b)

Fig. 6. Change of rotation speed of steel rotor during tests (a)
and the correlation with loading force applied to piezoelectric contact (b).

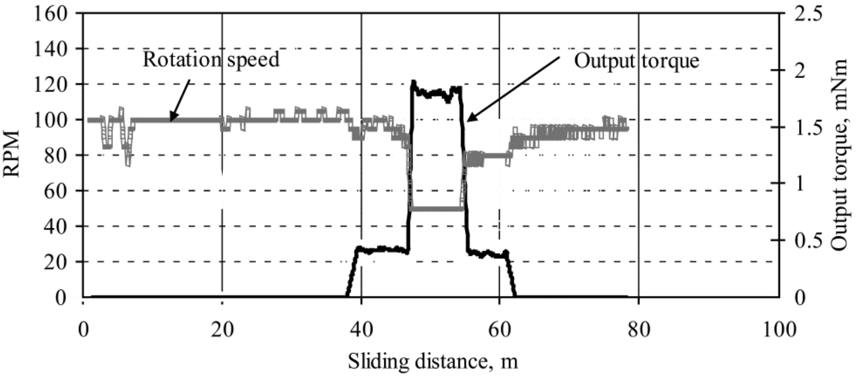
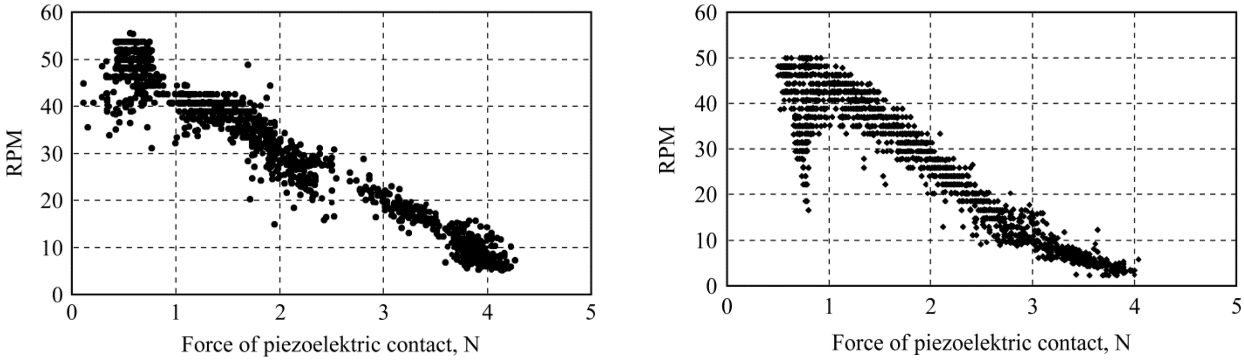


Fig. 7. Influence of output torque on rotation speed of piezoelectric actuator.



(a) (b)

Fig. 8. Dependence of rotation speed on output radial force of piezoelectric actuator for rotors of steel (a) and bronze (b).

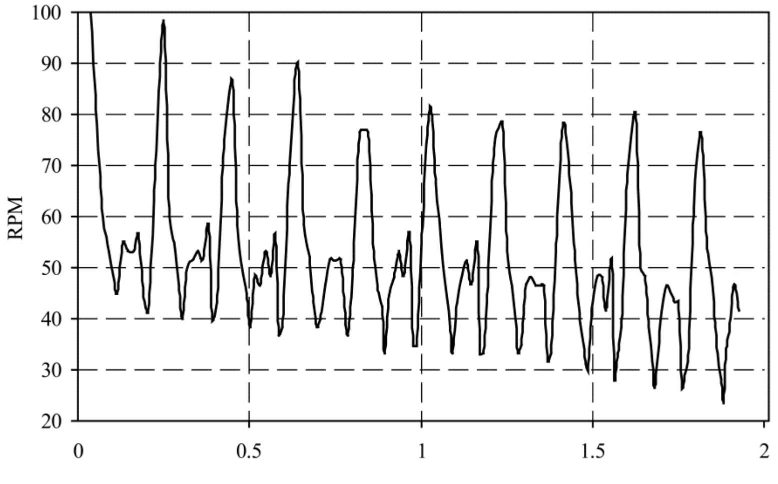


Fig. 9. Variation of rotation speed of rotor during the operation of piezoelectric contact.

with the axial polarity, made of PZT 401 (Morgan Electro Ceramics Ltd., UK Manufacturing site: Bursledon Road, Thornhill, Southampton, SO19 7TG). The operation parameters were: harmonic voltage – 100 V, frequency 49 kHz, impedane 5 kΩ, capacitor, realizing phase shift by 90^0, was 2400 pF.

The measurements of the rotor surface roughness were performed with the roughness meter MahrSurf GD25. The measurements of Ra, Rq and Rz values were made parallel to the operation direction before the tests and after each consequent running of the piezoelectric contact.

RESULTS AND DISCUSSION

The experiments according to the first scheme (Fig. 4) estimated the dependence of the rotor rotation speed and the output torque on the operation time of the piezoelectric surface, the hardness of the rotor, the normal loading force F_N and the change of roughness of the friction surface.

Fig. 6a presents the variation of the rotation speed of the steel rotor during tests.

Because of a regular impact of the friction force on the rotor surface, the consequent wear and adjustment of the surfaces the roughness of the surfaces reduces. The efficiency of the piezoelectric contact operation is based on the friction which is lower at the contacting of smoother surfaces. Therefore the rotation speed is constantly reducing. The loading force on the piezoelectric contact was constant up to 23 m of the sliding distance (Fig. 6b). A higher loading force increases the capacity of the piezoelectric contact, while a higher output torque and reduced roughness raise the reduction of the rotation speed because of the severe wear.

Fig. 7 illustrates the impact of the increased output torque on the rotation speed of the piezoelectric actuator. If the output torque of the piezoelectric actuator increases, then the rotation speed decreases accordingly. When the actuator is unloaded the rotation speed recovers but at a lower level because of the above mentioned reasons.

There is clear dependence of the rotation speed on the output radial force of the piezoelectric actuator. Such relation is presented for both steel (Fig. 8a) and bronze (Fig. 8b) rotors. In both cases the increase of the radial force leads to the decrease of the rotation speed.

There is no remarkable difference between the data on steel and bronze rotors. The results show that in both cases the most stable speed is when the loading force is 0.5–1.5 N. A slightly higher speed is used by the steel rotor. A lower rotation speed of the bronze rotor could be caused by a lower friction coefficient of its surface. Although the surface hardness of both rotors was the same, we can suppose that hardness is that factor which influences tribological efficiency of piezo actuators.

The uneven rotation of a rotor should be taken into account when evaluating the efficiency of the piezoelectric contact. Experiments with a piezoceramic ring (Fig. 5) displayed a saltatory rotation with the tendency to decrease (Fig. 9). The reasons of this uneven rotation could be several: disbalance of a rotor, the change of the surface roughness and the non-elliptic vibration at the travelling wave signal (covering the standing and travelling waves).

One cycle of a rotation signal (Fig. 10) during the tests presents the saltatory rotation which can be responded to non-equal position of electrodes on both counter sides of piezoelement ring. It can be very important in constructive solutions of a piezoelectric transducer.

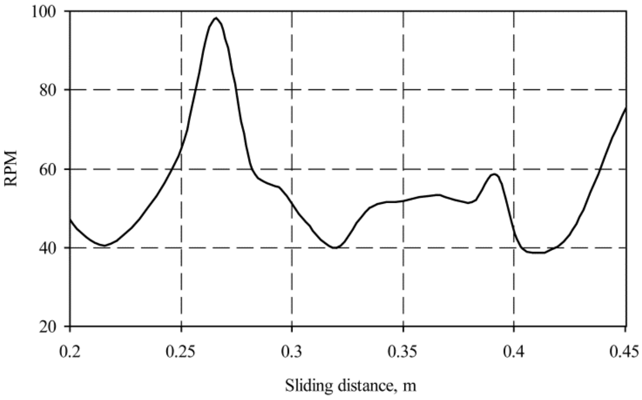


Fig. 10. One cycle of rotation signal of piezoelectric element in experiment.

One of the most important reasons of the tendency to reducing rotation speed is the decrease of the surface roughness because of the wear and adjustment of friction surfaces. The measurements of the steel rotor roughness at the beginning of tests and after three consequent 1 hour runs of the piezoelectric contact according to the first Scheme (Fig. 4) are presented in Fig. 11.

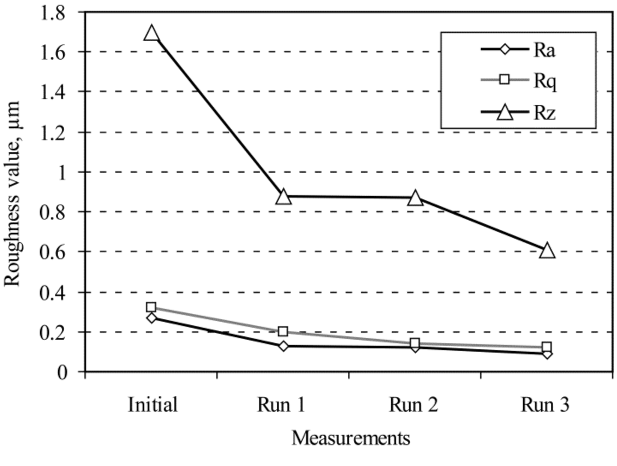


Fig. 11. Measurements of Ra, Rq and Rz roughness of steel rotor surface before tests and after each consequent run of piezoelectric contact.

There is an evident decrease of the surface roughness revealed in each of the roughness parameter measurements. Such decrease is caused by an intensive wear and adjustment of surfaces which run at a high friction coefficient under dry sliding conditions. Especially clear was the decrease of roughness atthe beginning of tests when the surfaces running-in and friction pair adjusted.

CONCLUSIONS

- Rotation speed of a piezoelectric actuator depends on the running time of the piezoelectric contact and is influenced by the output torque of the actuator. The efficiency of a piezoelectric motor is strongly related to the normal loading force F_N and the change of roughness of the friction surface.
- Disbalance of a rotor, the change of surface roughness and the non-elliptic vibration at the travelling wave signal cause the uneven rotation of a piezoelectric motor.
- Development of a self-diagnostic adaptive smart bearing with adaptive self-repair functions requires detailed investigations of the tribological reliability and materials selection for a piezoelectric transducer that capable to generate both standing and travelling waves of diagnostic signals and to ensure the self-restoring function by the generation of radial travelling waves controlling the bearing parameters.

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Реферат

Целью работы является описание способов повышения надежности пьезоэлектрических двигателей, обусловленных трибологическими процессами в зоне контакта *пьезоэлектрический преобразователь – ротор* или *ползун*, в котором действуют как статические силы, так и ультразвуковые колебания. Проблемы износа рассматриваются в перспективе реализации концепции адаптивной трибологической пары с оптимальными реологическими параметрами ее составных элементов, что позволит осуществлять самодиагностику этой пары за счет использования прямого пьезоэлектрического эффекта уже существующих пьезоэлектрических преобразователей. Использование новых современных материалов (в том числе наночастиц) позволяет прогнозировать повышение долговечности пьезоэлектрических двигателей. В статье приведены некоторые результаты испытаний, в том числе корреляции диагностических сигналов с параметрами износа.

Ключевые слова: пьезоэлектрический двигатель, бегущая волна, трибологические свойства, надежность контактной зоны, пьезоэлектрический преобразователь.