4th INTERNATIONAL CONFERENCE
TRANSPORT SYSTEMS TELEMATICS TST'04

ZESZYTY NAUKOWE
POLITECHNIKI ŚLĄSKIEJ 2004
TRANSPORT z.55, nr kol. 1657

*piezoelectronic,
transducers,
piezomechatronics*

Zbigniew KOSIŃSKI[1]
Włodzimierz WRONA[1]
Wojciech PIETRASINA[2]

PIEZOMECHATRONIC CONTROL OF REVERSIBLE ULTRASONIC MOTORS IN AUTOMATION OF ELASTIC TRANSPORT SYSTEMS

New generation of piezoelectric electromechanical transducers, so called piezoelectric motors with a disc vibrator, is presented in the paper. These motors should be very interesting to specialists of fine mechanics. Tests done on prototypes of piezoelectric motors have proved that the motors have high electromechanical and service properties. The work on development of piezoelectric motors has essential scientific and practical significance. The aim of these activities is a preparation of new type of electric drives as well as the use of elementary technological processes in automation and robotics as well as in automation of elastic transport systems.

PIEZOMECHATRONICZNE UKŁADY STEROWANIA REWERSYJNYM SILNIKIEM ULTRADŹWIĘKOWYM W AUTOMATYZACJI ELASTYCZNYCH SYSTEMÓW TRANSPORTOWYCH

W artykule przedstawiono nową generację piezoelektrycznych przetworników elektromechanicznych (PPE-M) w postaci rewersyjnych silników piezoelektrycznych z tarczowym rezonatorem (SP – T/R), które powinny wzbudzić zainteresowanie wśród automatyków i specjalistów precyzyjnej mechaniki z zakresu „mikro" i „nanotechniki" ze względu na kinematyczną rozdzielczość i dynamiczne charakterystyki pracy przetwornika w stanach nieustalonych tj. w czasie rozruchu i wyłączenia silnika.

1. INTRODUCTION

First designs of piezoelectric electromechanical transducers (PPE-M) as piezoelectric ultrasonic motors (SP) emerged in the sixties of twenty's century as a result of interdisciplinary achievements of solid state physics, materials engineering and piezoelectronis, leading to development of highly efficient polycrystalline composites with watt-hour efficiency up to 90%. The materials in the shape of piezoelectric ceramic with

[1] University of Bielsko - Biala, Willowa 2, 43-309 Bielsko - Biala, Poland
[2] Evatronix S.A., 1 Maja 8, 43-300 Bielsko-Biała, Poland, wojpie@bielsko.evatronix.com.pl

distinct crystalline asymmetry made possible designing of energy transducers like generators, transformers and piezoelectric motors.

It should be noticed, that motors based on friction coupling between rotor and stator, what it is assumed a negative property of such drive, because „stator – rotor" kinematic pair worn out as a result of friction in sliding on the micro-level, have positive feature in that there is braking torque in power off state. So the motor automatically changes to be a brake.

This structural property makes possible to build piezoelectric motors with high electrodynamic performance in transient states, i.e. in start – stop work modes.

For example: SP dynamic resolution, elementary step, equals:

- fraction of second for rotor revolutions
- about 0.1 μm for linear motion of a runner.

This advantages promotes applications of such electric drives in following branches:

- process automation of elastic manufacturing systems (ESP) and transport systems,
- robotic – for precise manipulator driving,
- biocybernetics – for driving of ultrasonic cardiograph, artificial heart, manipulators and pedipulators,
- military equipment and space technique,
- technology of rapid prototyping in „micro-technique" (in the future in „nano-technique") with the aid of digital technique, piezoelectronics and computer-aided control of PPE-M driven working models.

1.1 PIEZOELECTRIC MOTOR WITH DISK RESONATOR (SP-T)

In the search of new designs of electromechanical, piezoelectric transducers, were made experiments with toroidal oscillators – rollers and rings, in piezoelectric motors with disk resonator (SP-T).

Superiority of this SP design is expressed by following technical characteristics:

- Output stability in longterm work with a continuous wave,
- Possibility of revers with any input / output and any revolution direction (SP – T/R),
- SP-T/R version with simultaneous coaxial work in left and right revolution direction and with different outputs: M, n, P, as in clock-work.
- Possibility of SP-T/R computer control by microprocessor drivers logically programmable in accordance with a impulse – reversible flow chart of transducer work.

SP-T is distinguished by its design variety, satisfying most demands of automatics and fine mechanics designers.

Analysing piezoelectric drive in respect of control flexibility, one shall develop following parameters and characteristics:

- Radial resonant frequency of piezoceramic disk (fR),
- Nominal input / output data: U_N, I_N, M_r, M_N, n_0, n_N, P_N,
- SP-T/R mechanical load characteristic [2],
- Equivalent SP-T linear model corresponding to motor with oscillator in the shape of piezoceramic plate [2].

1.2. EQUIVALENT LINEAR SP – T/R MODEL

Analysing piezoelectric electromechanical transducer load and influence of thermal losses on its work one shall develop equivalent electromechanical model with linear approximation, showing motor members dynamic interdependencies and piezoelectric oscillator vibration to SP rotor revolution transformation mechanism.

Reversible piezoelectric motor with disk resonator is shown in the equivalent PPE-M electric schema as two identical four-terminal networks frictional coupled by resistance R_F expressing frictional mechanism losses resistance (Fig.1).

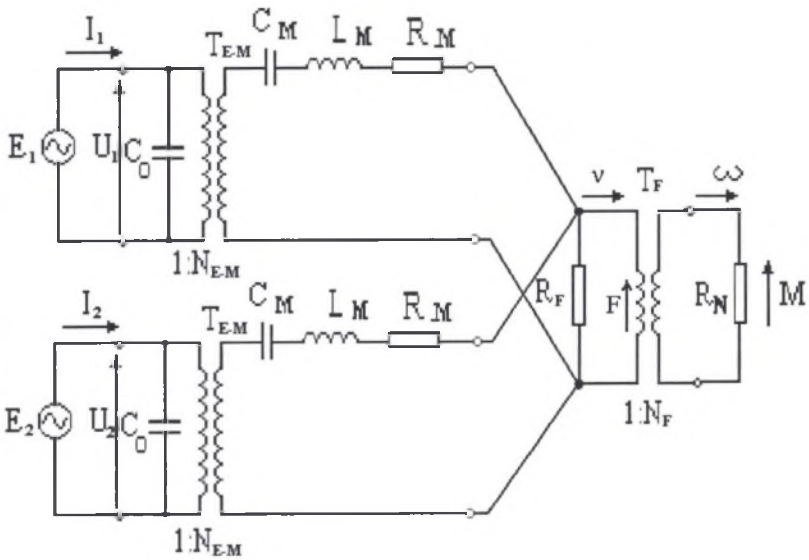

Fig.1. Equivalent schema showing SP-T/R as frictional coupled four-terminal networks

Transformer $T_{E\text{-}M}$ is characterised by ideal electromagnetic coupling of disk oscillator with transformation coefficient $N_{E\text{-}M}$:

$$N_{E-M} = \frac{2 * \pi * b * d_{31}}{S_{11}^{E}} \tag{1}$$

Transformer T_F is characterised by ideal oscillator to rotor frictional coupling with transformation coefficient N_F:

$$N_F = \frac{M}{F} \tag{2}$$

and following properties of linear four-terminal network [2]:
- C_0, oscillator static capacity in off-power state,
- C_M, L_M, dynamic mechanical capacity and inductance of oscillator,
- R_M, resistance of mechanical losses within oscillator material (piezoceramic),
- R_F, resistance of frictional losses in kinematic pair frictional contact,
- R_N, SP- T/R resistance of mechanical load.

$$R_N = \frac{M}{\omega} \tag{3}$$

where:

M – SP shaft torque,
F – variable frictional force on the oscillator vibration microlevel,
ω - angular frequency in rad/s,
d_{31}, S_{11}^E – deformation and stress modules – catalogue values for piezoceramic.

1.3. RADIAL RESONANT FREQUENCY (F_R) OF TOROIDAL PIEZOCERAMIC DISK

Assuming that disk thickness „**t**" is much less than its diameter „$\mathbf{D_0}$" ($t \ll D_0$) and polarization **P** is developed in relation to piezoceramic thickness, one can calculate the piezoelectric disk radial vibration resonant frequency f_R using:
- Piezoelectric state equations,
- Motion differential equations for radial displacements and developing from them admittance equation for disk resonator with following solutions: (R_h) for the first 3 harmonics of radial vibrations of the disk with radius „R_0" for mean catalogue data for used piezoceramic [1]:

$$R_h = \frac{\omega_0 * R_0}{v_c} \tag{4}$$

where: $R_{1h}=2.0488$; $R_{2h}=5.39$; $R_{3h}=7.57$

(a) own frequency of disk resonator without aperture ($d_0=0$) for this vibration harmonics including first harmonic one can calculate from following equations:

$$f_{Rh} = \frac{\omega_0}{2*\pi} = \frac{R_h * v_c}{2*\pi*R_0} = \frac{R_h * v_c}{\pi * D_0} \tag{5}$$

$$f_{R1} = \frac{2.0488 * v_c}{\pi * D_0} \tag{6}$$

(b) For the disk with aperture „d_0" and $t \le b$, own frequency of radial vibrations first harmonic (f_{R10}) is counted from:

$$f_{R10} = \frac{\left(R_{h1} - \frac{r_0}{R_0}\right) * v_c}{2*\pi*R_0} = \frac{\left(2.0488 - \frac{d_0}{D_0}\right) * v_c}{\pi * D_0} \tag{7}$$

where:

ω_0 – resonant angular frequency of piezo-element in rad/s,

v_c – voice velocity in piezoceramic in m/s.

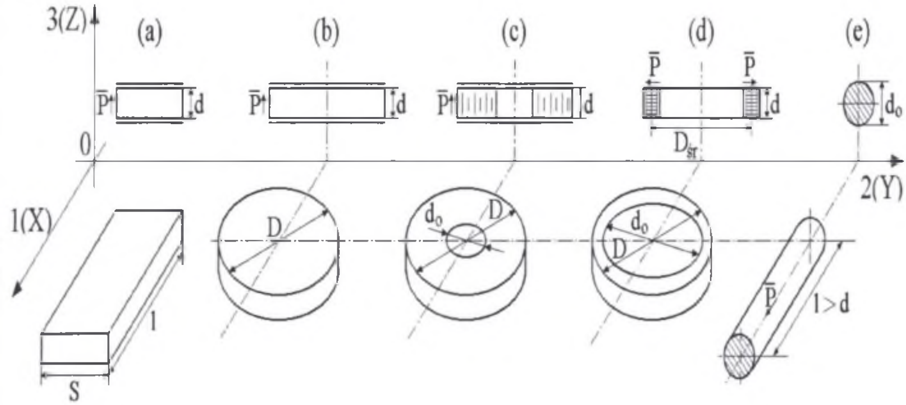

Fig.2. Examples of the most frequently used regular geometric forms of polarized piezoresonators

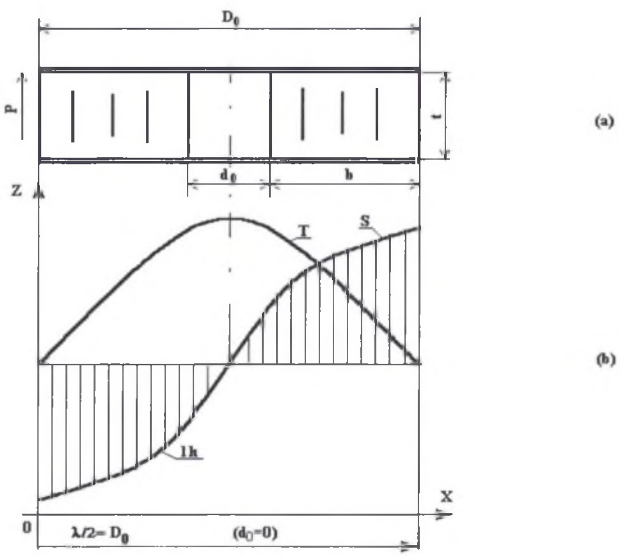

Fig.3. Piezoceramic disk resonator. a) geometric dimensions of polarized (P) piezoelectric disk b) diagrams of deformation (S) and stress (T) for radial vibration (1h) first harmonic for a disk without aperture (d_0=0)

1.4. SP-T/R MECHANICAL LOAD CHARACTERISTIC

Reversible piezoelectric motor nominal power P_N one can calculate from mechanical characteristic (Fig. 3) with linear approximation for a slide s = 0.5 by which the adhesion friction coefficient μ_a attains equilibrium with the deformation friction coefficient μ_d. The efficiency reaches maximum value and kinematic friction coefficient μ_k is equal:

$$\mu_k = \mu_a + \mu_d \rightarrow \eta = \eta_{max} \tag{8}$$

In order to attain this, one shall make idle run test for both revolution directions ($+n_0$, $-n_0$) and mechanical coupling (+/- M_r) by motor starting and nominal voltage supplying with the resonant frequency f_0.

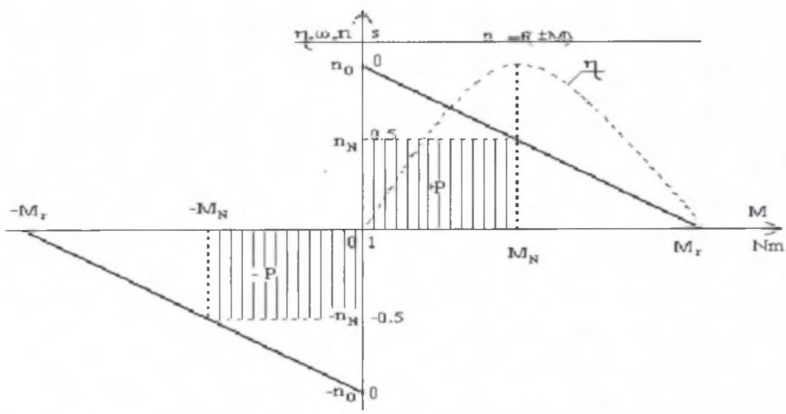

Fig.4. SP-T/R mechanical characteristic

2. CIRCUITS – SP -T/R SUPPLY AND AUTOMATIC CONTROL SYSTEMS

SP-T/R was supplied by voltage inverter with a structure modified compared with the one described in [2]. Modification consists in phases control changing, so it is possible to make decoupled control of each circuit channel (Fig.4). Decoupling consists in independent setting of working parameters: U_1, U_2, f_1, f_2, t_{1p}, t_{1l}, so there is possibility of using reversible motor with various parameters in both revolution directions. The software for driver control enables interactive setting of any driver work algorithms.

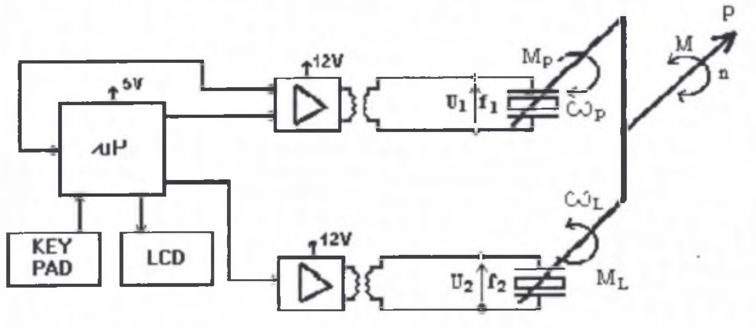

Fig.5. SP-T/R supply block diagram

2.1 CONTROL ALGORITHMS OF SP-T/R WORK IN IMPULSE MODE

Proposed control circuit makes possible to program any algorithms of SP reversible work by precise quantization of electric supply energy (U, f) in accordance with program of impulse – reversible load of piezoelectric drive (± M, ± n, tp, ts, Tc, TΣ)

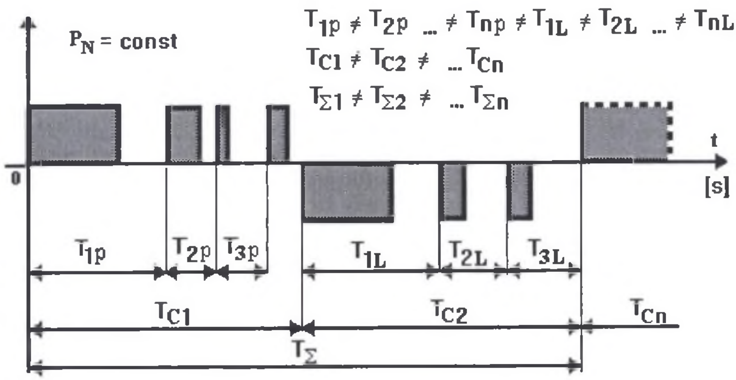

Fig.6. Intermittent impulse – reversible work with asymmetric and variable load period: T_{cn}= var, T_{Σ}= var

3. CONCLUSIONS

Progress in piezoelectric materials technology allows for design of new generation of piezoelectric energy transducers (PPE-M), including piezoelectric motors (SP) with following parameters:

- Maximum momentum ~ 10 Nm,
- Linear motor thrust, up to 50 N.
- Revolutions frequency (0 – 10000) min^{-1},
- Watt-hour efficiency η=(40 – 80)%,
- No fault service life: (5000 – 10000) h.

Development of SP design, in particular in shape of reversible piezoelectric motors with disk or ring resonator is of great scientific and practical signification in developing of new generation of precise electric drive and in automation of elementary technologies in automatic manufacturing systems ASP and in elastic transport systems EST.

BIBLIOGRAPHY

[1] SOLUCHA W., Wstęp do piezoelektroniki, Wydawnictwo komunikacji i Łączności, Warszawa, 1980
[2] KOSIŃSKI Z., PIETRASINA W., Systemy informatyczne sterowania piezoelektrycznymi przetwornikami elektromechanicznymi w automatyce i robotyce. I Krajowe Warsztaty Technologii Szybkiego Prototypowania, Kraków AGH 1998, str.33 – 40
[3] KOSIŃSKI Z., PIETRASINA W., The new aspects of piezoelectric reverse linear engine. Transport Systems Telematics. III International Conference 13-15 November 2003 Zeszyty Naukowe Politechniki Śląskiej 2003 Transport z. 51, nr kol. 1608
[4] SCHONFELD R., Digitale Regelung elektrischer Antrriebe, Verlag Technik, Berlin, 1987
[5] DMOWSKI A., Energoelektroniczne układy zasilania prądem stałym. WNT Warszawa 1998

Reviewer: Prof. Marek Pałys