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THEORY OF THE MOTION PRINCIPLE OF A PIEZOELECTRIC DRIVEN MICROROBOT

Gábor FELSŐ

Department of Control Engineering and Information Technology
Budapest University of Technology and Economics
H–1521 Budapest, Hungary

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Abstract

Microrobots are promising tools for miniaturized manufacturing or surgery. Piezoelectric driven mobile microrobots apply the inverse piezoelectric effect for motion and manipulation. Current specimens are built based on experimental results, however, a mathematical model presented in this article can be used both for construction and control of microrobots.

Keywords: microrobotics, piezoelectric activator, robot model, micromanipulation, microrobot motion.

1. Introduction

During the last decade microrobotics became an important research field of manufacturing technologies on small-sized pieces with great accuracy. The applications of microrobotics include handling and manufacturing of miniature objects, testing and repairing of microchips and unreachable areas of macro-objects (e.g. inner side of a pipeline). In addition, microrobots could be excellent tools in the surgery of cells as well.

Microrobots are developed in order to employ them in industrial environment; it can transport materials between different workstations and can perform several tasks on them. Nevertheless, the miniaturizing of lots of parts of a machine generated demand to develop automatic equipment for handling, transporting and manufacturing of small-sized pieces.

The microrobot research project, which is carried out at the Department of Control Engineering and Information Technology, Technical University of Budapest, focuses on vision sensor systems developed for microrobot environment in order to perform accurate tasks by the microrobot. The project is carried out in close cooperation with Institute for Process Control & Robotics (IPR), University of Karlsruhe. In the project a working-cell is developed, where the microrobot movements are controlled by a vision sensor system, in order to perform transport and assembly operations in the range of cm till μm [2], [3] and [5].

The moving principle of the microrobot is based on the inverse piezoelectric effect. 'Miniman' robot, which was originally developed by the University of Karlsruhe, is one of the most successful examples in this field. The body of the robot is standing on three piezoelectric legs equipped with electrodes. Every leg can be lengthened, contracted and bent applying voltage to the electrodes. The body of the microrobot can step if every leg is contracted, bent, lengthened and then re-bent in a certain sequence.

The control system, however, requires information of the system behavior. This paper presents a theoretical analysis of motion of piezoelectric driven microrobots. The basis of the analysis is the physical characteristics of the major robot assemblies and the behavior of the piezo leg. The second part of the paper analyzes the motion effect generated by applying voltage to the piezo legs. Although, the research focused on the system analysis especially for controlling purposes, an important relation has been discovered that could be useful for planning piezoelectric microrobot systems.

2. Bending of a Cylindrical Piezoceramics

2.1. Distribution of Mechanical Stress in the Ceramics

Let us examine one leg of a piezorobot, which is a cylindrical piezoceramics as shown in *Fig. 1*. The linear matrix equation of the indirect piezoelectric effect is as follows[1]

$$\mathbf{s} = \mathbf{dE} + \mathbf{St}. \tag{1}$$

In our case the following scalar form is used

$$s_z(x, y) = d_{31}(x, y) \cdot E(x, y) + S_{11}^E(x, y) \cdot \sigma_z(x, y), \tag{2}$$

where $E(x, y)$ is the electric field, $d_{31}(x, y)$ is the piezoelectric constant (in the case of strain perpendicular to the electric field – negative), $\sigma_z(x, y)$ is the mechanical stress and $S_{11}^E(x, y)$ is the mechanical compliance constant.

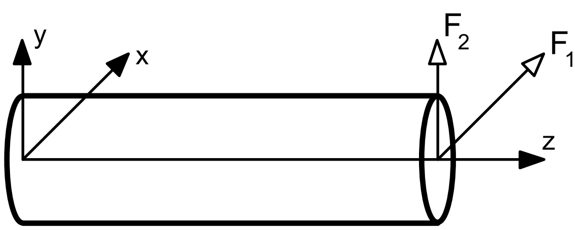

Fig. 1. Robot leg: a piezoceramics cylinder

[1] **s**: strain vector, **d**: piezoelectric strain coefficients in tensor form, **E**: electric field vector, **S**: mechanical elastic compliance tensor, **t**: mechanical stress F/A in vector form.

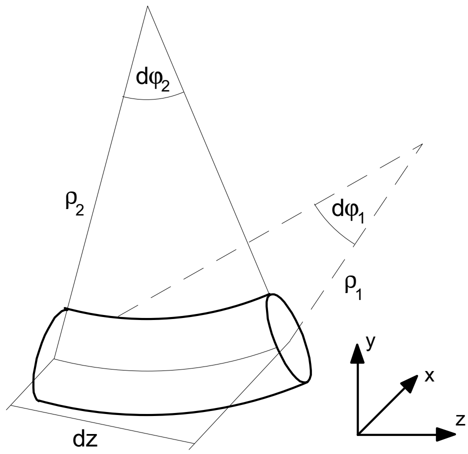

Fig. 2. Mechanical bend: part of the piezo cylinder

On the other hand, using the geometry shown in *Fig. 2* the relative strain on the longitudinal axis within the piezo cylinder

$$s_z(x, y) = \frac{(\rho_1 - x)\,\mathrm{d}\varphi_1 - \mathrm{dz} + (\rho_2 - y)\,\mathrm{d}\varphi_2 - \mathrm{dz}}{\mathrm{dz}}. \tag{3}$$

The piezo leg can be loaded and bent, but it is still in mechanical equilibrium if the following equation is valid for each cross-section A

$$\int_A \sigma_z(x, y)\,\mathrm{d}A = 0. \tag{4}$$

Expressions of σ_z can be substituted using the piezo equation and the geometrical model of bending, respectively [4]. The equation of equilibrium can be simplified into the following form using the cylindrical symmetry of the ceramics

$$\rho_1 \frac{\mathrm{d}\varphi_1}{\mathrm{dz}} + \rho_2 \frac{\mathrm{d}\varphi_2}{\mathrm{dz}} = 2\left(1 + \frac{\alpha}{2}\right) \tag{5}$$

with

$$\alpha = \frac{\displaystyle\int_A \frac{d_{31}(x, y)}{S_{11}^E(x, y)} E(x, y)\,\mathrm{d}A}{\displaystyle\int_A \frac{1}{S_{11}^E(x, y)}\,\mathrm{d}A}. \tag{6}$$

'x' and 'y' curvatures of the neutral fiber cannot be determined simultaneously from the above equation. Due to the geometrical symmetry, the following statement can be accepted

$$\rho_1 \frac{\mathrm{d}\varphi_1}{\mathrm{d}z} = \rho_2 \frac{\mathrm{d}\varphi_2}{\mathrm{d}z} = 1 + \frac{\alpha}{2}. \tag{7}$$

Now, the moment produced by the mechanical stress along the bending axis can be determined.

$$\mathbf{M} = \int_A \mathbf{r} \times \mathbf{k}\sigma_z(x, y)\,\mathrm{d}A = M_x \mathbf{i} + M_y \mathbf{j}. \tag{8}$$

Substituting σ_z the moment can be calculated, but it still depends on the distribution of the electric field in the piezoceramics. In mechanical equilibrium, M_x and M_y are equal to the moments of external forces F_1 and F_2 measured from the fixed ends of the legs, i.e. $M_x = -F_2(l - z)$, $M_y = F_1(l - z)$.

2.2. Consequences of a Distribution of the Mechanical Stress and Electric Field

Let us examine a cross-section of the piezo tube and selected point located on it $\mathbf{P}(x, y) = \mathbf{P}(r, \vartheta)$. In the polar coordinate system the following variables are used: $x = r\cos\vartheta$, $y = r\sin\vartheta$, $h = R_2 - R_1$, $\mathrm{d}A = r\,\mathrm{d}r\,\mathrm{d}\vartheta$.

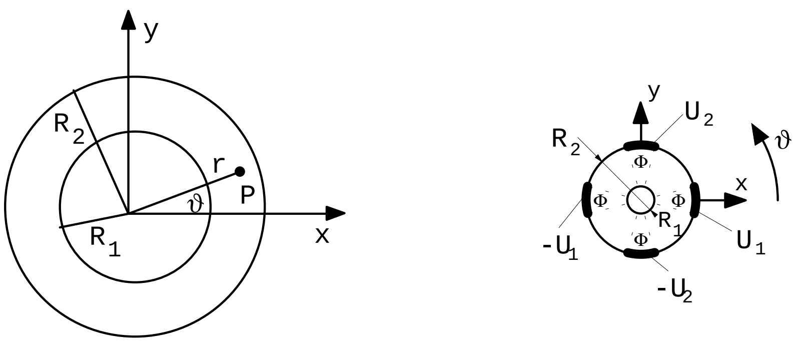

Fig. 3. Cross-section of a tubular type piezo leg

The piezoelectric d_{31} and compliance constant S_{11}^E refer to the piezoceramics of the outer ring. The electric field is a function of two variables. Due to the zero potential electrode on the internal superficies $E(r, \vartheta) = 0$ if $r < R_1$. Four electrodes are put on the external cylindrical superficies in 90° relative position to each other. In order to simplify the control of the legs, identical but opposite polarity voltages are applied to the facing electrodes. Therefore, two variables can be used to indicate the status of the electrodes U_1 and U_2. If the approximation is used then the electric field E is independent of the radius and has a function of angle according to *Fig. 4*. This corresponds to a model when the piezo tube would be a multielectrode capacitor and the scattered field among the neighbor electrodes is neglected compared to the field between the electrodes.

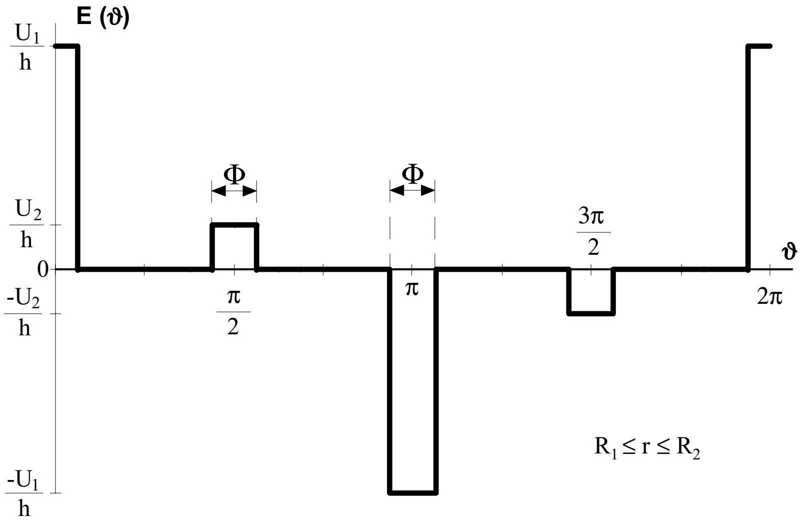

Fig. 4. Distribution of the electric field in the piezo tube

Substituting the above functions into the expression of the moment, the mechanical distortion of the piezo tube caused by external force and electric voltage can be determined:

$$\left.\begin{aligned} \xi &= k_F \cdot F_1 + k_U \cdot U_1 \\ \eta &= k_F \cdot F_2 + k_U \cdot U_2 \end{aligned}\right\} \tag{9}$$

with the following constants

$$\left.\begin{aligned} k_F &= \frac{4}{3\pi} S_{11}^E \frac{l^3}{R_2^4 - R_1^4} \\ k_U &= -\frac{8}{3\pi} d_{31} l^2 \frac{R_1^2 + R_1 R_2 + R_2^2}{R_2^4 - R_1^4} \cdot \sin\frac{\Phi}{2} \end{aligned}\right\} . \tag{10}$$

It is necessary to note that both constants are positive. The most important meaning of the above equation is that the external force and the electric voltage are linearly related to the deflection.

3. The Moving Principle of the Microrobot

The motion of the microrobot is a complex process, which is principally similar to that of continental vertebrae (with two or four legs). The piezoelectric legs can be bent by applying voltage to their electrodes according to the relations described above. In order to move the microrobot, the legs are fixed to the lower part of the body. To achieve a stable equilibrium three legs are used. Basically, two possible motion principles of the robot platform are possible: ‘walking’ and ‘shuffling’.

At the beginning of a ‘walking’ type motion, no voltage is applied to the piezoceramics. To move the robot, the legs are bent relatively slowly at first so that they stay in contact with the base. The platform is thereby displaced into the desired direction of motion. Second, the polarity of the voltage energizing the actuator electrodes is suddenly reversed so that all three legs bend quickly in the opposite direction. Simultaneously, the robot lifts all three legs at once and performs a microjump, which prevents sliding friction between legs and base. The bent legs are then lodged in their new position. Third, the legs are straightened out and the platform moves a little more in the desired direction, taking the step. The last leg actuation is again carried out relatively slowly to keep the legs from sliding on the glass base. As this sequence is repeated, the robot platform performs a continuous ‘galloping’ motion.

‘Shuffling’ is a simplified motion principle of the microrobot. First the legs are bent slowly, and then they take a very quick step. In contrast to ‘walking’, a leg is not lifted but slides on the surface. The legs slide on the glass surface due to the inertia of the robot platform and their high speed, since the sliding friction between the ruby spheres and the glass is relatively low with a lightweight robot. The platform jerks back a little, but this is usually negligible compared to the entire step length. The legs stretch out again when the new position is reached and the step is completed.

A sawtooth voltage function applied to one electrode and its inverse applied to the opposite electrode are suitable for generating microrobot ‘shuffling’. The equations below represent the voltage function for one period in the time domain and its Laplace transform:

$$U_T(t) = -\frac{2U_0}{T} t \cdot \varepsilon(t) + 2U_0 \cdot \varepsilon\left(t - \frac{T}{2}\right), \tag{11}$$

$$U_T(s) = -\frac{2U_0}{Ts^2} + \frac{2U_0}{s} e^{-s\frac{T}{2}}. \tag{12}$$

Advantage of the ‘shuffling’ type motion is that control of legs is simpler than in the case of ‘walking’. Moreover, when the robot walks its platform is rocking due to lifting its legs successively, which makes the positioning of the endeffector difficult. The disadvantage of ‘shuffling’ is a more unstable platform motion, which is highly dependent on the robot’s mass.

3.1. One-Leg Robot Model

In order to analyze the motion of the robot, we use the following ‘one-leg robot model’. The robot platform is represented by a solid body with the mass of m, and is standing on one piezoceramic leg. The leg’s axis is going through the mass center of the body. Due to the small distortion of the leg during the robot motion, this statement is considered to be valid when the robot steps. In reality, this kind of robot would be in unstable position, but the platform might be kept in a stable position continuously by applying small lateral forces, however, this has only a negligible influence on the validity of the model. The one-leg robot model is shown in *Fig.5*.

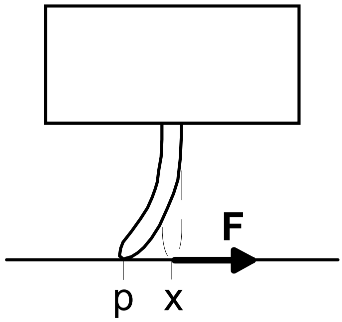

Fig. 5. One-leg robot model

3.2. The Equation of Microrobot Motion

The acceleration of the robot is caused by external forces. In horizontal direction the sliding force is effective causing the robot acceleration. The mass of the piezo leg is negligibly small compared to the mass of the robot platform. So the moving equation of the one-leg microrobot model is the following: $F = m \cdot a$, where F represents the sliding or adhesive forces and a is its acceleration. *Fig.5* shows the leg in a bent position. x indicates the movement of the mass center point of the robot from the origin, ξ represents the deviation of the leg's end point from the stress free (straight) position and p stands for the position of the leg's end point in the coordinate system. Now we can write $x = p - \xi$. Moreover, *Eqs.* (9) are valid; however, we only use the equation along the **x**-axis. The $U(t)$ applied voltage function is defined so that the electrodes on the positive side of the **x** axis have the voltage function of $u_+(t) = U(t)$, the opposite electrode has the function of $u_-(t) = -U(t)$. In summary, the above equations can be simplified into form (13) that is referred to as the *motion equation of piezoelectric microrobots*:

$$\ddot{x}(t) + \omega_0^2 x(t) = \omega_0^2[p(t) - k_U U(t)] \tag{13}$$

with

$$\omega_0^2 = \frac{1}{mk_F}. \tag{14}$$

However, function $U = U(t)$ is known, the differential equation is containing two unknown variables $x = x(t)$, $p = p(t)$, so the equation has no unambiguous solution without additional information. The motion equation can be solved applying conditions of sliding, which plays the major role during the motion. If the leg is sliding on the surface the sliding force is constant and known $|F| = \mu mg$, where μ represents the friction constant. When the lower end of the leg sticks to the surface, this point will not move and p is constant, in this case $|F| \le \mu mg$. In order to analyze the motion of the microrobot we observe the motion in the frequency domain. Let's compose the Laplace transformation of the motion equation of the microrobot

$$s^2 X(s) - sx(-0) - \dot{x}(-0) + \omega_0^2 X(s) = \omega_0^2 P(s) - \omega_0^2 k_U U(s), \qquad (15)$$

from that $X(s)$ may be determined

$$X(s) = -\frac{k_U \omega_0^2}{s^2 \omega_0^2} U(s) + \frac{\omega_0^2}{s^2 + \omega_0^2} P(s) + \frac{s}{s^2 + \omega_0^2} x(-0) + \frac{1}{s^2 + \omega_0^2} \dot{x}(-0). \quad (16)$$

3.3. *Stationary Solution of the Motion Equation*

Conditions of the Solution

The (motion) answer function has the following form:

$$x(t) = \varepsilon_T(t) x_T(t) + x_{tr}(t). \qquad (17)$$

Long time after departure of the robot the $x_{tr}(t)$ transient part of the motion disappears and the answer becomes pure periodic. Let's choose $t = 0$ in this interval. In this case if we substitute $U(s) = L\{U_T(t)\}$ into *Eq.* (16), we get $x(t) = L^{-1}\{X(s)\}$ if $t \in [0, T]$ as the expression of $x_T(t)$ in an appropriate way[2].

As it was mentioned, the movement of the base point of the piezo leg is essential in order to determine the stationary solution. Let's take the two possible cases:

a) The piezo leg continuously adheres without sliding except where the voltage function has a steep rise at $T/2$.
b) The piezo leg slides in some intervals of period T, beyond neighborhood of $T/2$.

Not detailed here, but in the case[3] of $f > 2f_0$, statement b) leads to contradiction since the force would remain within the limits of adherence, i.e. legs cannot slide

[2] $L\{\ldots\}$ stands for the Laplace-transformation and $L^{-1}\{\ldots\}$ designates the inverse Laplace- transformation.

[3] $f = 1/T$ designates the frequency of the applied voltage, $f_0 = \omega_0/2\pi$ designates the resonance frequency of the microrobot.

according to the solution except at $T/2$. Therefore, the equation shall be solved for frequencies $f > 2f_0$ according to the condition a). Based on this solution, statements can be done for frequency domain of $f < 2f_0$.

Solution of the First Semiperiod

According to the condition a), the microrobot leg does not slide in interval $t \in [0, T/2)$. Choosing an appropriate coordinate system $p(t) = 0$ and $P(s) = 0$. The initial values are $x_0 = x(-0)$, $v_0 = \dot{x}(-0)$. Substituting them into *Eq.* (16) of $X(s)$ and performing the inverse Laplace transformation we can get $x(t)$ for interval $[0, T/2)$. The expressions of $v(t)$, $F(t)$ and $\xi(t)$ can be determined by derivation.

Solution at $T/2$

The voltage function has a steep rise at $t = T/2$. However, in reality voltage changes polarity within a finite time of τ, this time, during which the voltage rises from $-U_0$ to $+U_0$, is considerably less than the period time of T. The force that accelerates the robot in this τ interval is also finite; at most it is μmg, which has a negligible speed change effect within τ time. Therefore, the change of position of the robot approximates to zero within τ.

As the voltage increases within the interval of τ, the adherence force first decreases to zero, then its absolute value increases (negative value). If the adherence force did not reach its (negative) maximum within τ, the leg would adhere all the way and the robot would not step anyhow. If the force reaches the maximum the leg slides, therefore, its value will be the sliding force. Then at $T/2 + \tau$ (using index number of $_2$):

$$\xi_2 = \xi\left(\frac{T}{2} + \tau\right) = k_F F\left(\frac{T}{2} + \tau\right) + k_U U\left(\frac{T}{2} + \tau\right) = -k_F \mu mg + U_0 k_U, \tag{18}$$

$$p_2 = p\left(\frac{T}{2} + \tau\right) = \xi\left(\frac{T}{2} + \tau\right) + x\left(\frac{T}{2} + \tau\right) = -k_F \mu mg + U_0 k_U + x\left(\frac{T}{2}\right). \tag{19}$$

The exact condition when the leg can slide within τ will be discussed later.

Solution of the Second Semiperiod

The second semiperiod $t \in (T/2 + \tau, T]$ is analyzed as a switch on phenomenon at $T/2$. Now the leg adheres, therefore, its base point will not move. Substituting $U(s)$ and $P(s)$ as the Laplace transforms of $U(t)$ and $p(t)$ into *Eq.* (16) again, and initial values of x_2 into $x(-0)$ and v_2 into $\dot{x}(-0)$ and performing the inverse transformation we get the time function of $x(t)$ in the interval $(T/2, T]$. Functions of $v(t)$, $F(t)$ and $\xi(t)$ can we get as usual.

The Entire Solution

The above equations describe the stationary motion of the robot model. The time function still contains unknown variables. Nevertheless, based on the periodic motion the following statements can be used to determine them:

$$\left.\begin{aligned} v(T) &= v(0) = v_0 \\ F(T) &= F(0) = -mx_0\omega_0^2 \end{aligned}\right\}. \tag{20}$$

Substituting the above expressions into the time functions and disregarding the calculations we get

$$x_0 = 0, \tag{21}$$

$$v_0 = \frac{2U_0k_U}{T} - \frac{\mu g}{\omega_0 \sin\dfrac{\omega_0 T}{2}}. \tag{22}$$

Interval $0 \leq t < T/2$

$$x_T(t) = \left[\frac{2U_0k_U}{T}t - \frac{\mu g}{\omega_0^2 \sin\dfrac{\omega_0 T}{2}} \sin\omega_0 t\right] \cdot \varepsilon(t), \tag{23}$$

$$v_T(t) = \left[\frac{2U_0k_U}{T} - \frac{\mu g}{\omega_0 \sin\dfrac{\omega_0 T}{2}} \cos\omega_0 t\right] \cdot \varepsilon(t), \tag{24}$$

$$F_T(t) = \frac{\mu m g}{\sin\dfrac{\omega_0 T}{2}} \sin\omega_0 t \cdot \varepsilon(t). \tag{25}$$

Interval $T/2 < t \leq T$

$$x_T(t) = \left[\frac{2U_0k_U}{T}t - \frac{\mu g}{\omega_0^2}\left(\frac{\sin\omega_0(t-T)}{\sin\dfrac{\omega_0 T}{2}} + 2\right)\right]\cdot\varepsilon\left(t - \frac{T}{2}\right), \tag{26}$$

$$v_T(t) = \left[\frac{2U_0k_U}{T} - \frac{\mu g}{\omega_0}\frac{\cos\omega_0(t-T)}{\sin\dfrac{\omega_0 T}{2}}\right]\cdot\varepsilon\left(t - \frac{T}{2}\right), \tag{27}$$

$$F_T(t) = \mu mg\frac{\sin\omega_0(t-T)}{\sin\dfrac{\omega_0 T}{2}}\cdot\varepsilon\left(t - \frac{T}{2}\right). \tag{28}$$

3.4. *Stationary Motion Characteristics by Average Values*

The complex motion can be well characterized by two average values: the step length (L) and the average speed $(\overline{v})$. The step length is the distance stepped within one period (T time)

$$L = x(T) - x(0) = 2\left(U_0k_U - \frac{\mu g}{\omega_0^2}\right). \tag{29}$$

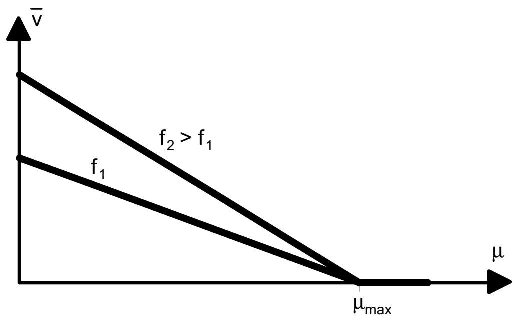

Fig. 6. Characteristics of average speed in function of friction constant

The average speed of the microrobot is the route divided by the time used, which is approximately in the case of $t \gg T$

$$\overline{v} \approx \frac{x(T) - x(0)}{T} = Lf = 2f\left(U_0k_U - \frac{\mu g}{\omega_0^2}\right) = 2f(U_0k_U - \mu mk_F g). \tag{30}$$

4. Conditions of the Periodic Motion

4.1. Planning Guides

The applied voltage function was chosen to move the robot platform to the positive part of the **x**-axis. Therefore, its average speed, i.e. *Eq.* (30) might not be negative, because that would contradict the preconditions of the motion.

$$\overline{v} \geq 0 \tag{31}$$

after substitution we get the following condition

$$\mu \leq \mu_{\max} = \frac{U_0 k_U \omega_0^2}{g} = \frac{U_0}{mg}\frac{k_U}{k_F} = -\frac{2U_0 d_{31}(R_1^2 + R_1 R_2 + R_2^2)\sin\dfrac{\Phi}{2}}{mgl \cdot S_{11}^E}. \tag{32}$$

It can be proved that this formal condition is equivalent to that, which is necessary for sliding of the leg between $T/2$ and $T/2 + \tau$. The condition means that the adhesion coefficient shall be less than $\mu_{\max}$ otherwise the robot oscillates rather than steps forward. The above condition might be the basic expression for planning piezoelectric microrobot systems.

4.2. Slow Motion of the Microrobot

In the case of frequencies $f > 2f_0$ the solution describes the motion of the robot unambiguously. During the first and second semiperiods except the neighborhood of $T/2$ the robot leg is adhering, the robot moves without sliding. At $T/2$ the piezo leg suddenly slides, which is the actual 'step' of the robot.

In the case of frequencies $f < 2f_0$, the characteristic of the motion changes. Let us suppose that the frequency is decreasing from a larger value than $2f_0$ under f_0. The sine curve in *Eq.* (23) $\sin\omega_0 t$ runs less than a quarter period till $T/2$. If $f = 2f_0$, the sine curve takes exactly a quarter period and reaches its maximum at $T/2$. If the frequency is decreasing, the sine curve takes a longer part than a quarter till $T/2$, which means that before $T/2$ $\sin\omega_0 t/\sin\omega_0 T/2 > 1$, so $F(t) > \mu mg$, which is impossible. In this case the leg slides and the sliding force takes effect, which has a value of μmg. If the frequency is still decreasing, the sine curve might take one entire or more periods before reaching $T/2$. During this period the adhesive force would exceed its maximum several times, which means that the leg would slide and then return within the limits of adhesion. However, the above is not exact because our precondition was that the leg is not sliding before $T/2$, but it shows that the complexity of the motion increases containing several adhesive and sliding parts. The motion can be described if the subsections will be solved alone depending on the frequency. This has, however, only a theoretic importance because this type of motion cannot be used for practical purposes, i.e. for moving the robot due to its complexity. If we want to move the robot slowly, it is more advantageous to apply higher frequency impulses with longer zero voltage intervals, i.e. rare impulses.

5. Summary

The paper presented a simplified model in order to describe the complex motion of a piezoelectric driven microrobot. A linear relationship is found for controlling the leg's mechanical distortion applying external force and electric voltage. Using the leg's characteristics the stationary motion of a one-leg robot model is solved, providing a lower average speed as the robot moves in an environment with higher friction constant. The results of the theoretical model shows good coincidence with experimental results measured on the test 'Miniman' type microrobot at our Department. The results presented in this paper are essential for planning and controlling [1] of piezoelectric driven microrobot systems.

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