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# Control of Oscillation Amplitude of Oscillating Motors

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## Introduction

Efficiency of reactive oscillating motors is low, so a problem of its expansion is topical. The dependence of permeance of a motor which pendulum moves along magnetic lines on coordinate of moving part is hyperbolical. Therefore rapidity of permeance $\lambda(h)$ is the biggest when air gap between stator and pendulum is small. In this case power parameters of a motor are the best [1]. But when the pendulum is being moved closer to the stator and a load is changing, possibility for pendulum to impact the stator increases. That is the reason, why it is hard to achieve the optimal motor's power parameters, therefore an air gap must be increased.

This paper deals with one of the possible simple ways of problem solving. The best position between pendulum and stator may be achieved when a motor is controlled. When a load changes rapidly an impact of pendulum to stator could be avoided by controlling a motor. The best way of control is positioning of oscillation amplitude [2], because then the determined size of controlled value is spatial coordinate of mechanical oscillations amplitude, which may be determined providing small air gap between pendulum and stator. Stabilization of oscillation amplitude can not ensure the desirable result due to possible displacement of a centre of oscillation [3-8].

Two targets are achieved, when a motor with hyperbolical changing of permeance is controlled: 1) the sharp rise part of characteristic of permeance is used, so the power parameters of drive are improved; 2) the better operating stability when the load is changing and this allows expanding the area of practice.

The case when a position of moving part is measured by simple one bit sensor for that principle realization, is analysed in this paper. Therefore measurement of pendulum position and transfer data to system microcontroller are realised by using the simple means.

## Research method

Oscillating motors, especially reactive ones, are often used for drive of simple low power device. In those cases when it is possible to improve performance of device by controlling of the motor, is advisable to use it. At the same time control has not to influence the price of product greatly. It can be achieved realising control process by using of simple means: a) motor's voltage of controlled supply source must be rectangular pulses with const amplitude and controlled width of pulse; b) microcontroller for system control; c) simple one bit sensor for feedback signal.

For analysing efficiency of that system it is necessary: 1) to create mathematical model and to control algorithm of such system; 2) to create modelling software 3) to analyse modelling of system and to evaluate the results.

## Mathematical model of system

The scheme of construction of reactive oscillating motor and its load is shown in Fig. 1, *a*, graph of permeance function in Fig. 1, *b*.

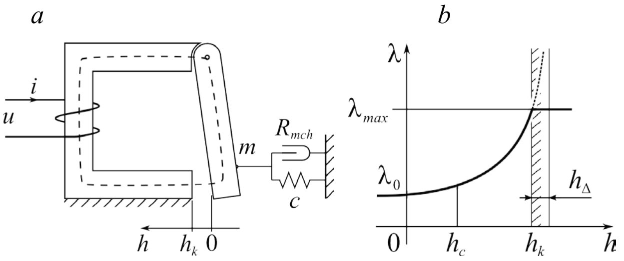

**Fig. 1.** Scheme of motor's construction and the load – *a* as well the graph of permeance function – *b*

Equation of balance of voltages of a motor

$$u = iR + w^2\lambda\frac{di}{dt} + w^2 i\frac{d\lambda}{dt}, \tag{1}$$

here $u$ and $i$ – voltage and current of a motor; $\lambda$ – permeance of air gap; $R$ – resistance of active losses of a motor; $w$ – number of turns of winding.

Hyperbolical permeance function

$$\lambda = \frac{\lambda_0 h_k}{h_k - h}, \tag{2}$$

here $h_k$ – maximal oscillating amplitude restricted of motor's construction; $h_c$ – coordinate of centre of oscillations; $h$ – coordinate of pendulum of a motor ( $h = 0$ when motor is switched off); $\lambda_0$ – air gap permeance when $h = 0$.

Permeance function (2) does not evaluate the reluctance of core. It is necessary to evaluate reluctance (Fig. 1., *b*) in case when $h=h_k$, permeance $\lambda=\lambda_{\max}$, and permeance function

$$\lambda = \frac{\lambda_0 (h_k + h_\Delta)}{(h_k + h_\Delta) - h}, \tag{3}$$

here

$$h_\Delta = \frac{\lambda_0 h_k}{\lambda_{\max} - \lambda_0}. \tag{4}$$

During approximation by using permeance function (3) it goes exactly through measured points $\lambda(0) = \lambda_0$ and $\lambda(h_k) = \lambda_{\max}$ as well between and beyond them is hyperbola.

Differential equation of reactive motor it is obtained by writing (3) to (1)

$$u = iR + w^2 \lambda \frac{di}{dt} + \frac{w^2 \lambda_0 (h_k + h_\Delta)}{(h_k + h_\Delta - h)^2} i \frac{dh}{dt}. \tag{5}$$

When a pendulum is not close to stator

$$h \le h_{\max} \tag{6}$$

equation of balance of motor's mechanical forces

$$m \frac{d^2 h}{dt^2} + R_{mch} \frac{dh}{dt} + ch = \frac{1}{2} (iw)^2 \frac{d\lambda}{dh}, \tag{7}$$

here $m$ – a mass of pendulum; $R_{mch}$ – reluctance of a load; $c$ – rigidity of a pendulum.

When the pendulum impacts to the stator

$$h > h_{\max} \tag{8}$$

the impact force appears in equation of motor's load

$$m \frac{d^2 h}{dt^2} + R_{mch} \frac{dh}{dt} + ch = \frac{1}{2} (iw)^2 \frac{d\lambda}{dh} - c_k (h - h_k), \tag{9}$$

here $c_k$ – rigidity of parts of the motor which are under the influence of an impact

$$c_k = ES; \tag{10}$$

here $E$ – rigidity of the core, $S$ – area of contact of an impact.

System of first order differential equations for modeling of the motor and its load is composed (11).

The simplest supply source is rectangular form impulses with controlled width of pulse. The mathematical model of such source (for one period of voltage $0 \le t < T$) is given in (12).

$$\begin{cases} \dfrac{dx_1}{dt} = -\dfrac{1}{w^2 \lambda} \left( R + \dfrac{w^2 \lambda_0 (h_k + h_\Delta)}{(h_k + h_\Delta - h)^2} x_2 \right) x_1 + \dfrac{u_d}{w^2 \lambda}, \\ \begin{cases} \dfrac{dx_2}{dt} = -\dfrac{R_{mch}}{m} x_2 - \dfrac{c}{m} x_3 + \dfrac{w^2 \lambda_0 (h_k + h_\Delta)}{2m (h_k + h_\Delta - h)^2} x_1^2, \text{ when } h \le h_k, \\ \dfrac{dx_2}{dt} = -\dfrac{R_{mch}}{m} x_2 - \dfrac{c}{m} x_3 + \dfrac{w^2 \lambda_0 (h_k + h_\Delta)}{2m (h_k + h_\Delta - h)^2} x_1^2 - c_k (h - h_k), \\ \text{when } h > h_k, \end{cases} \\ \dfrac{dx_3}{dt} = x_2, \end{cases} \tag{11}$$

here $u_d = u,\ \left[ x_1\ x_2\ x_3 \right]^{\mathrm{T}} = \left[ i\ \dfrac{dh}{dt}\ h \right]^{\mathrm{T}}$.

$$u_d(t) = \begin{cases} U_m, \text{ when } 0 \le t \le \tau, \\ -U_m, \text{ when } \dfrac{T}{2} \le t \le \dfrac{T}{2} + \tau, \\ 0, \text{ when } \tau < t < \dfrac{T}{2}, \text{ or } \dfrac{T}{2} + \tau < t < T. \end{cases} \tag{12}$$

here $u_d(t)$ – the instantaneous value of supply voltage; $U_m$ – an amplitude of pulses of supply voltage; τ – duration of positive or negative impulse of supply voltage. The measuring results by using one bit sensor for measure the position of oscillating amplitude $h_{mr}$

$$y = \begin{cases} 0, \text{ when } h < h_{mr}, \\ 1, \text{ when } h \ge h_{mr}. \end{cases} \tag{13}$$

## System's control algorithm

The nodes 3 – 9 of modelling algorithm, Fig. 2 are intended for the amplitude measuring sensor, node 10 – for control regulator of drive, nodes 11 – 18 for controlled supply source and node 19 for motor modelling. Additionally, these marks are used: $T$ – period of supply voltage, $T_0$ – sampling reference, $t_f$ – time of the end of modelling.

Control is synchronized with supply voltage of the motor. The motor does perform one oscillation period during half of period of supply voltage; therefore every half of period signal (13) of sensor position of pendulum is under examination, after its end it needs to calculate a new term τ of impulse of supply voltage. The term of supply voltage impulse of the next half of period is equal to calculated value. Through passing to real time this place of algorithm should be changed by saving the main feature – minimal delay.

Information about sign of deviation may be obtained from positioned coordinate measuring principle which is used, but the absolute value of deviation remains unknown. The possibilities of choosing of control principle are limited by this circumstance: the two positions or integration principles of control can be used. The two positions control principle lets have the simpler supply voltage source, but in this case an accuracy of positioning is too small, therefore the integration principle was applied in process of modelling of the system.

The quality of digital regulation depends on supply source voltage pulse wide τ, integration difference $\Delta\tau$. The transient process time is decreased. When integration difference $\Delta\tau$ is const, it is not possible to find out such value, which can make sure desirable control process.

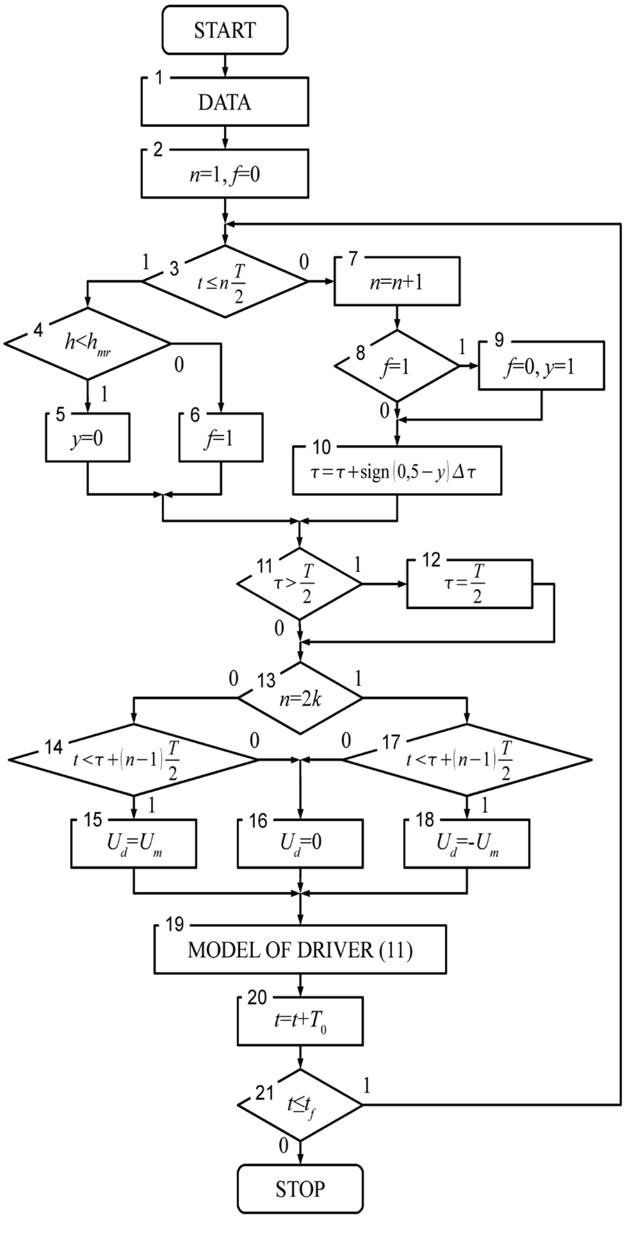

**Fig. 2.** The graph of drive modelling algorithm

When integration reference $\Delta\tau$ is changed the possibilities of tuning expand. Calculating method based on changed integration reference was created for case when sign of deviation is known but absolute value is unknown. Value of integration reference is changed evaluating time while the sign of deviation was not changed:

$$\Delta\tau = \Delta\tau_{i+1} = \begin{cases} \Delta\tau_i + k_1\Delta\tau_i, \text{when } y_i = y_{i-1} = y_{i-2}, \\ \Delta\tau_i - k_2\Delta\tau_i, \text{when } y_i = y_{i-1}, \\ \Delta\tau_i - k_3\Delta\tau_i, \text{when } y_i \ne y_{i-1}, \end{cases} \tag{14}$$

here $k_3 < k_2 < k_1$ are const coefficients chosen at tuning moment.

Formula for calculating the width τ of supply voltage is in the node 10 of graph (Fig. 2) of the drive modelling algorithm for the case when integration reference $\Delta\tau$ is const. When integration reference is changed this node has to be supplemented by formula (14) for calculating of integration reference.

## Results of drive modelling

When the drive for modeling was chosen it was oriented to the particular one, but it was not pursued high accuracy of data, because it was not necessary to do this for all drives with the hyperbolical function of permeance. The data of the motor of the drive and its load are: $U = 220\mathrm{V}$, $T$=20ms, $R = 640\Omega$, $L_0 = w^2\lambda_0 = 7{,}11\mathrm{H}$, $L_{\max} = 17{,}7\ \mathrm{H}$, $h_k = 2\cdot 10^{-3}\mathrm{m}$, $c = 1{,}1\cdot 10^4\mathrm{N/m}$, $m = 0{,}034\mathrm{kg}$, $R_{mch} = 13\mathrm{N\cdot s/m}$. Amplitude of impulses of voltage $U_m$ of the supply source when τ=10ms is such as its amplitudes of the first harmonic and motor's nominal voltage would be equal. Modeling programme for this drive applying mathematical model (4), (11)-(14) as well modeling algorithm Fig. 2 was created.

Accuracy and stability of control in the big sharp rise of the characteristic of permeance λ($h$) have been reached very hard, therefore in process of creating of mathematical model of the drive, modelling algorithm and modelling programme, there were made some assumptions that decrease stability of the system and increase reliability of positive investigation results which were obtained.

Four investigated tests of drive were modeled: Nr.1 – controlled drive was tested by positioning amplitude of pendulum; Nr.2 – the same drive was supplied only from source of electrical energy (uncontrolled); Nr.3 – the same uncontrolled drive is supplied from electrical network system by replacing the origin of coordinate system in such way as pendulum does not reach the stator when the load decreases; Nr.4 – the dependence efficiency on the position of origin of coordinates of controlled and uncontrolled drive was investigated.

The modeling results are presented in the table 1. To make it easier to compare the power is expressed in percent regarding to the power of nominal regime of uncontrolled drive.

1. Coefficients of the regulator by modeling drive (Nr.1): $k_1$=0,25, $k_2$=0,1, $k_3$=0,08, $h_{mr}$=1,85mm. Transient process when mechanical resistance $R_{mch}$ rapidly decreases 25% is shown in Fig. 3. When the load increases by the same value, reaction is different only that the pendulum does not impact to the stator. There it is not other principal differences.

**Table 1.** Modeling results

| $R_{mch}$ | Para-meters | Nr.1 | Nr.2 | Nr.3 |
|---|---|---|---|---|
| $R_{mch} = 13\mathrm{N \cdot s / m}$ | $P_{el}$ % | -3,86 | -5,29 | **±0** |
| | $P_{mch}$% | 3,14 | 0,99 | **±0** |
| | η | 0,419 | 0,417 | 0,391 |
| 0,75$R_{mch}$ | $P_{el}$ % | -8,40 | - | 12,07 |
| | $P_{mch}$% | -8.27 | - | 18,58 |
| | η | 3,915 | - | 0,414 |
| 1,25$R_{mch}$ | $P_{el}$ % | -1,57 | -13,5 | -8.14 |
| | $P_{mch}$% | 9,42 | -13,48 | -14,33 |
| | η | 4,346 | 0,391 | 0,365 |

The reaction when the load decreases 50% comparing with the case that was mentioned above (when decreasing was only 25%) Fig. 3 also is without principal differences, only the transient behavior time is longer. The main variables which characterize working of the control system, are shown in Fig. 4.

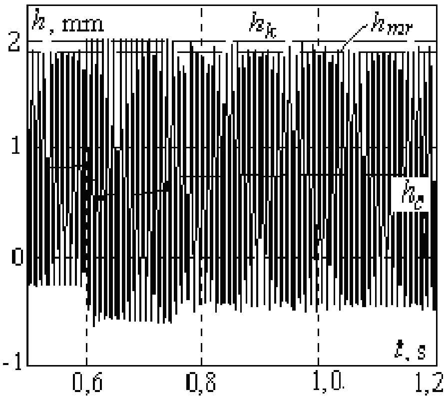

**Fig. 3.** Reaction of oscillations of controlled drive to the sharp 25% decreasing of the load when $h_k$=2 and $h_{mr}$=1,85 mm

Only positive oscillating amplitude is positioned, therefore negative amplitude and at the same time position of the centre of oscillation is changed when the load is changed. So, with the changing of the load of controlled drive, mechanical power is changed due to the load as well to the change of oscillating amplitude, but less as in case of uncontrolled drive, because oscillating amplitude is more constant.

2. The same drive was modeled as uncontrolled supplying it from electrical 220V net (test Nr.2) for evaluating the properties of controlled drive. Oscillation amplitude $h_m$=$h_{mr}$=1,85mm was obtained in case of nominal load. At the moment $t$=0,6s (Fig. 5) when the load suddenly decreases 25% the pendulum begins to impact to the stator. At the moment $t$=0,8s when the load suddenly decreases 50% the impacts come to a stop and oscillation amplitude $h_m$<1,85mm. Though power rates of an uncontrolled drive differs only a little from controlled one before stray but to use it is not always possible.

3. The initial position of the pendulum was displaced to avoid of impacts the pendulum to the stator of uncontrolled drive (test Nr.3). It is necessary to recalculate the values which depends on this displacing of the initial position (origin of coordinates Fig. 1, *b*) of the pendulum. Permeance at the origin of displaced system of coordinates

$$\lambda_0' = \frac{\lambda_0 (h_k + h_\Delta)}{(h_k + h_\Delta) - \Delta h_0}, \tag{15}$$

$$h_k' = h_k - \Delta h_0. \tag{16}$$

here $\Delta h_0$ – displacement of the origin of coordinates. All marked values belong to the new system of coordinates.

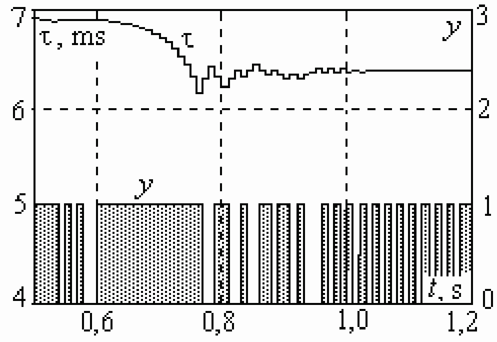

**Fig. 4.** The diagrams of the sensor's signal and of the impulse's width of supply voltage when the load decreases rapidly 25% and $h_k$=2 as well $h_{mr}$=1,85 mm

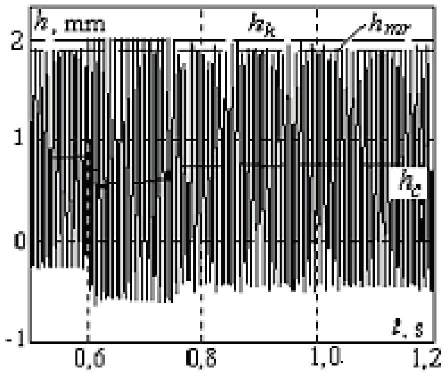

**Fig. 5.** Reaction of oscillations of uncontrolled drive to the sharp 25% decreasing and after 0,2 s sharp 50% increasing of the load when $h_k$=2 mm and $h_k$=2,15 mm

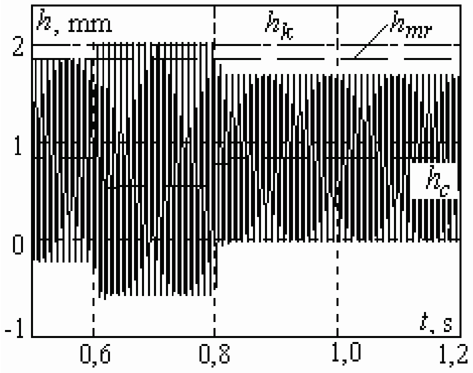

**Fig. 6.** Reaction of oscillations of uncontrolled drive to the sharp 25% decreasing and after 0,2 s sharp 50% increasing of the load when $h_k$=2,15 mm

The minimal displacement $\Delta h_0$=-0,15 mm of the origin of coordinates was found out experimentally. Then the pendulum does not reach the stator when the load deacreases and other conditions as in case Nr. 2. Power rates of uncontrolled drive when the load is nominal are worse than of controlled one.

4. Velocity of oscillations has no permanent component, therefore the component of the load of the motor which depends on $R_{mch}$ also has no permanent component. There are mechanisms which load has permanent component that is inconstant (e.g. saw). Analyzing the dependencies of efficiency on the position of the origin of coordinates (Fig. 7) it is seen that controlled drive is advantaged than uncontrolled one when the load has permanent inconstant component.

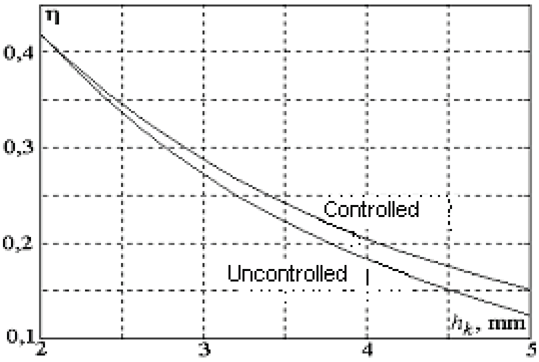

**Fig. 7.** The dependencies of efficiency of the controlled and uncontrolled drives on the position of the origin of coordinates

After displacing of the origin of coordinates from $h_k$=2mm to $h_k$=5mm input power of controlled drive has increased 2,8 times and uncontrolled one only 2,5 times.

## Conclusion

1. In this paper positioning of amplitude of oscillating motors regarding stator is analysed. There is problem, when a load is decreased it is needed to protect stator from impact of pendulum. It is proposed case how to improve characteristics of drive using the part of sharp rise of permeance characteristic.

2. From all possible cases to achieve this purpose in this paper is analyzed case when positioning is realized by simple technical means, for this purpose creating mathematical model of the system, algorithm and after by modeling.

3. Experimental results confirmed: validity of theoretical results, effectiveness of used control mode and possibility of improving of efficiency as well performance of drive.

4. It is proposed original algorithm of counting of integration difference which is adapted to the case, when sign of deviation is certain, but value of absolute deviation is unknown. This method is different from the methods of counting of reference which are used solving non-linear equations or optimization tasks, because the information about absolute deviation value and changing speed is not used there.

5. Modeling confirmed effectiveness of proposed control mode, but realizing that method in reality needs to evaluate range of factors: accuracy of measuring sensor of oscillating amplitude position. That accuracy can be influenced by its mounting, vibrations and other factors, which is hard to predict before. Experimental investigation can answer to this question. In this work received experimental results [8] has qualitative character, confirmed positive effect of oscillating amplitude positioning, but does not ensure accurate quantitative data.

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**A. Brazaitis, E. Guseinovienė, V. Jankūnas. Control of Oscillation Amplitude of Oscillating Motors // Electronics and Electrical Engineering. – Kaunas: Technologija, 2010. – No. 3(99). – P. 77–82.**

The problem of increasing of performance parameters and efficiency of oscillating motors with hyperbolical dependence of permeance is analyzed in this paper. For this purpose it is used sharp rise part of dependence of permeance on coordinate of pendulum $\lambda(h)$ approaching pendulum to the stator at most. It was used positioning of oscillating amplitude regarding the stator with aim to avoid of impacts the pendulum to the stator when working conditions change. Method was certified by modeling. In process of drive modeling for realizing of this principle simple modern technical means were used: microcontroller for system control, motor’s voltage of controlled supply source must be rectangular pulses with const amplitude and controlled width of pulse, simple one bit sensor for feedback signal. Modeling results confirm that purpose can be achieved. Ill. 7, bibl. 8, tabl. 1 (in English; abstracts in English, Russian and Lithuanian).

**А. Бразайтис, Э. Гусейновене, В.Янкунас. Управление амплитудой колебаний синхронных двигателей колебательного движения // Электроника и электротехника. – Каунас: Технология, 2010. – № 3(99). – С. 77–82.**

В статье анализирована проблема улучшения эксплуатационных качеств и коэффициента полезного действия двигателей колебательного движения с гиперболической зависимостью магнитной проводимости от координаты подвижной части. Для достижения цели используется часть характеристики магнитной проводимости от координаты подвижной части $\lambda(h)$ с наибольшим подъемом – подвижную часть максимально приближая к статору. Использовано позиционирование амплитуды колебаний по отношению к статору с целью избежания удара подвижной части в статор. Метод проверен при помощи моделирования. Моделирован привод, в котором для реализации принципа использованы простейшие современные технические средства: для управления системы использован микроконтроллер, выходное напряжение управляемого источника питания – импульсы управляемой ширины прямоугольной формы, датчик одного бита для измерения позиции подвижной части. Результаты моделирования показали, что цель достигнута. Ил. 7, библ. 8, табл. 1 (на английском языке; рефераты на английском, русском и литовском яз.).

**A. Brazaitis, E. Guseinovienė, V. Jankūnas. Švytuojamųjų variklių švytavimų amplitudės valdymas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 3(99). – P. 77–82.**

Straipsnyje sprendžiama švytuojamųjų variklių, kurių magnetinio laidžio funkcija yra hiperbolinio pobūdžio, naudingumo koeficiento ir eksploatacinių savybių gerinimo problema. Tikslui pasiekti maksimaliai panaudojama magnetinio laidžio $\lambda(h)$ priklausomybės didžiausio statumo dalis – švytuoklę maksimaliai priartinant prie statoriaus. Kad, keičiantis darbo sąlygoms, švytuoklė neatsitrenktų į statorių, švytavimų amplitudė pozicionuojama statoriaus atžvilgiu. Metodas patikrintas modeliuojant. Modeliuojama pavara, kurioje principui realizuoti yra panaudotos paprasčiausios šiuolaikinės techninės priemonės: sistemai valdyti – mikrovaldiklis, valdomo maitinimo šaltinio išėjimo įtampa – stačiakampės formos valdomo pločio impulsai, švytuoklės pozicijai matuoti – vieno bito jutiklis. Modeliavimo rezultatai rodo, kad tikslas pasiekiamas. Il. 7, bibl. 8, lent. 1 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).