530. Control possibilities of oscillating electrical motor using FFT analysis data

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Abstract. The paper considers the issue of control of linear springless oscillating electrical motor by means of FFT analysis data of motor total current. The main idea of this control is the usage of relationships between harmonics information and oscillation velocity, distance; the controller would calculate the control signal for the next period. This control would have an advantage of fewer sensors – just current measuring sensor, and there would be no need for distance or velocity sensors, but the current sensor should be reserved. Other problem of this control is to determine relationships $h=f(\alpha, f, i_0, i_1, i_2,..)$, $v = f(\alpha, f, i_0, i_1, i_2,..)$, $P = f(\alpha, f, i_0, i_1, i_2,..)$, $F_{elm} = f(\alpha, f, i_0, i_1, i_2,..)$. These relationships differ for various types of devices due to the hysteresis effect and construction of the devices, however they would be similar for the same series.

Keywords: oscillating electrical motor, FFT analysis, control, approximation, harmonics, total current feedback.

Introduction

The most popular oscillating motors are rotary and linear in respect to movement type. The type of motor analyzed in this paper is oscillating linear motor, but the similar analysis can be adapted to the rotary oscillating motors. The applications of linear oscillating electrical motor (LOEM) in cryogenic devices, pumps, piston compressors, vibrofeeders, hair cutters and other devices are widely spread and control of LOEM is very important for changing the output parameters of mentioned devices.

The main control output parameters of the LOEM are [1, 3, 4, 7]:

- oscillating amplitude H_m=var or coordinate h=var;
- oscillating centre stabilization $\Delta h_c \to 0$ or control of its movement Δh_c=var;
- oscillating velocity control v=var [9];
- output power P and electromagnetic force F_{elm} stabilization, when the load of the motor changes [9];
- collision detection in the double-sided springless LEOM and etc.

The control can be realized by controlling supply source parameters such as output voltage, pulse duration, frequency variations of sine and square wave forms and using feedback of the mentioned output parameters [1-4].

The most common feedbacks are from oscillating coordinate h, oscillating velocity v and total current i_T [1, 3, 4]. Also the breaking force of linear motor was examined in accordance with spectrum analysis [10]. These all feedbacks use sensors for each of the parameters thus making the device dependable on the reliability of several sensors mounted on the vibrating device. In this paper an idea is presented that makes use of only one feedback from the total current and using its spectrum for taking all the needed information for the control of the LOEM. This feedback is almost invariant to the vibration affect on the sensor though it has one main disadvantage – it needs to be reserved, because the defect of the sensor will lead to the uncontrolled work of the device. But this disadvantage is common to other feedbacks as well.

Theoretical approach

The theoretical research was limited to the double-sided springless LOEM with pulsating current source with the piston compressor load (Fig. 1).

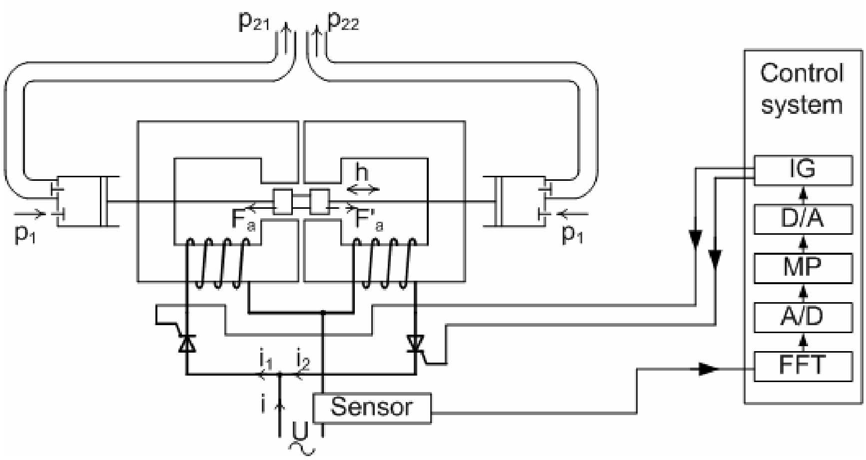

Fig. 1. Double-sided springless LOEM with pulsating current source with the piston compressor load. Where FFT is Fast Fourier Transform block, A/D – analog/digital converter, MP – microprocessor or microcontroller, D/A – digital/analog converter, IG – control impulse generator

The main aim of the research is to find the relationships:

$$h=f(\alpha, f, i_0, i_1, i_2,..), \quad (1)$$

$$v = f(\alpha, f, i_0, i_1, i_2,..), \quad (2)$$

$$P = f(\alpha, f, i_0, i_1, i_2,..), \quad (3)$$

$$F_{elm} = f(\alpha, f, i_0, i_1, i_2,..), \quad (4)$$

where α is thyristor firing angle, f is supply voltage sine or pulse frequency, i_0 is a constant value of the total current, i_1, i_2, i_3 and etc. are the main, higher harmonics of the total current i and the other parameters mentioned above.

The relations (1)-(4) are very common and are difficult to realize because the current harmonics depend on the time t, harmonics amplitude I_m and phase φ. So for the more realized control there are some assumptions made, which are listed below:

- due to the double-sided springless LOEM the total current spectrum does not have even harmonics;

- the total current i spectrum has sufficiently informative 1st, 3rd and 5th harmonics as shown in Fig. 2, other harmonics are very small and their usage is limited due to the noise influencing them;

- constant value i_0 of the total current i gives the information about the centre displacement which is presented in papers and is not investigated here [7, 9];

- phase φ influence is not analyzed in this paper, but it could also give an additional information for the control algorithm;

- the control will be based on the total current relative harmonics' amplitudes:

$$\mathbf{i_m} = \{i_{0m}, i_{1m},\ i_{2m}, ...\} = \{\frac{I_0}{I_{1m}}, \frac{I_1}{I_{1m}}, \frac{I_2}{I_{1m}}, ...\}, \tag{5}$$

where I_{1m} is the 1st harmonic amplitude, when thyristor firing angle α=0°, i_{nm} – is a n-th relative harmonic amplitude;

- the influence of the hysteresis effect, which depends on the materials and the construction of the magnetic circuit is not analyzed, but in general it can be involved in the equations (1)-(4) by using the coefficient k_{hist}=f(f, material properties, curvature of the magnetic curve, lamination thickness of the material,…);

- the coordinate control h is not so important for the compressor as its oscillating amplitude H_m;

- frequency f was not changed for the modeling, so f=const (50 Hz was used for the investigation).

These assumptions are made for the model and some of them are general like 2nd, 4th, 5th, the others are more suitable for the double-sided LOEM-compressor drive.

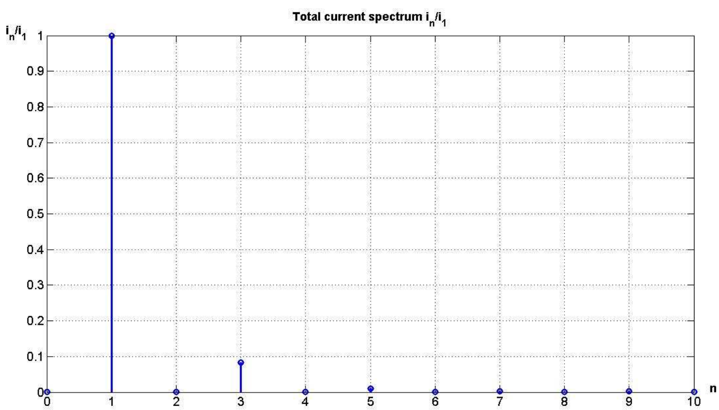

Fig. 2. Total current i relative spectrum modeled for the double-sided springless LOEM with pulsating current source with the piston compressor equivalent load

After these assumptions equations (1)-(4) can be rewritten respectively:

$$h = f(\alpha, i_{1m},\ i_{3m}, i_{5m}), \tag{6}$$

$$v = f(\alpha, i_{1m},\ i_{3m}, i_{5m}), \tag{7}$$

$$P = f(\alpha, i_{1m},\ i_{3m}, i_{5m}), \tag{8}$$

$$F_{elm} = f(\alpha, i_{1m},\ i_{3m}, i_{5m}). \tag{9}$$

The equations (6)-(9) are multivariable and are difficult to represent in graphical form so they can be represented more efficiently in tables as data collections and can be represented graphically with two arguments (3-D graphics).

The equations (6)-(9) for the double-sided springless LOEM with other type of supply voltage source will have little difference:

- frequency variations of sine or square wave form voltage supply:

$$h = f(f, i_{1m}, i_{3m}, i_{5m}), \quad (10)$$

$$v = f(f, i_{1m}, i_{3m}, i_{5m}), \quad (11)$$

$$P = f(f, i_{1m}, i_{3m}, i_{5m}), \quad (12)$$

$$F_{elm} = f(f, i_{1m}, i_{3m}, i_{5m}). \quad (13)$$

- PWM variations square wave form voltage supply:

$$h = f(T, i_{1m}, i_{3m}, i_{5m}), \quad (14)$$

$$v = f(T, i_{1m}, i_{3m}, i_{5m}), \quad (15)$$

$$P = f(T, i_{1m}, i_{3m}, i_{5m}), \quad (16)$$

$$F_{elm} = f(T, i_{1m}, i_{3m}, i_{5m}). \quad (17)$$

- complex supply voltage variations:

$$h = f(\alpha, f, T, i_{1m}, i_{3m}, i_{5m}), \quad (18)$$

$$v = f(\alpha, f, T, i_{1m}, i_{3m}, i_{5m}), \quad (19)$$

$$P = f(\alpha, f, T, i_{1m}, i_{3m}, i_{5m}), \quad (20)$$

$$F_{elm} = f(\alpha, f, T, i_{1m}, i_{3m}, i_{5m}). \quad (21)$$

Application of analytical approach to these equations is difficult due to the nonlinearity of the electromagnetic system of LOEM. So the investigation of these dependencies will be analyzed using mathematical modeling and will be more empirical than theoretical.

Mathematical model

The mathematical model for double-sided LOEM without considering mutual inductance is presented below as a differential equation system. The model was analyzed more explicitly in papers [5, 6], so here we present only the main equations.

$$\begin{cases} \dfrac{dh}{dt} = v, \\ \dfrac{dv}{dt} = \dfrac{1}{2 \cdot m} \cdot i_{Ll}^2 \cdot \dfrac{dL_1(h)}{dh} + \dfrac{1}{2 \cdot m} \cdot i_{L2}^2 \cdot \dfrac{dL_2(h)}{dh} - \dfrac{R}{m} \cdot v - \dfrac{C}{m} \cdot h, \\ \dfrac{di_{L1}}{dt} = \dfrac{1}{\tau_1(h) \cdot r_{11}} \cdot u - \dfrac{1}{\tau_1(h)} \cdot i_{L1} - \dfrac{\tau_{11}(i_{L1}, h)}{\tau_1(h)} \cdot v, \\ \dfrac{di_{L2}}{dt} = \dfrac{1}{\tau_2(h) \cdot r_{21}} \cdot u - \dfrac{1}{\tau_2(h)} \cdot i_{L2} - \dfrac{\tau_{22}(i_{L2}, h)}{\tau_2(h)} \cdot v. \end{cases} \quad (22)$$

where in the model h is a double-sided LOEM oscillation coordinate, i_{L1} and i_{L2} are double-sided LOEM the 1st and 2nd winding induction currents, u is a supply voltage – sinusoidal or square wave, r_{11} and r_{21} are double-sided LOEM the 1st and 2nd winding resistances, which estimate the power losses in the electrical circuit of the motor (values for modeling: $r_{11} = r_{21} = 45\ \Omega$), r_{12} and r_{22} are double-sided LOEM the 1st and 2nd winding resistances, which estimate the power losses in the magnetic circuit of the motor (values for modeling: $r_{12} = r_{22} = 3000\ \Omega$ for the frequency of 50 Hz and it will be changed by changing the frequency, because hysteresis losses are proportional to frequency $P_h \sim f(f)$ and eddy current losses are proportional to f^2- $P_{eddy} \sim f(f^2)$), L_1 and L_2 are double-sided LOEM the 1st and 2nd winding inductions, which depends from the coordinate h and this dependency is sinusoidal [7] (values for modeling: L_{min} = 0,96 H; L_{max} = 4,14 H; L_0 = 2,55 H), R is viscous friction coefficient (22) (values for modeling: R = 10 Ns/m),

C is spring coefficient, which as air spring in cylinder chamber is dependent from piston stroke h and then it will be modeled as a linear mechanical system (22) (values for modeling: C = 20000 N/m; 22500 N/m; 25000 N/m; 27500 N/m and 30000 N/m).

The modeling was carried out changing the firing angle α of the thyristors and changing the load (C coefficient). The results are presented in the next chapter.

Results of analysis

Modeling of the system was performed by observing such parameters of double-sided LOEM as:

- oscillating amplitude H_m;
- rms value of oscillating amplitude h_{rms};
- rms value of oscillating velocity v_{rms};
- rms values input $P_{in.rms}$ and output powers $P_{out.rms}$;
- rms value of electromagnetic force $F_{elm.rms}$;
- total current i spectrum relative values i_{1m}, i_{3m} and i_{5m}.

The modeling results when spring parameter C=25000 N/m are presented in Table 1.

Table 1. Results of modeling of the double-sided LOEM

No.	α	H_m	h_{rms}	v_{rms}	$P_{in.rms}$	$P_{out.rms}$	$F_{elm.rms}$	I_{1m}	i_{1m}	i_{3m}	i_{5m}
-	**°**	**m**	**m**	**m/s**	**W**	**W**	**N**	**A**	**-**	**-**	**-**
1	0	0,0132	0,0094	2,956	219,16	131,02	40,48	1,4125	1	0,0825	0,0104
2	5	0,0132	0,0094	2,946	217,90	129,88	40,30	1,4048	0,995	0,0822	0,0100
3	10	0,0131	0,0093	2,920	214,58	126,87	39,83	1,3843	0,980	0,0816	0,0092
4	15	0,0129	0,0092	2,877	209,49	122,29	39,12	1,3532	0,958	0,0811	0,0088
5	20	0,0126	0,009	2,818	202,61	116,14	38,15	1,3116	0,929	0,0811	0,0092
6	25	0,0124	0,0088	2,767	197,02	111,20	37,35	1,2783	0,905	0,0811	0,0098
7	30	0,012	0,0085	2,673	187,20	102,58	35,94	1,2206	0,864	0,081	0,0107
8	35	0,0115	0,0081	2,556	175,76	92,67	34,24	1,1549	0,818	0,0802	0,0119
9	40	0,0108	0,0077	2,413	162,89	81,74	32,25	1,0823	0,766	0,0771	0,0135
10	45	0,0101	0,0071	2,245	148,85	74,04	29,95	1,0052	0,712	0,0718	0,0152
11	50	0,0095	0,0067	2,120	139,00	62,16	28,25	0,9519	0,674	0,0668	0,0162
12	55	0,0086	0,0061	1,912	123,84	50,30	25,46	0,8708	0,616	0,0575	0,0169
13	60	0,0076	0,0054	1,687	108,72	39,02	22,44	0,7895	0,559	0,0473	0,0163
14	65	0,0065	0,0046	1,452	94,24	28,92	19,31	0,7105	0,503	0,0372	0,0144
15	70	0,0058	0,0041	1,297	85,21	23,09	17,25	0,6602	0,467	0,0311	0,0124
16	75	0,0048	0,0034	1,073	72,79	15,89	14,29	0,5894	0,417	0,0241	0,0088
17	80	0,0039	0,0028	0,869	61,85	10,50	11,61	0,5247	0,371	0,0207	0,0067
18	85	0,0031	0,0022	0,691	52,39	6,70	9,27	0,4664	0,330	0,0222	0,0096

Results listed in the Table 1 indicate that the increase of the thyristor firing angle α results in reduction of such parameters as: H_m, h_{rms}, v_{rms}, $P_{in.rms}$, $P_{out.rms}$, $F_{elm.rms}$, I_{1m}, i_{1m}. But the harmonics i_{3m} and i_{5m} demonstrate different type behavior. The third harmonic decreases till the α=85°, and the 5th harmonic of the total current of double-sided LOEM has an oscillating form of behavior. This just represents the analyses of the same load - in other cases the behavior is similar. Fig. 3 illustrates the results of the modeling.

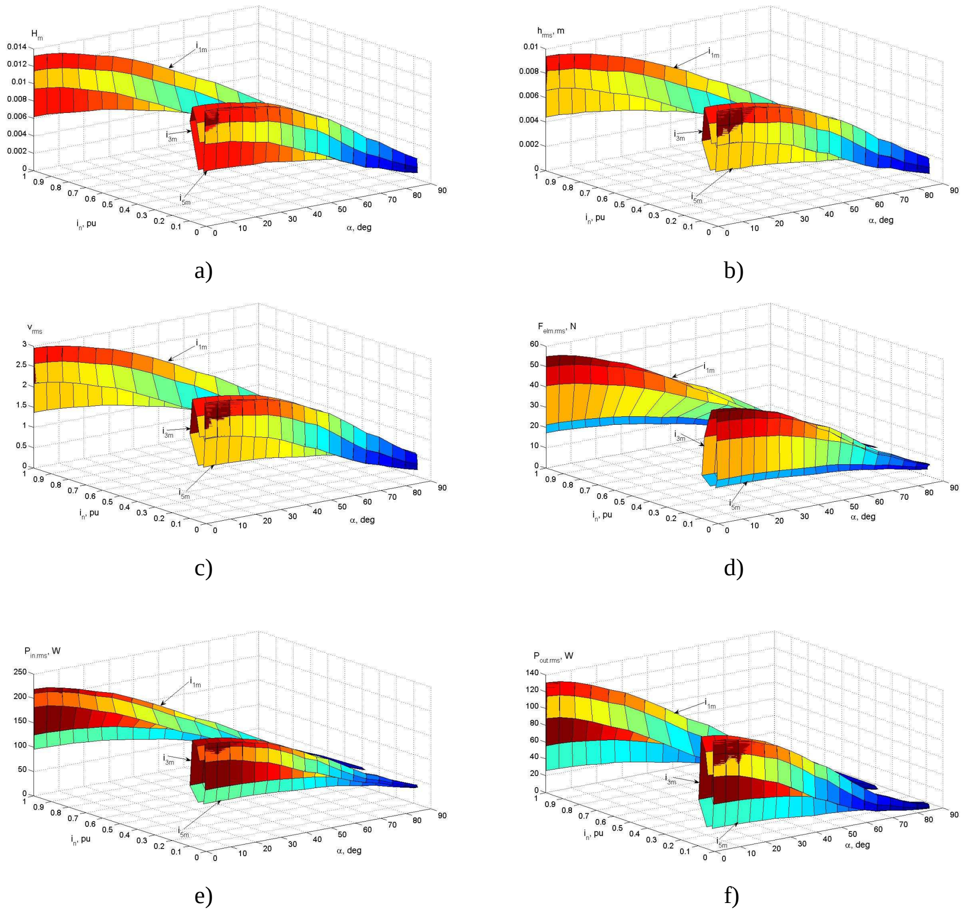

Fig. 3. Dependences illustrating modeling results: a – oscillating amplitude H_m=$f(\alpha,\ i_{1m},\ C)$, H_m=$f(\alpha,\ i_{3m},\ C)$ and H_m=$f(\alpha,\ i_{5m},\ C)$, b – oscillating coordinate rms h_{rms}=$f(\alpha,\ i_{1m},\ C)$, h_{rms}=$f(\alpha,\ i_{3m},\ C)$ and h_{rms}=$f(\alpha,\ i_{5m},\ C)$, c – oscillating velocity rms v_{rms}= $f(\alpha,\ i_{1m},\ C)$, v_{rms}=$f(\alpha,\ i_{3m},\ C)$ and v_{rms}=$f(\alpha,\ i_{5m},\ C)$, d – electromagnetic force rms $F_{elm.rms}$= $f(\alpha,\ i_{1m},\ C)$, $F_{elm.rms}$=$f(\alpha,\ i_{3m},\ C)$ and $F_{elm.rms}$=$f(\alpha,\ i_{5m},\ C)$, e – input power rms $P_{in.rms}$= $f(\alpha,\ i_{1m},\ C)$, $P_{in.rms}$=$f(\alpha,\ i_{3m},\ C)$ and $P_{in.rms}$=$f(\alpha,\ i_{5m},\ C)$, f - output power rms $P_{out.rms}$= $f(\alpha,\ i_{1m},\ C)$, $P_{out.rms}$=$f(\alpha,\ i_{3m},\ C)$ and $P_{out.rms}$=$f(\alpha,\ i_{5m},\ C)$

The results demonstrate the complexity of the mentioned dependences (6)-(9), but they have similarity to each other. Fig. 3 was presented by changing the load also, but if the load had been kept the same the result would have been a complex 3D curve. The surfaces do not suggest any analytical dependences, but by the curves similarity to each other, they should be present. This sets the task for analyzing more different loads and using simpler equations for describing mentioned parameters as an example for oscillating coordinate of LOEM:

$$h = f(\alpha,\ i_{1m}, C, R), \tag{23}$$

$$h = f(\alpha,\ i_{3m}, C, R), \tag{24}$$

$$h = f(\alpha, i_{5m}, C, R), \tag{25}$$

and etc.

Analysis of systems of the equations (23)-(25) might give more analytically describable results. Also the analysis of the phase φ of each harmonic could present more information needed for the analytical analysis.

Conclusions

Results of modeling of double-sided springless LOEM yielded the following conclusions about the ability to understand the behavior of the total current spectrum, which information could be applied for the control of this device:

1. Each harmonic provides a different response to the load and changing thyristor firing angles therefore the harmonics may be analyzed separately.
2. The obtained dependencies (in Fig. 3) are complex surfaces and do not have a clear analytical description, thus it requires more modeling and variation of the parameters in order to reveal analytical tendencies and relationships.
3. Further analysis will be conducted by changing load (*C* and *R* parameters) and analyzing harmonic phases.

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