OPERATION OF ELASTIC COUPLING WITH NONLINEAR MECHANICAL FEEDBACK IN THE MOTOR STARTING MODE

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ABSTRACT

Modeling the work of elastic couplings with nonlinear mechanical coupling linkage in the mode of transmission starting from a technical system whose harmonic disturbance has been carried out.

An estimation of efficiency of elastic couplings application for solving problems of oscillatory processes optimization has been done. Recommendations concerning the use of elastic couplings for overcoming "multiple" resonances without the use of additional dissipation devices have been developed.

Key words: *elastic coupling, mechanical feedback, elastic characteristic.*

1. INTRODUCTION

Elastic couplings with metal elastic elements have become widely spread in modern mechanical engineering. This is facilitated by the ability of these devices not only to transmit torque, but also to prevent negative demonstrations of oscillations in a technical system. Studies using mathematical models proved that elastic couplings with a nonlinear elastic characteristic show the most positive results [1]. However, already existing elastic couplings do not fully meet the stated requirements due to their narrow working range [2]. Up to now created potential designs of elastic couplings that implement a nonlinear elastic characteristic are not widely used due to the small number of their actual mechanical constructions.

2. RESEARCH OBJECTIVE

Mathematical modeling of oscillatory process of transmission starting of a machine assembly with an asynchronous electric motor, which consist of an elastic coupling with nonlinear mechanical feedback and studying the effect of elastic characteristics on the magnitude of the amplitude, frequency of the oscillatory process and its time.

3. EXPOSITION OF MAIN STUFF OF THE RESEARCH

The chosen research aim is based on the fact that the results of the researches carried out in the field of nonlinear oscillation mechanics indicate that the nonlinearity of elastic characteristics of one of the components of machine assembly can significantly change the nature of oscillatory processes.

In the given research area it is believed that the starting torque M_{start} of the asynchronous motor shaft is a torque that advances on the shaft of an asynchronous electric motor under the following conditions: the speed of rotation is equal to 0, the current is a constant, the electric motor windings are connected to rated supply frequency and voltage, the winding connection corresponds to rated operating mode of electric motor.

In mathematical modeling of oscillatory processes of a machine assembly the starting torque $M_s(t)$ is modeled by a time function characterized by two time intervals: build-up time to the maximum valuet_1 and decrease time to the rated value t_2. To calculate the maximum starting torque the following formula is used

$$M_{max} = M_r k_{tr} \quad (1)$$

where M_r – rating moment on the electric motor shaft; k_{tr} – starting torque ratio. The value of this parameter varies within 1.5 ... 6 for different types of engines and loads.

Duration of the starting torque is determined experimentally, depending on the type of engine and the type of its load (usually it varies within 0,5...1,6 s).

In order to achieve this goal a two-mass rotatory mechanical system (J_1 – main rotating mass, subject to protection against negative demonstration of the starting torque), which includes the proposed passive elastic coupling with a nonlinear mechanical linkage(J_2 – the second rotating mass, which is the mass of the coupling) should be subject to mathematical modeling. Thus the system of differential equations has the following form

$$\begin{cases} J_1\ddot{\varphi}_1 + b_1\dot{\varphi}_1 - b_2(\dot{\varphi}_2 - \dot{\varphi}_1) + c_1\varphi_1 - c_2(\varphi_2 - \varphi_1) = 0 \\ J_2\ddot{\varphi}_2 + b_2(\dot{\varphi}_2 - \dot{\varphi}_1) + c_2(\varphi_2 - \varphi_1) = M_s(t) \end{cases} \quad (2)$$

However, the rotating mass of the J_2coupling in several cases is less than the rotating mass of J_1 transmission objects ($J_2 >> J_1$) and the stiffness of the shaft sections, which determines the torsion angle φ_1, is several times greater than the stiffness of the elastic coupling, which determines the torsion angle φ_2($\varphi_2 >>\varphi_1$).

It is advisable to carry out mathematic studies of transmission starting process of a machine assembly with an asynchronous electric motor, which includes the proposed elastic coupling, using a mathematical model of a single-mass rotatory system. In this case, the model treats the rotating mass J_1 as an object to be protected from negative demonstration of the starting torque, and the elastic coupling is considered as an elastic linkage between it and the engine. Then the corresponding differential equation will have the following form

$$J\ddot{\varphi} + M_{el}(\varphi) + M(\dot{\varphi}) = M_s(t), \qquad (3)$$

where J – moment of inertia of the rotating mass; $M_{el}(\varphi)$ – elastic characteristic, which depends on the stiffness of elastic elements applied in the coupling; $M(\dot{\varphi})$ – moment of dissipation, which determines the irreversible energy dissipation; $\dot{\varphi}$ and $\ddot{\varphi}$ – corresponding derivatives of the angular displacement in time$t$.

Initial conditions are as follows

$$\varphi(0)=0,\ \dot{\varphi}(0) = 0,\ M_s(0)=0 \qquad (4)$$

On the basis of the equation (3) mathematical modeling of the oscillatory processes of transmission starting of a machine assembly with an asynchronous electric motor AIR112MV6 was carried out with the following characteristics: P = 4 kW, n = 1000 rpm; rating moment M_{rat}= 34,5 Nm; starting torque ratio k_{tr}= 1,8; time of the starting torque t_s= 0,8 s.

In calculations the starting torque is presented in the form of two non-linear sections associated with time and has a maximum $M_{s\max}(0,026)$ = 61 Nm (fig. 1, a)

$$t_{s1} = 0...0{,}026\text{s}$$
$$M_{mot} = M_{s1}(t) = 162299t^2 + 6312{,}1t + 3{,}4857;$$
$$t_{s2} = 0{,}026…0{,}8\text{ s}, \qquad (5)$$
$$M_{mot} = M_{s2}(t) = 16229t^2 - 4512{,}1t - 2{,}5734;$$
$$t_s > 0{,}8\text{ s},\quad M_{mot} = M_r, = 34{,}5\text{ Nm}$$

For the possibility of conducting a comparative analysis in order to determine the appropriate efficiency ratios, the calculation of the accepted conditions of the system, containing an elastic coupling with a linear elastic characteristic, was carried out (fig. 1, b). Using the Maple 18 mathematical package, where the corresponding function implements the Runge-Kutta method, the solution of equation (3) was carried out in numerical form, taking into account the initial conditions (4) and external load (5). Emerging at the process of transmission starting of a machine assembly with an asynchronous electric motor, the oscillatory process is fading and low frequency with a constant frequency T = 2 Hz (fig. 1, c). Oscillatory processes with the frequency of the first frequency octave (T = 2, 4, 8, 16, 31.5, 63 Hz) refer to the low-frequency oscillatory process. The system response to external disturbance in the form of M_{J1} = 59,3 Nm occurs with delay after the appearance of the maximum external load (t^* = 0,18 s), which is due to the presence of an elastic linkage. Oscillation decay time under condition of $M_{J1} = M_r$ equals t = 6,7 s.

The coefficient that determines the efficiency of usage of an elastic coupling with a linear elastic characteristic is the coefficient of vibration isolation

$$k_R = \frac{M_0}{A_0}, \qquad (6)$$

whereM_0 – amplitude of the moment behind the coupling; A_0 – amplitude of the moment of disturbance.

In this case the coefficient of vibration isolation is

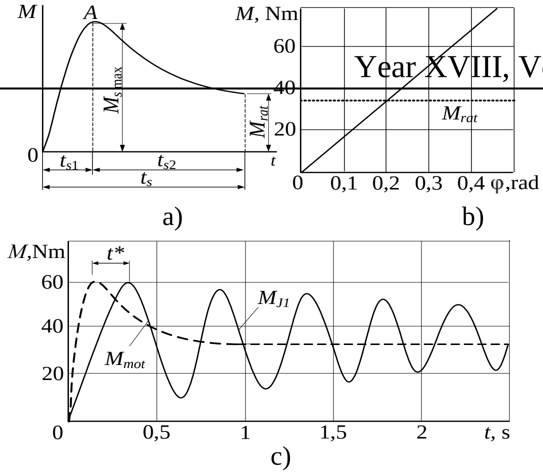


Figure 1.Modelling of oscillatory processes of transmission starting of a machine assembly: starting torque (a); linear elastic characteristic (b); oscillatory process of transmission starting of a machine assembly with a coupling that possesses linear elastic characteristic (c)

$$k_R = \frac{M_0}{A_0} = \frac{59{,}3}{61} = 0{,}97. \qquad (7)$$

Numerical solution of the equation (3) is carried out in cases where the elastic characteristic of the coupling is nonlinear, taking into account the general parameters of the system, the initial conditions (4) and the external load (5).

In the first case the coupling determined an elastic characteristic of a "soft" Duffing type. The value of the elastic torque at a certain nominal torsion angle of half-couplings φ = 0,2 rad. was equal to the value of the elastic torque of the previously considered linear characteristic M = 34,5 Nm (fig. 2, a). Emerging at the start of the transmission of the machine assembly with an asynchronous electric motor, the oscillatory process is fading and low frequency with frequency T, which increases over time (fig. 2, b).

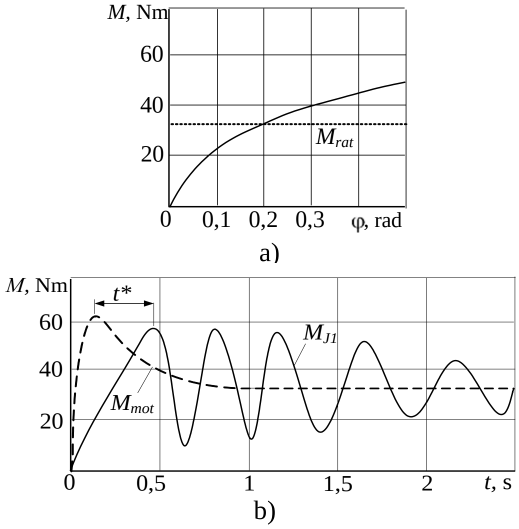
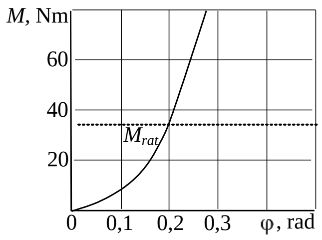


Figure. 2.Oscillatory process of asynchronous motor starting: elastic characteristic of a “soft” Duffing type coupling (a); oscillatory process (b).

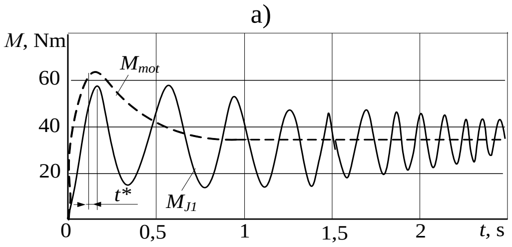
The response of the system to external disturbance (M_{J1} = 57,23 Nm) occurs with delay after the appearance of the maximum external load (t^* = 0,38 s), which is defined by the elastic torque. It should be noted that in this case the value of elastic torque is less than the similar one in the linear system, and lays in the range of the torsion angle of the half-couplings (φ = 0,2...0,6 rad). Oscillation decay time, which is determined by $M_{J1} = M_r$, equals t = 8,3 s. The coefficient of vibration isolation k_R in this case is

$$k_R = \frac{M_0}{A_0} = \frac{57{,}34}{61} = 0{,}94. \qquad (8)$$

In the second case the coupling determined an elastic characteristic of a "hard" Duffing type. The elastic torque value at a certain nominal torsion angle of half-couplings φ = 0,2rad was equal to the elastic torque value of the previously considered linear characteristic M = 34,5 Nm (fig. 3,a).



a)



b)

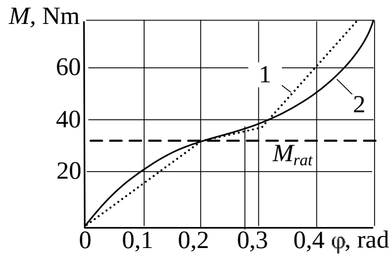
Figure. 3.Oscillatory process of asynchronous motor starting: elastic characteristic of a "hard" Duffing type coupling (a); oscillatory process (b).

Emerging at the start of the transmission of a machine assembly with an asynchronous electric motor, the oscillatory process is fading and low frequency with a frequency T decreasing over time (fig. 3, b). The response of the system to external disturbance (M_{J1} = 59,16Nm) occurs with delay after the appearance of the maximum external load (t^* = 0,16 s), which is defined by the elastic torque. In this case the value of elastic torque is higher than the similar one in the linear system, and lays in the range of the torsion angle of the half-couplings (φ = 0,2...0,6 rad). The decay time of the oscillatory process is determined by$M_{J1} = M_r$ and equals t = 3,4s. The coefficient of vibration isolation k_R in this case is

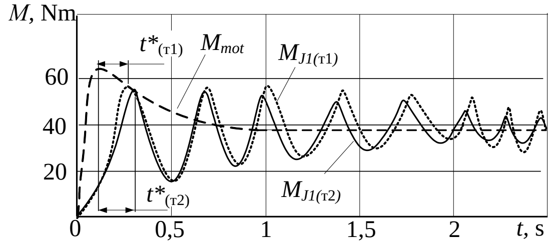
$$k_R = \frac{M_0}{A_0} = \frac{59{,}13}{61} = 0{,}96. \qquad (9)$$

Results of mechanical studies conducted to optimize the oscillatory process during transmission starting with an asynchronous motor show that the use of nonlinear couplings with elastic characteristics of a "hard" Duffing type can reduce the time of the oscillatory process; however it determines the transmission load close to the starting torque. Application of nonlinear couplings with elastic characteristics of a "soft" Duffing type allows slight reduction of the transmission load, at the same time it lengthens the time of the oscillatory process. Taking this into account it is proposed to use nonlinear couplings with a combined characteristic in order to solve such a problem. The basis for such a proposal is the results of research done by Professor G.V. Arkhangelskiy [3]. It has been established that optimization of the oscillatory process, occurring at the start of transmission with an asynchronous motor, can be obtained by applying a nonlinear elastic coupling in the transmission, which implements a combined characteristic with two sections, determined by the value of the rating rotary moment. The first section ($M = 0 \ldots M_r$) must correspond to the elastic characteristic of the "soft" Duffing type and the second section ($M = M_r \ldots 1{,}3M_s$) must relate with the elastic characteristic of the "hard" Duffing type. The researcher has proposed a specialized design of an elastic coupling that implements a similar characteristic, but because of structural constraints its elastic characteristic corresponds to the target characteristic with a compliance coefficient equal to k_c = 0,89 and is fragmentarily linear (line 1, see fig. 4, a).

From this perspective the calculations of the oscillatory process during the start of the transmission with the asynchronous motor have been carried out [4]. During the calculations we applied the proposed coupling, both with mentioned above elastic characteristic (combined, type 1) and with the synthesized target characteristic with the coefficient of compliance k_c = 0,99 (hereafter combined, type 2). The synthesized elastic characteristic consists of the corresponding nonlinear sections that share borders at a



a)



b)

Figure. 4.Oscillatory process of asynchronous motor starting: combined elastic characteristics (a); oscillatory process (b).

certain value of the elastic torque and determine the rating rotary moment of half-couplings φ = 0,2 rad. (curve 2, fig. 4, a). Emerging at the transmission start of a machine assembly with an asynchronous motor, in two calculation cases the oscillatory process is fading and low frequency with the frequency T, which varies over time (fig. 4, b). In the first case the system response to external disturbance $M_{J1(t1)}$= 56,26 Nm occurs with delay after the appearance of the maximum external load equal to $t^*_{(t1)}$ = 0,18 s. and in the second – $M_{J1(t2)}$ = 56,26 Nm with the delay equal to $t^*_{(t2)}$ = 0,21 s. Thus the average value of the elastic torque lays in the range of the torsion angle of the half-coupling φ = 0,2...0,6 rad., which is higher than in the linear system and less than in a system with a "hard" Duffing type characteristic. The decay time of the oscillatory process is determined by $M_{J1} = M_r$ and in the first case $t_{(t1)}$ = 3,18 s, while in the second case $t_{(t2)}$ = 2,8 s, being the smallest indicators in the performed calculations. This is due to the fact that elastic characteristics cause an increase in their frequency at high amplitudes of oscillations. This, in turn, indicates the presence of high velocities and the greater effect of dissipative forces than in the previous considered variants. In this case the coefficient of vibration isolation k_R for the first calculation is as follows

$$k_R = \frac{M_0}{A_0} = \frac{56,79}{61} = 0,931, \qquad (10)$$

and for the second calculation

$$k_R = \frac{M_0}{A_0} = \frac{56,13}{61} = 0,92 \qquad (11)$$

The results of the conducted analytical studies are presented in the table 1.

3.1 Tables

Table 1 Coefficients of vibration isolation k_R and oscillation decay time at the transmission start with asynchronous motor with an elastic coupling

Type of elastic characteristic of coupling	Coefficient of vibration isolation k_R	Oscillation decay time t,(s)
Linear	0,98	6,7
"Soft" Duffing type	0,94	8,3
"Hard" Duffing type	0,96	3,4
Combined, type 1	0,93	3,2
Combined, type 2	0,92	2,8

4. CONCLUSIONS

Implementation of elastic characteristics of the "soft" Duffing type of the coupling in comparison with the case of implementation of a linear elastic characteristic of the coupling enables reduction of negative demonstrations of oscillations by 3...4%, however it leads to an increase in duration of oscillatory process 1,5...2 times. Implementation of elastic characteristics of the "hard" Duffing type of the coupling in comparison with the case of implementation of a linear elastic characteristic of the coupling allows to reduce negative demonstrations of oscillations by 2...3% and leads to a decrease in duration of oscillatory process 1,5...2 times.

Results of research of prof. G.V. Arkhangelskiy, concerning optimization of oscillatory process in case of transmission start of a machine assembly with an asynchronous motor using elastic coupling with a combined nonlinear elastic characteristic, have been confirmed. Mathematical modeling of the system starting with the proposed coupling structure, which implements the target characteristic as a fragmentarily linear characteristic with a compliance coefficient k_c = 0,89, resulted in a decrease of negative demonstration of oscillations by 5...6% and reduction of the time of oscillatory process 1,5...2,5 times, comparing with the case of realization of a linear elastic characteristic by a coupling.

Mathematical modeling of the system starting using an elastic coupling with mechanical feedback, that implements a nonlinear target combined characteristic with a compliance coefficient k_c = 0,98, caused a decrease of negative demonstration of oscillations by 7 ... 10 %, and reduction of the time of oscillatory process 2.8...3 times, compared with the case of realization of a linear elastic characteristic by a coupling.

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