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Choice of Parameters and Stability of Nonlinear Vibration Isolation Device

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Abstract. Work of active vibration isolation devices with single-mass electromagnetic suspension taking into account of real characteristics of the voltage regulators is described. The analytical researches are carried out; the areas of stability of work of nonlinear vibration isolation device are defined.

1. Introduction

Reliable and accurate information on device operation is required to control and monitor current processes [1]. Vibration protection devices are widely used in engineering [2–3]. They are used to make systems with high performance characteristics. These devices are non-linear since the power characteristics of electromagnets and characteristics of the system for electromagnetic suspension stabilization are non-linear. The parameters of an active vibration isolation device should be chosen so that to ensure effective oscillation damping at a given frequency band of external disturbances and sufficient stability margin [4].

Non-linear modes of active vibration isolation devices with single-mass electromagnetic suspension [5] were analysed for objective parameters of the voltage regulator. Protected against vibrations, the object of mass m is suspended in the field of the electromagnet mounted on the basis producing oscillations. The vibrations (deviations) of the body suspended along the electromagnet, an absolute coordinate which determines the position of an object of mass m with respect to the ground. The voltage and current of the electromagnet in a position of the suspended body static equilibrium the variable components of the voltage and current of the electromagnet.

The parameters of the active vibration isolation devices should be chosen to ensure effective damping of oscillations at a given frequency band of external disturbances and sufficient stability margin. The stability margin can be provided by increasing the overall gain, however, the voltage of the inverter to convey the supply voltage for the electromagnet reaches the saturation level (figure 1), i.e. vibration isolation device is essentially nonlinear. In figure 2 is the feedback voltage controlling the voltage at the input of the nonlinear element; is the converter output voltage.

Analyze the operation of an active vibration isolation device considering that the converter to form voltage is non-linear [6]. Determine the effect of the feedback non-linearity on the performance of the tested device. For the vibration isolation device with a one-mass electromagnetic suspension the control voltage is formed as follows:

$$U_{cont} = \alpha\delta + \beta\delta',$$

where α and β are the coefficients of the control circuit to change the air gap δ and its velocity.

When studying the nonlinear active vibration isolation device, use the method of harmonic linearization to analyze the modes of the system operation affected by harmonic effects. At the input of the tested object, the wave signal

$$U_{cont} = \mathrm{A}\sin\omega t. \quad (1)$$

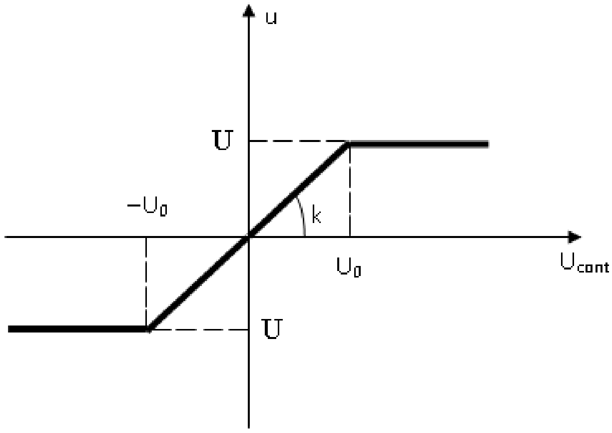

Figure 1. Plot of the voltage of the feedback U_{cont} versus the voltage at the converter output U.

2. Research object and method

Due to the electromagnetic properties of the filter, we take into account only the first harmonic of the nonlinear voltage at the converter output and using the harmonic linearization method; substitute the saturation characteristic with ratio

$$U = q(A)\,U_{cont.}$$

Coefficients $q(A)$ of the harmonic linearization for the nonlinearity have the form [4]

$$q(A) = \mathrm{k} \text{ with } U_0 < A < U_0, \quad (2)$$

$$q(A) = \frac{2k}{\pi}\left[\arcsin\frac{U_0}{A} + \frac{U_0}{A}\sqrt{1-\frac{U_0^2}{A^2}}\right] \quad \text{with } A \geq U_0, \quad (3)$$

i.e. in the saturated region, the converter is replaced by the linear element with gain $q(A)$ which decreases as the amplitude grows.

The analysis of expressions (2) and (3) shows that the nonlinearity in the feedback circuit causes decrease in equivalent coefficient q, which depends on amplitude A, in the saturation region, i.e. the effect of the nonlinear feedback on the vibration oscillation properties of the electromagnetic suspension are to be studied [6].

The linearized equations of the electromagnet winding and its traction in the operator form are

$$\begin{cases} U(s) = (R + sL_0)I(s) - a\Delta(s)S, \\ F(s) = aI(s) - b\Delta(s) \end{cases} \quad (4)$$

where R is the resistance of the electromagnet winding; L_0 is the inductance corresponding to the equilibrium point for the body of mass m suspended in the electromagnet field; $a = 2K\frac{I_0}{\delta_0^2}$ is the coefficient; K is the constant determined under the static equilibrium condition; δ_0 is the air gap in static equilibrium; $b = 2K\frac{I_0^2}{\delta_0^3}$ is the coefficient; a and b are the coefficients of linearization of the equations nearby the point of equilibrium conditions.

$$U_{cont} = (\alpha + \beta\ s)\Delta(s). \tag{5}$$

According to the harmonic linearization method the characteristic in figure 2 is replaced by the following expression:

$$u(s) = q(A)u_{cont}(s), \tag{6}$$

where $q(A)$ is determined according to expressions (2) and (3). Expanding equations (4–6) with the equation of the mechanical system motion

$$mX(s)s^2 = -F(s),$$

find the system transfer function

$$W(s) = \frac{X(s)}{Y(s)} = \frac{\left[q(A)\alpha\beta + a^2 - bL_0\right]\ s + q(A)a\alpha - bR}{mL_0 s^3 + Rms^2 + \left[a\beta\ q(A) + a^2 - bL_0\right]\ s + q(A)a\alpha - bR}.$$

The characteristic equation of the harmonically linearized system will be written in the form

$$mL_0 s^3 + Rms^2 + \left[a\beta q(A) + a^2 - bL_0\right]\ s + q(A)a\alpha - Rb = 0, \tag{7}$$

or

$$a_3 s^3 + a_2 s^2 + a_1 s + a_0. = 0.$$

According to the Hurwitz stability criterion, the following conditions for the third-order systems must be meet:

$$a_3 > 0,\ a_2 > 0,\ a_1 > 0,\ a_0 > 0,\ a_2 a_1 > a_3 a_0,$$

that is $$\alpha > \frac{Rb}{aq(A)};\ \beta > \frac{bL_0 - a^2}{aq(A)};\ \beta > \frac{L_0\ \alpha\ q(A) - aR}{Rq(A)}. \tag{8}$$

Since the linearization coefficient $q(A)$ are restrained by the following limits:

$$0 < q \le k,$$

The stability conditions (8) for the tested system will take the form

$$\alpha > \frac{Rb}{ak};\ \beta > \frac{bL_0 - a^2}{ak};\ \beta > \frac{L_0\ \alpha\ k - aR}{Rk}.$$

Replace s by $j\omega$ in equation (7)

$$\left[q(A)a\ \alpha\ - Rb - \omega^2 Rm\right]\ + j\omega\ \left[a\beta\ q(A) + a^2 - bL_0 - \omega^2 mL_0\right] = 0, \tag{9}$$

extracting the real and imaginary components in equation (9), we obtain the equation to determine periodic solutions (1) for the input value of the voltage converter

$$\begin{cases} X(A,\omega) = q(A)a\alpha - Rb - \omega^2 Rm = 0, \\ Y(A,\omega) = (a\beta\ q(A) + a^2 - bL_0 - \omega^2\ mL_0)\omega = 0. \end{cases} \tag{10}$$

Solve equation system (10) to determine frequency ω of the periodic solution through the system parameters and find the expression to determine equivalent gain $q(A)$

$$\omega = \frac{b(\alpha\ L_0 - R\beta) - a^2\alpha}{m(\beta\ R - \alpha\ L_0)}, \qquad q(A) = \frac{aR}{(\alpha\ L_0 - R\beta)}. \tag{11}$$

Substitute relation (2), (3) into (11) to obtain the formula relating the amplitude of periodic solution A with the system parameters

$$\frac{2k}{\pi}(\arcsin\ \frac{U_0}{A}+\frac{U_0}{A}\sqrt{1-\frac{U_0^2}{A^2}})=\frac{aR}{\alpha\ L_0-R\beta}. \qquad (12)$$

To determine the value of critical gain k_{cr}, which determines the system stability limit and the region of auto-oscillations, in formula (12), take $A = U_0$ and obtain

$$k_{cr}=\frac{aR}{\alpha\ L_0-R\beta},$$

i.e. oscillations occur when $k \geq k_{cr}$.

Determine the conditions of the linear system stability limit calculating in the system of equations (10) $q(A) = k$:

$$\begin{cases} ka\alpha - Rb - \omega^2 Rm = 0, \\ ka\beta + a^2 - bL_0 - \omega^2 mL_0 = 0. \end{cases}$$

$$k_{LG}=\frac{aR}{\alpha L_0-R\beta}. \qquad (13)$$

That is $k_{LG} = k_{cr}$ and considering this, the stability region limit is determined by the following equations:

$$\alpha=\frac{Rb}{ak_{cr}};\ \ \beta=\frac{L_0\alpha\ k_{cr}-aR}{Rk_{cr}}\ .$$

The value of k_{cr} is determined by relation (13) through substituting the linear system limit values α, β.

3 Results and considerations

Hence, we can conclude that if $k < k_{cr} = k_{LG}$, the active vibration isolation device is stable in both a linear response and a nonlinear (figure 2).

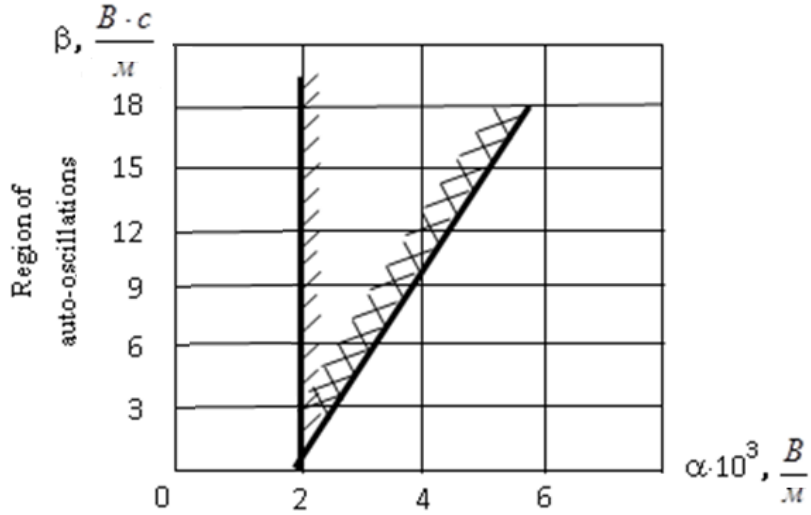

Figure 2. A graph of the stability domain of work.

Vibration When $k \geq k_{cr}$ the nonlinear device operates as a self-oscillating mode at a certain amplitude, whereas in the linear system under this condition ($k \geq k_{LG.}$) divergent oscillations would occur, i.e. the non-linear element introduced extends the stable region of the device, the device has a nonlinear vibration isolation compared to a linear high stability (figure 3).The controlled active vibration isolation devices with variable structure consist of several fixed structures which switching is made by the logical elements (*LE*) on the basis of algorithm of switching.

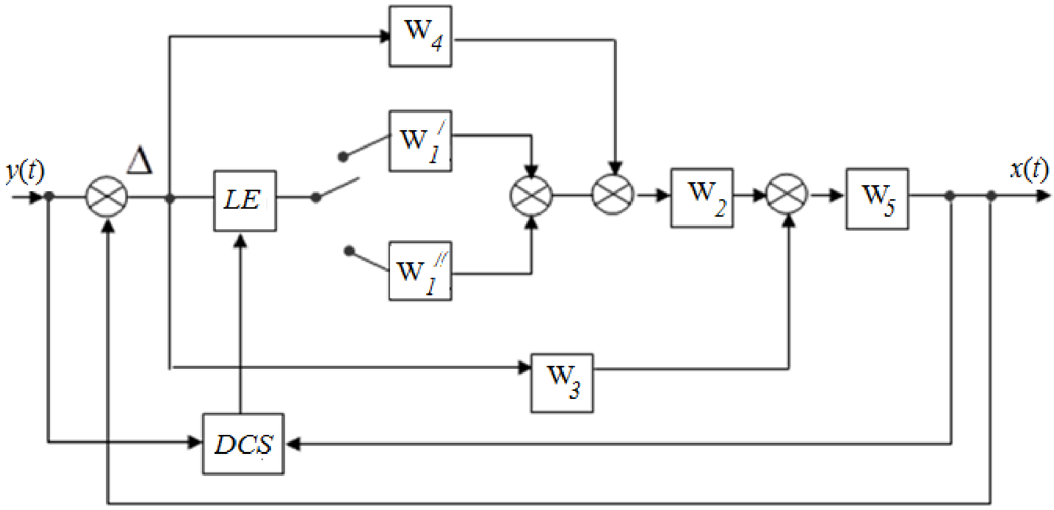

Figure 3. Algorithm of formation of information.

On figure 3 the block diagram with stepwise changing of rigidity and damping is; it is reached by automatic change of coefficients of strengthening of circuit of control of electromagnet current. The algorithm is formed based on the information about the value of external disturbance and condition of the object of vibration protection in the device of changing of structure (*DCS*). On figure 3 *y(t)* – harmonic oscillations of basement of the active vibration isolation device (external disturbance), *x(t)* – oscillations (deviations) of suspended body along the axis of the electromagnet, the absolute coordinate that defines the position of the object of vibroprotection relative to the earth. Variable parameters are the stiffness, mass, damping, etc.

4. Summary

Use in active vibration isolation device of the electromagnetic suspension with movable core allows refusing of use of accelerometers, which are relatively complex devices. In addition, the range of sensitivity is often limited, while the electromagnetic suspension with movable core provides the vibroprotection in almost the entire frequency range of external disturbances.

Thus it is established that the active vibration isolation device using the elastic forces of the electromagnetic suspension with variable structure is effectively at almost any value of frequency of the external disturbing force and the introduction of a nonlinear converter for forming voltage extends the range of stable work of the device.

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