Analysis and Experiment Results of Reactor Plant Turbomachine Rotor Model Investigations

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Abstract

Analysis and experiment results of reactor plant turbomachine rotor model investigations are described. It is shown that application of linearization by feedback to produce the control algorithm allows system linearizing without use of bias current. The system linearized in this way has better dynamic qualities, particularly, the frequencies in rotor oscillation spectrum, which are different from rotation speed, are eliminated.

1 Introduction

JSC “Afrikantov OKBM” has developed the large test facility with flexible vertical rotor in electromagnetic suspension, which was designed subject to the conditions of equality between the number of natural frequencies and bending modes of reactor plant turbomachine rotor model.

During the first test stage, the flexible rotor was balanced as a part of test facility using the program developed for calculation of residual unbalance. Balancing was performed sequentially with compensation of residual unbalance for each critical frequency of rotor model [1].

2 Investigations

As is known, the electromagnet force depends non-linearly on current and gap between the rotor and electromagnet [2]. To linearize this nonlinear dependence, bias currents are usually used [3]. Coordinate nonlinearity is eliminated by introduction of coordinate feedback signal into the control signal. When using bias currents in the control system, the energy consumed by the electromagnetic bearing (EMB) increases and additional EMB positive hardness occurs. Without bias currents, the system is highly nonlinear that results oscillation spectrum frequencies (sub-and ultraharmonics) differing from rotation speed during rotor startup (Fig. 1). This fact increases the rotor oscillation net amplitudes (Fig. 2).

To solve this problem, JSC «Afrikantov OKBM» used the non-linear feedback-linearized control algorithm.

The suspension in radial direction is described by differential equations

$$
\begin{aligned}
&J\ \ddot{\alpha} = -l_1(F_2^{up} - F_1^{up}) + l_2(F_2^{low} - F_1^{low}) - J_z\omega\dot{\beta},\\
&J\ddot{\beta} = l_1(F_3^{up} - F_4^{up}) - l_2(F_3^{low} - F_4^{low}) + J_z\omega\dot{\alpha},\\
&m\ddot{x} = F_3^{up} - F_4^{up} + F_3^{low} - F_4^{low},\\
&m\ddot{y} = F_2^{up} - F_1^{up} + F_2^{low} - F_1^{low}.
\end{aligned}
\tag{1}
$$

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where *x*, *y* – coordinates of rotor mass center, α , β - rotation angles of rotor relative to *y* and *x* axes respectively, l_1, l_2 - distance up to the upper and lower EMBs respectively, indices *up* and *low* show the electromagnetic forces effecting on the rotor from the upper and lower EMBs, J - principal moment of inertia of the rotor, ω - specified angular frequency of rotor rotation speed vs. z axis.

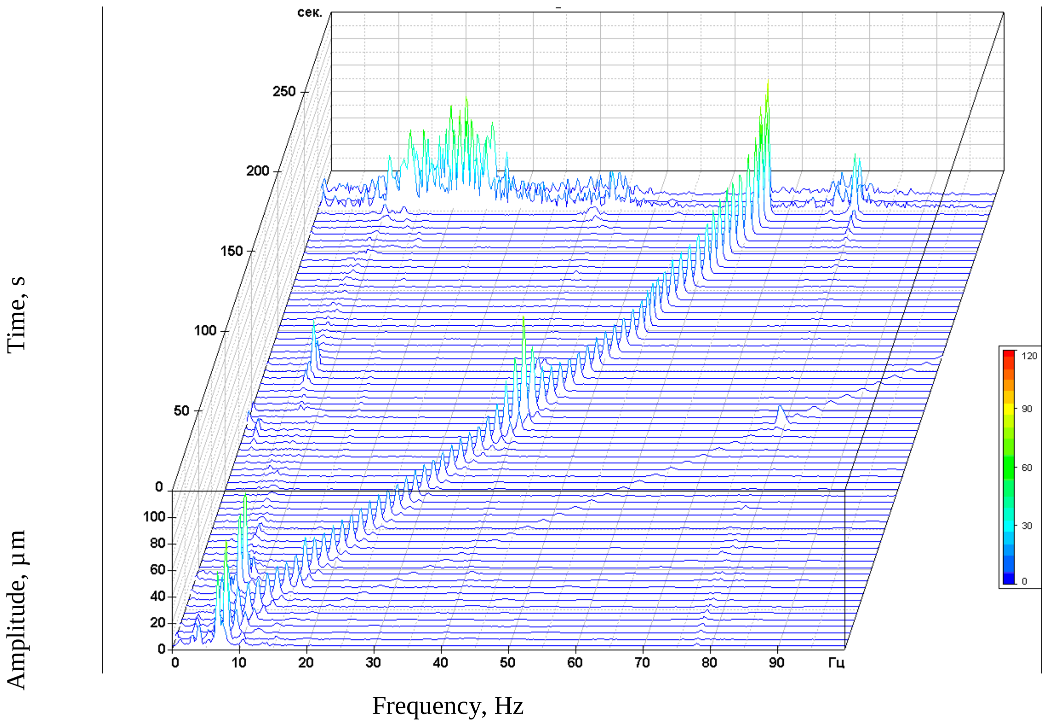

Fig. 1 – Experimental 3D spectrum of rotor startup under PD control

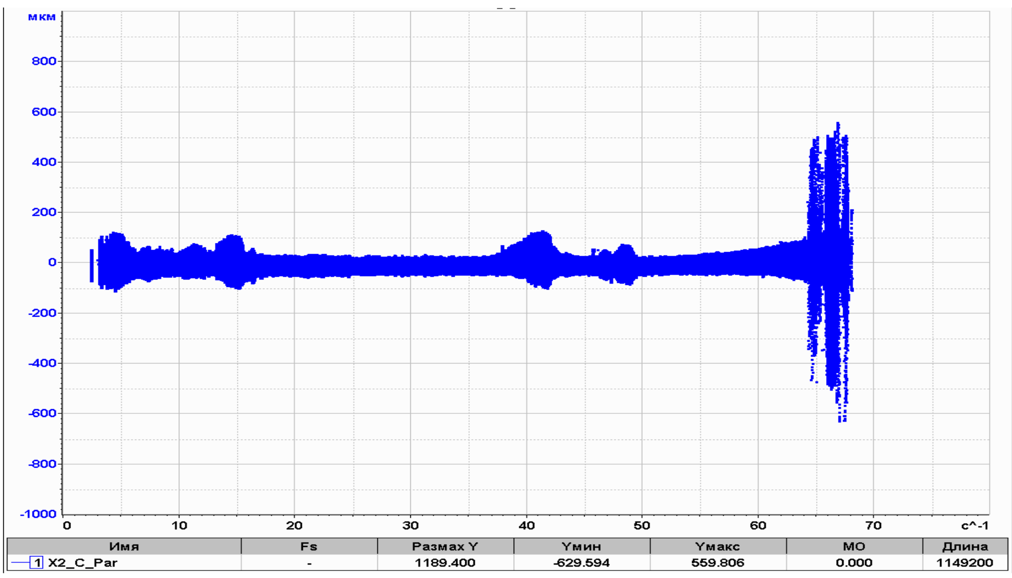

Fig. 2 – Experimental amplitude of rotor oscillations vs. rotation speed during startup with PD-regulator

Pairs of electromagnetic forces appearing in equations (1) are determined as follows

$$F_2^{up} - F_1^{up} = \frac{L_0 S_0}{2}\left[\left(\frac{I_{2up}}{S_0 - y_{up}}\right)^2 - \left(\frac{I_{1up}}{S_0 + y_{up}}\right)^2\right]$$

$$F_2^{low} - F_1^{low} = \frac{L_0 S_0}{2}\left[\left(\frac{I_{2low}}{S_0 - y_{low}}\right)^2 - \left(\frac{I_{1low}}{S_0 + y_{low}}\right)^2\right]$$

$$F_3^{up} - F_4^{up} = \frac{L_0 S_0}{2}\left[\left(\frac{I_{3up}}{S_0 - x_{up}}\right)^2 - \left(\frac{I_{4up}}{S_0 + x_{up}}\right)^2\right] \quad (2)$$

$$F_3^{low} - F_4^{low} = \frac{L_0 S_0}{2}\left[\left(\frac{I_{3low}}{S_0 - x_{low}}\right)^2 - \left(\frac{I_{4low}}{S_0 + x_{low}}\right)^2\right]$$

The concept of linearization by feedback is described in [2, 4] and consists basically in transition to new controls:

$$\begin{aligned} u_1 &= F_2^{up} - F_1^{up} = -\left(a_1 y_{up} + b_1 \dot{y}_{up}\right), \\ u_2 &= F_2^{low} - F_1^{low} = -\left(a_2 y_{low} + b_2 \dot{y}_{low}\right), \\ u_3 &= F_3^{up} - F_4^{up} = -\left(a_3 x_{up} + b_3 \dot{x}_{up}\right), \\ u_4 &= F_3^{low} - F_4^{low} = -\left(a_4 x_{low} + b_4 \dot{x}_{low}\right). \end{aligned} \quad (3)$$

Values x_{up}, y_{up}, x_{low}, y_{low} for rigid rotor are connected to variables x, y, α, β by kinematic relations

$$x_{up} = x + \beta\, l_1,\ x_{low} = x - \beta\, l_2,\ y_{up} = y - \alpha\, l_1,\ y_{low} = y + \alpha\, l_2. \quad (4)$$

The control currents can be selected such that the initial system (1, 2) becomes the linear one as per phase variables, e.g.

$$I_{1up} = \begin{cases} 0 & a_1 y_{up} + b_1 \dot{y}_{up} < 0 \\ \sqrt{\dfrac{\left|a_1 y_{up} + b_1 \dot{y}_{up}\right|}{F_{01}}} \cdot \left(S_0 + y_{up}\right) \quad \text{when} & a_1 y_{up} + b_1 \dot{y}_{up} \ge 0 \end{cases} \quad (5)$$

where $F_{01} = \dfrac{L_0 S_0}{2}$. The other currents are expressed by analogy. This control algorithm is designated as proportional-differential-linearizing control (PDL-control).

On substitution of current expressions (5) to initial system (1) in view of kinematic relations (4), one will receive the linear system of differential equations, presented as matrix-vector form

$$M\ddot{\zeta} = -D\dot{\zeta} - C\zeta + G\dot{\zeta} \quad (6)$$

where $\zeta = \left(\alpha\ \beta\ x\ y\right)^T$, matrix M defines the system inertia, matrix D, dissipative properties, matrix C, stiffness properties, matrix G, gyroscopic forces.

Fig. 3 and 4 show the estimated startup of the rotor model with specified uniform unbalance of 10 µm when controlled by PD- and PDL-control. It is seen that in this case too, the PDL-control gives the notable advantage in rotor oscillation amplitude. Figs. 3 and 4: electromagnetic loading device (EMLD) – oscillation amplitudes in EMLD (upper rotor end), REMB1 – oscillation amplitudes in the upper EMB, REMB2 – oscillation amplitudes in the lower EMB.

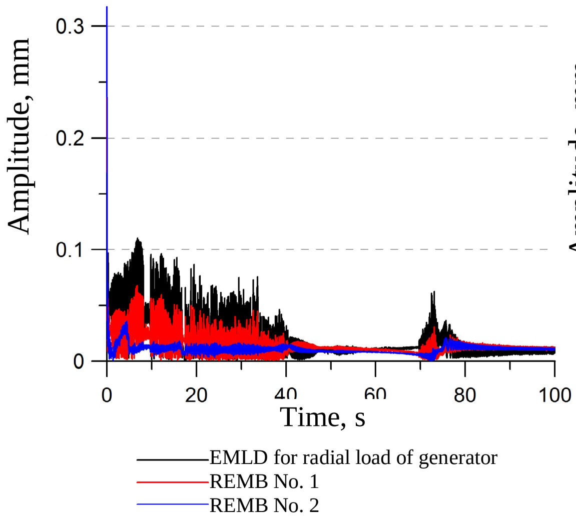

Fig. 3 –PD-control

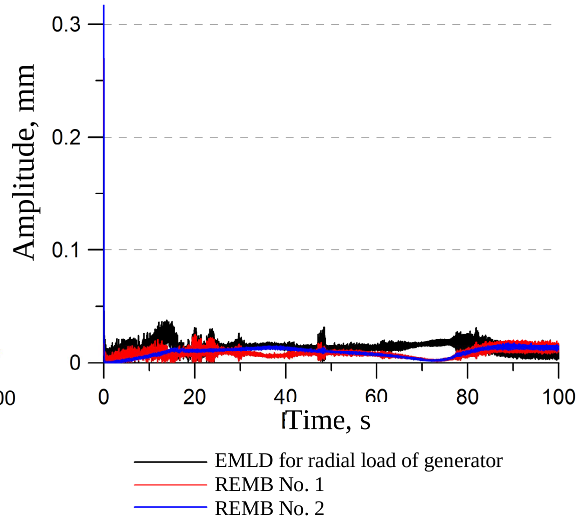

Fig. 4 – PDL- control

Practical use of this control allowed system linearization and startup prior to nominal rotation speed of the rotor with acceptable rotor oscillation amplitudes including passing through the four critical frequencies. Oscillation amplitudes lessened as compared with PD-control without displacement currents (Fig. 5), the frequency spectrum expresses only the instantaneous rotation speed of the rotor, and sub- and ultraharmonics do not practically appear (Fig. 6).

The non-linear control effectiveness differs from that of PD-control by considerable decrease (by ~30 times) of subharmonics in the oscillation spectrum (see Figs. 1 and 6).

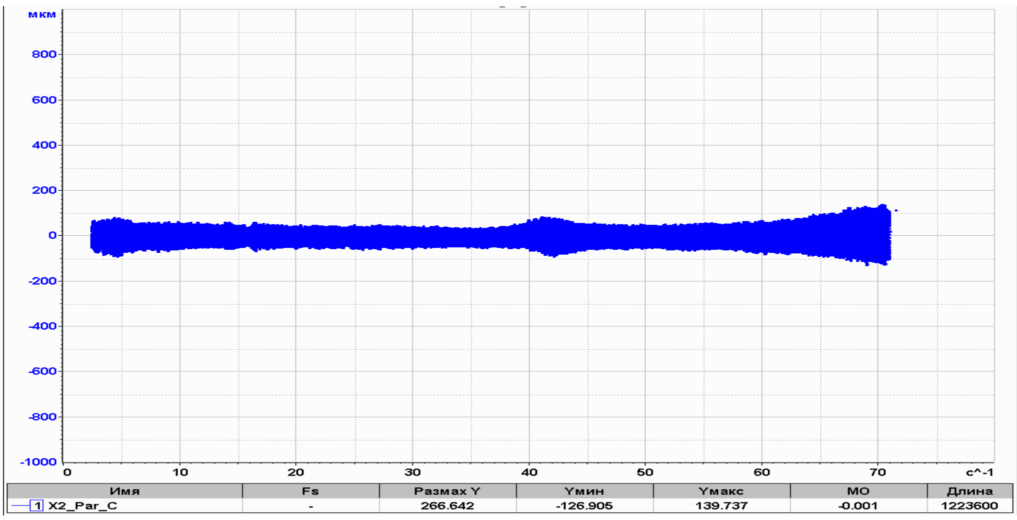

Fig. 5 – Experimental amplitude of rotor oscillations vs. rotation speed during startup with PDL-control

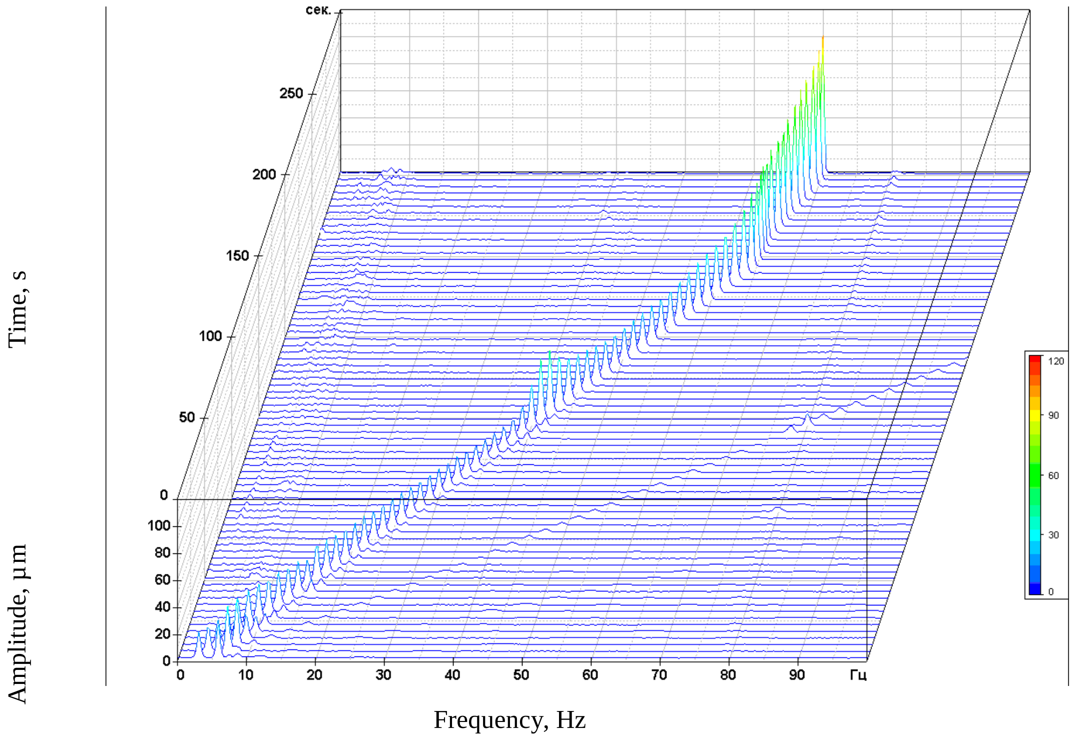

Fig. 6 – Experimental 3D-spectrum of rotor startup under PDL-control

3 Conclusion

Rotor control algorithm synthesized using method of linearization by feedback was checked by experiment and analysis. This algorithm ensured system linearization and allowed practically complete excluding of sub- and ultraharmonics in the oscillation spectrum.

Further, it is planned to perform analytical and experimental studies of the other rotor model control laws, such as linear quadratic and optimum control as per H_∞ criterion (transfer function norms).

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