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# ALGORITHM FOR COMPENSATION OF RESIDUAL IMBALANCE OF A FLEXIBLE ROTOR ON ACTIVE MAGNETIC BEARINGS

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**Abstract**
This article presents the algorithm for controlling a flexible rotor on active magnetic bearings that reduces rotor oscillation amplitude when the rotor is rotating at critical frequencies by identifying inertia forces caused by residual imbalance and by forming control system forces that compensate the inertia ones.

**Key words**
Active magnetic bearings, control algorithm, flexible rotor, residual imbalance.

## 1 Introduction

Rotors on active magnetic bearings (AMB) have a few key advantages that make them very promising for use in nuclear power plants with gas heat-transfer agents and high-power wind plants [Kodochigov, Golovko and Ganin, 2013] and [Mitenkov et al, 2016] and [Wang, Zhang and Ding, 2012]. The advantages are near-zero friction, almost full independence of environment and nearly no need of maintenance. After the complex flexible rotor is assembled residual imbalance is always present, and such imbalance could lead to substantial increase of rotor oscillation amplitude at critical rotation frequencies in spin up and shutdown modes as well as to certain nonlinear effects [Boikov, Andrievsky and Shiegin, 2016]. As control system is based on digital processing unit, it can form arbitrary control laws. Measuring system of the active magnetic suspension can take continuous measurements of rotation speed, rotor angle and displacement and of currents in magnets in the AMB.

These capabilities coupled with computer model of dynamics of the flexible rotor on AMB are the prerequisites for identifying the parameters of residual imbalance of the rotor during its operation and for creating control law that reduces the effect of residual imbalance when rotation frequency is passing critical values.

## 2 Control Algorithm

The algorithm presented in this paper is derived from already known base control algorithm for controlling a flexible rotor on AMB.

### 2.1 Base Control Algorithm

The base control algorithm of a flexible rotor on AMB [Balandin et al, 2017] assumes that for each of $N$ radial AMBs with index $n$ the following correction forces $\boldsymbol{R}_n$ are applied:

$$\boldsymbol{R}_n = a_n \boldsymbol{U}_n + b_n d\boldsymbol{U}_n/dt, \tag{1}$$

where $\boldsymbol{U}_n$ and $d\boldsymbol{U}_n/dt$ are vectors of cross displacement and cross speed of the rotor respectively; $a_n$ and $b_n$ are proportional and differential coefficients of the control system.

### 2.2 Suggested Control Algorithm

The suggested control algorithm presented for controlling active magnetic suspension system of a flexible rotor proposes to form additional control forces that compensate residual imbalance. The additional forces are constructed based on computer model of dynamics [Ovchinnikov et al, 2012] that reflects main features of the system in question.

Computer model is used to determine critical rotation frequencies of the flexible rotor $\Omega_k$ and to compute eigenmodes $\varphi_k(x)$ corresponding to critical rotation frequencies. Here $x$ is the rotation axis, $k$ is the index of critical rotation frequency and of eigenmode corresponding to that frequency.

In spin up mode of the flexible rotor position sensors in each radial AMB are used to measure the displacement of the rotor from centrality. When residual imbalance is present and rotation frequency is approaching next critical frequency the increase in oscillation amplitude in all the AMBs is observed.

If such amplitudes are approaching the posed limit (about half of clearance in the safety bearings) the spin up process is stopped and the rotor is let to rotate freely until it slows down to the frequency with low enough amplitude. During this slowdown process the control system measures all the positions as well as rotor angle, rotation frequency and current values in the magnets of the AMB suspension system. Coupling this data with mathematical model of dynamics of the flexible rotor according to imbalance identification methodology [Mitenkov et al, 2007; Lauridsen et al, 2015] it is possible to compute the modal imbalance vector $\boldsymbol{Q}_k$ for the flexible rotor for $k$-th critical rotation frequency. The imbalance vector in coordinate system attached to the rotor is time-independent and is expressed as follows:

$$\boldsymbol{Q}_k = \int_0^L \mu(x)\, \boldsymbol{e}(x)\, \varphi_k(x) dx = \boldsymbol{e}_k\, M, \qquad (2)$$

where $\mu(x)$ is linear mass of the flexible rotor; $L$ and $M$ are length and mass of the rotor; $\boldsymbol{e}(x)$ vector is the eccentricity given in the plane intersecting the rotor at $x$ coordinate. In the global fixed coordinate system imbalance vector is harmonic function of time.

If the magnets of radial AMBs will generate additional forces $\boldsymbol{F}_n$ when rotation frequency is near $k$-th critical frequency where $\boldsymbol{F}_n$ are expressed as following:

$$\sum_{n=1}^{N} \boldsymbol{F}_n\, \varphi_k(x_n) = -\boldsymbol{e}_k\, M\, \omega^2, \qquad (3)$$

then such forces will compensate the effect of residual imbalance on dynamics of the flexible rotor. Here $x_n$ is the coordinate of $n$-th radial AMB on rotor axis, $\omega$ is angular speed. Equation (3) is the system of linear algebraic equations for unknown quantities $\boldsymbol{F}_n$, and there are more unknowns than equations. Thus for unambiguous definition of the forces an additional clause is needed which is proposed to be: $\boldsymbol{F}_n$ selected should yield minimal quadratic form $\sum_{n=1}^{N}(\boldsymbol{F}_n)^2$.

With this applied the solution for (3) is the following:

$$\begin{aligned} \boldsymbol{F}_n &= -A_{kn}\omega^2 \boldsymbol{l}_k, \\ A_{kn} &= e_k\, M\, \varphi_k(x_n) / \sum_{i=1}^{N} \varphi_k^2(x_i), \quad n = \overline{1, N}, \end{aligned} \qquad (4)$$

where $e_k$ is the modulus of $\boldsymbol{e}_k$ vector, $\boldsymbol{l}_k$ is the dimensionless unit vector parallel to $\boldsymbol{e}_k$, $A_{kn}$ are the imbalance parameters being identified.

Similar to modal imbalance vector, additional forces (4) in global fixed coordinate system are harmonic functions of time with frequency being equal to rotation frequency.

The suggested control algorithm proposes to create compensation forces (4) in addition to base forces (1) that are only turned on during passing of critical rotation frequencies.

## 3 Numerical Experiments

Efficiency of the suggested control algorithm of the flexible rotor on AMB is demonstrated via computer modelling of dynamics of specific system.

### 3.1 Simulation Object of Computer Model

Simulation object of computer model is the generator part of a scale model of the rotor [Drumov et al, 2010]. Vertical rotor in the scale model is suspended on two radial AMBs; its length is 5.4 m, weight is 640 kg. Operating frequency is 60 Hz. Several first eigenfrequencies for the flexible rotor in the scale model as calculated are: 7.5 Hz, 8.2 Hz, 15.8 Hz, 39.3 Hz and 77.5 Hz. Residual imbalance being modelled is placed at three sections: 20 mm, 2770 mm and 4103 mm from the topmost section. Imbalance values are 334 g·mm, 3579 g·mm and 2938 g·mm, imbalance angles are 0°, 150° and 30° respectively. On operating frequency of 60 Hz rotor displacement is in limit of 0.05 mm which is an order of magnitude less than clearance in safety bearings.

### 3.2 Results of Computer Modelling

Problems arise during spin up and shutdown operation modes of the flexible rotor.

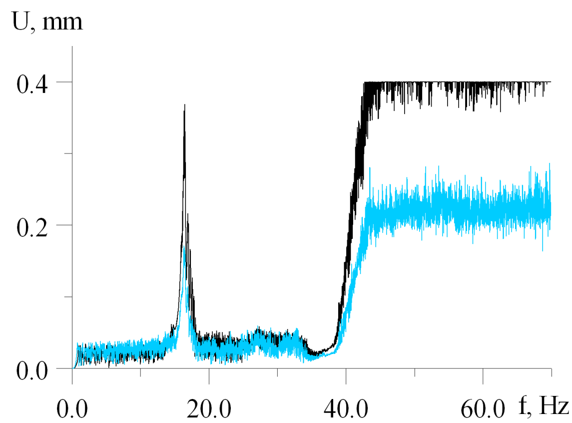


Figure 1. Dependence of displacement from rotation frequency in sections of upper and lower AMBs for the base control algorithm.

Figure 1 depicts the dependence of modulus of cross displacement vector from rotation frequency in the section of top AMB (black curve) and bottom AMB (blue curve) when rotor is accelerated at 0.5 Hz/sec when controlled by base control algorithm (1).

Figure 1 shows that when rotation frequency of the rotor is in near first or second bending mode rotor displacement is around 0.5 mm. Such displacement leads to intolerable situation when the rotor touches the safety bearings. This means that control forces calculated via base control algorithm are insufficient for keeping the rotor safely within required limit.

To apply the control algorithm presented in this paper the data measured during running out was analyzed for identifying extra parameters needed for additional forces (4). The values of $A_{kn}$ and initial phases (IP) of additional forces, which depend on the direction of modal imbalance vector and latency time in the control system, are listed below (see table).

| Frequency range, Hz | Top AMB | | Bottom AMB | |
|---|---|---|---|---|
| | $A_{k1}$, g·mm | IP, deg | $A_{k2}$, g·mm | IP, deg |
| $<$ 13.5 | 0 | 0 | 0 | 0 |
| 13.5 – 20.6 | 3398.5 | 14.76 | 1942.19 | 188.61 |
| 20.6 – 33.8 | 0 | 0 | 0 | 0 |
| 33.8 – 51.0 | 796.29 | 45.82 | 303.59 | 196.79 |
| $>$ 51.0 | 0 | 0 | 0 | 0 |

Figure 2 depicts the dependence of modulus of cross displacement vector from rotation frequency in the section of top AMB (black curve) and bottom AMB (blue curve) when the rotor is accelerated at 0.5 Hz/sec when controlled by the control algorithm (4) suggested in the paper.

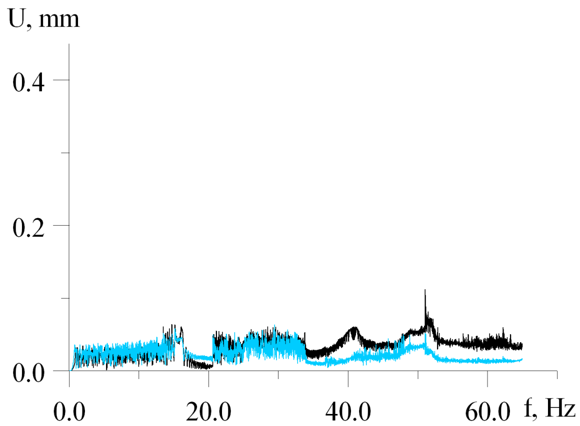


Figure 2. Dependence of displacement from rotation frequency in sections of upper and lower AMBs for the suggested control algorithm

Figure 2 shows that rotor displacement is no bigger than 0.12 mm (compared to 0.4 mm for base control algorithm).

## 4 Conclusion

Comparison of figures of dependency of rotor displacement for base and suggested control algorithms (figures 1 and 2) shows effectiveness of the suggested control algorithm for compensation of residual imbalance for dynamics of the flexible rotor on AMB.

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