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Controlled Passage through Resonance for Two-Rotor Vibration Unit: Influence of Drive Dynamics[1]

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Abstract: The problem of controlled passage through resonance zone for mechanical systems with several degrees of freedom is analyzed. The simulation results for two-rotor vibration unit illustrating efficiency of the control algorithm based on speed-gradient method are presented. The novelty of the results is in evaluation of the closed loop system performance when the electric drive dynamics are taken into account. An interesting fact is that for vibration unit model taking into account the electric drive dynamics the time of passage through resonance zone sometimes may be less than for the simplified model neglecting the drive dynamics.

Keywords: vibration unit, resonant frequencies, drive dynamics, resonance zone, control algorithms, unbalanced rotors.

1. INTRODUCTION

An important problem for systems based on vibration technologies is the passing of vibroactuators through resonance for systems operating in the post-resonance modes. Such a problem needs special attention in the case when the power of a motor is not sufficient for passage through resonance zone due to Sommerfeld effect (Blekhman, 2000). Dynamics of near resonance behavior are nonlinear and very complicated. Publications related to this problem can be found in the literature during about 50 years (Kononenko, 1964; Quinn *et al*., 1995; Cvetićanin, 2010).

Perhaps the first approach to the problem of controlled passage through resonance zone was the so-called "double start" method (Gortinskii *et al*., 1969). This and other nonfeedback methods are characterized by difficulties in calculation of switching instants of a motor and sensitivity to inaccuracies of model and to interferences. In (Leonov, 2008) it is proved that the Sommerfeld effect does not occur for any passage through resonance for a synchronous electric motor with an asynchronous start-up, mounted on an elastic base.

A prospective approach to the problem is based on feedback control. Feedback control algorithms for passing through resonance zone of mechanical systems were studied in (Malinin and Pervozvansky, 1983; Viderman and Porat, 1987; Kinsey and Mingori, 1992). In (Malinin and Pervozvansky, 1983) an optimal control algorithm for passage of an unbalanced rotor through critical speed was proposed. For the same problem several control methods are evaluated, and the necessary number of dampers and their optimal location were determined in (Viderman and Porat, 1987). In (Kinsey and Mingori, 1992) a nonlinear controller reducing resonance effects during despin of a dual-spin spacecraft was designed. A method of vibration suppression for rotating shafts passing through resonances by switching shaft stiffness was proposed in (Wauer and Suherman, 1998). In (Balthazar *et al*., 2001) the dynamics of passage through resonance of a vibrating system with two degrees of freedom was examined. However the early algorithms did not have enough robustness with respect to uncertainties and were hard to design.

For practical implementation of control system it is important to develop reasonably simple passing through resonance zone control algorithms, which have such robustness property: keeping high quality of the controlled system (vibration unit) under variation of parameters and external conditions. Perhaps the first such a simple controller was proposed in (Tomchina, 1997) based on the speed-gradient method previously used for control of nonlinear oscillatory systems (Andrievskii *et al*., 1996). A number of speed-gradient algorithms for passage through resonance in 2-DOF systems were proposed in (Fradkov *et al*., 2011). The approach of (Tomchina, 1997; Fradkov *et al*., 2011) was applied to two-rotor vibration set-up in (Fradkov *et al*., 2014).

In this paper the system designed in (Fradkov *et al*., 2014) is analyzed taking into account the electric drive dynamics particularly the DC motor EMF. Unlike (Leonov, 2008), which proved the absence of Sommerfeld effect for a

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synchronous motor, this effect is topical for a DC motor. In Section 2 the problem statement for control of passage through resonance zone for mechanical systems with several degrees of freedom adopted from (Fradkov *et al.*, 2011) is presented. The control algorithm based on the speed-gradient method for two-rotor vibration units is exposed in Section 3. The simulation results illustrating efficiency and robustness of the proposed algorithm in presence of drive dynamics are described in Section 4.

2. PROBLEM STATEMENT AND IDEA OF SOLUTION

To describe the dynamics of a mechanical system with n degrees of freedom the standard Euler-Lagrange equations are used:

$$A(q)\dot{q} + C(q,\dot{q}) + G(q) = Bu, \ (1)$$

where $u=u(t)$ is n-dimensional input vector; $q=q(t)$ is n-vector of generalized coordinates, $A(q)$ is $n\times n$ inertia matrix; $C(q,\dot{q})$ is the n-vector of Coriolis and centrifugal forces; $G(q)$ is the n-vector of gravity forces; B is the $m\times n$ control matrix. However, for the purpose of control algorithm design it is often convenient to use equations in Hamiltonian form:

$$\dot{p} = -\left(\frac{\partial H}{\partial q}\right)^T + Bu, \quad \dot{q} = \left(\frac{\partial H}{\partial p}\right)^T, \ (2)$$

where $p=p(t)$ is the generalized momenta vector, $H=H(p, q)$ denotes the Hamiltonian function – total energy of the free (uncontrolled) system:

$$H(p,q) = \frac{1}{2} p^T \left[A(q)\right]^{-1} p + \Pi(q), \ (3)$$

where $\Pi(q)$ is the potential energy. First of all, let us define the auxiliary control goal as the approaching of energy of the free system to a surface of the given energy level

$$H(p(t),q(t)) \to H^* \quad \text{when} \quad t \to \infty. \ (4)$$

Introducing the objective function

$$Q(p,q) = \frac{1}{2}\left[H(p,q) - H^*\right]^2, \ (5)$$

the goal (4) can be reformulated as:

$$Q(q(t),p(t)) \to 0 \quad \text{when} \quad t \to \infty. \ (6)$$

Control algorithm for passing through resonant frequencies for an unbalanced rotor is based on the speed-gradient method (Balthazar *et al.*, 2001), which allows to synthesize control algorithms for significantly nonlinear plants. The model of the system is split into two subsystems: carrier and rotating bodies. Then the total energy can be represented in the following form:

$$H(p(t),q(t)) = H_1(p(t),q(t)) + H_2(p(t),q(t)) + H_{12}(p(t),q(t)), \quad (7)$$

where H_1 is the energy of rotating subsystem, H_2 is the energy of a carrier subsystem, H_{12} is the energy of interaction.

The idea of control algorithms described below, is in that slow motion $\Psi(t)$ is being isolated and then "swinging" starts to obtain rise of energy of a rotating subsystem. To isolate slow motions, low-pass filter is being inserted into energy control algorithms. Let slow component appears in oscillations of angular velocity $\dot{\varphi}$ of a rotor. Then we start with the control algorithm proposed in (Tomchina, 1997) is:

$$u = -\gamma \operatorname{sign}((H - H^*)\dot{\psi}), \quad T_\psi \dot{\psi} = -\psi + \dot{\varphi}, \ (8)$$

where ψ is the variable of the filter, performing slow motions, T_ψ is the time constant of the filter. At low damping, slow motions also fade out slowly, that gives control algorithm an opportunity to create suitable conditions to pass through resonance zone. Thus the effect of "feedback resonance" (Fradkov, 1999) is created. After passing the resonance zone it is suggested to turn off the "swinging" and then to switch the algorithm to controlling with constant torque. For a proper work of a filter, it should suppress fast oscillations with frequency ω and pass slow oscillations with ω_B frequency, where ω_B is the Blekhman frequency (Blekhman *et al.*, 2008). I.e. time constant of a filter T_ψ should be chosen from the inequality

$$T_\psi \dot{\psi} < 2\pi/\omega_B . \ (9)$$

Algorithms of passing through resonance zone for the two-rotor vibration units are described in (Fradkov *et al.*, 2014). Below we analyze the closed loop system with the algorithm of (Fradkov *et al.*, 2014) taking into account the electric drive dynamics.

3. MODEL OF TWO-ROTOR VIBRATION UNIT TAKING INTO ACCOUNT THE DRIVE DYNAMICS

Consider the problem of two-rotor vibration unit start-up (spin-up) (Blekhman *et al.*, 1999). The unit SV-2 consists of two rotors installed on the supporting body (Fig. 1).

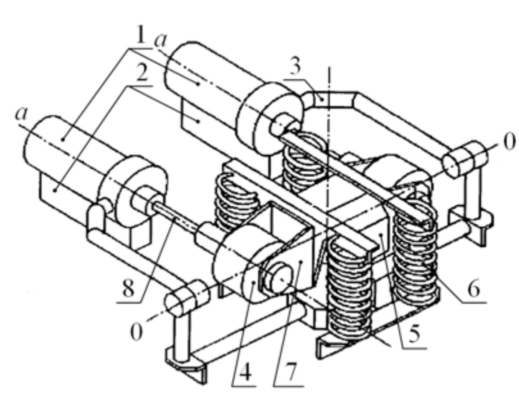

Fig. 1. Schematics of two-rotor vibration unit: 1 – motors; 2 – motor supports; 3 – frame of the unit; 4 – unbalanced rotors; 5 – vibrating platform; 6 – carrying springs; 7 – rotor bearings; 8 – cardan shafts.