MODELING AND CONTROL OF THE MECHATRONIC VIBRATIONAL UNIT

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Abstract: The description of the multi-degree-of-freedom mechatronic vibrational unit is presented. The control problems for nonlinear oscillations of the unit are discussed. The results of modeling and experimental evaluation are given. *Copyright 2001 IFAC*

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1. INTRODUCTION

The excitation and control of oscillations and vibrations play significant role in many fields of science and technology. The control methods for oscillatory systems are based either on conventional linear control theory or on recently developed nonlinear control (Hansen and Snyder, 1996; Chernousko et al., 1980; Fradkov and Pogromsky, 1998). For the purposes of vibrational units control all variety of modes can be split into three main classes: start, speeding up and synchronization.

During the start-up mode maximum power of driving motor is required (Blekhman, 2000). Therefore, decrease of the start-up power is important problem: its solution leads to decrease of nominal power and, therefore to decrease of weight and size of the motor. Furthermore, in order to obtain the desired mode of vibration it is necessary to control the rotor speed in a broad range including both pre-resonance and post-resonance regions. Thus, the problem of passing through resonance during speeding up arises naturally.

The third class of control problems is connected with appearing and robustness of the synchronization. Synchronization in multi-degree-of-freedom vibration machines is an interesting for science and useful for industry phenomenon (Blekhman, 1988, 2000). In most of industry applications only self-synchronization mode is used. Therefore, studying controlled synchronization is promising direction of research.

For the purposes of control design it is useful to divide control tasks into two levels: *local control* on the lower level and *global control* on the upper one. The local control is designed within traditional schemes of electrical motors regulation and solves the local problems of actuator performance (local stability and operating characteristics). The global control ensures specified performance of the unit as a complex system. It is based on the use of more complicated objectives. It is important for engineering practice to design global control on the basis of local controllers using the same control inputs without low-level control loops destruction.

To study the control of vibrations the mechatronic vibrational unit was designed in St.Petersburg Education and Research Center “Problems of Machine-Building, Mechanics and Control Processes” in 1997-2000. In this paper the results of modeling and experimental evaluation of the unit are given[1].

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2. DESCRIPTION OF THE MECHATRONIC VIBRATIONAL UNIT

The unit consists of three blocks: electromechanical double-rotor bench (Fig.1), electronic transducer amplifier and controller.

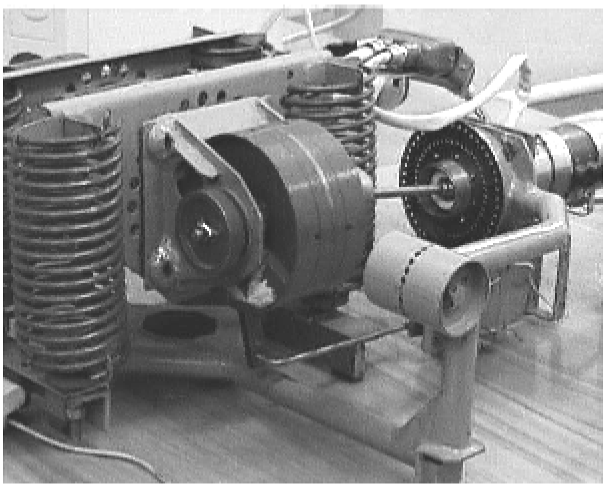


Figure 1: Fragment of double-rotor bench of the mechatronic vibrational unit.

The base of the electromechanical part is a pair of unbalanced vibration exciters, mounted on the vibration isolator. Each exciter contains the DC electrical motor, Cardan joint and unbalanced rotor. During unbalanced rotors rotation the centrifugal forces appear. They can be combined in controlled manner producing a variety of body oscillations. The unit is equipped with eight sensors for generating signals of the two rotors angular position and speed and vibrational body translations. Details and operating characteristics of the unit are given in (Blekhman et al., 1999).

The unit allows studying a variety of phenomena. First, we consider synchronization of the two unbalanced rotors during speeding up as tending to zero the difference between rotor velocities.

3. MODELING THE UNIT DYNAMICS

Mechanical and electromagnetic processes in the unit are interconnected. They are described as complex nonlinear oscillations. Small-deflection linearization of these oscillations often does not allow to analyze synchronization, because nonlinear weak interactions are of significance for synchronization arising.

To examine speeding up and speed maintenance modes an adequate computer-based model of the unit dynamics was created. The original algorithm of computer creation of the model in each step of computation is based on the algorithm for rigid body systems mechanics (Konoplev, 1996). The novelty is in including electromagnetic equations in the algorithm. The efficiency of the algorithm is characterized by the following properties:

1) Universality of the algorithm for analytical and numerical forms of models of electromechanical systems;
2) High computational efficiency based on high percentage of recursive procedures;
3) Most of computations could be provide as concurrent ones;
4) Absence of additional differential modules;
5) Elimination of holonomic and nonholonomic constraints equations creation;
6) Simple taking into account mechanic flexibility, rotating masses (for example, electrical motor rotor, elements of transmission, gyroscope) and inertial environment.

The main idea of the algorithm is in using a model assembling from different modules according to the system graph. The obtained model of the vibrational unit dynamics including electromagnetic process is of 20th order.

4. UNIT TESTING AND CONTROL

All results of computer modeling were confirmed by experimental testing. Both numerical and experimental tests showed similar results. Below only experimental oscillograms as more trustworthy results are presented.

The first group of tests illustrate different modes of the unit with local control only. As it was revealed, the structure of an electrical drive control was of great importance for passing through resonance and synchronization appearing and robustness. Our tests showed a complicated dependence of the synchronization phenomenon upon the number of characteristics. The traditional for vibrational machines scheme with open-loop control of drive speed and proportional current regulator is one of the most appropriate for self-synchronization. In addition, the robustness of the synchronization strongly depends on the value of the current gain: drives with "soft" mechanical (load) characteristics provide more stable synchronization modes. The power of drives is of large significance too.

A number of typical modes are shown in Fig.2-7. Start-up, steady-state mode and one motor cutoff are illustrated with oscillograms in Fig.2. Values of the motors power are equal and large enough to exclude 'sticking' during speeding-up (Sommerfeld effect). The motor with upper oscillogram is cutoff at the moment of 65 sec.: speed values of the motors drop, but both of them continue rotate with identical speed. Power of the motor alive is distributed through the oscillating body. When power of the motors was dropped and energization moments were slightly mutually shifted a short-time 'sticking' of the second motor during speeding-up was observed (Fig.3). After this motor cutoff it stops when the first one speeds up.

Oscillograms in Fig.4 illustrate separate motors energization. In this case speeding-up of the second motor leads to decreasing the second motor speed. This decreasing liberates additional power and shortens the duration of the second motor speeding up by half.

Robustness of the self-synchronization is illustrated in Fig.5. At the moments of 62 sec. and 85 sec. the motor with upper oscillogram is slightly braked. The dips of another motor speed are clearly seen at these moments, but then the both motors continue to rotate with identical speed. The same mode is shown in Fig.6 but with full cutoff of the motor with upper oscillogram at the moments of 15 sec. Speed decreasing of both motors is seen. At the moments of 50 sec. and 90 sec. the electrically dead motor is slightly braked: both motors continue to rotate with identical speed after short-time speed dip. Power of one life motor is distributed between the both exciters approximately equally.

The motors cutoff is demonstrated in Fig.7. At the moments of 25 sec. both motors are cut simultaneously. The further rotation takes place at the expense of accumulated energy. The oscillograms of both rotors braking are identical.

The second group of results illustrates start and speeding up modes of the unit with local and global control. The global control of these modes can improve performance of vibrational machines and reduce their size and weight. The key idea of motor power reduction is based on eccentric rotors swinging during start up by nonlinear feedback control (Blekhman et al., 1997). The control algorithm is based on the speed-gradient method using energy-based goal functionals (Fradkov, 1996).

The speed-gradient algorithms for energy control of conservative systems allow achieving an arbitrary energy level by means of arbitrarily small level of control power (so-called *swingability* property (Fradkov, 1996). Therefore, using this approach for dissipative systems allows to spend energy only for compensation of losses. However, reduction of the motor power may increase the influence of resonance and appearance of Sommerfeld phenomenon (see Fig.3). Hence, it is important to develop global control both for swinging and passing through resonance.

The first solution for swinging control design was proposed in (Blekhman et al., 1997), where two kinds of speed-gradient algorithms were designed and examined. Later a number of new control algorithms facilitating passage through resonance were developed (Tomchina, 1997; Tomchina et al., 1998, 1999, 2000). The global control $u_g(t)$ combining both start and passing through resonance can be described by equations (Tomchina et al., 2000):

$$u_g(t) = \begin{cases} \gamma, \ \mathit{if} \ \gamma_1(t) = 1 \ \mathit{and} \ H(t) < H^*, \\ \gamma, \ \mathit{if} \ \gamma_1(t) = 0 \ \mathit{and} \ \psi(t) - \dot{q}(t) < 0, \\ 0, \ \mathit{else}, \end{cases}$$

with time-varying gain

$$\gamma_1(t) = \sup_{0 \le \tau \le t} \operatorname{sgn}[H(\tau) - H^*]$$

where $H(t)$, H^* are total energy of the unit and desired total energy correspondingly, $\dot{q}$ is angular velocity of rotor,

$$\operatorname{sgn}(x) = \begin{cases} 1, \ x \ge 0, \\ 0, \ x < 0. \end{cases}$$

Signal ψ is produced from angular velocity $\dot{q}$ with help of nonlinear filter:

$$T\dot{\psi} = \Psi(t)[-\psi + \dot{q}],$$
$$\Psi(t) = sign(\pi - q(t)),$$

where $q(t)$ is the angle of the rotor. The variable $\Psi(t)$ is included in order to switch on the filter as soon as the gravity center of the rotor crosses the upper position.

Results of testing the two-level control with above global algorithm are shown in Fig.8. To emphasize the role of the global control, the two-level control signal is applied only to one drive; another motor is controlled by local regulator. Both drives have equal power restrictions. At time 10 sec power is supplied to both motors. The oscillogram indicates that the first motor begins to rotate and overcomes resonance zone after some 'sticking' while the other one cannot even start rotation.

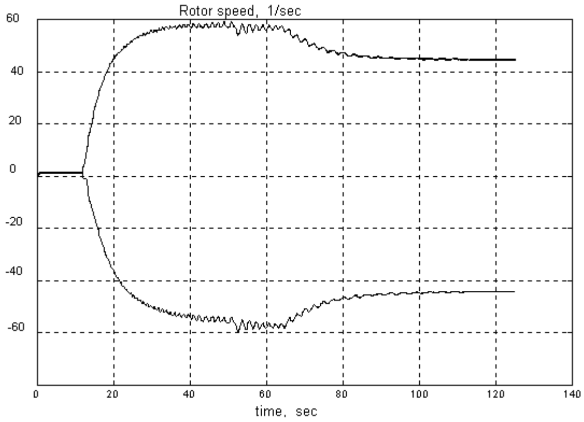
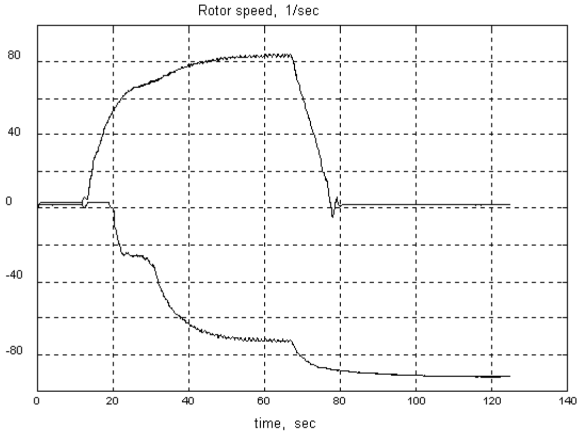


Figure 2.



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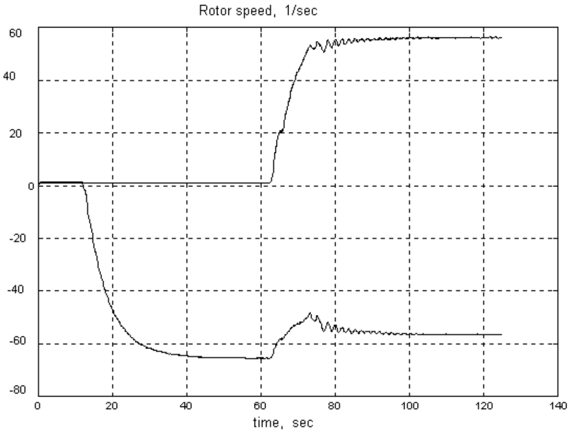

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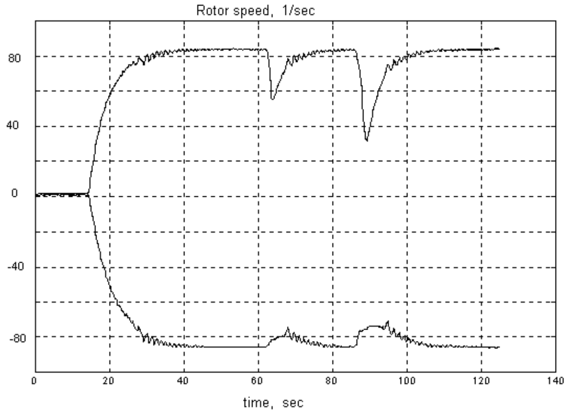

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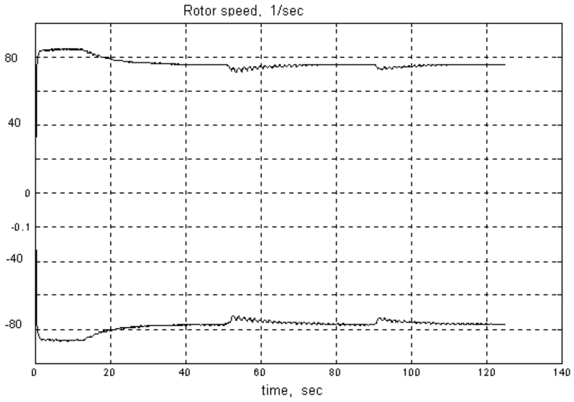

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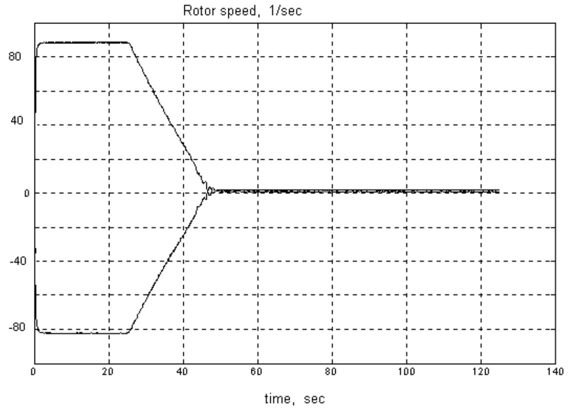

Figure 7.

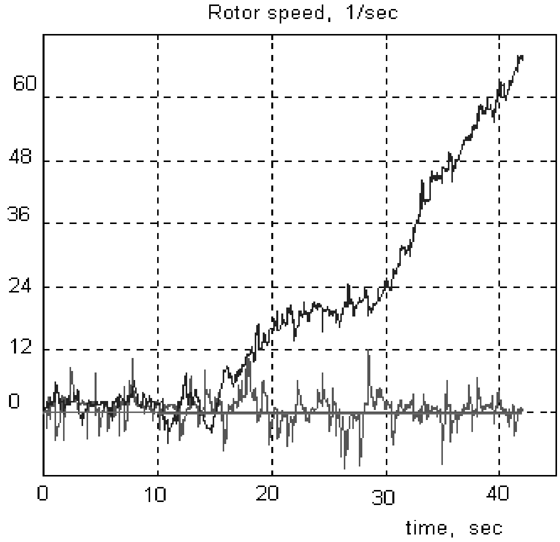

Figure 8.

5. CONCLUSIONS

The study of the developed models and control algorithms has demonstrated their good performance. Solutions to main classes of control problems: start, passage through resonance and synchronization are obtained. The efficiency of the vibrational unit for educational and research purposes has been confirmed. Further results will be published in (Andrievsky et al., 2001).

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