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Computer-Controlled Vibrational Set-Up for Education and Research

I.I. Blekhman[1]; Yu.A. Bortsov[2]; A.A. Burmistrov[2]; A.L. Fradkov[1]; S.V. Gavrilov[2]; O.A. Kononov[3]; B.P. Lavrov[1]; V.M. Shestakov[4]; P.V. Sokolov[2]; O.P. Tomchina[4]

[1] Institute for Problems of Mechanical Engineering, 61, Bolshoy, V.O., 199178, St.-Petersburg, Russia

e-mail: alf@ccs.ipme.ru

[2] St.-Petersburg State University of Electrical Engineering, 5, Prof.Popova str., 197376, St.-Petersburg, Russia

[3] Baltic State Technical University, 1, 1-ya Krasnoarmeiskaya str., 198005, St.-Petersburg, Russia

[4] St.-Petersburg University of Machine Building, 14, Poliustrovskii ave., 197376, St.-Petersburg, Russia

EXTENDED ABSTRACT

The description of the vibrational laboratory equipment is given. The ways of its applications in education and research are discussed.

KEYWORDS

• **Nonlinear control** • **Control of oscillations** • **Control education**

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COMPUTER-CONTROLLED VIBRATIONAL SET-UP FOR EDUCATION AND RESEARCH

I.I Blekhman * **Yu.A.Bortsov** ** **A.A.Burmistrov** **
A.L.Fradkov * **S.V.Gavrilov** ** **O.A.Kononov** ***
B.P.Lavrov * **V.M.Shestakov** **** **P.V.Sokolov** **
O.P.Tomchina ****

* *Institute for Problems of Mechanical Engineering, 61, Bolshoy, V.O., 199178, St.-Petersburg, Russia, e-mail: alf@ccs.ipme.ru*
** *St.-Petersburg State University of Electrical Engineering, 5, Prof.Popova str., 197376, St.-Petersburg, Russia*
*** *Baltic State Technical University, 1, 1-ya Krasnoarmeiskaya str., 198005, St.-Petersburg, Russia*
**** *St.-Petersburg University of Machine Building, 14, Poliustrovskii ave., 197376, St.-Petersburg, Russia*

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Keywords: Nonlinear control, control of oscillations, control education.

1. INTRODUCTION

The control of oscillations and vibrations plays an important role in many fields of science and technology. For example, suppression of vibrations is a traditional class of problems for acoustics and mechanical engineering. A newer class is excitation of oscillations which is important for vibrotechnologies, spectroscopy and some physical studies. Another important class of problems is controlled synchronization which has applications in radiophysics, electronics and telecommunications. The control methods for oscillatory systems are based either on conventional linear control or on more recent nonlinear control theory [Hansen and Snyder, 1996; Chernousko *et al.*, 1980; Fradkov and Pogromsky, 1998].

Previously the control of oscillations did not receive much attention in control engineering courses in Russia. One of the reasons is the lack of textbooks and the laboratory equipment. Recently the possibility of development of such an equipment arose due to launch of the Russian Government Federal Program "Integration" aimed at the improvement of the university education quality based on the recent achievements of the researchers from Russian Academy of Sciences.

In this paper some results obtained in the framework of the project 2.1-589/1.2 of the Program "Integration" are presented.

2. DESCRIPTION OF THE EQUIPMENT

The project started in 1997. Its goal is the development of the mechatronics laboratory equipment, simulation and control algorithms and software for oscillatory mechanical systems. The total funding allocated in 1997-98 was about equivalent of $20,000. Within the first year the two prototype sets of multifunctional vibrational equipment were developed.

The first set, single-rotor a single pendulum mounted on the electric motor shaft. The center of inertia of the pendulum can be easily changed by screwing on a steel cylinder. All mechanical parts and electric motor are mounted on the vibroinsulating frame. The mass of the electromechanical parts is 6 kg. The set-up is controlled by personal computer with processor Pentium 166MMX with interface analog-digital card PCL-818L produced by ADVANTECH Ltd.

The second set is a desk-mounted double-rotor stand with complex mechanical construction. It consists of three blocks: electromechanical part with total mass of about 20 kg, transducer amplifier and control unit. Design of the electromechanical part included elaborated computations based on techniques of vibrational mechanics [Blekhman, 1988, 1994]. The base of this part is a pair of unbalanced vibration exciters. Each exciter contains a direct current electric motor, cardan shaft and unbalanced rotor. The shaft is mounted in the universal-joint fork which is attached to the vibrational body. The last one is mounted in the frame with spring vibroinsulator. During unbalanced rotors rotation the centrifugal forces appear. They are added together in the controlled manner and excite body oscillations of different types. The cardan shafts and spring vibroinsulators reduce significantly transfer of oscillations to the frame. The debalance of each rotor possesses the two values. The set-up design allows to change independently positions of rotor rotation axes. The set-up is equipped with eight sensors for generating signals of the two rotors angular position and speed and vibrational body translations. The main operating characteristics of the mechanical unit are as follows. Overall dimensions:
length - 520 mm,
width - 570 mm,
height - 240 mm (with horizontal rotor rotation axes),
height - 510 mm (with vertical rotor rotation axes);
static unbalanced moment of the rotor: low level - 1.2 kg sm; high level - 4.8 kg sm; (level changing at the most 10 sec.);
controlled rotational speed - 300..3000 rpm, corresponding to vibration frequency - 5..50 Hz;
natural resonant frequency of the vibrational body - 3.33 Hz;
total mass of vibrating parts - 12 kg;
vibrational amplitude - 2..8 mm. The possible oscillation shapes are as follows:
line segment; circle; ellipse; Lissajous figures; circle segment. The set-up design allows additional gadgets up to 5 kg to be mounted. The frame can be replaced by another one, similar in dimensions, representing a model of vibrating mill, shaker, vibrohammer and so on.

The transducer amplifier provides signals of essential power according to analog control signals from the control unit and generates four analog feedback signals from motor current, motor speed and angular position and vibrational body mechanical motion. The mass of the amplifier unit is 16 kg; overall dimensions of amplifier unit are 300x300x120 mm;

electric supply - single-phase voltage of 220±10 V, 50 Hz;
consumed power at the most - 250 W;
maximum output voltage - 20 V;
maximum load current - 3 A;
voltage gain - 2 V/V;
current sensor gain - 3 V/A;
speed transducer gain - 0.003 V/ revolution;
encoder gain - 8 V/ revolution;
rated motor torque - 0.11 Nm;
rated motor voltage - 30 V.

The control unit is a common use PC with processor Pentium 166 MMX and high-speed analog-digital interface card AD-512 produced by HUMUSOFT Ltd. This card includes 16-channel 12-bit analog-digital transducer with reference frequency up to 100 kHz, 2-channel 12-bit digital-analog transducer with operation time at the most 30 mcs and 8 digital input-output channels. All software for simulation and control is developed in MATLAB, version 4.2, with Real Time Toolbox and essential drivers.

The stand allows to demonstrate and to study a variety of phenomena:

1. Self-synchronization of the two identical unbalanced rotors in three modes: - rotation in the opposite directions when antiphase rotation is stable;
- rotation in the identical directions when either inphase or antiphase rotation is stable depending on parameters values.

2. Self-synchronization of the two unequal unbalanced rotors in three modes, mentioned in point 1.

3. Change of phase shift during synchronous rotation in the presence of self-synchronization in three modes from point 1; limits of difference in phase are ±30 degrees.

4. Energy transfer from the active (driving) rotor to the passive (driven) one.

5. Control of reduced-power start of unbalanced rotor by its swinging.

6. Zommerfeld effect if an additional load is attached to the vibrational part with a spring:
- 'sticking' when spin up a rotor;
- significant rise of oscillations amplitude when free vibrations are coming to a stop;
- significant rise of oscillations amplitude when vibrations are coming to a stop with beats of an additional load, suspended freely;

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7. Effect of dynamic suppression of oscillations.

8. Stabilization of upper unstable equilibrium of each unbalanced rotor under control.

9. Rotors synchronization in different modes with help of motor control with either constant or variable phase difference.

10. Handling abilities if additional gadgets are mounted:
- pseudoliquid properties of granular materials under vibration conditions and circulation of the material in a bucket;
- heaving of 'heavy' body in light medium;
- pumping effect, producing by a funnel in liquid and another valveless pump effects;
- density stratification of granular material;
- size stratification of granular material;
- vibroconveyance of bodies and granular materials in different modes;
- separation of material particles according to effective friction coefficient on vibrating surfaces.

3. USING THE EQUIPMENT FOR CONTROL EDUCATION AND RESEARCH

Several universities of St.-Petersburg (see title page) share the facilities described above.

The single-rotor stand is used mainly for testing and modifying the newly developed algorithms for control of swinging and stabilization of unstable pendulum equilibrium.

The double-rotor stand is significantly multifunctional. We consider here only two typical problems of control design and analysis. The first problem is organization of rotational mode of the rotor (pendulum) around the horizontal axis with power-limited control signal and the second one is synchronization of the two rotors. In both cases analysis of the closed loop system first is performed by means of computer simulation and after that the algorithms are compared and evaluated experimentally.

The approximate model of double-rotor stand dynamics can be described by the equations [Blekhman, 1994]:

$$\begin{aligned}
&I_i\ddot{\alpha}_i = L_i(\omega,u) - R_i(\omega) + m_i\epsilon_i(\ddot{x}\sin\alpha_i + \\
&\ddot{y}\cos\alpha_i - \ddot{\varphi}r_i\cos\alpha_i + g\cos\alpha_i);\ i = 1,2;\\
&M\ddot{x} + k_x\dot{x} + c_x x = \\
&\qquad \sum_{i=1}^{2} m_i\epsilon_i(\ddot{\alpha}_i\sin\alpha_i + \dot{\alpha}_i^2\cos\alpha_i);\\
&M\ddot{y} + k_y\dot{y} + c_y y = \qquad\qquad (1)\\
&\qquad \sum_{i=1}^{2} m_i\epsilon_i(\ddot{\alpha}_i\cos\alpha_i - \dot{\alpha}_i^2\sin\alpha_i);\\
&I\ddot{\varphi} + k_\varphi\dot{\varphi} + c_\varphi\varphi = \\
&\qquad \sum_{i=1}^{2} m_i\epsilon_i r_i(\dot{\alpha}_i^2\sin\alpha_i - \ddot{\alpha}_i\cos\alpha_i)
\end{aligned}$$

where I_i is a moment of inertia of debalance 'i';
M is a total mass of vibrating parts;
m_i, ϵ_i is a mass and eccentricity of debalance 'i' correspondingly;
α_i is a phase of debalance 'i' rotor;
$u(t)$ is a control signal;
ω is a rotational speed of rotors;
$L_i(\omega, u)$ is a controlled torque of debalance 'i';
$R_i(\omega)$ is a resistance torque of debalance 'i';
x, y are oscillatory coordinates of vibrating body;
φ_i are rotary coordinate of vibrating body;
g is a gravitational acceleration;
k_x, k_y, k_φ are coefficients of viscous friction;
c_x, c_y, c_φ are stiffness coefficients of springs.

The model (1) is simulated for several constant values of control, and then the simulation results are compared with the results of measurements. It can be a final year (diploma) undergraduate project or a part of a master of Ph.D. project.

In order to organize rotational mode of the rotor (pendulum) around the horizontal axis with power-limited control signal the problem is split into two stages. At the first stage the rotor should be made swinging until it achieves the upright position. At the second stage the rotor should rotate in certain direction and speed up until it achieves the desired average angular velocity or the desired energy level. It is clear that required controlling torque may be different at different stages. Indeed, at the first stage external torque should increase the energy of the system for rotor could achieve the upright position. On the other hand, at the second stage the external energy should be spent only to compensate losses (mechanical friction, losses of the heating and so on). To solve the problem of rotational motion excitation the energy-speed-gradient approach described e.g. in [Fradkov and Pogromsky, 1998] can be used (as well as some other methods). In the typical master degree project the four algorithms were tested both by simulation and by experimental study on the set-up:

1. Relay algorithm

$$u(t) = \begin{cases} -\gamma & \text{if } \dot{\varphi} > \Delta,\ H \le H_* + \Delta, \\ \gamma & \text{if } \dot{\varphi} < \Delta,\ H \le H_* + \Delta, \\ 0 & \text{else} \end{cases} \tag{2}$$

where H is the mechanical energy of the system; H_* is the potential mechanical energy, corresponding to the upright position of the rotor; Δ is small threshold introduced to organize the autostart of the rotor.

2. Directed relay algorithm

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$$u(t) = \begin{cases} -\gamma \text{ if } & \dot\varphi > \Delta, \quad \varphi < 0, \\ & H \le H_* + \Delta, \\ \gamma \text{ if } & \dot\varphi < \Delta, \quad \varphi > 0, \\ & H \le H_* + \Delta, \\ 0 & \text{else} \end{cases} \tag{3}$$

According to algorithm (2) the control action is applied only when the rotor is moving down. It allows to decrease the heat losses.

3-4. Linear and linear-relay speed-gradient algorithm

$$\dot u(t) = -\gamma(H - H_*)\dot\varphi \tag{4}$$

$$u(t) = -\gamma \operatorname{sign}\left[(H - H_*)\dot\varphi\right] \tag{5}$$

Algorithms (4) and (5) provide decreasing control value as far as system trajectory approaches either the goal set or equilibrium.

The experiments show that the results for all these four algorithms are almost similar, with slight difference in the transient time t_k and equivalent current I_e , determining the motor heating (see Table 1). The gain was chosen significantly less then it could be for the larger motor power.

Table 1. Typical experimental results for different strategies.

	Strategy			
	(2)	(3)	(4)	(5)
I_e, A	0.141	0.138	0.156	0.154
t_k, s	1.8	1.8	2.2	1.5

The above study can also grow up into a Ph.D. project, if some modified control problem is considered and new algorithms will be designed Then evaluation and comparison of the new and some existing algorithms can be performed using the laboratory complex and, finally, some application problem will be solved (e.g. control system design for the crashing mill, see [Blekhman *et al.*, 1997], using the proposed algorithms.

Another master degree project consists in design and comparison of several algorithms for synchronization of the two rotors. E.g. the algorithms based on feedback linearization and speed-gradient method can be studied as follows.

Assuming that the coefficients of viscous friction k_x, k_y, k_φ are small and $L_2(\omega) = L\omega$; $R(\omega) = R_i(\omega) = R_i\omega$, the feedback linearization algorithms is derived from the relation

$$\begin{aligned} I\ddot\alpha + k\dot\alpha &= 2V_0 \sin\alpha + d_0 + d_1 u \\ &\quad -(R_1 + L_2 + R_2)\omega \end{aligned} \tag{6}$$

where $\alpha = \alpha_1 - \alpha_2$ is the rotors phase shift; $d_0 > 0$, $d_1 > 0$ are coefficients.

Then the algorithm of controlled synchronization algorithm is as follows.

$$\begin{aligned} u = 1/d_1[&-2V_0 \sin\alpha - d_0 - R_1\omega - L_2\omega \\ &+ R_2\omega + q(\alpha_1 - \alpha_2 - \alpha_*)] \end{aligned} \tag{7}$$

where α_* is the specified phase shift. The closed-loop system consisting of the double-rotor (1) and control algorithm (7) is described then by simple equation

$$I\ddot\alpha + k\dot\alpha = -q(\alpha - \alpha_*).$$

The solution $\alpha(t)$ of this linear equation tends to α_*. which corresponds to the synchronization.

The control algorithm based on the speed-gradient method is

$$u = -\gamma(\dot\alpha_1 - \dot\alpha_2).$$

The designed algorithms are compared first by simulation and then experimentally. One of the experimental results is that algorithm (7) with simple structure is sensitive to a level of input control signal and requires its high level, i.e. large power of supply. At that moment a series of undergraduate laboratory projects related to different courses of Control Engineering Curriculum is in preparation.

4. CONCLUSIONS

The described laboratory units with supporting software and brainware have shown themselves convenient for teaching and research purposes. An important advantage of each set-up is its *integrity*. The unified environment for dynamical modeling of the stands (controlled plants), for simulation and for control design is realized by means of MATLAB software. It allows students to feel the interplay of different stages of the control system design: synthesis, simulations and experimental testing.

Another advantage is usability of the complexes for related disciplines: Mechanical Engineering, Sensors and Instrumentation, Computer Science. The possibility of using changeable and programmable interface cards makes the set-up attractive for studying electronics and electric drives.

Finally, our experience has shown that the joint development of such an advanced educational equipment has a big potential for future, because it opens the way of utilizing and cross-fertilization of research achievements for several scientific schools from related fields.

Some problems discovered during our joint work on the project are also discussed in the talk.

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