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IFAC-PapersOnLine 49-14 (2016) 001–006

Mechatronic Laboratory Setup For Study Of Controlled Nonlinear Vibrations ⋆

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Abstract: In the paper the results of first experimental studies with the setup are described, including motor parameters identification, state estimation and control of rotation velocity. The presented results demonstrate that the setup is useful for study and for control of complex nonlinear oscillatory systems.

Keywords: laboratory techniques, education, engineering, oscillation, nonlinear, control, estimation

1. INTRODUCTION

Mechatronics education requires an appropriate experimental facilities allowing instructors to implement modern project-based teaching and learning technologies. A number of educational laboratory setups for relatively simple and traditional units are described in the literature: for motors (Pogromsky and Van Den Berg, 2014), pendulum-like oscillators (Fradkov et al., 2014; La Hera et al., 2009; Oud et al., 2006), tanks (Pan et al., 2005; Starkov et al., 2012), etc. However there are only a few setups with multiple DOF systems allowing teachers to demonstrate complex nonlinear behavior and students to learn how to estimate and control it (Fradkov et al., 2012; Mayr et al., 2015).

This article describes a new teaching and research setup – the *Multiresonance Mechatronic Laboratory setup* (MMLS) and outlines its possible applications to control engineering education.

The rest of the paper is organized as follows. A brief description of the setup is presented in Sec. 2. Section 3 is devoted to modeling and parameter identification of the electric motor. The state estimation problem is addressed in Sec. 4. Section 5 presents some results on computer control of the vibrational stand, includi ng design of the PI-controller in the angular velocity loop and comparison of simulation and experimental results. Concluding remarks and an outline of possible applications of the setup are given in Sec. 6.

⋆ The work was performed in the IPME RAS and supported by the Russian Science Foundation (grant 14-29-00142). The sample-data control system analysis (Sec.5.2) is supported by SPbSU (grant 6.38.230.2015)

2. SETUP DESCRIPTION

The new device has been developed on the basis of many years of experience on creating vibrational stands at the Mekhanobr Engineering JSC and the IPME RAS (Blekhman, 2013; Tomchin and Fradkov, 2005). The MMLS includes the vibrational stand, electrical engines, sensors, and personal computer (PC). All the devices constitute an integrated system, where the electrical and mechanical processes are inextricably linked each other, which gives a basis to call the setup a *mechatronic* one. The mechanical part of the MMLS is an electrically driven vibrational device, see Fig. 1.

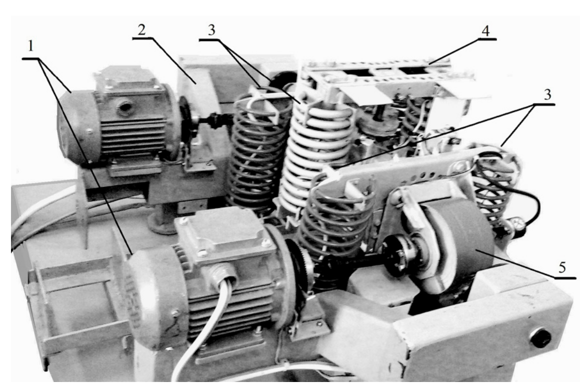

Fig. 1. Photo of the two-rotor vibrational stand. 1 – AC induction motors, 2 – support frame, 3 – springs, 4 – additional frame, 5– unbalanced rotor.

The key part of the stand is a pair of the unbalanced (centrifugal) actuators. Each actuator includes three-phase AC induction motor (1) with computer-controlled rotation velocity, the unbalanced rotor (5), which rotates on the motor shaft in a vertical plane on the stand carrier body.

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.07.963

Unbalance of the rotor is provided by the eccentrically located weight. The drive shafts and the anti-vibration screw springs repeatedly reduce the stand table vibration transmission to the support frame (5) and to the basis, where the frame is located. The additional frame (4) is mounted on the stand table on the springs (3) for installing an additional weight.

The stand is equipped with five optical sensors measuring the table and the extra weight positions, velocity sensors with a resolution of 1000 pulses/revolution for two independently rotating rotors, as well as with the sensors of electric motor current. Set of the sensors can serve as a source of signals for studying and demonstrating the measuring systems, the signal processing, and the real-time control. For measuring positions of the stand table and the extra weight, the assemblies including eight linear and angular displacement sensors are installed. Each platform bears three angular and three linear optical encoders. Measured data from all the 12 sensors are transmitted to computer. The PC is supplied with the *ICP DAS* connector boards. 18 analog sensors are connected to the board for measuring the stand physical quantities. Four pulse sensors (encoders) *PISOEncoder600* of the shafts rotation angles of the stand are connected to the board.

Real-time data processing and control are carried out by means of Simulink Desktop Real-Time™ of MATLAB© software. Control signal computation can be performed with a sampling rate up to 1000 Hz. In parallel, time histories of the chosen variables may be displayed on the PC monitor.

More detailed description of the MMLS may be found in (Andrievsky et al., 2016).

3. IDENTIFICATION OF THE ELECTRIC MOTOR PARAMETERS

3.1 Asynchronous motor model

The input of the frequency converter is fed by the dimensionless digital control signal u from the range of $[0, 65000]$, the measured output is angular velocity ω of the unbalanced rotor.

The initial part of the students' research includes the electric motor model parameter identification based on the experimental data, obtained from the setup. For the sake of simplicity, the following motor transfer function from control signal u to angular velocity ω (including the frequency converter, induction motor as such, and the unbalanced rotor) is taken:

$$W_d(s) = \left\{\frac{\omega}{u}\right\} = \frac{K_d}{(Ts+1)(\tau s+1)}, \qquad (1)$$

where K_d denotes the motor static gain; T and τ are time constants; $s \in \mathbb{C}$ denotes the Laplace transform variable. Since model (1) gives only a linear representation of the nonlinear AC motor dynamics for a certain operation area and does not describe the complex influence of revolving the unbalanced rotors and vibrating mechanical parts of the stand to the motor behavior, an essential part of the students' research is an experimental evaluation of the accepted assumptions for the real-world control and estimation problems. In what follows, the angular velocities in the range of $[80, 120]$ rad/s are picked up for the example.

3.2 Application of the optimization procedure

Firstly, consider minimization of the mean-square error between actual $\omega(t)$ and simulated $\omega_{\rm sim}$ outputs for the same control input signal $u(t)$. The cost function is chosen in a form $J = \frac{1}{T_f - t_0}\int_{t_0}^{T_f} e^2(t)\,dt$, where $e(t) = \omega(t) - \omega_{\rm sim}(t)$, t_0, T_f are, respectively, the initial and the final instants for error evaluating. Signals $u(t)$, $\omega(t)$ are recorded during the experiment, $\omega_{\rm sim}(t)$ is calculated by means of Simulink toolbox with zero initial conditions and $u(t)$ as an input signal. The value of $J = J(T, \tau, K_d)$ is used as an optimization cost for direct search Nelder-Mead MATLAB routine *fminsearch*.

Results of the identification procedure are illustrated by Fig. 2, where the time histories for initial ("guessed") parameter values $\hat{K}_d = 0.006$, $\hat{T} = 2$ s, $\hat{\tau} = 0.1$ s) and the optimized ones ($\hat{K}_d = 0.004$, $\hat{T} = 1.34$ s, $\hat{\tau} = 0.22$ s) are plotted. For the "right" motor this procedure leads

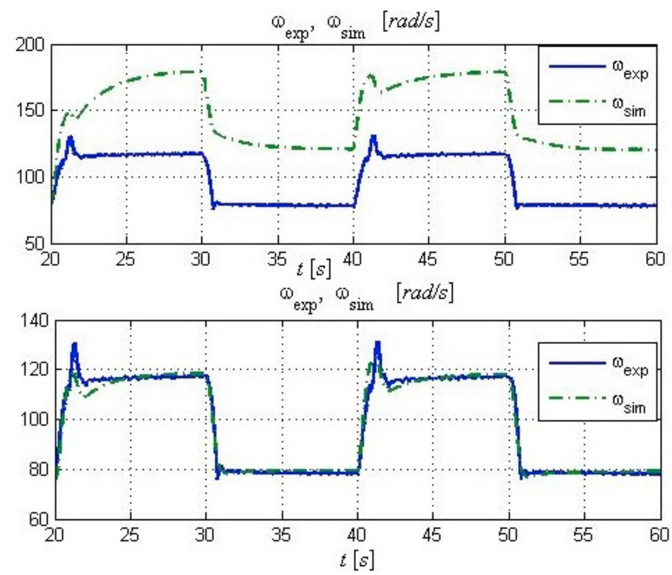

Fig. 2. Transients for initial (upper plot) and optimized (lower plot) parameters of the "left" motor.

to $K_d = 0.0040$ rad/s, $T = 1.28$ s, $\tau = 0.25$ s.

3.3 Application of non-recursive LSE method

Secondly, let us apply the least-square estimation (LSE) method. To this end, model (1) is expressed as the *linear regression* equation:

$$y[k] = \varphi[k]^{\rm T}\theta + v[k], \qquad (2)$$

where $y \in \mathbb{R}^1$ denotes the plant output at step $k = 1, 2, \ldots, N$, vector $\varphi[k] \in \mathbb{R}^m$ is the *regressor*, $\theta \in \mathbb{R}^m$ is the vector of plant model parameters, subjected to identification, m is a number of plant parameters, $v[k]$ is an additional noise (see (Ljung, 1999) for details).

The non-recursive LSE procedure leads to the following estimate of θ: $\hat{\theta} = \Phi^{\dagger}Y$,