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Adaptive multiple synchronization and rotors phase shift tracking for two-rotor vibration machine

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Abstract. The paper presents the results of simulation and experiments of the adaptive control algorithm for various values of the multiplicity of the rotor's rotational frequencies and a given phase shift between them for the twin-rotor vibratory unit SV-2M. The simulation and experimental results demonstrate the rotational speeds and phase shifts between the rotors. Also, the process of adaptive controller adjustment is shown. The performance of the vibration machine demonstrates the effectiveness of the proposed algorithm in wide operating modes. Further on, the development of automated control algorithms in vibration machines promises the transition toward intelligent vibration technologies. It allows regulating the type of vibration fields of the table in real-time, including improving the process of vibration mixing by chaotizing its movement.
Keywords: nonlinear oscillations, PI controller, asynchronous drive, unbalanced rotor, self-synchronization, vibration technologies, intelligent control

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1. Introduction

Vibration technologies are a crucial automation component in various industries that allows for expanding the technical and economic effects. The development and improvement of vibration technologies and equipment do not stop and are closely related to the study of nonlinear oscillations and the possibility of their practical application [1]. The oscillatory effects of vibration machines are widely used in manufacturing and agriculture for bulk solid separation, vibrational transportation, vibration grinding, pile driving, mixing, etc. Despite all the advantages, vibration machines have a drawback associated with the lack of control over vibration oscillations during operation. In this connection, the issues of automation and the use of an adjustable drive in this direction are highly relevant.

For more than a hundred years, work has been underway to create new vibration technologies and designs of vibration machines in various scientific schools. It includes the well-known St. Petersburg Mekhanobr-Tekhnika Corp., based on the design and scientific departments of the Institute for the Ore Dressing. Differ areas of research work in Mekhanobr are carried out in cooperation with several scientific and educational institutions [2]. Recently, on the initiative of Prof. Alexander Fradkov, based on laboratory equipment of the Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences, the direction of feedback control of vibration machines with an unbalance vibration exciter began to develop. Modern automatic control methods can allow the controlling of all vibration parameters in real-time by changing the frequencies and phases of rotation of drive motors. The solution to such problems is attractive from scientific and engineering points of view. This is especially in demand in the case of using vibration equipment in cyber-physical systems [3]. It may be promising for smart vibration technologies since it will allow changing the type of platform vibration fields during operation and chiefly will open the way to chaotization of vibration mixing.

The synchronization phenomenon is widely used in vibration technology to obtain various forms of body vibrations, ensuring the stability of the vibration machine and maximum productivity. Based on the self-synchronization property, such classes of vibration machines as grain cleaners, conveyors, feeders, screens, crushers, and mills have been created. The single synchronization mode can occur naturally and is called self-synchronization [4]. The self-synchronization phenomenon of mechanical exciters leads to the fact that unrelated rotors of vibration exciters rotate with the same absolute value or multiples of the average angular velocities, and certain phase ratios are established between the rotors. Coordinated synchronous rotation of vibration exciters with a given phase shift between them is provided due to the internal properties of the oscillatory system itself. In the study of vibrations, it is assumed that the shafts of vibration exciters rotate uniformly on average throughout oscillations. There is also a connection between the vibrational and rotational coordinates of the system. This connection manifests itself in the mutual influence of the unbalanced shaft support vibration on the rotors and the reactive moments of the forces of inertia emanating from the uneven rotation of the rotors on the supports. The effect of self-synchronization is not always stable, for example, in the case of providing specified shifts in the phases of the rotors or multiple synchronizations. Under the varying mass conditions of the processed material, the synchronization can be ensured by control algorithms. Thus, the engineers are faced with the task of controlled synchronization of vibration machines. Multiple frequency synchronization is meant the proportionality of the speed of unbalanced rotors ω_i to the synchronous frequency ω^* for integers n_i [4]:

$$\omega_i = n_i \cdot \omega^*, i = 1, \dots, n. \quad (1)$$

Multiple coordinate synchronizations assume that the phases of vibration exciters ϕ_i satisfy the equality [3]:

$$\frac{\phi_i}{n_i} - \frac{\phi_k}{n_k} = L_{ik}, k = 1, \dots, n, i \neq k. \quad (2)$$

Formalized issues of controlled synchronization were considered in [4-6], where the presented general definition of controlled synchronization allows us to formulate the problem of synthesizing the controller of a dynamical system. There are several studies on the control of the synchronization of vibration machines [7-9]. In [7], the synchronization problem is solved using the speed gradient method [10], where the goal of control is to reach a given level of the system's total energy, which is determined by the steady-state average speeds of the rotors. The results of the proposed control law have been tested on a three-rotor vibrating machine with a varying mass of the processed load. In [8,9], it was found that the multiple synchronization region is limited for high speeds due to the tendency for rotors to self-synchronize when controlling the phase shift between two unbalanced rotors using a proportional-integral (PI) controller in the speed and phase control loops. Thus, shaped and non-uniform fields of trajectories of points of vibration exciter cannot be obtained due to the action of self-synchronization. The purpose of this paper is to ensure multiple speed synchronizations with a given phase shift.

2. Description of two-rotor vibration machine SV-2M

To conduct experiments on the reproduction of complex dynamic phenomena, study vibrational processes, and test algorithms for controlling rotational and oscillatory motion, several vibration stands were created [2,11,12]. The source of oscillations of the vibration machine is the actuator, in which an inertial element (vibration exciter) is installed in bearings, connected to the housing, and unbalanced relative to the entire axis of rotation. In this paper, we study the control of a two-rotor vibrating machine, shown in Fig. 1, and consisting of the following components. Three-phase asynchronous motors *1* are installed on the supporting frame *2*, connected through a shaft with unbalanced rotors *3*. The nominal motor output is 0.09 kV·A, and the rotor speed is 288 rad/s. The pre-resonant operating frequency range of the engines lies in the interval [30, 120] rad/s. The axes of the exciter rotors are perpendicular to the plane parallel to which the platform moves. The unit is equipped with lower springs for vibration isolation of platform *5* from the carrier frame and upper springs for securing the load.

Electric motors *1* are controlled in real-time through power frequency converters connected to the computer and current sensors in the motor power supply circuit. The rotor's rotation angles are measured by encoders. The oscillatory movements of the platform are measured by inductive displacement sensors. All components are used to create a complex mechatronic system in which all processes are inextricably linked.

The vibration machine can operate in the self-synchronization and controlled synchronization mode of vibration exciters. The rotation of the vibration exciters creates vibrations of platform *5*, the oscillation frequency of which is controlled.

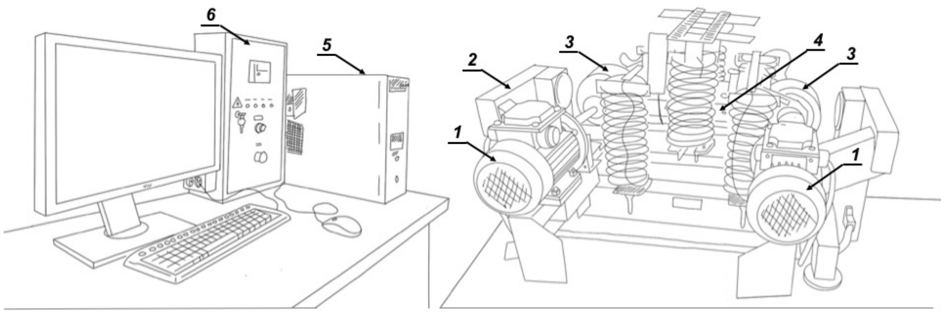

Fig. 1. System of two-rotor vibration unit

Before carrying out experiments on a vibration machine, it is advisable to conduct a computer simulation of the system to test a new control algorithm and select its unknown parameters. Although the accurate model of a vibration machine is very complex, it can be replaced by the following simplified model. As shown in [7,9], due to the principle of averaging for operating frequencies and also due to the presence of local controllers of asynchronous motors, their dynamics can be approximately described by the transfer function from the control signal $u(t)$ to the angular frequency of rotation of the rotor $\omega(t)$:

$$W_u^{\omega}(s) = \frac{K_d}{(T_1 s+1)(T_2 s+1)}, \quad (3)$$

where K_d is the drive gear ratios, T_1 and T_2 are the time constants.

Model (3) parameters were identified by the standard method of nonrecursive least squares estimation [6,8]. The results of the identification procedure showed that the variations of model parameters (3) for different operating frequency ranges are low, and their average values for both drives are: $K_d = 0.041$ rad/s, $T_1 = 1.75$ s, $T_2 = 0.246$ s.

3. Adaptive control of multiple synchronizations

The choice of the adaptive control law is associated not only with a complex mathematical description and change in time of its internal parameters but also with the possibility of changing the given input parameters the rotational speed of the rotors and the magnitude of the phase shift between them, without additional adjustment of the controller. In this paper, an adaptive PI controller with an implicit reference model (IRM) is used [13-15]. To describe it, consider the following equation for a minimum-phase single-input single-output (SISO) system:

$$A(p)\omega(t) = B(p)r(t), \tag{4}$$

where $\omega(t)$ and $r(t)$ are the actual and reference rotor speeds, $A(p)$ and $B(p)$ are polynomials in the time differentiation operator $p = d/dt$, which coefficients are unknown.

The desired dynamics of the stabilization process of the object (4) can be specified by an implicit differential equation. To do this, we introduce the stabilization error $e(t) = \omega(t) - r(t)$, its integral $\dot{\xi}(t) = e(t)$ and the adaptation error $\sigma(t)$ as follows [15]:

$$\sigma(t) = \tau\xi(t) + e(t), \tag{5}$$

where τ is the coefficient of the reference model, which is set according to the desired stabilization dynamics.

The PI speed control law for each rotor is written in the standard form [9]:

$$u(t) = -(K_i(t)\xi(t) + K_p(t)e(t)), \tag{6}$$

where $K_i(t)$ and $K_p(t)$ are integral and proportional coefficients.

Then the structure of the adaptation algorithm is written as [15-17]:

$$\dot{K}_i(t) = \gamma\sigma(t)\xi(t) - \lambda(K_i(t) - K_i^0), K_i(0) = K_i^0, \tag{7}$$

$$\dot{K}_p(t) = \gamma\sigma(t)\xi(t) - \lambda\big(K_p(t) - K_p^0\big), K_p(0) = K_p^0, \tag{8}$$

where γ is the adaptation coefficient, λ is the adaptation parametric feedback gain, K_i^0 and K_p^0 are the initial values of adjustable coefficients of the regulator.

To control the phase shift, by analogy with (5), (6), (7), and (8), it is proposed to introduce an adaptive control law with IRM into the phase control loop as follows:

$$\sigma_\psi(t) = \tau\xi_\psi(t) + e_\psi(t), \tag{9}$$

$$u_\psi(t) = -(K_{i\psi}(t)\xi_\psi(t) + K_{p\psi}(t)e_\psi(t)), \tag{10}$$

$$\dot{K}_{i\psi}(t) = \gamma\sigma(t)\xi_\psi(t) - \lambda\big(K_{i\psi}(t) - K_{i\psi}^0\big), K_{i\psi}(0) = K_{i\psi}^0, \tag{11}$$

$$\dot{K}_{p\psi}(t) = \gamma\sigma(t)\xi_\psi(t) - \lambda\big(K_{p\psi}(t) - K_{p\psi}^0\big), K_{p\psi}(0) = K_{p\psi}^0. \tag{12}$$

Thus, the resulting control signal for the left and right motors of the vibration machine, considering (10), is described as:

$$u_l(t) = u(t) + u_\psi(t), u_r(t) = u(t) + u_\psi(t). \tag{13}$$

For each rotor, a restriction on the control signal is introduced using the saturation function: $\mathrm{sat}_u(u) = \mathrm{sign}(u)\min\{|u|, u\}, u > 0$.

4. Results

Let us carry out a simulation and a physical experiment on a two-rotor vibrating machine using the adaptive control law (6)-(8), (10)-(13) model of the vibrating machine (3) for the frequency ratio of the right and left engines equal to $n = 1/2$ so that $\omega_r = 120$ rad/s, $\omega_l = 120$ rad/s with their antiphase rotation (Fig. 3). The parameters of the adaptive PI controller are chosen as follows: $\gamma = 1$, λ =0.01, $\tau = 1$, $K_i^0 = 450$, $K_p^0 = 450$, $K_{i\psi}^0 = 450, K_{p\psi}^0 = 450$. The upper limit value of the control signal is u = 40 rad/s, the lower limit is 0.

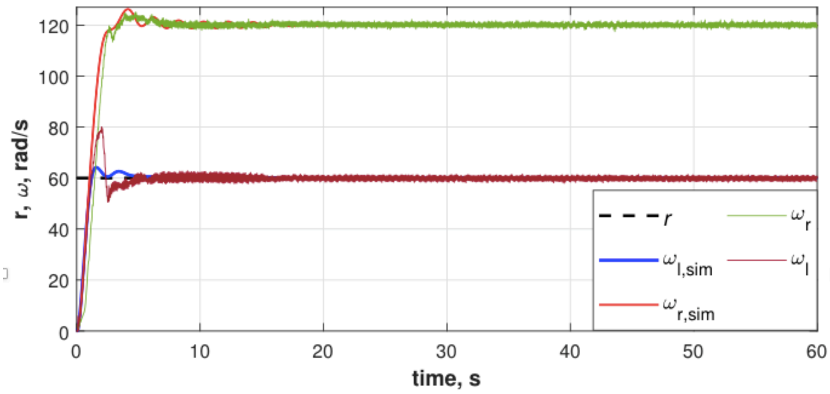

Fig. 2. Rotation speed

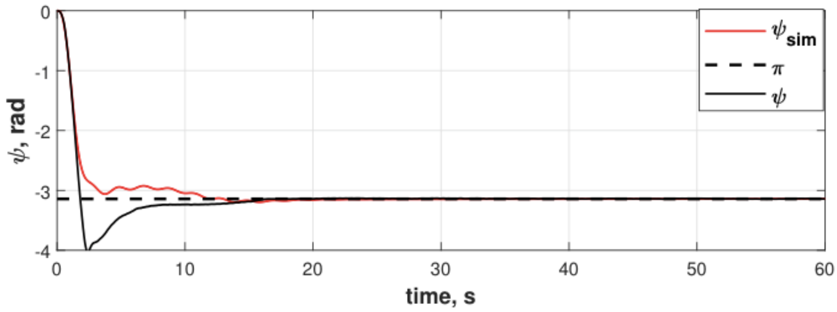

Fig. 3. Phase shift between rotors

From Figures 2 and 3 it can be seen that the adaptive control law maintains the given rotor speeds and phase shift. Figure 4 shows the process of adjusting the controller coefficients, from which it can be seen that the proportional coefficients K_p, K_i obtained experimentally coincide with the coefficients obtained from the simulation results. Figure 5 shows the change in the adaptation error for the speed loop of each rotor and the phase shift, which shows the agreement between the simulation and experiment results for the frequency control loop.

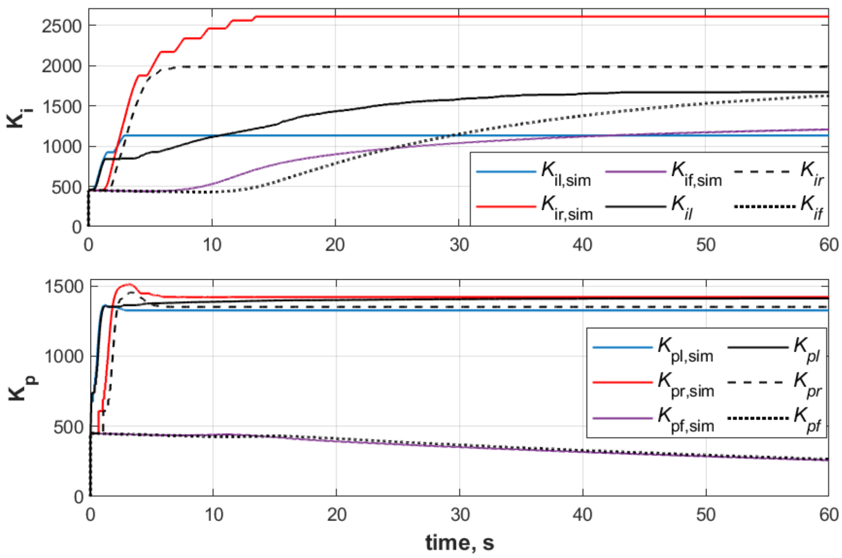

Fig. 4. Adaptation of controller gains

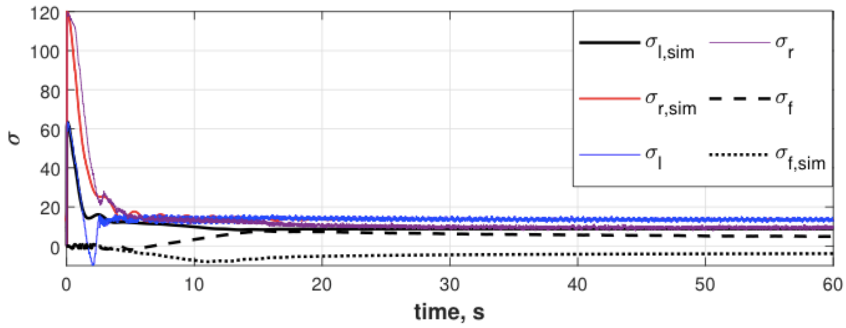

Fig. 5. Adaptation error

A similar experiment was carried out for rotor speeds of $\omega_r = 90$ and $\omega_l = 45$ rad/s (Fig. 6). The reference phase shift between rotors is equal to $\pi/2$. Figure 7 shows the phase shift between rotors via time, Fig. 8 – the adaptation of controller gains, and Fig. 9 – the adaptation error via time. Note that a further increase in the rotational speed of the rotors leads to a loss of phase shift control under the action of self-synchronization. The phase shift acquires a periodic dependence on time.

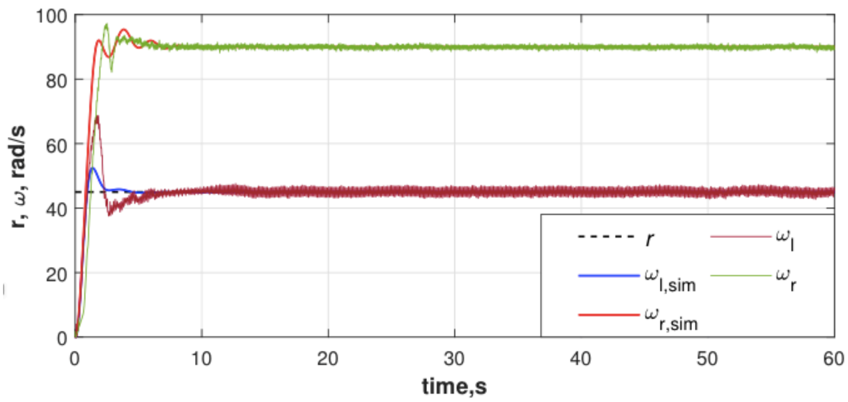

Fig. 6. Rotation speed

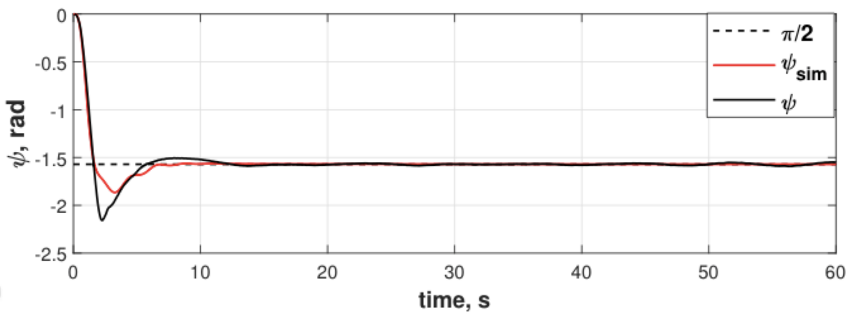

Fig. 7. Phase shift between rotors

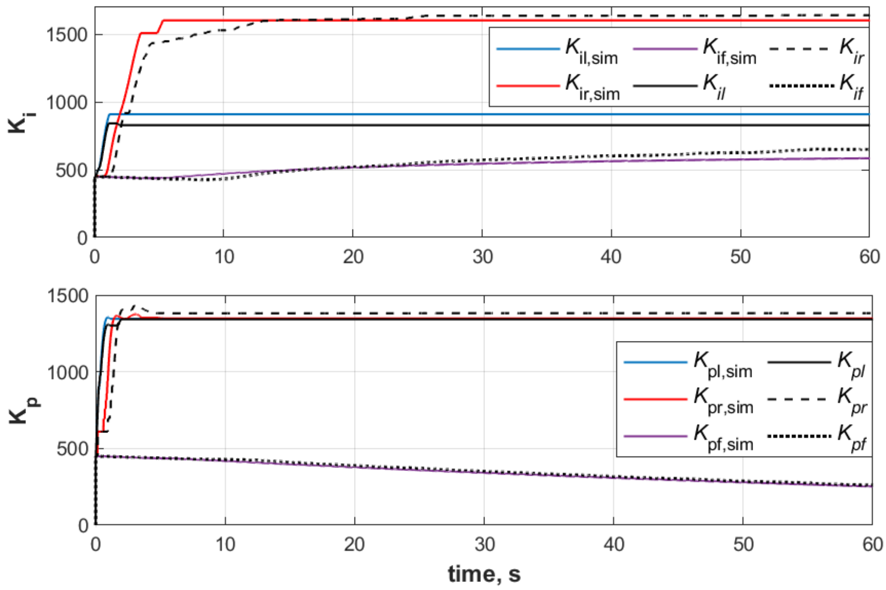

Fig. 8. Adaptation of controller gains

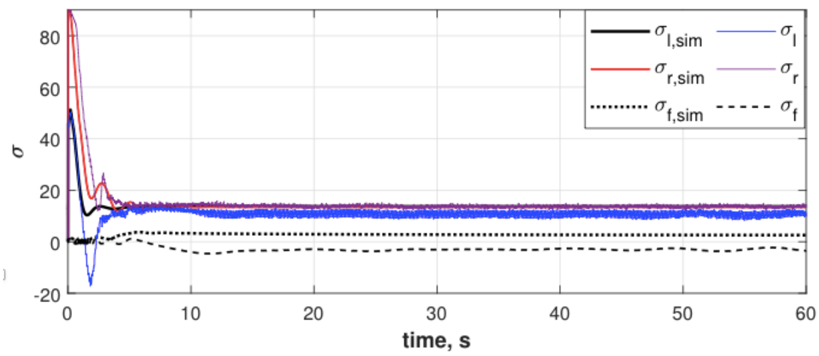

Fig. 9. Adaptation error

Also, experiments were carried out at a reference rotation speed of each rotor equal to 40 rad/s and applied phase shift between the rotors, given by the following periodic law: $\psi^*(t) = \pi \cdot \sin(0.3t)$. Figures 10-13 show the simulation and experimental results for this case.

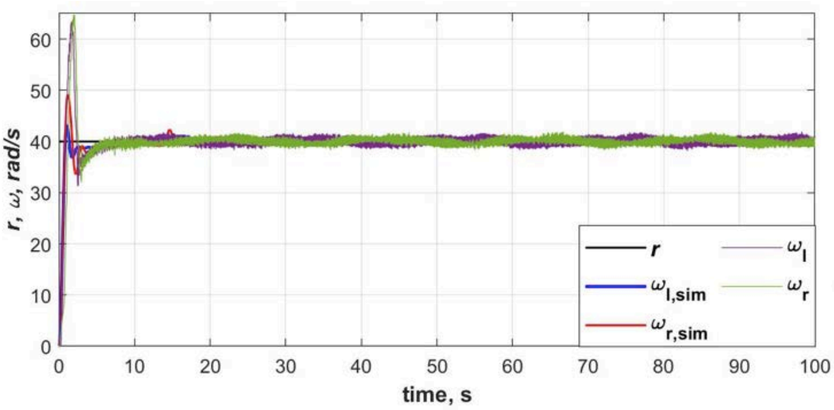

Fig. 10. Rotation speed

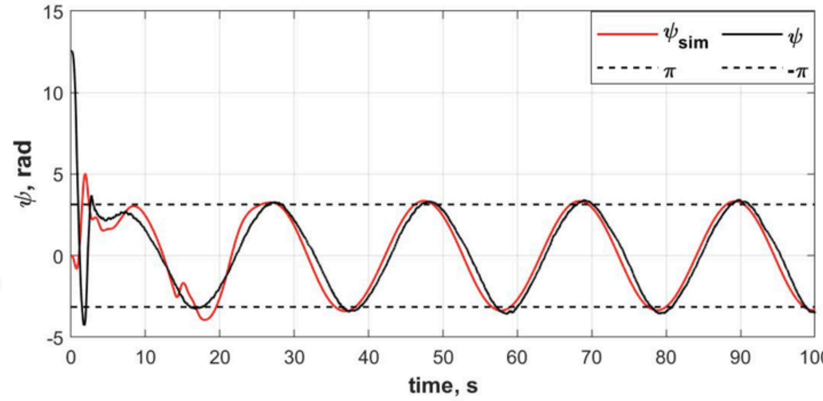

Fig. 11. Phase shift between rotors

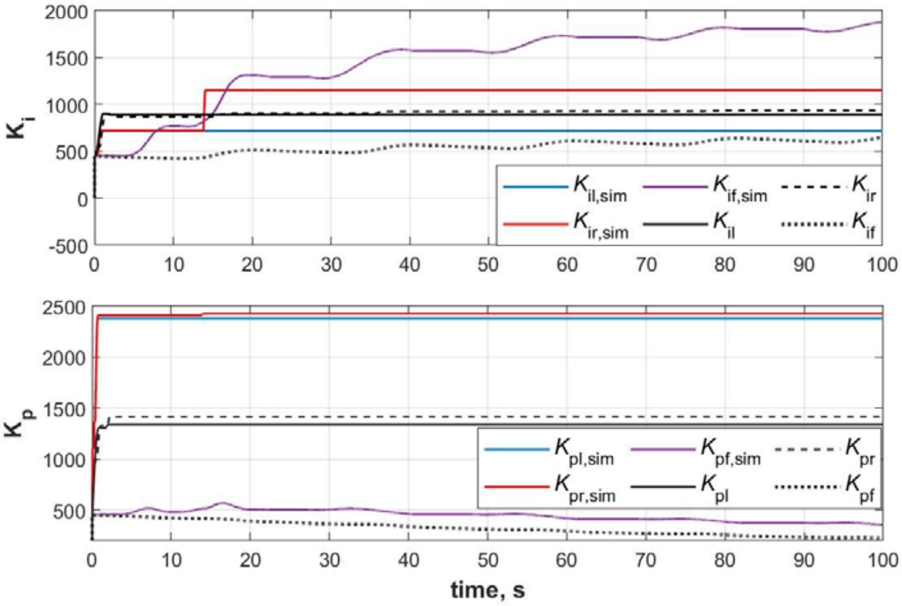

Fig. 12. Adaptation of controller gains

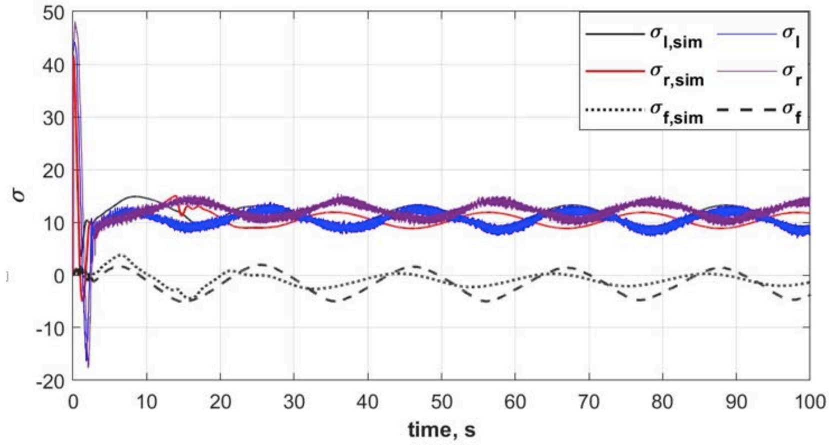

Fig. 13. Adaptation error

5. Conclusion

The paper proposes the use of an adaptive controller with IRM to control multiple synchronizations of a two-rotor vibratory machine. Simulation of a simplified model of the machine and an experiment were carried out, the results of which are close to each other, except for the integral coefficients of the controller. An adaptive IRM controller allows expanding the range of controlled frequencies and phases compared to a standard PI-controller, and also allows running transients more smoothly.

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