VIRTUAL TESTING OF VIBRATION MECHATRONIC SETUP WITH TECHNOLOGICAL ACCESSORIES

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Abstract

This paper presents the development of an additional module for the mechatronic vibration stand SM-2M at the Institute of Mechanical Engineering of the Russian Academy of Sciences. The module is designed to conduct experimental studies of various technological processes, including sieving, material mixing, and granulation. To evaluate the dynamic characteristics of the system, a virtual model of the equipment was developed, which includes elements of technological tooling represented by a working table accounting for its own mass. The model was implemented using the *ADAMS.View* software package, providing capabilities for visualization and dynamic analysis of the system. Testing of the novel mechanical design was carried out via co-simulation methodology, integrating a proportional-integral control algorithm implemented in *MATLAB/Simulink* with the physical model of the mechanical part realized in *ADAMS*. Several virtual experiments addressing the control of rotational speed and angular displacement of the drive motors of the vibrational setup equipped with technological tools and bulk materials are presented. Graphical dependencies depicting variations in motor rotation frequencies and trajectories of motion of the center of mass of the working components based on virtual sensor readings are provided. The results facilitate implementation of modern control methods, enhancing technology reliability and efficiency.

Key words

Vibration technologies, mixing, intensification, modeling, digital twins, vibration control.

1 Introduction

This paper is part of a research project dedicated to the digitalization of complex electromechanical equipment whose operation is based on the use of beneficial vibrations for material processing. Vibratory machines (VMs), including vibratory screens, feeders, conveyors, and separators, are used in the manufacturing and mining industries, which are known to be fundamental to the economy. However, this sector significantly lags in terms of computerization and the introduction of new technologies, cf. [Sivachenko, 2017]. Currently, there are a number of theoretical studies on digital transformation, dedicated to both production as a whole and its individual components [Nikitin et al., 2024; Verenitsyn, 2021]. Technological advancements in this area can not only increase the efficiency of production processes but also significantly reduce the amount of waste during material processing, thereby supporting the “green” agenda. These tasks are consistent with the modern trend towards the creation of smart factories and the transition to sustainable economic development [Tian and Zhang, 2022].

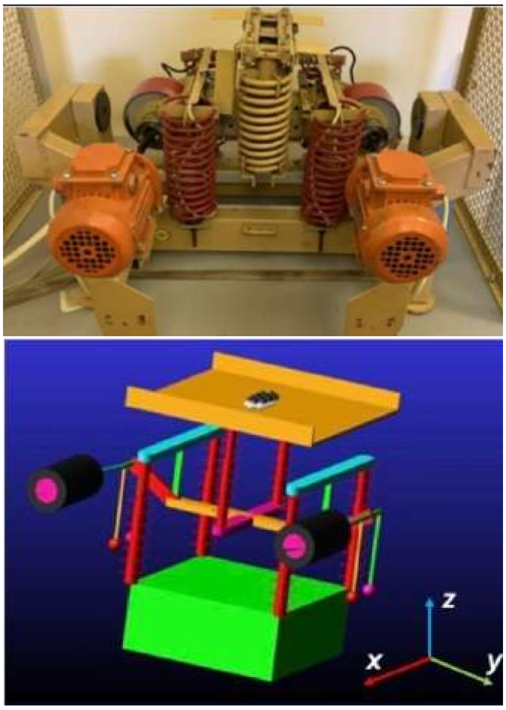


Figure 1. Photograph of the vibration setup with a technological accessory (upper plot) and its virtual model with a tray and bulk material (lower plot).

VMs generate vibrations of varying amplitude and frequency [Blekhman et al., 2002; Blekhman et al., 2022]. Initially, mechanical control was used for this purpose, which significantly limits the functionality of the equipment and increases the time required to perform operations. For VMs operating in controlled synchronization mode without external control signals, the synchronization process of electric motors is characterized by low stabilization stability, and changes in load can lead to system instability. The introduction of computer control with feedback from measurements solves not only these problems but also plays a crucial role in ensuring stable operation in certain modes, such as multi-frequency synchronization. To date, several algorithms are known [Gorlatov et al., 2015; Tomchin et al., 2021; Gerasimov and Zaitceva, 2024; Shagniev et al., 2022; Tomchina, 2022; Fradkov et al., 2024], many of which have been experimentally tested on the SV-2M two-rotor VM, a photograph of which with a technological accessory is depicted in Figure 1 (upper plot). Descriptions of the models of the two-rotor vibration setup SV-2M, taking into account the technological equipment, are given in [Tomchina et al., 2017], where a methodology for obtaining a comprehensive model of a multi-rotor vibration unit is proposed, taking into account the dynamics of electric drives, the elasticity of cardan shafts, and changes in the mass of the processed material. Therefore, the development of new approaches to solving the problem of ensuring stable multiple synchronous rotation of vibratory actuators is a relevant technical task. One promising approach is controlled synchronisation. Several studies [Blekhman et al., 1997; Miroshnik and Nikiforov, 1995; Blekhman et al., 1999; Blekhman et al., 2001] are devoted to the control of synchronization of oscillatory mechanical systems. The promising results for ensuring a stable multiple synchronous mode are related to the energy-based approach in conjunction with the so-called Speed-gradient method [Fradkov et al., 1999; Galitskaya and Tomchina, 2012; Andrievsky and Fradkov, 2021; Shagniev et al., 2022; Fradkov and Andrievsky, 2022]. In its framework, new control algorithms for multiple synchronization were proposed and studied, providing improved characteristics of the processes in the vibration system. The experimental and simulation results for the SV-2M are presented, which are consistent with the calculated data. Some interesting recent results can be also found in [Tomchina, 2023; Andrievsky et al., 2024].

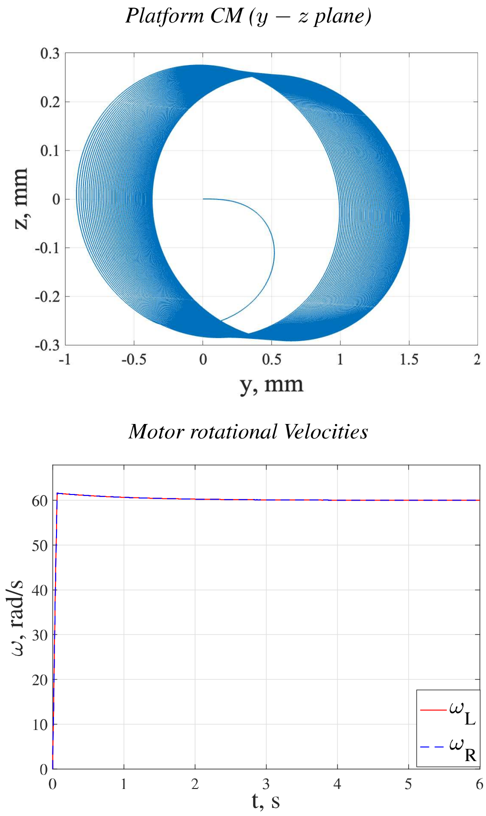
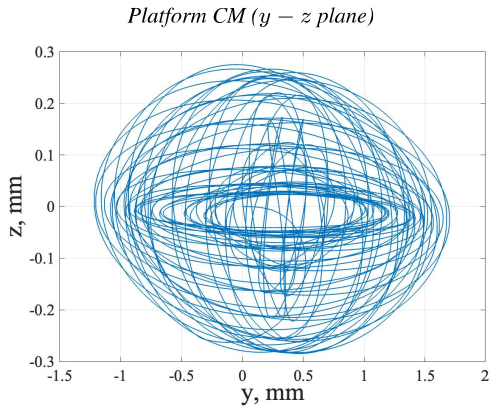


Figure 2. Results of experiment 1.

Each induction motor is rigidly connected via a shaft to a mechanical unbalance, the axis of which is offset from the axis of symmetry. The motors rotate in opposite directions. The vibrations generated by these motors are transmitted to the working surface, which serves as a platform for placing a load, such as bulk material. The springs are used to support the platform and facilitate its oscillatory motion. The assembly also includes amplifying and converting power devices for the motors, a sensor system (including encoders and linear displacement sensors for the working surface), and a computer



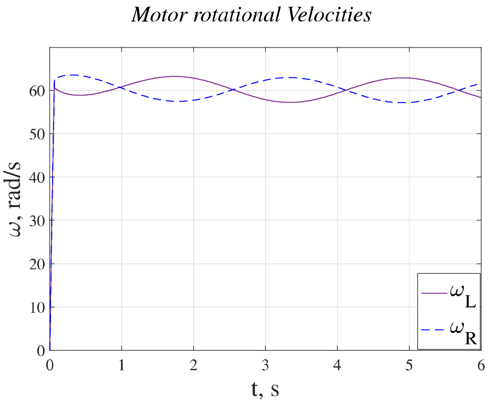


Figure 3. Results of experiment 2.

with interfacing devices [Blekhman et al., 2017]. In the context under consideration, the VM generates circular oscillations. The algorithmic control of these oscillations has enabled the resolution of several tasks: starting the motors and traversing the resonance frequency [Gorlatov et al., 2015], ensuring a mode of stable multiple synchronization of the unbalances [Tomchina, 2023], reproducing the mode of asymmetric oscillations [Gerasimov and Zaitceva, 2024], and generating irregular oscillations [Andrievsky et al., 2024; Fradkov et al., 2024] of the working platform. As demonstrated in [Andrievsky et al., 2024], the required technological task can be realized through a specific control algorithm, significantly expanding the functionality of a single machine. Algorithmic control allows for the execution of various technological tasks without altering the machine's design. Given that the precise mathematical model of the machine is of high order and unsuitable for regulator synthesis, it is practically convenient to use a simplified model represented by a second-order transfer function [Gerasimov and Zaitceva, 2024; Blekhman et al., 2017]. However, this model does not fully capture the dynamics of the machine and does not allow for the simulation of the movement of the working platform. Investigating material movement while varying control methods necessitates conducting extensive physical experiments, with results recorded by various sensors. Due to the complexity of operational conditions, installing sensors on the VM may be labor-intensive, costly, or even impractical. Specifically, the VM under consideration lacks a vibration speed sensor for the platform and a high-speed camera. These challenges can be mitigated by creating a virtual model of the setup and employing software complexes for mathematical analysis, as illustrated in [Bushuev et al., 2020; Ahmad et al., 2025]. In this case, developing a virtual model will also conserve energy consumed by the induction motor and protect the actual setup from impact modes and various operational failures during experiments.

2 Virtual Model of SV-2M Vibration Machine with Technological Equipment

Alterations in the construction of vibratory machines, such as installing a worktable with its own mass, can significantly affect their original dynamics. Attaching additional masses alters the distribution of total mass relative to the axis of eccentric rotation, leading to changes in oscillation amplitudes, frequencies, and trajectory shapes of the working surface. Additional moments introduced by new structural elements may disturb the overall balance of the system, potentially causing unwanted vibrations, resonances, or even loss of stability. The *ADAMS.View* software allows creating detailed models of complex mechanical systems, including kinematic chains, elastic components, and control subsystems [Hexagon, 2023]. Computer simulations enable precise selection of appropriate new structural elements without tedious calculations of system dynamics under altered mass distributions, making them an optimal solution for performing virtual tests [Bushuev et al., 2020; Andrievsky et al., 2025a]. The other related approaches to the problem can be found in [Shagniev, 2025; Tomchin and Gorlatov, 2025].

To construct the mechanical model, geometry of the main components of the SV-2M type vibratory machine was transferred into *ADAMS*. Here, dimensions of all parts are specified, necessary connections between elements are established, masses and inertia moments of eccentrics are defined, and contact interactions between the working surface and processed materials are configured. Key parameters – such as inertia moments of eccentrics, spring stiffness, and viscous friction coefficient in bearings are taken from [Gorlatov et al., 2015; Tomchina, 2023].

The *ADAMS.View* software [Hexagon, 2023] enables the creation of detailed models of complex mechanical systems, including kinematic chains, elastic elements, and control systems. This makes it an optimal solution for conducting virtual experiments [Bushuev et al., 2020; Andrievsky et al., 2025a]. The virtual model is depicted in Figure 1 (lower plot). This model incorporates all major components of the machine and includes a working platform and bulk material. An absolute coordinate system ($OXYZ$) is employed. The mechanics of particle movement for bulk materials are described using *ADAMS/EDEM* tools, which are based on the discrete element method: configuration of physical interaction models, contact characteristics, and external influences, cf. [Wang et al., 2018; Wang et al., 2021; Alcaraz et al., 2022; Zhang et al., 2025]. The assumption of particle impact implies that interactions between particles occur as a result of instantaneous contact. When simulating impacts, factors such as contact elasticity, friction coefficients, trough surface geometry, and the physical-mechanical properties of the material particles are taken into account. Material parameters are specified to be similar to those of fine fractions of gravel sized $8 - 14$ mm. The simulation results allow for the observation of the trajectories of each particle, as well as their velocities, accelerations, and deformations. Virtual sensors measure the rotational frequency and angle of rotation of the motors, the linear displacement of the center of mass of the working platform, and the linear displacement of each particle in three-dimensional space.

The control system for the motor rotational frequencies is implemented within a *Simulink* model, which integrates a block from *ADAMS.View*. The data from virtual sensors regarding the angle of rotation and rotational frequency of each motor are fed back to a summation point at the input of three regulators. Details of the control law are described below. This study employs a simple and reliable standard Proportional-Integral (PI) control law for the motor rotational frequencies, where the control signal is generated proportionally to the discrepancy in rotational frequencies between the right and left motors individually. The control signal for the rotational frequency of each motor is expressed as follows [Andrievsky et al., 2024; Andrievsky et al., 2025b; Fradkov et al., 2024]:

$$\begin{aligned} u(t) &= K_i \int_0^t e(\tau)d\tau + K_p e(t), \\ e(t) &= \omega^*(t) - \omega(t), \end{aligned} \tag{1}$$

where K_i and K_p are integral and proportional gains of the motor speed controller, respectively, τ is the integration variable, e stands for the drive speed error, ω^* and ω are the set and actual motor speeds.

The phase shift control loop also uses a PI controller:

$$\begin{aligned} u_\varphi(t) &= K_{i\varphi} \int_0^t e_\varphi(\tau)d\tau + K_{p\varphi} e_\varphi(t), \\ e_\varphi(t) &= \varphi^*(t) - \varphi(t), \end{aligned} \tag{2}$$

where, analogous to (2), $K_{i\varphi}$ and $K_{p\varphi}$ are the phase shift controller integral and proportional gains, respectively; e_φ denotes the phase shift error; φ^* and φ represent the desired and actual phase shift between the angular positions of the motors. The resulting control law for the motors of the virtual machine, which incorporates (1) and (2), is expressed as follows:

$$\begin{aligned} u_1(t) &= u_L(t) - u_\varphi(t), \\ u_2(t) &= u_R(t) + u_\varphi(t). \end{aligned} \tag{3}$$

3 Simulation Results

Three experiments were carried out for comparison purposes, one of which does not involve the phase shift control loop. The rotational speed of the engines is set by means of a constant signal, while a periodic input signal is applied to the phase shift control loop.

Experiment 1 involves disabling the phase shift control loop. Parameters used in the Simulink model include: $K_i = 450$, $K_p = 500$ and $\omega^*_{L,R} = 60$ rad/s. Figure 2 illustrates time-dependent readings from virtual sensors including displacement of the platform's center of mass in the frontal plane (ZY) and engine rotational frequencies. The center of mass exhibits minor circular motion relative to the x-axis. Material transport occurs predominantly within the frontal plane (ZY), whereas there is virtually no displacement in the horizontal plane (XY).

Experiment 2 involves enabling the phase shift control loop. The parameters of the Simulink model are: $K_i = 450$, $K_p = 500$, $\omega^*_{L,R} = 60$ rad/s, and $\varphi^*(t) = \pi \sin(2t)$. Figure 3 presents measurements obtained from virtual sensors. Observing the trajectory of the platform's center of mass reveals more intense motions in various directions compared to experiment 1. Along the z-axis, the oscillations exhibit a beating form due to the harmonic variation of the phase shift introduced in the control law.

Experiment 3 involves enabling the phase shift control loop also. The parameters of the Simulink model are: $K_i = 450$, $K_p = 500$, $\omega^*_{L,R} = 90$ rad/s, and $\varphi^*(t)$ varies according to a chaotic law as described in [Andrievsky et al., 2024; Fradkov et al., 2024]. Figure 4 shows the results of experiment 3, where an increase in the oscillation frequency along the z-axis is evident.

Experiments 1–3 demonstrate that introducing algorithmic control can change the operational mode of the vibratory machine without modifying its construction. In accordance with the stated objective, this approach allows controlling the oscillation parameters, thus enhancing the irregularity of oscillations in both the technological fixture and the material placed upon it when continuous mixing of the material is required.

The motion of the virtual platform on the vibratory machine demonstrates a high degree of correspondence with the results of real experimental studies in [Andrievsky et al., 2024; Fradkov et al., 2024]. As numerical simulations show, the simulated oscillations of the platform are similar to those observed in physical tests: the center of gravity undergoes small circular movements around the specified axis, and the distribution pattern of the material on the platform replicates the regularities identified in field experiments. These correspondences confirm the adequacy of the developed virtual model and allow confident extrapolation of the calculated data to actual operating conditions of vibratory equipment.

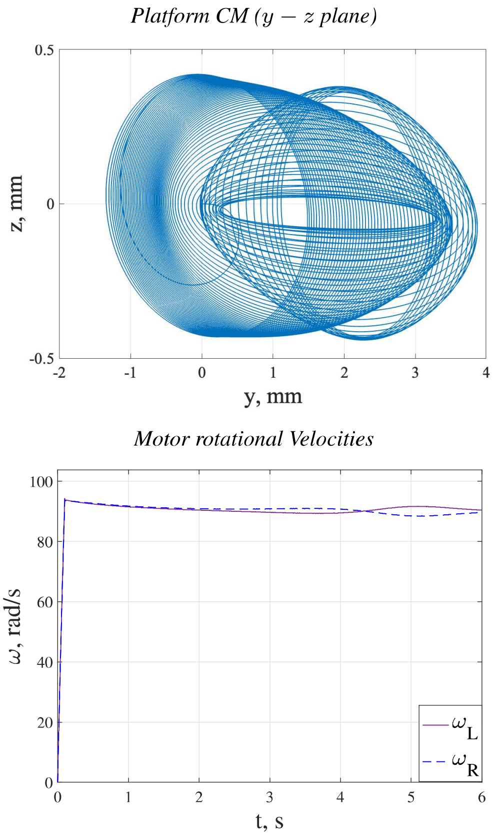


Figure 4. Results of experiment 3.

4 Conclusion

A virtual model of an algorithmically controlled vibratory installation equipped with a tray for bulk material as technological equipment has been developed in the complex *ADAMS.View* integrated with *MATLAB/Simulink*. Virtual experiments have been conducted on this system such that all necessary measurements are accessible via computer using virtual sensors. The simulation process allows visualization of trajectories and velocities of material movement which cannot be directly observed on the physical setup. A specially designed control law incorporating phase-shift feedback between rotation angles of motors enables transformation of vibration direction to facilitate mixing of materials. This enhances the functionality of the vibratory machine without altering its structure and permits investigation into how amplitude and frequency affect dynamics of bulk materials, potentially leading to optimization of vibrating machinery design and improved efficiency. Future research efforts will focus on conducting experiments with different media types as well as modeling and studying processes involving simultaneous transportation and mixing of materials under vibration.

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