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Studying the Dynamics of Vibratory Finishing Machine Providing the Single-Sided Lapping and Polishing of Flat Surfaces †

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Abstract: The improved design of a vibratory lapping machine is developed in the SolidWorks software on the basis of the suspended double-mass oscillatory system. The system is set into motion by three pairs of electromagnets generating periodic excitation forces applied between the upper lap and the lower one. By adopting the same forced frequencies and the certain phase shifts of the excitation forces, it is planned to provide the antiphase translational (circular) oscillations of the laps. In such a case, the best accuracy and operational efficiency of the lapping (polishing) process can be reached. The present research is aimed at analyzing the dynamic behavior of the lapping machine's oscillatory system. In particular, the motion trajectories of the laps, as well as their kinematic characteristics (displacements, velocities, and accelerations) are considered. The mathematical model of the oscillatory system is developed using the Euler-Lagrange equations. The numerical modelling of the system motion is performed in the Mathematica software with the help of the Runge-Kutta methods. The computer simulation of the laps oscillations is conducted in the SolidWorks software under different friction conditions. The experimental prototype of the vibratory lapping machine is implemented in the Vibroengineering Laboratory of Lviv Polytechnic National University. The possibilities of providing the controllable translational (circular) oscillations of laps are theoretically studied and experimentally confirmed. Further investigations on the subject of the present paper can be focused on the physical-mechanical and technological parameters (surface flatness, roughness, hardness, wear resistance, etc.) obtained due to performing the lapping and polishing processes using the proposed vibratory finishing machine.

Keywords: lapping machine; double-mass oscillatory system; circular oscillations; dynamic behavior; kinematic characteristics; numerical modelling; computer simulation; experimental prototype

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1. Introduction

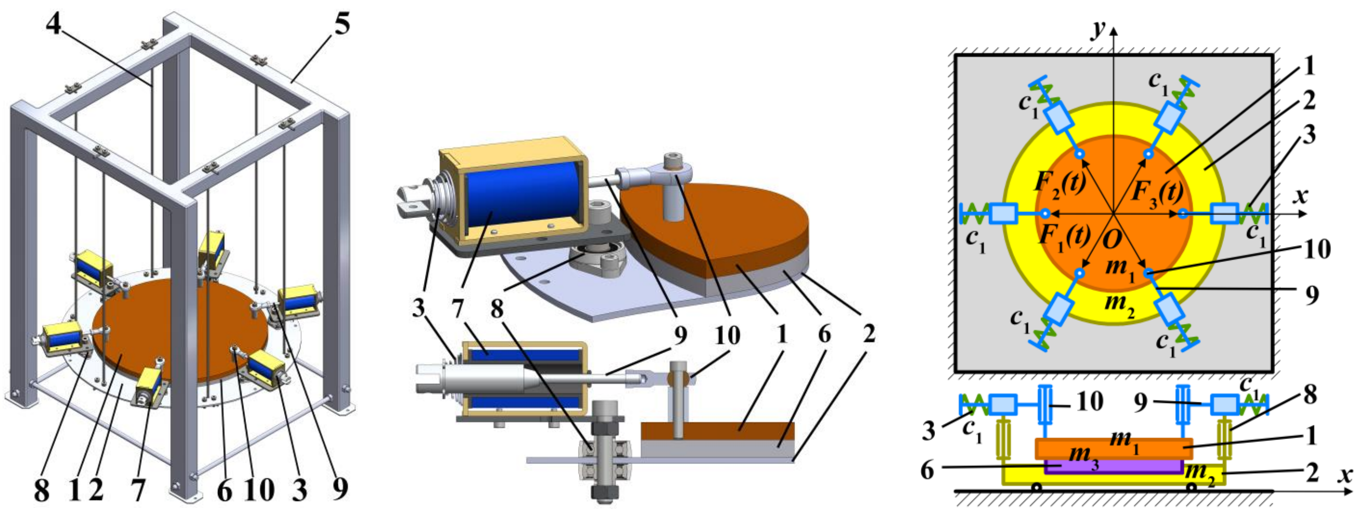
The polishing and lapping processes are of the most widespread ones considering the finishing treatment of flat surfaces. Numerous scientific papers are focused on studying the technological efficiency of these operations. Various mathematical models describing the material removing processes during the double-sided polishing are compared in [1]. The analysis of the laps kinematics and the problems of optimizing the treatment parameters are considered in [2]. The paper [3] is dedicated to improving the methods of defining the friction coefficients between the movable parts of the double-sided lapping machine. In [4], the authors developed the mathematical and simulation models allowing for optimizing the lapping operations. The models describing the tool wear processes taking place during the single-sided lapping are analyzed in [5]. The novel design of the driving system of the single-sided planetary-type lapping machine is proposed in [6]. The paper [7] is focused on the theoretical and experimental investigations of the kinematic parameters characterizing the double-sided cylindrical lapping process.

In distinction to the traditional methods of the finishing treatment, the vibratory ones are currently gaining an increased interest. The general review of the existent vibratory finishing technologies is presented in [8]. The simplified mathematical models describing the vibratory finishing treatment processes are considered in [9,10]. The paper [11] is dedicated to the theoretical and experimental investigations on the kinematics of the particles during the vibratory finishing process. Similar study on the dynamic behavior of the vibratory finishing machine with the fixed parts being treated in the rotary devices is presented in [12]. The present paper is based on the previous investigations of its authors presented in [13,14]. The initial idea of developing the vibratory lapping machine equipped with the complex electromagnetic exciter has been proposed and theoretically investigated in [13]. The 3D-model of the machine and some results of its experimental testing are presented in [14]. The major purpose of the present research consists in analyzing the dynamic behavior of the lapping machine's double-mass oscillatory system driven by six pairs of electromagnets. Based on the obtained results, the corresponding recommendations for designers and researchers of similar equipment can be drawn.

2. Materials and Methods

2.1. General Design and Simplified Kinematic Diagram of the Vibratory Lapping Machine

The improved design of the vibratory machine for single-sided lapping of flat surfaces is presented in Figure 1a,b. The corresponding kinematic diagram of the machine's oscillatory system is shown in Figure 1c. The lower lap 2 is suspended from the stationary body 5 by the metal ropes 4. The parts 6 being treated by the upper lap 1 are fixed on the lower lap 2. The laps are connected with one another by the system of six coil springs 3. The vibration exciter is formed of six electromagnets 7 hingedly mounted on the lower lap 2 with the help of the bearing units 8. The electromagnets' armatures (retractable (sliding) rods) 9 are connected with the upper lap 1 by the hinges 10.



(**a**) (**b**) (**c**)

Figure 1. Vibratory lapping machine: (**a**) 3D-design; (**b**) electromagnets connection scheme; (**c**) kinematic diagram.

The system is set into motion by three pairs of electromagnets generating periodic disturbing forces applied between the upper and lower laps. By applying the same forced frequencies and the certain phase shifts of the excitation forces, the antiphase translational (circular) oscillations of the laps can be generated. The major difference between the improved machine and the previous one considered in [14] is following: new electromagnets with retractable rods (sliding armatures) are used. They are hingedly joined with the lower lap with the possibility of turning. The previous machine was equipped with the principally different electromagnets with the air gap between the electromagnet and the armature. The previous electromagnets were fixed (rigidly connected) to the machine's lower platform without any possibility of turning (rotating). This allows for increasing the energy efficiency of the machine's drive and the accuracy of the surface treatment.

2.2. Mathematical Model of the System Motion

In order to study the laps oscillatory motion, the inertial coordinate system xOy and the corresponding generalized coordinates $x_1,\ x_2,\ y_1,\ y_2$ are applied (see Figure 1c). The latter describe the displacements of the upper lap and the lower lap relative to the adopted coordinate system. The origin O is placed at the upper lap's mass center in its equilibrium position (state of rest). The masses of the upper lap, lower lap, and the parts being treated are denoted as $m_1,\ m_2,\ m_3$, respectively. The spring elements are characterized by the stiffness coefficients c_1. The energy dissipation during the lap sliding over the parts being treated is taken into account by the viscous friction coefficient μ, which depends on numerous factors: physical and mechanical properties of the contacting materials, specific features of the abrasive medium, lapping (polishing) conditions, etc. Therefore, the coefficient μ is usually determined experimentally.

Using the Euler–Lagrange equations, the simplified mathematical model describing the machine's oscillatory system motion can be written as follows:

$$m_1 \cdot \ddot{x}_1(t) + \mu \cdot \left(\dot{x}_1(t) - \dot{x}_2(t)\right) + c_x \cdot \left(x_1(t) - x_2(t)\right) = F_1(t) \cdot \cos 0 + F_2(t) \cdot \cos(\pi/3) + F_3(t) \cdot \cos(5\pi/3), \quad (1)$$

$$(m_2 + m_3) \cdot \ddot{x}_2(t) + \mu \cdot \left(\dot{x}_2(t) - \dot{x}_1(t)\right) + c_x \cdot \left(x_2(t) - x_1(t)\right) = -F_1(t) \cdot \cos 0 - F_2(t) \cdot \cos(\pi/3) - F_3(t) \cdot \cos(5\pi/3), \quad (2)$$

$$m_1 \cdot \ddot{y}_1(t) + \mu \cdot \left(\dot{y}_1(t) - \dot{y}_2(t)\right) + c_y \cdot \left(y_1(t) - y_2(t)\right) = F_1(t) \cdot \sin 0 + F_2(t) \cdot \sin(\pi/3) - F_3(t) \cdot \sin(5\pi/3), \quad (3)$$

$$(m_2 + m_3) \cdot \ddot{y}_2(t) + \mu \cdot \left(\dot{y}_2(t) - \dot{y}_1(t)\right) + c_y \cdot \left(y_2(t) - y_1(t)\right) = -F_1(t) \cdot \sin 0 - F_2(t) \cdot \sin(\pi/3) + F_3(t) \cdot \sin(5\pi/3), \quad (4)$$

where $F_1(t) = F \cdot \sin(\omega t)$, $F_2(t) = F \cdot \sin(\omega t + \pi/3)$, $F_3(t) = F \cdot \sin(\omega t + 2\pi/3)$ are the excitation (disturbing) forces; F is the maximal (amplitude) value of the excitation (disturbing) force; ω is the forced frequency. The projections of the reduced (equivalent) stiffness coefficients on the Ox and Oy axes can be expressed as follows:

$$c_x = c_1 \cdot \cos 0 + c_1 \cdot \cos(\pi/3) + c_1 \cdot \cos(5\pi/3) \approx 2c_1, \quad (5)$$

$$c_y = c_1 \cdot \sin 0 + c_1 \cdot \sin(\pi/3) - c_1 \cdot \sin(5\pi/3) \approx 1.732c_1. \quad (6)$$

The numerical modeling is carried out by solving the derived system of differential equations with the help of the Runge-Kutta methods in the Mathematica software.

2.3. Experimental Prototype of the Vibratory Lapping Machine

Based on the proposed 3D-design of the vibratory lapping machine (see Figure 1a), its experimental prototype has been developed at the Vibroengineering Laboratory of Lviv Polytechnic National University (see Figure 2a). The machine's frame (stationary body) 1 is welded using the square-shape tubes. The lower lap 2 is suspended from the frame 1 by the metal ropes 3. The cylindrical part (disc) 4 being treated is fixed to the lower lap 2 and is made of the mild (soft) AISI 1018 steel. The electromagnets (push-pull-type linear solenoids ZUIDID KK-1564B) 5 are fixed on the lower lap 2. The electromagnets' retractable rods (sliding armatures) are spring-loaded and hingedly joined with the upper lap 6 made of the synthetic-resin bonded (SRB) paper laminate. The fine-grained abrasive medium Abro GP-201 is applied between the contacting surfaces of the part (disc) 4 being treated and the upper lap 6.

The experimental tests are focused on studying the machine's free damped oscillations with the help of the WitMotion BWT901CL accelerometer 7. The processing of the experimental data is carried out using the corresponding WitMotion software (see Figure 2b). The instantaneous value of the upper lap acceleration during the machine stopping conditions is registered by the accelerometer 7. Based on the obtained experimental data, the approximate value of the reduced (equivalent) damping coefficient μ has been determined according to the technique described in [14].

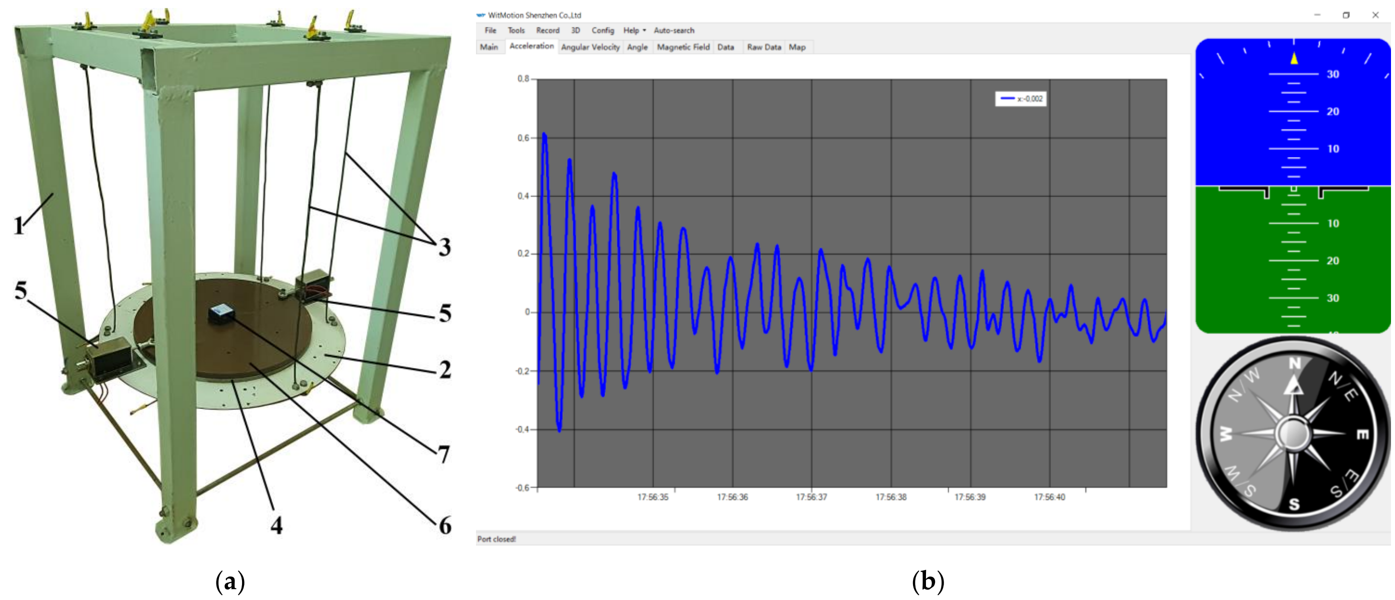
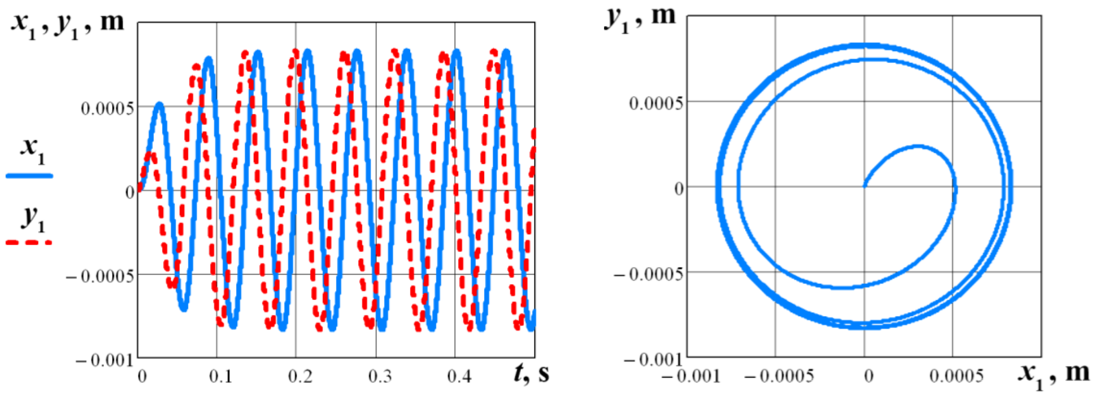


Figure 2. Experimental testing of the lapping machine: (**a**) experimental prototype; (**b**) WitMotion software window.

3. Results and Discussion

3.1. Results of Numerical Modeling of the Oscillatory System Motion

The numerical modeling has been performed in the Mathematica software, and the following input parameters were applied: $m_1 = 0.42$ kg, $m_2 = 0.5$ kg, $m_3 = 0.75$ kg, $\omega = 100.5$ rad/s (16 Hz), $F = 4$ N, $c_1 = 3700$ N/m, $\mu = 20$ N·s/m. The time dependencies of the instantaneous displacements of the upper lap (x_1, y_1) are presented in Figure 3a, while the upper lap motion trajectory is shown in Figure 3b.



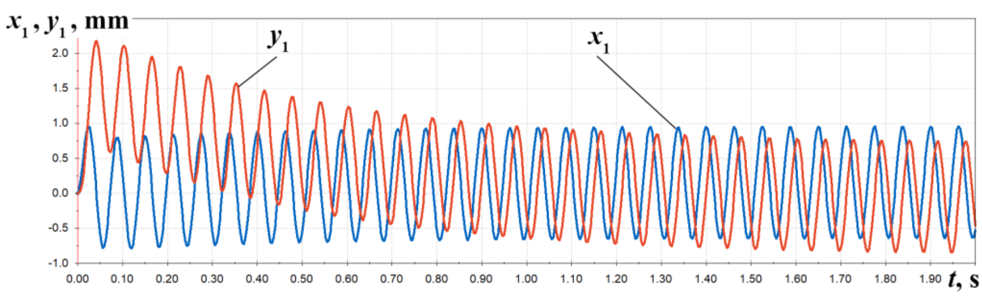
(**a**) (**b**)

Figure 3. Results of numerical modeling of the upper lap oscillations: (**a**) time response curves; (**b**) lap trajectory.

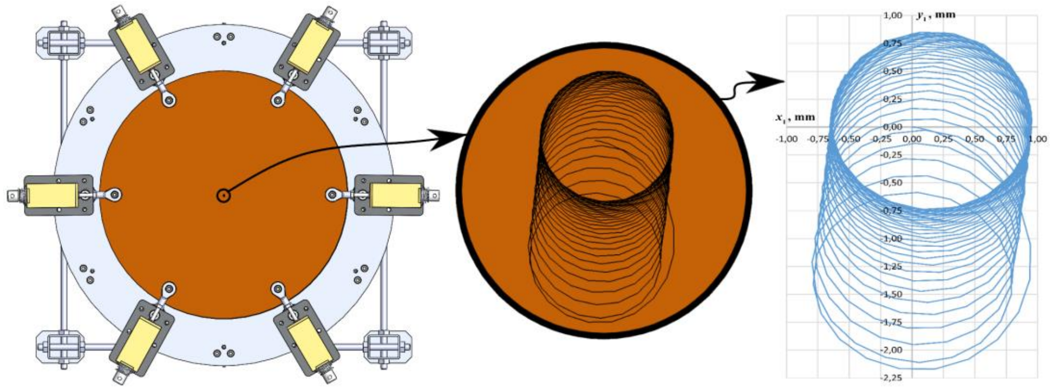
Considering the steady-state operational conditions, the lap's maximal horizontal displacement is equal to the vertical one, and takes the value of 0.0008 m (0.8 mm). The transient mode duration is about 0.2 s. Analyzing the modeled trajectory of the lap motion, it can be concluded that the initial idea of the proposed machine design is satisfied: the lap performs the translational (circular) oscillations, which are characterized by the uniform speed of each point of the lapping plate. In such a case, the best accuracy and operational efficiency of the lapping (polishing) process can be reached.

3.2. Results of Computer Simulation (Virtual Experiments)

The computer simulation (virtual experiment) has been carried out in the SolidWorks Motion software using the developed 3D-model of the vibratory lapping machine. The corresponding results are presented in Figure 4. All the input parameters correspond to the ones mentioned above. In general, the simulation results satisfactorily agree with the ones obtained by numerical modeling. After the transient conditions lasting about 0.8 s, the lap describes the circular trajectory (path) of the radius equal to 0.8 mm. The only difference is that the center of this circle moved upwards and to the right. This fact can be described by the complex friction conditions taking place during the lapping process. The simplified mathematical model has not considered this phenomenon.



(**a**)



(**b**)

Figure 4. Computer simulation of the lap oscillations: (**a**) time response curves; (**b**) lap trajectory.

4. Conclusions

The paper considers the improved design of the vibratory lapping (polishing) machine based on the suspended double-mass oscillatory system and driven by six pairs of electromagnets. The corresponding kinematic diagram of the machine's oscillatory system is developed, and the differential equations describing its motion are derived. The numerical modeling of the upper lap oscillations is performed in the Mathematica software. Based on the developed 3D-design of the lapping machine, the computer simulation (virtual experiment) of its operation is carried in the SolidWorks software. The experimental prototype has been implemented in practice at the Vibroengineering Laboratory of Lviv Polytechnic National University. The experimental data allowed for defining the reduced (equivalent) damping coefficient taking place during the lapping process.

Considering the steady-state operational conditions, the lap's maximal horizontal displacement is equal to the vertical one, and takes the value of 0.8 mm. The results of numerical modeling and computer simulation allows for stating that the initial idea of the proposed machine design is satisfied: the lap performs the translational (circular) oscillations, which are characterized by the uniform speed of each point of the lapping plate. In such a case, the best accuracy and operational efficiency of the lapping (polishing) process can be reached. The obtained results can be used by designers and researchers of similar technological equipment, as well as by technologists implementing the vibratory finishing operations. The scopes of further investigations on the subject of the paper can be focused on analyzing the machine's drive power consumption under different operational conditions and forming the optimization criteria for minimizing the power consumption and maximizing the machine's technological efficiency.

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