593. Experimental analysis of the robotized assembly applying vibrations

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Abstract. Main stages of the vibratory assembly, i.e. part-to-part alignment and joining of the cylindrical parts are considered in the presented paper. The shaft is movably based in the remote compliance center device, which is attached to robotic gripper, while the bushing is immovably located on the platform of the vibrator and provided with vibratory excitation along the joining axis direction. The experimental setup and research technique are presented. Vibratory alignment duration dependences on bushing excitation frequency, amplitude of the acceleration and on the axial misalignment of parts were established. The areas of excitation and system parameters sets for reliable part-to-part alignment were determined. Dependences of shaft and bushing joining stages durations on bushing excitation frequency, amplitude and axial misalignment of the parts were analyzed. It was determined that vibratory excitation during the joining provides possibility to avoid jamming of the parts.

Keywords: vibrations, parts alignment, assembly.

Introduction

During recent years vibratory technological processes, which implementation requires a particular vibratory excitation, have been more widely used in manufacturing and engineering. In some cases, application of vibrations enables substantial intensification of the technological processes, which may be implemented without the applied vibrations. In other cases, the technological process may be accomplished only applying the vibrations. Vibratory technological processes are based on the distinctive effect of the vibratory action on the working environment or object. Having aim to expand the coverage of such processes, to increase the efficiency of the known processes and create the fundamentally new vibratory devices and technologies, it is necessary to carry out a detailed analysis of vibrations influence on objects or systems and define the peculiarities of the new physical processes caused by such influence.

One of the newest fields of application of vibrations is a vibratory assembly. To apply the method of the vibratory assembly, one of the parts in assembly position should be provided with vibrations of predefined direction, amplitude and frequency. Furthermore, one of the mating parts should be movably based, in order to have an ability to move within a limited space and one part should be pressed to the other by the predetermined force. Due to vibratory influence, the movably based part, being in contact with the mating part, is able to displace and turn in respect of the later. Thus, the part-to-part alignment in assembly position is reached, ensuring both the matching of their connective surfaces and prerequisites for unhindered assembly. The part-to-part position errors, which emerge while feeding the parts into assembly position and locating them in assembly devices, are compensated during the alignment. Applying the technology of the vibratory assembly it is possible to develop a more efficient assembly devices and systems, which are significantly simpler and less expensive, because part-to-part position errors may be eliminated without sensors, feedback systems and expensive positioning devices.

Vibratory technologies provide possibility to create significantly less-expensive and simpler systems for robotized assembly. Commonly in those systems the robots are feeding the parts into assembly position and sometimes also executing the joining operations. By using special devices for movable location of the parts and applying the vibrations of particular direction and intensity, it is possible to compensate for the errors of robot positioning and thereby ensure a reliable joining of the parts. Therefore, smaller accuracy positioning robots (positioning error up to ±1-2 mm), without the complex sensing and machine vision systems may be used for the robotized assembly. Vibratory excitation of the parts during the joining assists in preventing their jamming.

The process of vibratory assembly comprises the stages of the part-to-part alignment and their joining. During the alignment, as result of the vibratory influence, the movably based part performs a directional movement in respect of the immovably based part till the connective surfaces of the parts get matched. Then the joining stage of parts may be started. Vibratory excitation of one mating part during the joining helps to speed-up the joining process, reduce the joining force and prevent the jamming of the parts.

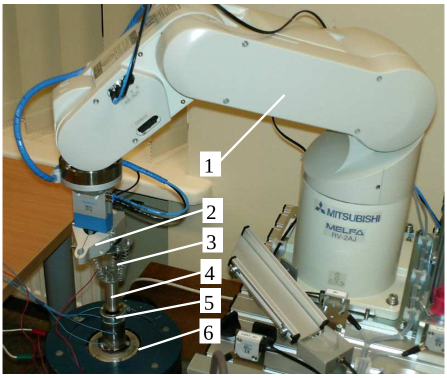
Up to know, the robotized vibratory assembly using vibrations for alignment and joining of the mating parts are not sufficiently analyzed. Vibratory part-to-part alignment and matching of the connective surfaces, which is based on random search strategy is analyzed in publications [1, 2]. One of the mating parts is provided with vibratory excitation along the perpendicular to joining axis direction. During the alignment the part-to-part position is controlled by the sensors. The analytical and experimental analysis of the assembled parts alignment and joining, when one of the parts is provided with vibratory excitation along the two perpendicular directions, are presented in [3-5]. The authors analyzed the vibration frequency, amplitude, frequency ratio and phase angle between the components of the vibrations influence both on the reliability and duration of the alignment and defined the cases of part jamming due to insufficient pressing and joining forces, geometrical restrictions of the assembly and because of insufficient accuracy of the robot positioning.

More reliable is the method of the part-to-part vibratory alignment as one of the parts is provided with vibrations along the joining axis direction. Due to provided vibratory excitation the movably based part performs the directional displacement towards the connective surfaces matching direction and is thereby aligned in respect of the immovable part. Simulation results of such process of alignment are provided in [6, 7]. Some results of analytical analysis of the part vibratory joining with clearance are presented in [8, 9].

This paper considers an experimental analysis of the interdependent vibratory alignment and clearance fit joining of the peg-hole parts, when the shaft is located movably in the attached to the robot hand device and the bushing is immovably based. A remote center compliance device or bellow is used in order to locate the shaft. Experimental study of alignment and joining was carried out by using the compliance device and providing the excitation to the immovable bushing located on the platform of the vibrator.

Experimental setup and method of the analysis

To carry out the experimental analysis of the vibratory alignment and joining the setup for the robotized vibratory assembly was designed and fabricated (Fig. 1). The setup consists of robot *1*, remote center compliance device 3 and electro-dynamic vibrator 6, on the moving platform of which the bushing *5* is located. The device with the fixed shaft *4* is attached to the robot gripper *2*. To analyze the shaft-to-bushing alignment the remote center compliance device which has adjustable rigidity, was used (Fig. 1, b). The remote center compliance device is made of two discs, which are connected by means of three elastic elements, having rigidity 2.45 N/mm. They are made of a set of metallic and rubber bushings. The length of the elastic elements is 60 mm, diameter 14 mm, number of layers is 10. The rigidity of the device may be adjusted by means of the particular length rods, which are inserted inside the elastic elements and define its rigidity along the perpendicular to the shaft axis direction. The axial misalignment between the shaft and the bushing is adjusted defining the position of the robot gripper in respect to the bushing. The force of the shaft pressing to the bushing is adjusted by deforming the elastic elements of the remote center compliance device along the joining axis direction. When the predefined pressing force is reached, the alignment starts from the moment as vibratory excitation is provided to the bushing. The electrodynamic vibrator, providing excitation to the bushing, receives the electric signal of the excitation from the oscillator using the amplifier.



a

b

Fig. 1. Experimental setup for robotized vibratory assembly: a – general view; *1* – robot; *2* – robot gripper; *3* – remote center compliance device; *4* – shaft; *5* – bushing of particular construction; 6 – vibrator; b – remote center compliance device of adjustable rigidity

To capture the end of the alignment an electric device, which sends the signal after the shaft is inserted into the bushing, is used. Mentioned signal and vibration signal of the bushing are displayed on the computer screen. This signal is received from the piezoelectric acceleration sensor. Both the signals from the device and the sensor are transferred to the digital oscilloscope. The signals are converted by the oscilloscope into the computer recognizable pattern and sent to computer through the USB connection. Both mentioned signals are displayed on time axis on the computer screen (Fig. 2).

The robot is controlled by means of the programme stored in the controller and using the position list. The computer executes the programme and displays the graphs, which are used to define the duration of the alignment. The curve *1* represents the signal from the acceleration sensor, while the curve *2* – the end signal of the alignment. As moving down robotic gripper reaches a particular height, vibrations are turned on. The emerging impulse of the curve *1* indicates the start of vibrations, whereas the emerging impulse of the curve *2* indicates the beginning of the insertion. The duration of the alignment is time interval from the vibrations turn-on moment till the end of the shaft falling into the bushing (beginning of the curve *2*). To analyze the vibratory joining of the shaft and the bushing, a special construction steel bushing *4* was designed and fabricated, which provides possibility to acquire the parameters of the joining process using the contact method (Fig. 3).

The bushing includes an electrically-insulated interdependent segments, i.e. chamfers, two sides and the bottom. When shaft touches different parts of the bushing, voltage jump occurs, which is acquired by the oscilloscope and displayed on the computer screen. Thereby it is possible to track all the stages of the joining process – shaft-chamfer contact, one-point and two-point contacts of the shaft with bushing hole, the end of the joining and to define the duration of these stages. The shaft *3* is attached to the remote center compliance device, comprising two discs, which are interconnected by three helical springs. The springs are allocated at a particular angle in respect to the device axis. Therefore, the compliance center of the device is located more closely to the bottom end of the shaft.

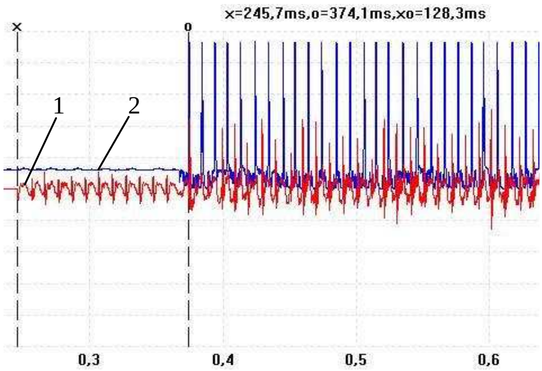


Fig. 2. Measurement scheme of the alignment duration: *1* – signal from the acceleration sensor; *2* – signal which indicates the end of alignment

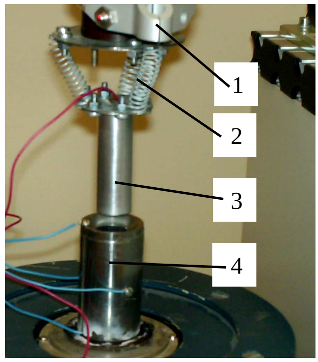


Fig. 3. Initial state of the parts in assembly position before the joining: *1* – robot gripper; *2* – remote center compliance device; *3* – shaft; *4* – bushing

The process of joining starts from the moment t_0 as the shaft contacts the chamfer. This moment indicates the start of the chamfer crossing stage and as a result of the shaft-chamfer contact the oscillogram displayed on the computer screen indicates a voltage jump (Fig. 4, *1*). The shaft slides over the chamfer till its cylindrical surface reaches the edge of the hole. The process of the joining proceeds into the one-point contact stage, the other voltage jump occurs and time t_1 value is obtained. The parameter t_1 indicates the duration of the chamfer crossing.

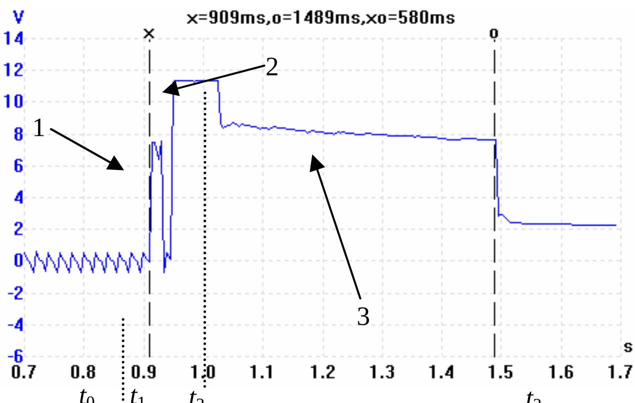


Fig. 4. Oscillogram of the joining process: *1* – contact with the chamfer; *2* – one-point contact; *3* – two-points contact

The shaft is in one-point contact state with the bushing (Fig. 4, *2*) till the bottom edge of the shaft reaches the internal surface of the hole. The process of joining proceeds into two-point contact stage (Fig. 4, *3*), the voltage jump occurs again and time t_2 value is obtained. Time duration t_2 includes the durations of the chamfer crossing time t_1 and time, within which the shaft is in one-point contact with the bushing state. The parameter t_2 indicates the duration from the beginning of the joining process till the beginning of the two-point contact. As the shaft touches the bottom of the bushing the process of the joining is finished, the oscillogram shows the voltage jump and the value of the time t_3 is obtained. The joining process duration, i.e. t_3, is time, indicating that the shaft is inserted into the bushing hole.

Analysis of the vibratory alignment

The experimental analysis was carried out performing the alignment of the 17.88 mm diameter shaft relative to the 18.10 mm diameter hole of the bushing, using the 30 and 40 mm length rods to fix the layers of the elastic elements. The analysis defines the duration, when the shaft gets aligned with respect to the vibratory excited bushing so, that connective surfaces get matched and joining of the parts may be accomplished. The experiments were carried out using two remote center compliance devices of different bending rigidity (k = 1.8 N/mm and k = 4.5 N/mm). The programme of the experimental analysis was implemented so that having the results it is possible to determine the ranges of the parameter variation, when alignment is the fastest.

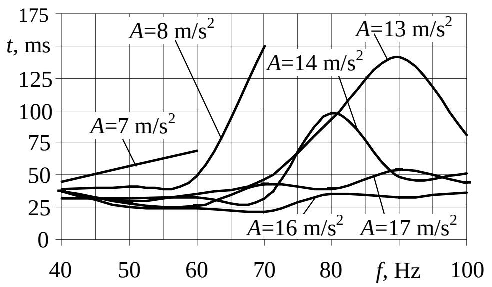


Fig. 5. Dependences of alignment time t versus the excitation frequency f, as pressing force F=9.81 N, axial misalignment Δ=1.75 mm

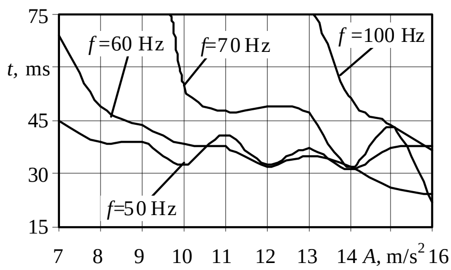


Fig. 6. Dependences of alignment time t versus the amplitude A of the excitation acceleration, as F=9.81 N, Δ=1.75 mm

Shaft alignment duration dependence both on the excitation frequency and amplitude of the acceleration changes non-uniformly (Figs. 5, 6). Having aim to obtain the minimum duration of the alignment, it is necessary to match mentioned parameters. The amplitude of the vibration acceleration has high influence on the character of the dependences of the alignment duration versus excitation frequency (Fig. 5). Within the 50 – 70 Hz frequency range the alignment has minimal duration and is less dependent on amplitude of the acceleration. If amplitude of the acceleration is not high enough (7 – 8) m/s^2, then the alignment takes place only within the (40 – 60) Hz excitation frequency range.

As amplitude of the vibrations acceleration increases, the duration of the alignment decreases despite of the excitation frequency (Fig. 6). However, different excitation frequencies lead to change in acceleration amplitude, when alignment of the parts is possible. Increase in frequency of the bushing excitation, results in increase in amplitude of the vibration acceleration, which ensures the displacement of the shaft in respect to the bushing.

The dependences of the alignment duration versus the shaft-to-bushing axial misalignment Δ are presented in graphs of Figs. 7-8. The increase in axial misalignment results in non-uniform increase in alignment duration. The character of the dependences depends on the amplitude of the vibration acceleration. Under small axial misalignment (Δ= 1.75 – 2.0 mm), the amplitude of the acceleration has non-significant influence on the duration of the alignment.

The duration and reliability of the alignment are highly dependent on the shaft-to-bushing pressing force. As pressing force increases, the duration of the alignment diminishes (Fig. 9). The range of bushing excitation frequencies, when positioning of the parts is still possible, is also dependent on the pressing force (Fig. 10). Under 9.81 N part-to-part pressing force the process of the alignment within the 60 – 80 Hz range is not occurring. Reliable alignment of the shaft is possible only having matched the excitation frequency of the bushing and part-to-part pressing force. The graphs presented in Figs. 5-10 were obtained at 1.8 N/mm bending rigidity of the elastic elements. The increase in bending rigidity results in the increase in alignment duration, whereas higher excitation frequencies of the bushing provide shorter duration and more uniform process of the alignment.

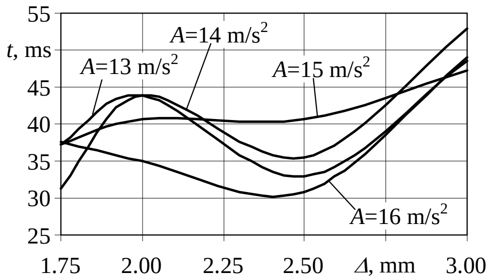


Fig. 7. Alignment time dependence on the shaft-to-bushing axial misalignment, as excitation frequency is 40 Hz, F=9,81 N

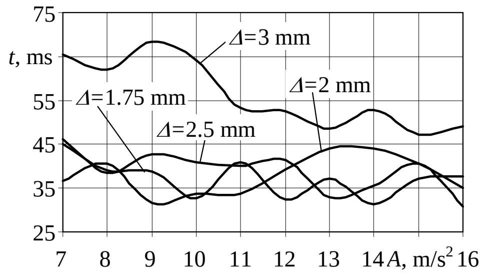


Fig. 8. Part alignment time t dependences on the amplitude A of the excitation acccleration, as F=9.81 N, f=40 Hz

Experimental results demonstrated that alignment of the shaft relative to the bushing is possible only under matched magnitudes of the bushing excitation frequency, amplitude of the vibration acceleration and parts pressing force. The areas of the parameters sets for reliable alignment of the parts were defined (Figs. 11-12).

When parameters are from the hatched areas, part-to-part alignment and automated joining is not possible. The increase in rigidity of the elastic elements of the remote center compliance device up to 4.5 N/mm results in the decrease of the area of the reliable alignment (Fig. 12). It was established from experiments that as axial misalignment between the shaft and the bushing increases, reliable alignment of the parts is possible by providing higher amplitudes excitation to the bushing. The increase in part-to-part pressing force expands the range of the excitation frequencies of the bushing, wherein the reliably alignment of the parts is possible.

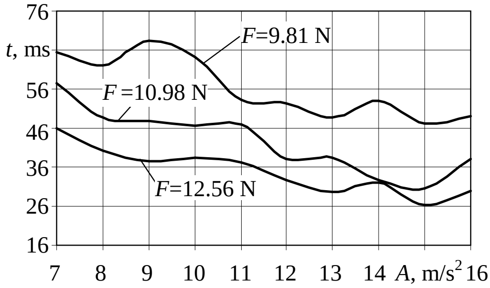


Fig. 9. Dependences of the parts alignment time t versus the acceleration amplitude of bushing's excitation, when Δ=3 mm

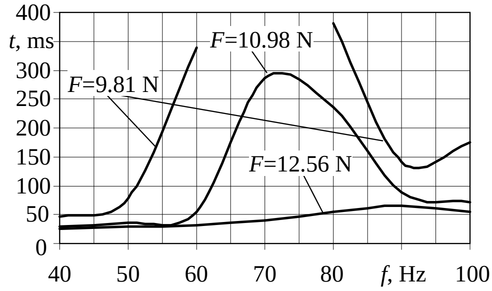


Fig. 10. Dependences of the parts alignment time t versus bushing's excitation frequency, as A=15 m/s^2, Δ=2 mm

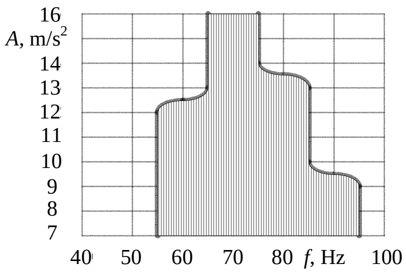


Fig. 11. Area of the reliable alignment (unhatched), depending on the amplitude *A* of the excitation acceleration and frequency *f*, when Δ=3 mm, F=9.81 N, *k* = 1.8 N/mm

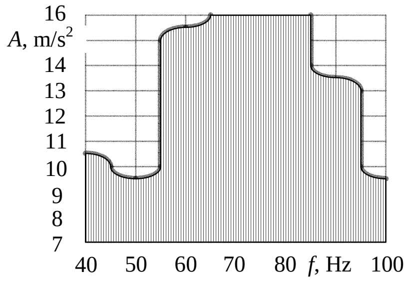


Fig. 12. Area of the reliable alignment (unhatched), depending on the amplitude *A* of the excitation acceleration and frequency *f*, when F=9.81 N, Δ=2 mm and *k*=4.5 N/mm

4. Analysis of the vibratory insertion process

Dependences of the durations of insertion process stages on vibratory excitation parameters of the bushing were experimentally determined using remote center compliance device with three helical springs. The experiments were performed inserting mass m = 0.1 kg shaft into the bushing which diameter is $D = 20$ mm, assembly clearance $\delta = 0.2$ mm. The other parameters of the parts arranged in the assembly position: chamfer angle of the bushing $\alpha = \pi / 4$ rad, initial tilt angle of the shaft $\theta_0 = 0.035$ rad, initial lateral positioning error $\varepsilon_0 = 2.25$ mm, remote center compliance device lateral stiffness $K_x = 2000$ N/m, axial stiffness $K_z = 5000$ N/m, angular stiffness $K_\theta = 20$ N·m/rad, distance from the lower end surface of the shaft to the centre of compliance $L_C = 10$ mm, insertion speed v = 0.18 m/s.

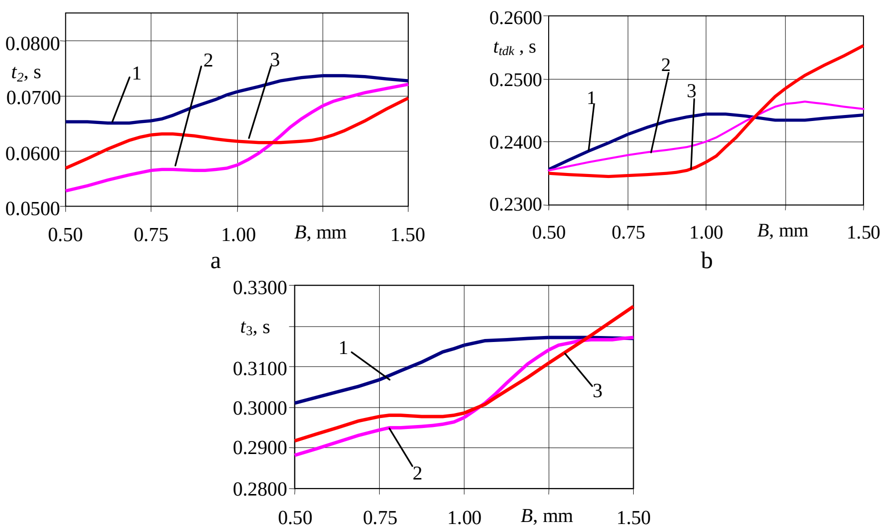


Fig. 13 Dependences of: a – duration t_2; b – two point contact stage duration t_{dtk}; c – insertion process duration t_3, on excitation amplitude *B*, excitation frequency: *1* – *f* = 50 Hz; *2* – *f* = 70 Hz; *3* – *f* = 100 Hz

When excitation amplitude B increases, the duration t_2, from the beginning of insertion till the beginning of two-point contact stage, slightly increases (Fig. 13, a). Two-point contact stage duration t_{dtk} increases, as excitation amplitude B increases (Fig. 13, b). Parameter t_{dtk} indicates the duration of the two-point contact stage. Total insertion process duration t_3 increases when excitation amplitude B increases (Fig. 13, c). Insertion process durations depend on excitation frequency in a highly uneven manner. When excitation frequency is increasing, two point contact stage duration (Fig. 14, a) and total insertion process duration (Fig. 14, b) have a tendency of a nonlinear decrease. It is more significant under higher excitation amplitudes.

When initial lateral positioning error ε_0 is increasing, the chamfer crossing duration t_1 significantly increases (Fig. 15, a). The duration t_2, from the beginning of insertion process until the beginning of two-point contact stage, is increasing as ε_0 increases, mainly due to higher chamfer crossing duration (Fig. 15, b). When ε_0 is increasing, two-point contact stage duration t_{dtk} increases (Fig. 15, c). This indicates that the two point contact appears at lower depth of the bushing hole. It is observed that wedging or jamming usually occurs when the two-point contact appears in a small depth. Besides, the probability that the shaft will jump out of the hole increases when the two-point contact appears in a small depth. Thus, the reliability of insertion process decreases when initial lateral positioning error is increasing.

Total insertion process duration t_3 increases also when ε_0 is increasing (Fig. 15, d). Under higher excitation amplitudes, the insertion process duration increases more significantly.

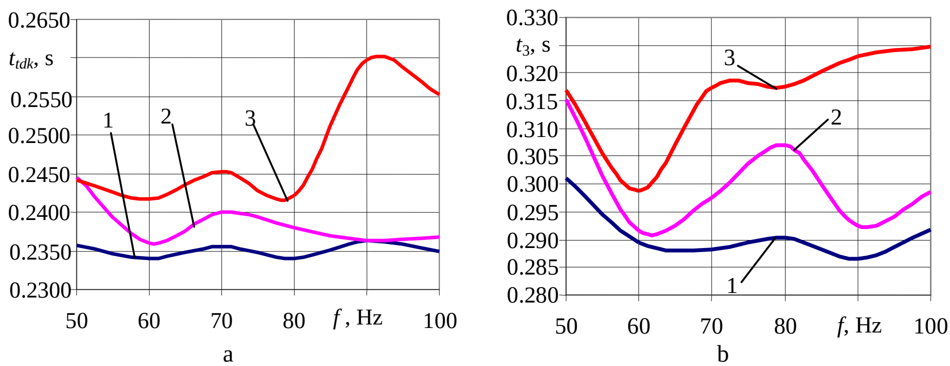
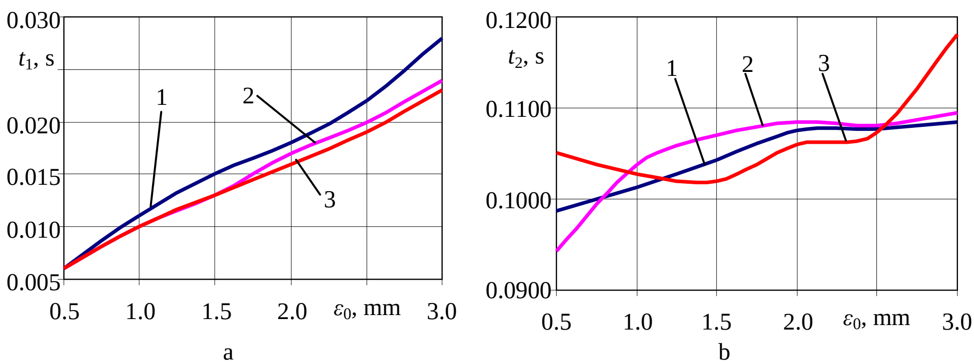


Fig. 14. Dependences of: a – two-point contact stage duration t_{dtk}; b – insertion process duration t_3, on excitation frequency and excitation amplitudes: 1 – B = 0.5 mm; 2 – B = 1.0 mm; 3 – B = 1.5 mm



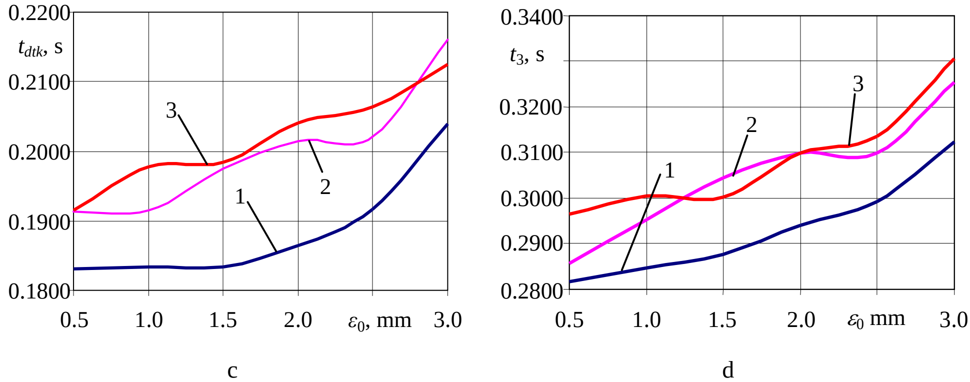


Fig. 15. Dependences of: a – chamfer crossing duration t_1; b – duration t_2, from the beginning of insertion process until the beginning of two-point contact stage; c – two-point contact stage duration t_{dtk}; d – insertion process duration t_3, on lateral positioning error of the shaft ε_0, when $\theta_0 = 0.0175$ rad, *1* – without vibratory excitation; *2* – exciting vibrations of the bushing with the frequency $f_2 = 70$ Hz and amplitude $B = 1.0$ mm; *3* – $f = 70$ Hz, $B = 1.5$ mm

Conclusions

While the shaft is movably located in the robotic gripper, attached to the remote center compliance device, the possibility to improve the reliability of the robotized vibratory assembly is ensured. The shaft is able not only to displace relative to the bushing, but also to turn around the remote compliance center. Therefore, more favorable conditions emerge not only for part-to-part positioning, but also for their joining.

Part-to-part positioning proceeds more rapidly under higher force of the shaft pressing to the bushing. As pressing force is not high enough, within the particular range of the bushing excitation frequency, the displacement of the shaft relative to the bushing axis may not occur. Reliable positioning of the parts takes place within the particular range of the excitation frequencies, which depends on the amplitude of the vibration acceleration. The positioning duration within the all range of the excitation frequencies gets smaller under higher amplitudes of the acceleration. The area of the parameters sets for reliable alignment is mainly dependent on the amplitude of the vibration acceleration, pressing force of the parts and on bending stiffness of the elastic elements of the remote center compliance device.

Insertion process duration increases when excitation amplitude and frequency of the bushing in axial direction, and lateral positioning error between the parts are increasing. The boundary of insertion duration variation is increasing under higher excitation amplitudes in the frequency range of reliable insertion. The insertion process takes more time under higher positioning error. It is possible to avoid jamming of the parts using vibratory excitation during insertion stage, thereby ensuring reliable insertion process.

Acknowledgments

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