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Experimental investigation of vibratory assembly with passive compliance

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1. Introduction

An assembly task is an important part of a manufacturing process. The use of robots in assembly entails the increase of the productivity and quality of assembly operations while allowing the performance of a vast range of tasks due to their flexibility. The consistency, speed and precision of robots are the suitable characteristics to repetitive assembly tasks. However, precision assembly can be difficult and complex when mating parts are not perfectly aligned and this way leads to unsuccessful assembly.

During the assembly process, a failure can be resulted from deviations of the position and angular errors of the parts which are caused by the accuracy, repeatability and resolution of a robot. Active and passive assembly techniques have become two primary approaches to solve these problems.

The active assembly technique, used in feedback control systems, automatically adjusts assembly strategies and the location of the compliant part by measuring the position and the force exerted on the assembling elements. Passive devices are the ones that contain no source of energy and therefore are made from components such as springs and other elastic elements. External constraints directly modify the trajectory of the movable part during assembly operation. In the case of passive compliance, passive resistance of the elastic elements in the system is designed such that generated forces will correct the error on the relative position between the parts.

The most famous compliance mechanism designed for assembly is the remote centre compliance (RCC) device introduced by Whitney and Newins [1]. The RCC defines a point in the space – the accommodation centre in such a way that the applied forces produce displacements and the applied torques produce rotations about this point, being the elasticity of the device a fixed parameter.

A survey of mechanical and electromechanical assembly task [2] highlights the importance of peg-in-hole assembly being one generic assembly operation. It is found that 69% of possible tasks are taken up with fitting a round or square peg with the majority exhibiting a chamfer aiding to the alignment of the mating parts. The mating of a peg with a hole requires the peg to be aligned with the hole and as a result an end-effector or compliability to successfully complete the process. Considering mating of the parts the assembly problem is to be analysed as a quasi-static or dynamic one.

The case of quasi-static assembly is analysed in the works [3, 4]. Using this approach it is assuming that a peg is inserted into a hole slowly and that static forces of the elastic elements of the end-effector are dominant. As the insertion speed increases the quasi-static assumption is not valid, because inertial forces of the robot and gripper become dominant. The study of geometrical and dynamical conditions for a successful insertion process has been presented in the works [5-7]. Also in these papers the conditions of jamming and wedging which can occur during the insertion at the two-point contact stage are analysed.

The process of vibratory assembly, which can be classified as a passive assembly technique, can be divided into two principal stages – the alignment of parts and the insertion of them. During the first stage, the alignment process of the compliant part in respect to the rigidly fixed part occurs due to the vibrational excitation. When the parts are aligned, it is possible to perform mating of the components to be assembled. Vibratory alignment of the compliantly supported peg in respect to the immovable bushing was simulated in works [8, 9]. Due to the vibratory excitation, the compliant peg performs the directional displacement towards axial alignment of the parts. To provide passive compliance of the peg, the device with elastic elements of bellows type is used. Some results of the analytical analysis of the compliantly supported peg insertion into the hole with clearance are presented in [10, 11]. The passive compliance of the peg is provided using the device with the RCC. During the peg-in-hole insertion at the two-point contact stage two undesirable phenomena – jamming and wedging can occur [7]. In order to prevent jamming and wedging it is necessary to prevent the balance of insertion and frictional forces.

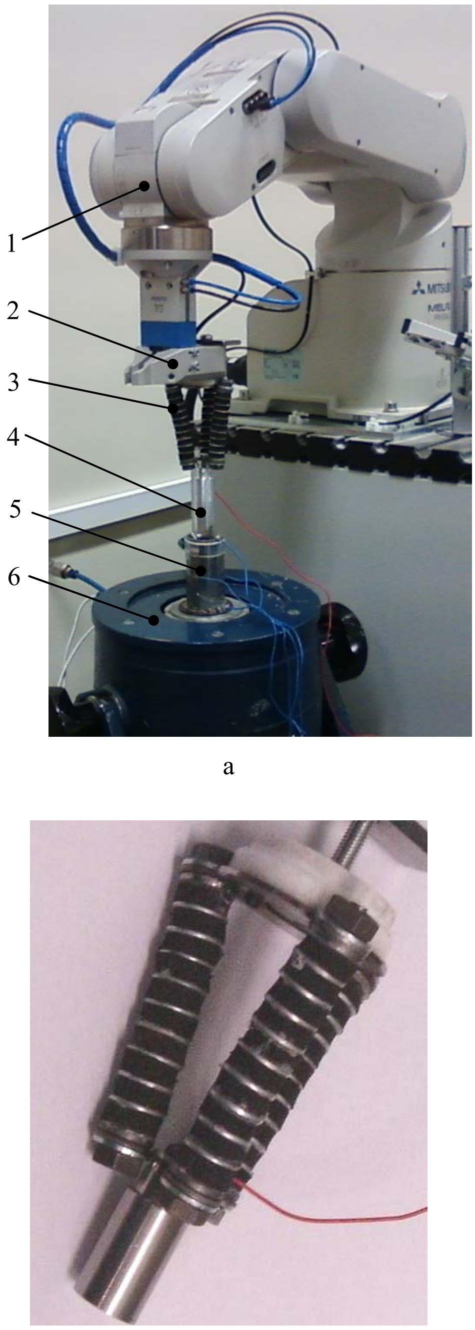
To apply the method of the vibratory assembly one of the parts in assembly position should be provided with vibrations of predefined direction, amplitude and frequency. The vibrations can be generated by an electromagnetic or piezoelectric shaker and the excitation can be applied to the peg and the bushing. The parts can be acted with longitudinal and transverse vibrations. Using piezoelectric elements in the structure it is possible to obtain complex trajectories of vibrations [12, 13].

Vibrations can be applied not only in an assembly process but also in other technological processes. For example, if a cutting tool is under ultrasonic vibrations cutting force decreases and roughness of the surfaces decreases [14]. Functioning of vibroactuators, precise positioning devices is based on the vibratory rotation and translation, which is caused by a high-frequency excitation.

In this paper we make efforts on the experimental analysis of the vibratory alignment and the insertion of peg-in-hole, when the peg is compliantly supported and the bushing is immovably attached on the platform of an electrodynamic shaker. The passive compliance device with the remote compliance centre for the peg is used. The influence analysis of the parameters of the assembly system and excitation on the alignment and the insertion process is presented.

2. Experimental setup and methodology for the investigation of vibratory assembly

To carry out experimental analysis of the vibratory alignment and insertion processes, a setup for the robotic vibratory assembly was designed and made (Fig. 1).



a

b

Fig. 1 Experimental setup for vibratory assembly: a – general view; *1* - robot; *2* - robot gripper; *3* - passive compliance device; *4* - peg; *5* - bushing; *6* - electrodynamic shaker; b – remote center compliance device of the peg

Assembly operations are performed by the robot *1* (Mitsubishi RV-2AJ). The robot gripper *2* holds the experimental remote centre compliance device *3*, which is attached to the peg *4*. The bushing *5* is attached on the platform of the electrodynamic shaker *6*. The electrodynamic shaker, providing excitation to the bushing in its axial direction, receives the electric signal of the excitation from an oscillator using an amplifier. The robot is controlled by means of the stored in the controller programme and using the position list. 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 (Fig. 1, b). They are made of a set of metallic and rubber bushings. The length of the elastic elements is 60 mm, diameter 14 mm. 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 peg axis direction. The axial misalignment between the peg and the bushing is adjusted defining the position of the robot gripper in respect of the bushing. The force of the peg 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.

To register the end of the alignment an electric device, which sends a signal after the peg is inserted into the bushing, is used. The vibration signal of the bushing is received from a piezoelectric acceleration sensor. Both the signals from the device and the sensor are transferred to a digital oscilloscope and displayed on a computer screen (Fig. 2). Curve *1* represents the signal from the acceleration sensor, while curve *2* – the end signal of the alignment. As the robot gripper moves down and reaches the particular height, vibrations are turned on. The emerging impulse of curve *1* indicates the start of vibrations, whereas the emerging impulse of curve *2* indicates the beginning of insertion. Duration of the alignment is the time from the turn-on moment of vibrations till the end of the peg falling into the hole (beginning of the curve *2*).

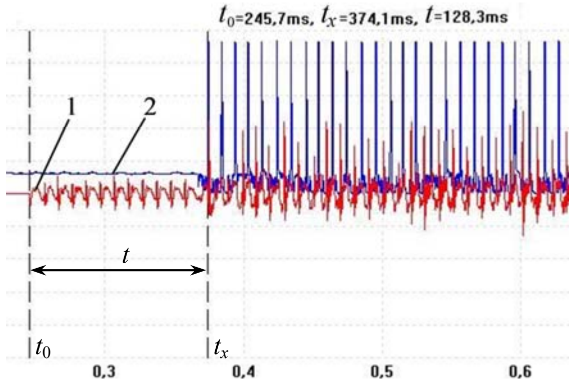


Fig. 2 Measurement scheme of the alignment duration *t*: *1* – signal from the acceleration sensor; *2* – signal which indicates the end of the alignment

To analyse the vibratory insertion process of a peg and a hole, the special construction steel bushing, which provides possibility to acquire the parameters of the insertion process using the electric contact method, was designed and made. The bushing comprises the electrically insulated interdependent segments, i.e. a chamfer, two sides and a bottom. These segments and the peg are connected to a microcontroller (ATmega16). The microcontroller is programmed in such a way that when the peg touches the different segments of the bushing, a voltage jump is send to the oscilloscope and displayed on the computer screen (Fig. 3).

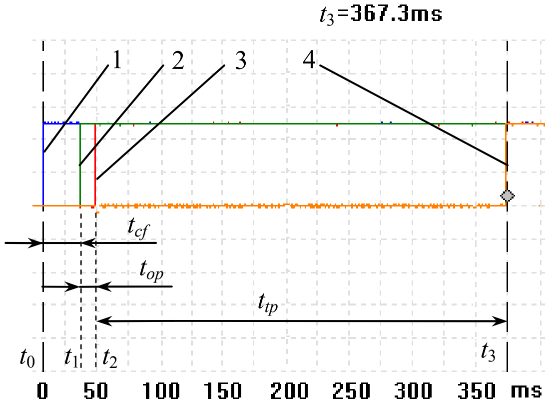


Fig. 3 Oscillogram of the insertion process: *1* – indication of the contact with the chamfer; *2* – indication of the one-point contact; *3* – indication of the two-points contact *4* – indication of the insertion process finishing

The insertion process starts from the moment t_0 as the peg contacts the chamfer. This moment indicates the start of the chamfer crossing stage and as a result of the peg-chamfer contact, the oscillogram displayed on the computer screen shows the voltage jump (Fig. 3, *1*). The peg slides over the chamfer till its cylindrical surface reaches the edge of the hole. The insertion process proceeds into the one-point contact stage, the other voltage jump occurs (Fig. 3, *2*) and time t_1 value is obtained. The parameter t_1 indicates the duration of the chamfer crossing. The peg is in the one-point contact state with the bushing till the bottom edge of the peg reaches the internal surface of the hole. The insertion process proceeds into the two-point contact stage, the voltage jump occurs again (Fig. 3, *3*) and the time value t_2 is obtained. The duration t_2 includes the chamfer crossing duration t_{cf} and the one-point contact duration t_{op}. The parameter t_2 indicates the duration from the beginning of the insertion process till the beginning of the two-point contact. As the peg touches the bottom of the bushing the insertion process is finished, the oscillogram shows the voltage jump (Fig. 3, *4*) and the value of the time t_3 is obtained. The peg is completely inserted into the bushing's hole at that moment. The duration t_{tp} is the two-point contact stage duration. The time t_3 is the insertion process duration.

3. Evaluation of the vibratory alignment process

Passive compliance devises by combination with a vibration technique are capable to carry out chamferless assembly operations. For the analysis and evaluation of the alignment process experiments were carried out performing the alignment of the chamferless peg with respect to the chamferless hole. The parts used in the experiments have the following parameters: peg diameter $d = 17.88$ mm, hole diameter $D = 18.10$ mm. The parts are made of stainless steel, ground rough. Under vibratory excitation, movement of the peg toward the axis of the hole appears in case the peg is pressed to the bushing by the force of sufficient magnitude. The pressing force of the parts is produced by deforming the elastic elements of the device along the hole axis. During the experiments we defined the alignment duration of the peg with respect to the vibratory excited bushing, so that connective surfaces get matched and insertion of the peg in the hole may be accomplished. Alignment duration dependences on the excitation frequency and amplitude, the pressing force of the parts and the axial misalignment are obtained. The program of the experiments was drawn up so that the obtained results provide the possibility to determine the ranges of the parameters variation when the alignment of the parts is successful.

The character of the peg motion towards matching of the connective surfaces of the parts depends on proper selection of the parameters of the dynamic system and excitation of the bushing. For the experiments it is considered that axial misalignment between the parts exists and the peg is pressed to the bushing by the predetermined force. Therefore, the peg tilts by a small angle in respect to the axis of the hole and takes the position of static equilibrium. Under vibratory excitation the peg is able to displace from the position of static to dynamic equilibrium. If misalignment between the axes of the parts is larger than the distance between the positions of static and dynamic equilibrium of the peg, alignment of the parts is impossible. The duration of the alignment is defined from the start movement of the excitation till the falling of the peg into the hole.

The amplitude of vibrations A of the bushing has an influence on the alignment duration (Fig. 4). When the amplitude A increases, the alignment duration t decreases. Such tendency of the diminishing duration is characteristic for various values of the pressing forces. An increase of the frequency of the generated vibrations yields a decrease in the vibrations amplitude.

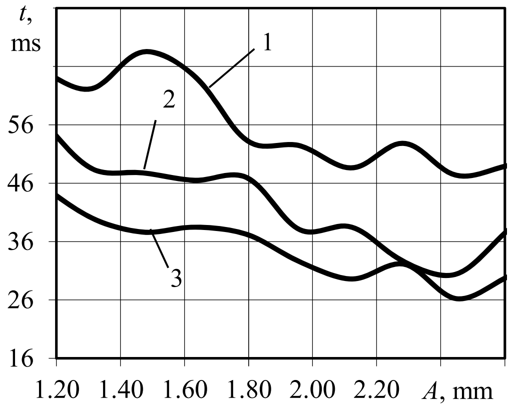


Fig. 4 Dependences of the alignment time t on the vibration amplitude A, as the excitation frequency $f = 40$ Hz, the axial misalignment $\Delta = 3.0$ mm; the pressing force: *1* – $F = 9.81$ N; *2* – $F = 10.98$ N; *3* – $F = 12.56$ N

When the amplitude A is decreased, then the alignment duration t considerably increases (Fig. 5). In the range of small amplitudes ($A = 0.1 – 0.3$ mm) an increase of the amplitude has a little influence on the alignment time.

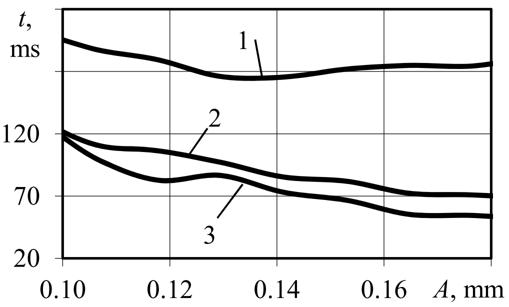


Fig. 5 Dependences of alignment time t on vibration amplitude A, as the excitation frequency $f = 100$ Hz, the axial misalignment $\Delta = 3.0$ mm; $1 - F = 9.81$ N; $2 - F = 10.98$ N; $3 - F = 12.56$ N

The range of bushing excitation frequencies, when alignment of the parts is still possible, depends on the amplitude of excitation acceleration and the part-to-part pressing force. The amplitude of vibration acceleration A_1 has a high influence on the dependence character of the alignment duration t versus the excitation frequency (Fig. 6).

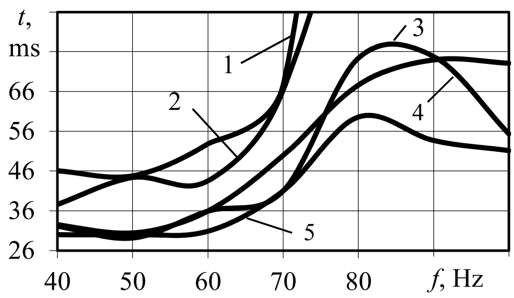


Fig. 6 Dependences of alignment time t on excitation frequency f, as the pressing force $F = 12.56$ N, the axial misalignment $\Delta = 3.0$ mm; $1 - A_1 = 7$ m/s²; $2 - A_1 = 10$ m/s²; $3 - A_1 = 12$ m/s²; $4 - A_1 = 14$ m/s²; $5 - A_1 = 16$ m/s²

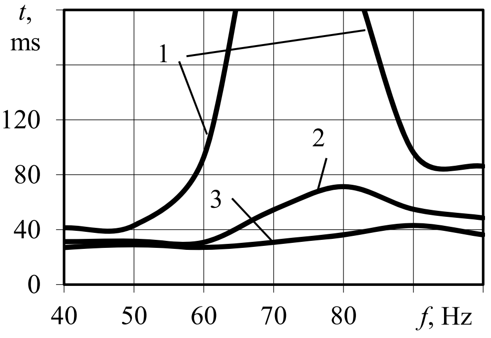


Fig. 7 Dependences of alignment time t on bushing excitation frequency, as the vibration acceleration $A_1 = 12$ m/s^2; $\Delta = 2.5$ mm; $1 - F = 9.81$ N; $2 - F = 10.98$ N; $3 - F = 12.56$ N

If amplitude of the vibration acceleration A_1 is not high enough (7 – 10) m/s^2, then alignment of the peg takes place only on the excitation frequency range (40 – 70) Hz. Within the frequency range 40 – 60 Hz the alignment duration changes little. As the frequency increases, the time t grows. When f is in the vicinity of 85 Hz, the time t reaches its respective maximal value. The alignment of the peg occurs only having matched the excitation frequency and the pressing force of the parts (Fig. 7). Under the pressing force 9.81 N, the process of alignment in the range (60 – 80) Hz does not occur. When the pressing force is sufficient, the peg will be successfully aligned in the large range of frequencies.

Pressing force of the parts has a substantial influence on displacement character of the peg and the duration of the alignment. Under the action of this force, the peg slightly tilts in respect to the bushing and takes the position of static equilibrium. Due to the tilt of the peg, horizontal component of the normal force between the contacting parts and elastic moment of the passive compliance device emerges. In such a way, force asymmetry of the mechanical system occurs. The vibratory excitation of the peg through the vibrating bushing results the kinematic asymmetry. Due to the both types of asymmetries of the mechanical system, the alignment motion of the peg can occur.

An increase in the pressing force F yields a smaller time t (Figs. 8 – 9). The tendency of the time diminishing persists for various amplitude excitations and axial misalignment of the parts.

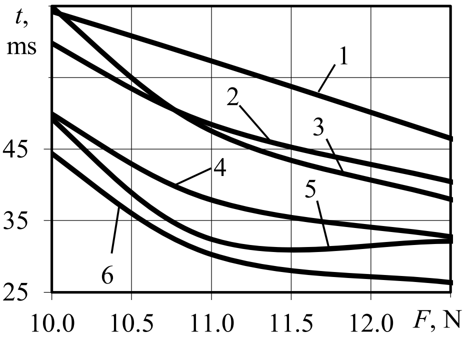


Fig. 8 Dependences of alignment time t on pressing force F, as the excitation frequency $f = 40$ Hz, the axial misalignment $\Delta = 3.0$ mm; $1 - A = 1.14$ mm; $2 - A = 1.31$ mm; $3 - A = 1.47$ mm; $4 - A = 1.96$ mm; $5 - A = 2.29$ mm; $6 - A = 2.45$ mm

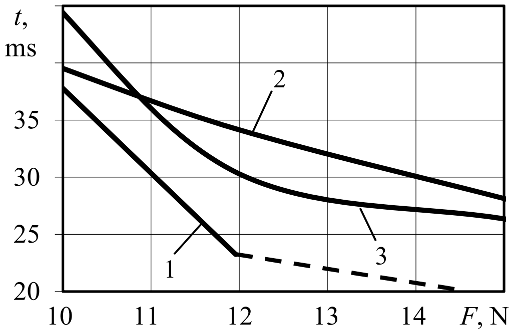


Fig. 9 Dependences of alignment time t on pressing force F, as the excitation frequency $f = 40$ Hz, the vibration amplitude $A = 2.45$ mm; $1 - \Delta = 2.0$ mm; $2 - \Delta = 2.5$ mm; $3 - \Delta = 3.0$ mm;

In Fig. 9 dependence $t = f(F)$ as $\Delta = 2.0$ mm is presented in the range of pressing force (10 – 12) N. When the force F is higher than 12 N, the peg will be aligned and inserted into the hole without vibrations. The range of the pressing force in which the peg can be aligned without vibrations is presented by the dashed line.

The results of the experiments show that the successful vibratory alignment of the peg in respect to the hole occurs only under the parameters of the mechanical system and the excitation being adjusted properly. To use in practice the obtained results of the experimental analysis, it is necessary to define the sets of the mentioned parameters, which ensure the successful alignment. The areas of the parameters sets for successful alignment of the parts are defined (Figs. 10 - 11).

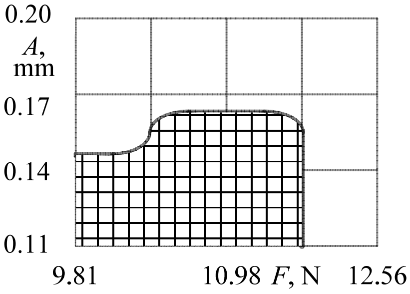


Fig. 10 Area of successful alignment (unhatched) on the amplitude *A* of vibrations and the pressing force *F*, then $f = 90$ Hz, $\Delta = 3.0$ mm

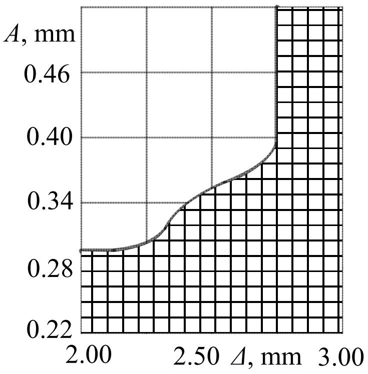


Fig. 11 Area of successful alignment (unhatched) on amplitude *A* of vibrations and the axial misalignment Δ, when $f = 70$ Hz, $F = 9.81$ N

If the parameters are selected from the hatched areas, the alignment of the peg is not possible. An increase in the part-to-part pressing force expands the range of the excitation amplitude of the bushing, wherein the alignment of the peg occurs (Fig. 10). When axial misalignment between the peg and the hole increases, the successful alignment is possible by providing higher excitation amplitudes to the bushing (Fig. 11).

4. Evaluation of the vibratory insertion process

The experiments of the vibratory insertion process were carried out when the assembly clearance $\delta = 0.2$ mm, the mass of the peg $m = 0.05$ kg, the diameter of the bushing hole $D = 20$ mm, the chamfer angle of the bushing $\alpha = \pi / 4$ rad, the initial tilt angle of the peg $\theta_0 = 0.035$ rad, the initial axial misalignment of the peg and the bushing axis in the lateral direction $\varepsilon_0 = 2$ mm, the depth of insertion $h = 50$ mm.

The experiments showed that the excitation parameters have an influence on durations of various insertion process stages. It was detected that the insertion process duration t_3 decreases when the excitation frequency *f* is increasing (Fig. 12, *1* and *2* curves). If the excitation amplitude is higher than 0.6 mm, the frequency of vibrations has a little influence on the duration t_3.

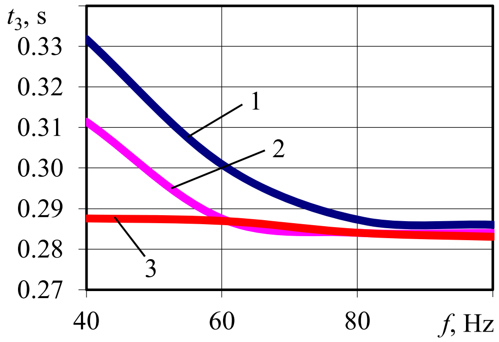


Fig. 12 Dependencies of insertion process duration t_3 on excitation frequency *f*, when the insertion speed $v = 0.16$ m/s; the excitation amplitude: *1* – $A = 0.2$ mm; *2* – $A = 0.6$ mm; *3* – $A = 0.8$ mm

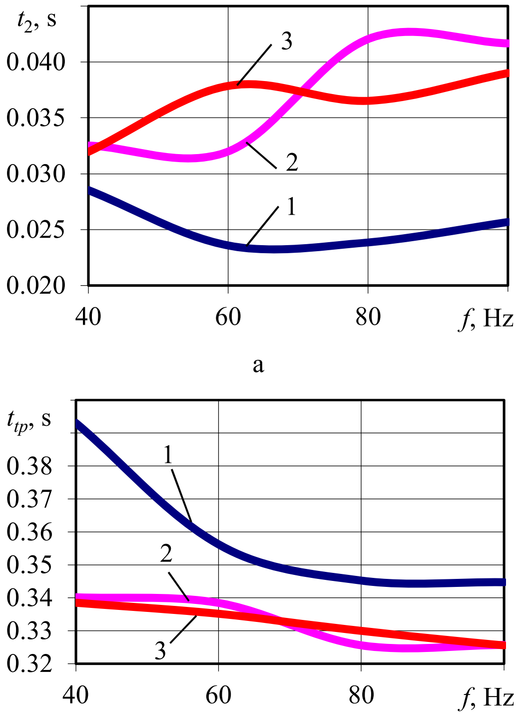


Fig. 13 Dependences of: a – the duration t_2; b – the two-point contact stage duration t_{tp} on the excitation frequency *f*, the insertion speed $v = 0.12$ m/s; *1* – $A = 0.2$ mm; *2* – $A = 0.6$ mm; *3* – $A = 0.8$ mm

Jamming and wedging are two undesirable phenomena in a peg-in-hole insertion and usually occur at the two-point contact stage [3, 4]. Jamming is a condition in which the peg will not move into the hole because insertion forces exerted by a robot will be balanced by the contact and friction forces. In a state of jamming, the ratios of the applied forces are so irrational that they result in improper reaction forces. Such a state of the peg occurs if the applied line of acting force passes in the wrong direction with respect to the hole axis and its action can be balanced by the contact forces, thus the insertion can not be accomplished. Wedging is a static geometrical phenomenon which is possible in the two-point contact state, when the peg can not move from wedged position despite a high insertion force. Wedging is synonymous with a force closure because no matter how much force the robot applies to the peg, the frictional contacts between the peg and the hole can balance its force. In wedging, the two reaction forces of contact points are pointing directly opposite to each other and each friction cone can contain the other's base. At the moment, when the frictional forces are in balance with the insertion force, the sliding velocity at the contact points reduce to zero and wedging can occur. It is noticed, that wedging or jamming usually occurs in a small insertion depth of the hole. When the excitation frequency f is increasing, the duration t_2, which takes time from the initial instant of the insertion to the two-point contact stage, slightly increases (Fig. 13, a), meanwhile the two-point contact stage duration t_{tp} decreases (Fig. 13, b). According to this, a conclusion could be made that when the excitation frequency f is increasing, the two-point contact appears as the peg is in a greater depth. Consequently, an increase of the excitation frequency facilitates the successful insertion process. Besides under the excitation of the bushing, tilt angle of the peg, which is in the hole, is periodically changing, the reaction forces in the contact points of the peg and the hole also change. Also, the direction and magnitude of frictional forces in the contact points periodically change due to bushing vibrations. Therefore, the probability decreases that the balance of insertion and frictional forces will occur during the insertion process. Therefore, the vibratory excitation of the bushing makes it possible to avoid jamming and wedging.

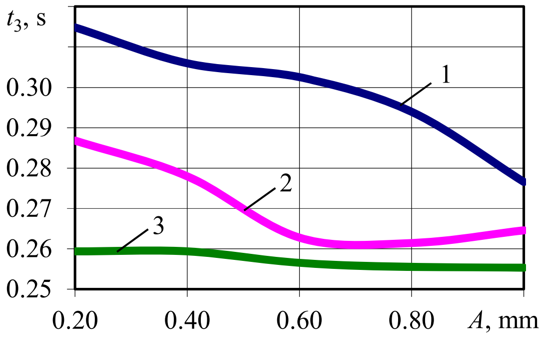
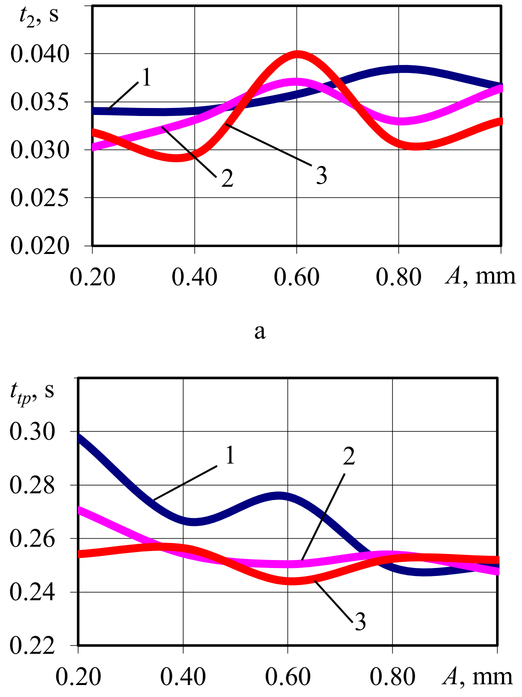


Fig. 14 Dependencies of the insertion process duration t_3 on the excitation amplitude A, when the insertion speed $v = 0.2$ m/s; the excitation frequency: *1* – $f = 40$ Hz; *2* – $f = 60$ Hz; *3* – $f = 80$ Hz



a

b

Fig. 15 Dependences of: a – the duration t_2; b – the duration t_{tp} on the excitation amplitude A, $v = 0.16$m/s; *1* – $f = 40$ Hz; $f = 60$ Hz; *3* – $f = 100$ Hz

The insertion process duration t_3 decreases when the excitation amplitude A is increasing (Fig. 14). The decrease is more significant under lower frequencies of the excitation.

When the excitation amplitude A is increasing, the duration t_2, slightly nonlinearly increases (Fig. 15, a), meanwhile the two-point contact stage duration t_{tp} decreases (Fig. 15, b). Therefore, when the excitation amplitude A is increasing, the two-point contact appears as the peg is in a greater depth. This gives a positive effect in terms of the successful insertion.

5. Conclusions

The experimental analysis of vibratory alignment and insertion processes is performed when the compliantly supported peg is assembled with the bushing, which is vibratory excited in the axial direction. The character of the peg motion during alignment of the parts and the alignment duration depend on the excitation amplitude and frequency, the pressing force and the axial misalignment. When the amplitude of vibrations is increasing, the alignment duration decreases. The alignment of the parts will occur in the certain range of bushing excitation frequencies. This range depends on the amplitude of excitation acceleration and the part-to-part pressing force. An increase of the pressing force yields the smaller alignment time. It was detected that when the excitation amplitude or frequency is increasing, the insertion process duration decreases. As the excitation frequency or the excitation amplitude increases, the two-point contact appears as the peg is in a greater depth, thus jamming and wedging can be avoided. Consequently, the vibratory excitation gives a positive effect in terms of the successful insertion.

Acknowledgments

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VIBRACINIO RINKIMO NAUDOJANT PASYVŲJĮ PASLANKUMĄ EKSPERIMENTINIS TYRIMAS

Reziumė

Straipsnyje pateikti strypo ir skylės centravimo ir strypo įstatymo į skylę vibracinio robotizuoto rinkimo metu eksperimentiniai tyrimai. Strypas paslankiai bazuojamas nutolusio paslankumo centro įtaise, o įvorė tvirtinama ant elektrodinaminio vibratoriaus platformos. Įvorės žadinimo virpesiai nukreipti detalių sujungimo ašies kryptimi. Pateiktas eksperimentinio įrenginio su CNC robotu ir tyrimų metodikos aprašymas. Atliktas vibracinio centravimo proceso vertinimas, atsižvelgiant į virpesių amplitudę ir dažnį, detalių prispaudimo jėgą ir ašių nesutapimą. Nustatytos sėkmingo centravimo sritys nuo virpesių amplitudės ir prispaudimo jėgos, amplitudės ir ašių nesutapimo. Pateiktos strypo įstatymo į skylę etapų trukmių priklausomybės nuo virpesių parametrų. Nustatyta, kad vibracinis žadinimas įstatymo metu padeda išvengti strypo įstrigimo ir užsikirtimo.

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EXPERIMENTAL INVESTIGATION OF VIBRATORY ASSEMBLY WITH PASSIVE COMPLIANCE

Summary

The paper presents an experimental investigation of peg-hole alignment and peg-in-hole insertion during the vibratory robotic assembly. The peg is compliantly supported in the remote compliance center device and the bushing is attached on the platform of an electrodynamic shaker. The vibratory excitation of the bushing is provided along the joining axis direction. The experimental setup with a CNC robot and the methodology for the investigation are presented. The evaluation of the vibratory alignment process considering on the vibrations amplitude and frequency, part-to-part pressing force and axial misalignment is made. The areas of successful alignment on the amplitude of vibrations and both the pressing force and axial misalignment are determined. The dependencies of peg-in-hole insertion stages durations on the parameters of vibrations are presented. It is determined that vibratory excitation during the insertion process makes it possible to avoid jamming and wedging.

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