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Experimental investigation of cylindrical parts robotic vibratory insertion

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1. Introduction

One of the most important stages in automated assembly is insertion of the parts to be assembled. The productivity of assembly operations highly depends on the speed of the insertion process. The productivity is very important factor in modern competitive manufacture. Therefore, it is important, that the parts would be inserted under high speed during assembly operations. The high speed insertion process is a complex dynamic process, which is under the influence of gravity, inertia, insertion speed, stiffness of basing device, friction etc. High insertion speed causes high insertion forces, therefore the probability of jamming increases. Quasi-static model of parts insertion, analyzed in the majority sources of literature [1-4], is not suitable for the research of high speed insertion process. As investigations show, jamming can be avoided by parameter selection of assembly system and exiting vibrations of the parts to be assembled [5, 6]. During vibratory assembly process, it is possible to excite vibrations of the part either as of solid body or elastic body [7, 8].

Insertion process without using vibratory excitation was analyzed theoretically in paper [9]. Mathematical model of insertion was presented. Conditions for the shortest duration and the highest reliability of insertion process were determined. The results of insertion process simulation under kinematical excitation were presented in paper [6]. The parameters, under which the parts get jammed, were determined using computer simulation methods. It was determined that connection of the jammed parts is possible by exciting vibrations of the peg in axial direction. Parameters of kinematical excitation, under which the duration of insertion process is the shortest and the process is the most reliable, were detected.

There is not a lot of literature sources about experimental investigations on vibratory assembly. Besides, the problem of alignment and matching of the parts is mainly investigated in the literature about vibratory assembly. Paper [10] presents experimental investigation of vibratory alignment and matching of the parts to be assembled automatically under kinematical excitation of mobile based part. Results obtained performing alignment of circular and rectangular chamferless parts under different excitation, initial pressing force and parts misalignment conditions are given. Excitation parameters which determine the reliability of alignment and matching of the parts were detected. Paper [11] investigates vibratory alignment and matching of the parts being assembled automatically as immovably based receiving part is vibratory excited. Experimental setup for alignment of the parts having rectangular and circular cross-sections is presented. Dependencies of alignment duration on excitation parameters, initial preload and axial misalignment for circular and rectangular chamferless parts are given. Areas of excitation and system parameters sets where the process of alignment is stable have been defined. Paper [12] analyses insertion process of the parts and a device for high speed and precision chamferless assembly, using vibratory technology is proposed. Experimental investigation is performed. The device consists of a work table driven by vibratory motion, provided by two pneumatic bellow actuators, piloted by the pseudo-random binary signal; and of a dynamic compliance device. At the beginning of assembly operation, the gripper is centered by a centering mechanism and it has only one degree of freedom in the insertion direction during the search of part alignment. When the parts are aligned, the peg slides into the hole by releasing the deformation energy accumulated in searching stage. At insertion stage, the centering mechanism is released and the gripper has six degrees of freedom. A displacement sensor is used for detection of the contact, of the search end, wedging and jamming. However, the proposed device is quite complex. The performed experiments are not described well enough. Too few experimental results are presented. The influence of insertion parameters on insertion process was not determined in the paper. Also the influence of vibrations on insertion process and its duration was not determined.

In order the process of vibratory assembly to be reliable and effective, it is necessary to ensure that the parameters, which make an influence on insertion process, were rationally selected.

This paper presents experimental analysis of the insertion process when mobile based peg is inserted into excited in axial direction immobile based bush, under guaranteed clearance by a robot. When the parameters of kinematical excitation are properly selected it is possible to obtain minimal duration of the insertion process.

2. Investigation methodology of parts insertion

Experimental setup of robotic vibratory assembly was designed and made (Fig. 1). Assembly operations are performed by robot *9* (Mitsubishi RV-2AJ). Robot gripper holds a remote center compliance device *4*, which is attached to a peg *5*. Special construction steel bush *6*, which can detect insertion process stages by electric contact method, was designed and made. The bush is made of electrically insulated from each other parts – chamfer, two sides and bottom. When the peg touches particular parts of the bush, voltage jump occurs. It is indicated in computer display using oscilloscope (Pico ADC 212). Using such method, it is possible to detect all the stages of insertion process, i.e. peg contact with the bush chamfer, peg one point and two point contact with the bush hole, end of the insertion and to find the durations of all these stages. The bush is mounted on the platform of electromagnetic vibrator *8* (VEB ROBOTRON MESS-ELEKTRONIK OTTO SHON). Low frequency signal generator *1* (G356/1) through amplifier *2* provides signal for the vibrator. The mobile based pegs are made of aluminium alloy in order the assembled parts not to attract each other due to magnetic fields, generated by electromagnetic vibrator. The experiments were performed with several different diameter pegs in order to compare the results under different assembly clearance $\delta = 0.6\cdot10^{-3} - 0.2\cdot10^{-3}$ m.

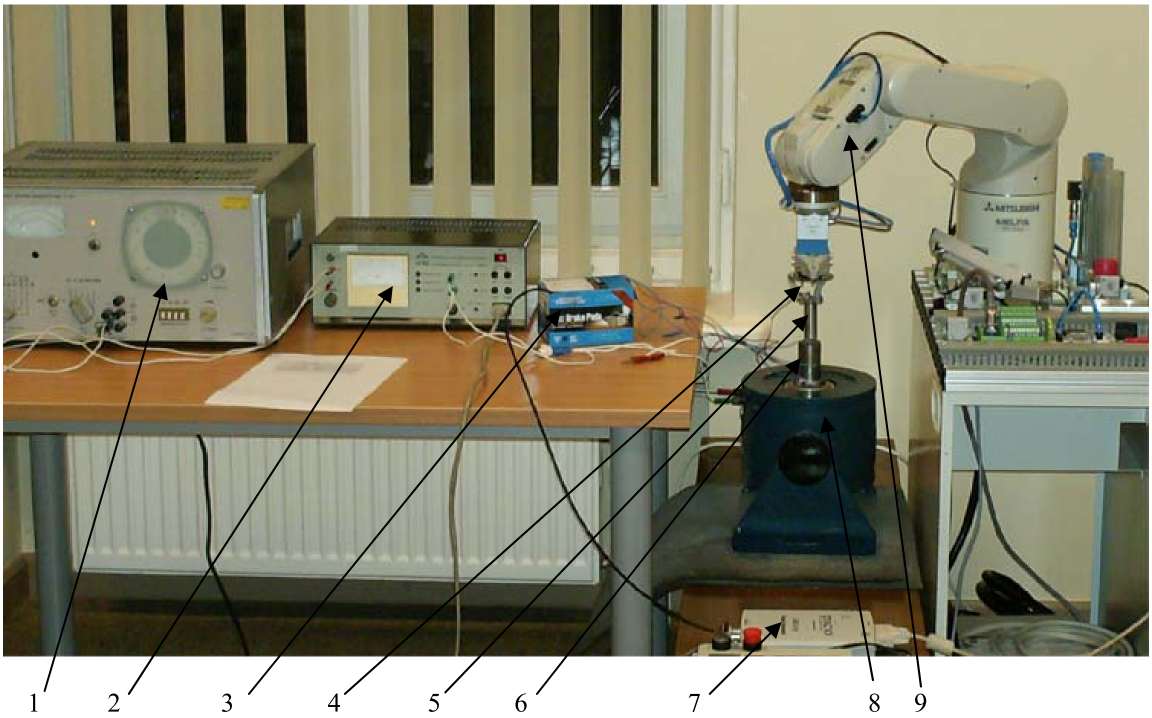


Fig. 1 Robotic vibratory assembly experimental setup: *1* – low frequency signal generator; *2* – amplifier; *3* – converter; *4* – experimental remote center compliance device; *5* – peg; *6* – special construction bush; *7* – oscilloscope; *8* – electromagnetic vibrator; *9* – robot arm

The peg is attached to the remote center compliance device (Fig. 2). The device is made of three helical springs, which are arranged at a particular angle, therefore the center of compliance occurs near the lower end of the peg. The device is attached to the robot gripper.

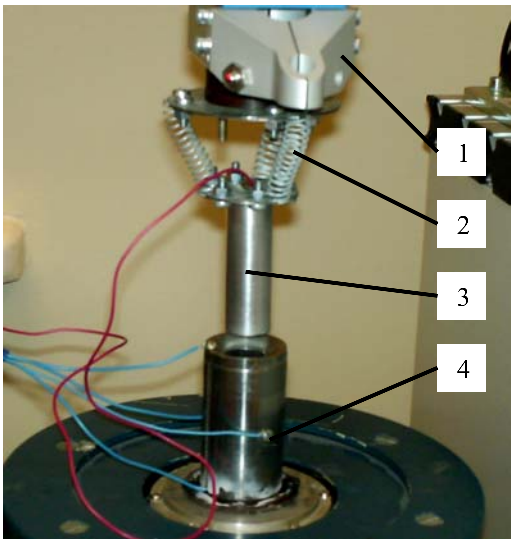


Fig. 2 Parts in assembly position before insertion process: *1* – robot gripper; *2* – remote center compliance device; *3* – peg; *4* – bush

The process of insertion starts when the peg touches the chamfer at time instant t_0. At that moment, chamfer crossing stage begins and voltage jump occurs in experimental oscillogram (Fig. 3, *1*).

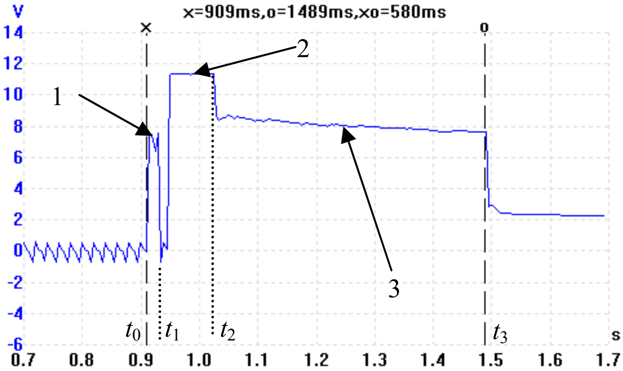


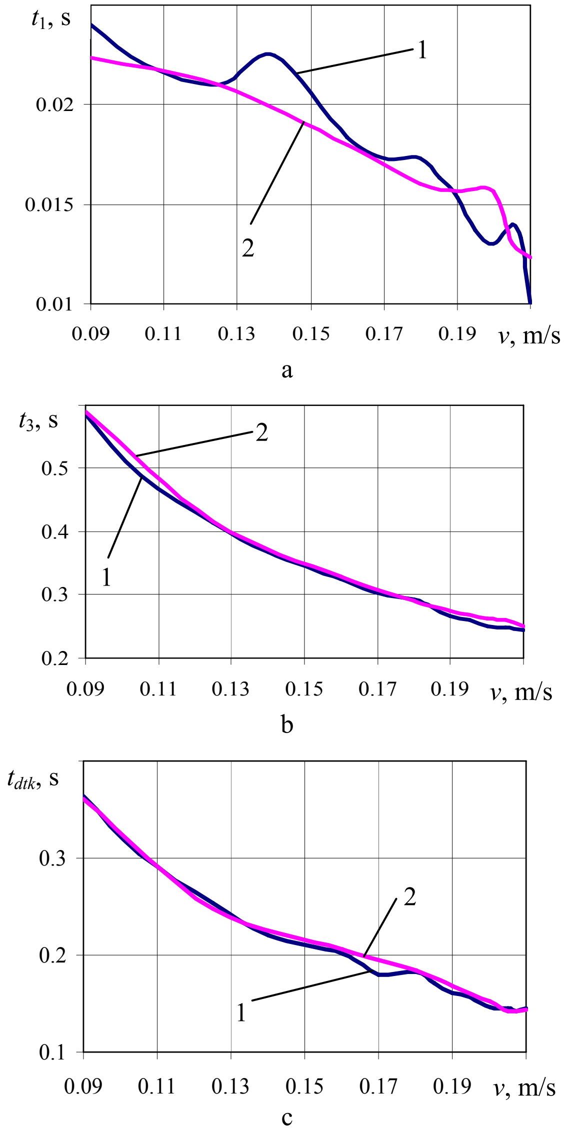
Fig. 3 Insertion process oscillogram: *1* – chamfer crossing stage; *2* – one point contact stage; *3* – two point contact stage

The peg slides down the chamfer until the cylindrical surface of the peg touches the edge of the hole. Insertion process steps into the one point contact stage, the other voltage jump occurs and time instant t_1 is defined. Parameter t_1 is the chamfer crossing duration. The peg contacts with the hole (Fig. 3, *2*) in one point until the lower edge of the peg reaches internal surface of the hole. Insertion process steps into the two point contact stage (Fig. 3, *3*), voltage jump occurs again and time instant t_2 is defined. Duration t_2 consists of chamfer crossing duration t_1 and the duration of two point contact stage. Parameter t_2 is the duration from the beginning of the insertion process to the beginning of two point contact stage.

When the peg touches the bottom of the bush, insertion process terminates, voltage jump occurs in the oscillogram and time instant t_3 is defined. Insertion process duration t_3 is the duration from the beginning of chamfer crossing stage to the termination of insertion process, when the peg is completely inserted into the bush.

3. Experimental investigation of insertion process

Insertion speed has the highest influence on insertion process duration.



a

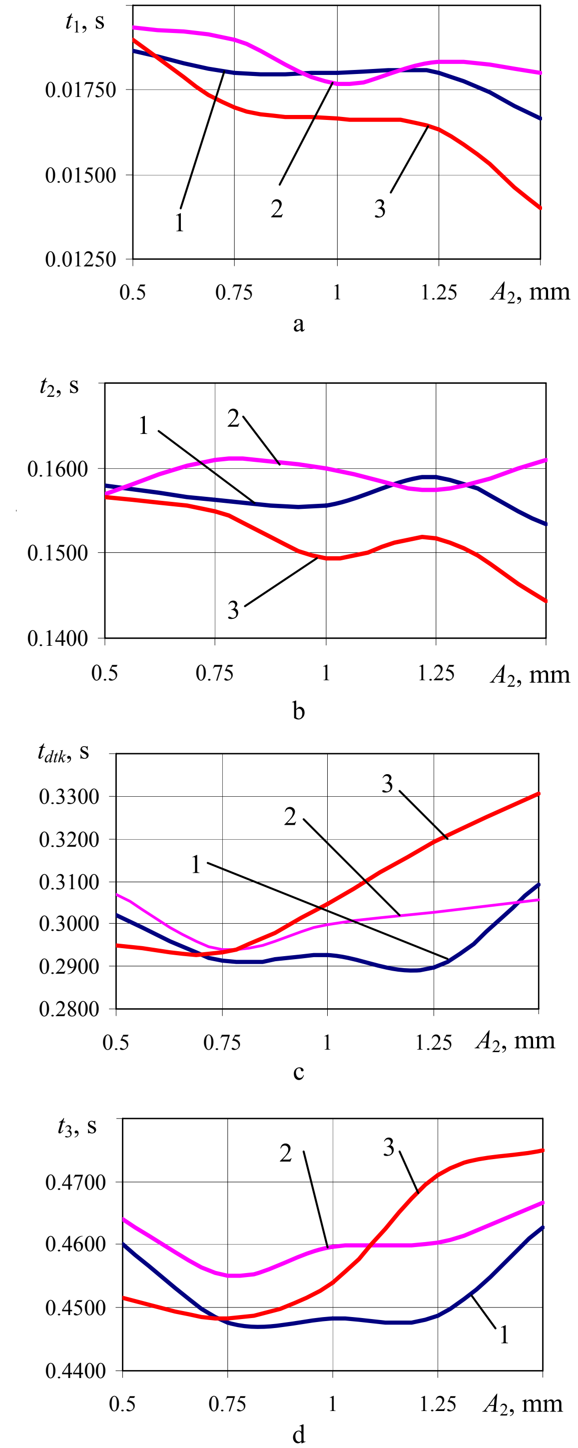
b

c

Fig. 4 Dependences of: a – chamfer crossing duration t_1; b – insertion process duration t_3, c – two point contact stage duration t_{dtk}, on insertion speed, *1* – without vibrations; *2* – exciting the bush vibrations of frequency $f_2 = 70$ Hz and amplitude $A_2 = 0.5$ mm

The insertion speed is controlled by changing robot gripper speed in insertion axis direction.

Dependences of the durations of insertion process stages on the insertion speed were determined when the assembly clearance $\delta = 0.6$ mm, mass of the peg $m = 0.05$ kg, diameter of the bush hole $D = 0.02$ m, chamfer angle of the bush $\alpha = \pi / 4$ rad, initial tilt angle of the



a

b

c

d

Fig. 5 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 excitation amplitude A_2, under different excitation frequencies: *1* – $f_2 = 50$ Hz; *2* – $f_2 = 70$ Hz; *3* – $f_2 = 100$ Hz peg $\theta_0 = 0.035$ rad, initial axis misalignment of the peg and bush in lateral direction $\varepsilon_0 = 2.25$ mm, remote center compliance device lateral stiffness $K_x = 167$ N/m, axial stiffness $K_z = 834$ N/m, angular stiffness $K_\theta = 0.26$ N·m/rad, distance from the lower end surface of the peg to the centre of compliance $L_C = 5$ mm.

When the insertion speed v is increasing, the peg faster crosses the chamfer (Fig. 4, a), insertion process duration significantly decreases (Fig. 4, b), two point contact stage duration decreases (Fig. 4, c).

The experiments showed that insertion process duration depends on the parameters of vibratory excitation.

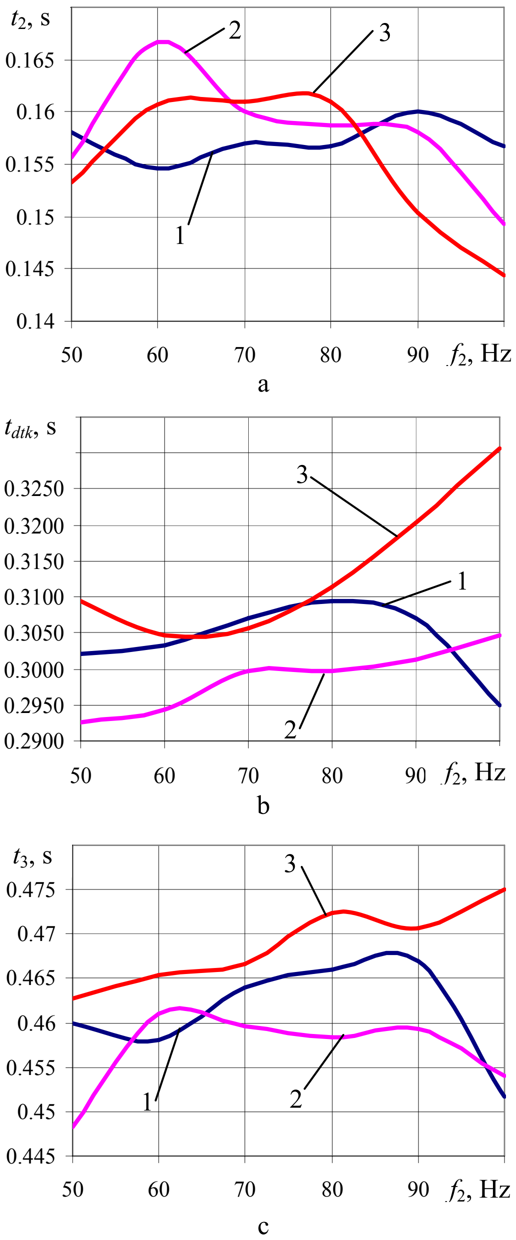


Fig. 6 Dependences of: a – chamfer crossing duration t_1; b – duration t_2, from the beginning of insertion process until the beginning of two point contact stage; c – two point contact stage duration t_{dtk}; d – insertion process duration t_3, on excitation frequency f_2, under different excitation amplitude: *1* – A_2 = 0.5 mm; *2* – A_2 = 1.0 mm; *3* – A_2 = 1.5 mm

The experiments were performed with another remote center compliance device, with lateral stiffness $K_x = 834$ N/m, axial stiffness $K_z = 2500$ N/m, distance to the center of compliance $L_C = 10$ mm, angular stiffness $K_\theta = 0.89$ Nm/rad, when initial tilt angle of the peg $\theta_0 = 0.0175$ rad, initial axial misalignment of the peg and bush in lateral direction $\varepsilon_0 = 2.25$ mm, assembly clearance $\delta = 0.6$ mm, insertion speed $v = 0.115$ m/s.

It was experimentally determined that chamfer crossing duration t_1 has a tendency to decrease when excitation amplitude A_2 is increasing (Fig. 5, a). This duration decreases more effectively under higher excitation frequency.

When excitation amplitude A_2 is increasing, duration t_2, from the beginning of insertion process until the beginning of two point contact stage, slightly decreases (Fig. 5, b), meanwhile two point contact stage duration t_{dtk} increases (Fig. 5, c). According to this, the conclusion could be made that when excitation amplitude A_2 is increasing, the two point contact appears as the peg is in lower depth. It is noticed, that wedging or jamming usually occurs when the two point contact appears in a small depth. Besides, the probability that the peg will jump out of the hole increases when the two point contact appears in a small depth, due to its uneven movement. Consequently, from the viewpoint of insertion reliability, it is more favorite to excite the bush by lower amplitude.

Dependences of total insertion process duration t_3 on excitation amplitude of the bush have a minimal value, independently on excitation frequency (Fig. 5, d). Under before-mentioned experiment conditions and excitation parameters this minimal value emerges when the excitation amplitude is approximately 0.75 mm. When excitation amplitude A_2 is increasing, insertion duration t_3 nonlinearly increases.

The character of the dependences of insertion process stages durations on excitation frequency is conditioned by excitation amplitude of the bush (Fig. 6). Time t_2, under lower (0.5 – 0.7 mm) excitation amplitudes, narrowly depends on excitation frequency (Fig. 6, a). When the bush is excited by 1.0 – 1.5 mm amplitudes, time t_2 has maximal value in excitation frequency interval 60 – 80 Hz. Two point contact stage duration t_{dtk} is higher also, when excitation amplitudes are higher (Fig. 6, b). Duration t_{dtk} is the lowest in frequency range f_2 = 50 – 70 Hz. Therefore, the two point contact appears in higher depth of the bush hole. Total insertion process duration t_3 depends both on excitation frequency and amplitude (Fig. 6, c). Insertion process is the longest when excitation amplitude is higher than 1.0 mm. Duration t_3 increases when the excitation frequency is increasing. Under lower excitation amplitudes, the highest insertion process duration is in excitation frequency range 60 – 90 Hz.

Dependences of the durations of insertion stages on initial axial misalignment of the peg and bush in lateral direction ε_0 were experimentally obtained under insertion speed v = 0.18 m/s. When initial axial misalignment ε_0 is increasing, chamfer crossing duration t_1 significantly increases (Fig. 7, a). Duration t_2, from the beginning of insertion process until the beginning of two point contact stage, increases when ε_0 is increasing, mainly due to increased chamfer crossing duration (Fig. 7, b).

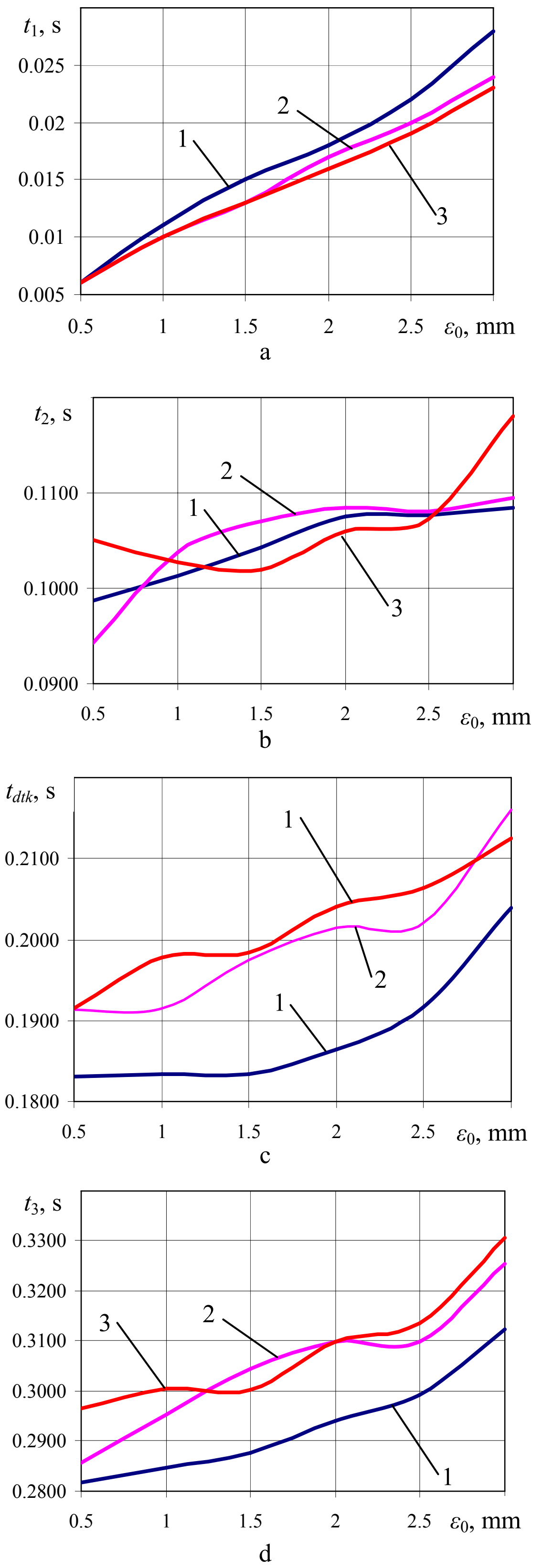


Fig. 7 Dependences of: a – chamfer crossing duration t_1; b – duration t_2, from the beginning of insertion process until the beginning of two point contact stage; c – two point contact stage duration t_{dtk}; d – insertion process duration t_3, on initial axial misalignment of the peg and the bush in lateral direction ε_0, *1* – without vibratory excitation; *2* – exciting vibrations the bush with the frequency f_2 = 70 Hz and amplitude A_2 = 1.0 mm; *3* – f_2 = 70 Hz, A_2 = 1.5 mm

When axial misalignment of the peg and the bush ε_0 is increasing, two point contact stage duration t_{dtk} increases (Fig. 7, c). Consequently, the two point contact appears in lower depth of the bush hole. Due to this, the probability of jamming, wedging and peg jumping out from the hole increases. So, the reliability of insertion process is decreasing.

Total insertion process duration t_3 increases also when initial axial misalignment ε_0 is increasing (Fig. 7, d). Under higher amplitude excitation, the insertion process duration t_3 increases more noticeably.

4. Conclusions

1. Dependences of durations of insertion process stages on insertion speed were experimentally determined. When the insertion speed is increasing, the insertion process duration significantly decreases.

2. The influence of excitation parameters on durations of insertion process stages was determined. When excitation amplitude A_2 is increasing, both chamfer crossing stage duration t_1 and duration t_2, from the beginning of insertion process until the beginning of two point contact stage, decrease. Two point contact stage duration t_{dtk} and total insertion process duration t_3 increase when the excitation amplitude is increasing.

3. When excitation frequency f_2 is increasing, durations of insertion process stages vary unevenly. It is possible to shorten total insertion process duration by selecting rational excitation frequency considering the value of excitation amplitude.

4. It was determined that from the viewpoint of insertion reliability, it is more favorable to excite lower amplitude vibrations of the bush.

5. Dependences of the durations of insertion stages on initial axial misalignment of the peg and the bush in lateral direction ε_0 were obtained experimentally. When initial axial misalignment ε_0 is increasing, the duration of chamfer crossing stage t_1, two point contact stage duration t_{dtk} and total insertion process duration t_3 increase. Also duration t_2, from the beginning of insertion process until the beginning of two point contact stage, increases mainly due to increased chamfer crossing duration. When ε_0 is increasing, the two point contact appears in a lower depth of the bush hole. Therefore, the reliability of insertion process is decreasing.

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ROBOTIZUOTO VIBRACINIO CILINDRINIŲ DETALIŲ SUJUNGIMO EKSPERIMENTINIS TYRIMAS

Reziumė

Straipsnyje eksperimentiškai nagrinėjamas strypo ir įvorės vibracinio sujungimo procesas. Strypas bazuojamas įtaise su nutolusio paslankumo centru ir robotu sujungiamas su ašine kryptimi žadinama standžiai bazuojama įvore, esant garantuotam sujungimo tarpeliui. Aprašytas eksperimentinis vibracinio robotizuoto rinkimo tyrimų stendas ir tyrimo metodika. Eksperimentiškai nustatytos sujungimo proceso etapų trukmės priklausomybės nuo sujungimo greičio, įvorės žadinimo parametrų. Gautos žadinimo parametrų vertės, kai detalių sujungimo procesas yra patikimas. Nustatyta jungiamųjų detalių pozicionavimo paklaidos įtaka sujungimo procesui ir jo patikimumui.

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EXPERIMENTAL INVESTIGATION OF CYLINDRICAL PARTS ROBOTIC VIBRATORY INSERTION

Summary

The process of peg insertion into a bush is experimentally analyzed in the paper. The peg, which is based in a remote center compliance device, is inserted into excited in axial direction immobile based bush, under guaranteed clearance by a robot. Experimental setup of robotic vibratory assembly and investigation methodology were presented. Dependences of the durations of insertion process stages on insertion speed and excitation parameters of the bush were experimentally determined. The values of excitation parameters, when insertion process is reliable, were obtained. The influence of positioning error of assembling parts on insertion process and its reliability was detected.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ВИБРАЦИОННОГО СОЕДИНЕНИЯ ЦИЛИНДРИЧЕСКИХ ДЕТАЛЕЙ ПРИ РОБОТИЗИРОВАННОЙ СБОРКЕ

Резюме

В статье рассматривается процесс вибрационного соединения стержня со втулкой. Стержень базируется в приспособлении с удаленным центром податливости и с помощью робота соединяется с неподвижно базируемой и в осевом направлении возбуждаемой втулкой в случае гарантированного зазора в соединении. Представлен экспериментальный стенд для исследования вибрационной роботизированной сборки и методика экспериментальных исследований. Экспериментально определены зависимости продолжительности этапов процесса соединения от скорости соединения и параметров вибрационного возбуждения втулки. Выявлены значения параметров возбуждения, обеспечивающие надежность процесса соединения. Определено влияние погрешности позиционирования соединяемых деталей на характер процесса соединения и его надежность.

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