338. Vibratory alignment of parts during robotized assembly

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Abstract. Paper deals with vibratory alignment of the components during robotized assembly as one of the parts is gripped by the robotic gripper and provided with vibratory excitation along the assembly direction. Numerical simulation of parts alignment was carried out. The dependencies of vibratory alignment duration on dynamic system and excitation parameters were determined. Existing areas of parameter sets, where reliable alignment is taking place, were defined.
Results of numerical simulation were verified experimentally. Obtained results of numerical simulation and experiments demonstrated that under properly chosen system and excitation parameters, vibratory method may be successfully applied in robotized assembly for peg-hole parts alignment.

Keywords: vibratory excitation, parts alignment, automated assembly.

Introduction

Automated assembly systems and devices play a significant role in manufacturing automation. They have direct impact on the production quality and efficiency. Statistical analysis of different branches of industry shows that assembly operations consume 20 to 60% in overall production time and costs. Nowadays, parts assembly automation by robots has a much wider range of application in different branches of industry. This helps to reduce inefficient handwork in manufacturing operations and assemble the parts of different shape and dimensions, including miniaturized mechanical, electronic and other components.

Main problem of robotized assembly is interdependent alignment of the connective surfaces of the parts. To align the parts being assembled it is necessary to eliminate linear and angular part-to-part location errors in assembly position. Because of mentioned errors robotized assembly may be unsuccessful, assembled parts or even the robot may be damaged due to induced large contact forces [1]. For performing part alignment and joining with a robot, it is necessary to match the part, picked by the manipulator into assembly position, with mating part that is immovably based in assembly position. Different versions of robotized assembly are investigated in scientific papers, as manipulator not only picks the part into assembly position, but also is able to perform some rotation of the part following the instruction of the control program [2]. Parts assembly by two manipulators is more flexible and may be accomplished fixing the components in robot gripper [3], but interdependent position of the parts is controlled by means of information from sensors. The operations of parts alignment and assembly may fail due to insufficient accuracy, repeatability or resolution of the robot manipulator [4]. Robotized assembly often involves complex control systems and mechanisms, uses information from different sensors and, consequently, this may be the source of errors.

Having objective to increase efficiency of the assembly processes, significant amount of research have been done related to the application of vibrations for automated assembly [5]. An analytical and experimental investigation of parts' mating aided by two orthogonal constant amplitude sinusoidal motions is analyzed in [6].

The interdependent vibratory alignment of circular or rectangular cross-section parts during robotized assembly is analyzed in this paper, as one of the aligned parts is movably based and subjected to low frequency excitation along the assembly axis. To base the part movably special gripper is used, which is attached to the robot arm. Vibrator that is mounted in the gripper provides excitation to the fixed part. Applying vibratory alignment, there are no stringent accuracy requirements for initial location of the components in assembly position. Therefore, it is possible to use low accuracy robots. Furthermore, the positioning of the grasped by the robot gripper part needs no sensors, feedback systems or control algorithms, as mating parts got aligned because of vibratory action. Reaction forces, arising at contact points of the components, provide assistance in matching of the parts' connective surfaces and assure unhindered assembly [7].

Scheme of robotized assembly and dynamic model of vibratory alignment

Case of robotized assembly is under consideration, as parts are picked into assembly by the robot (Fig.1). Movably based part *6* is grasped by a gripper *5*, which through the resilient elements of gripper holder *4* is attached to a robot arm *1*. Mating part *7* is immovably based in assembly position. Due to existing positioning errors of the robot manipulator, parts' location and other errors axes of the parts in assembly position are displaced by a particular value Δ. Under existing axial misalignment of the parts, movably-based part, which is approached and pressed with a predetermined force, is tilted with respect to the immovably-based part *7* and takes the position of stable equilibrium. An asymmetry of the forces in the mechanical system is predetermined by the turn of part *6* due to deformation of resilient elements, whereas kinematic asymmetry – due to vibratory excitation of the tilted part. Excitation is along the assembly direction, providing vibrations to the gripper holder *4* and so, through the resilient elements, gripped part *6* is subjected to excitation. Therefore, depending on excitation law and vibration trajectory, directional vibratory displacement and turn of the movably based part occurs, which predetermines matching of the contours of connective surfaces, orientation and unhindered assembly of the parts.

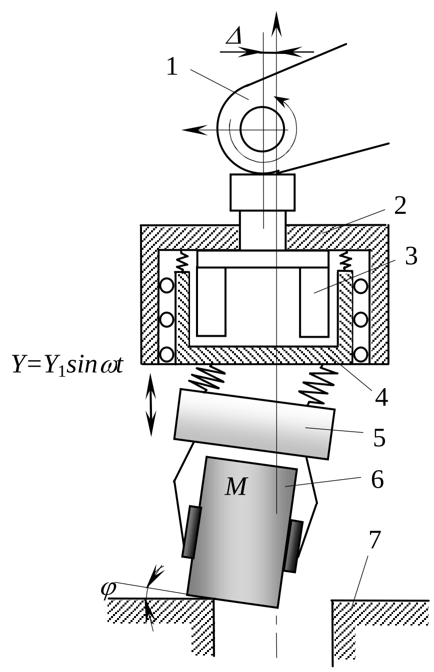


Fig. 1. Scheme of robotized assembly: 1 – robot arm; 2 – platform of electromagnetic vibrator; 3 – electromagnet; 4 – gripper holder; 5 – gripper; 6 – shaft; 7 – bushing

Dynamic model for vibratory alignment of the parts (Fig.2) is presented as 3D system, consisting of a grasped by the gripper *M* mass body, representing movably-based shaft *6*, and immovable base with a slot, associated with a coordinate frame *X*0*Y*, representing immovably-based connective part (bushing) *7*.

The shaft, picked into assembly position by the robot manipulator, has ability to displace along the *X*, *Y* axes and turn with respect of the *Y* axis. Position of the shaft, attached to vibrator through the resilient elements, in respect of the bushing, is characterized by the coordinates X_C, Y_C of inertia center point *C* and turn angle φ. Resting on a solid base immovably based part (bushing) is in assembly position.

At initial moment of the alignment process contours of the connective surfaces of the shaft and the bushing are misaligned. Pressed to the surface of the bushing, the shaft is tilted in respect of the immovably based bushing ($\varphi \neq 0$).

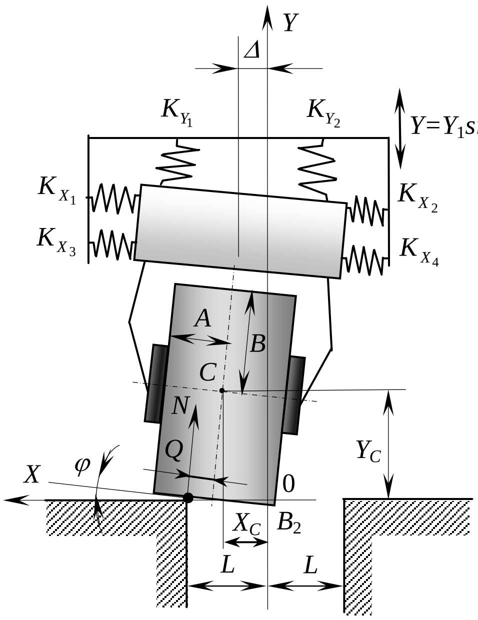


Fig. 2. Dynamic model of vibratory alignment

To align the parts, it is necessary to perform both the displacement of the shaft, in respect to the hole of the bushing, and turn so that directions of the axes would coincide. Fixed-in gripper shaft is provided with vibratory action along the assembly direction by means of the vibrator and through the resilient elements. Thus directional displacement and changing during that displacement turn of the shaft occurs, depending both on the stiffness of resilient elements and pressing force, so predetermining alignment of the assembled parts.

Applying d'Alambert principle, the equations of motion of the movable body in contact with the immovable base, in dimensionless form, may be written as follows:

$$\left.\begin{aligned} &U_1 n - h_x \dot{x}_c - k_x\left(x_c - x_{st}\right) - \ddot{x}_c = 0; \\ &U_2 n - h_y \dot{y}_c - y_c - \ddot{y}_c - f_0 = sin\nu\tau; \\ &U_3 n - h_\varphi \dot{\varphi} - k_\varphi\left(\varphi - \varphi_{st}\right) - I\ddot{\varphi} = 0. \end{aligned}\right\} \quad (1)$$

where $U_1 = sin\,\varphi - \mu\, cos\,\varphi;\ U_2 = cos\,\varphi + \mu\, sin\,\varphi;\ \mu$ is coefficient of friction; φ is tilt angle; $U_3 = Q + \mu B$ (Fig. 2); $I\ddot{\varphi}$ is rotation-preventing moment about mass centre C. The following non-dimensional parameters have been introduced:

$$\begin{aligned}
&\tau = pt;\ ^{\bullet} = d/dt;\ p^2 = K_Y/M;\ \nu = \omega/p;\ x_c = K_Y X_C/F_1;\\
&y_c = K_y Y_C/F_1;\ l = K_Y L/F_1;\ a = K_Y A/F_1;\ b = K_Y B/F_1;\\
&I_\varphi = (I/M)/(K_Y/F_1)^2;\ h_x = H_X\big/\sqrt{K_Y M};\ h_y = H_Y\big/\sqrt{K_Y M};\\
&h_\varphi = H_\varphi\left(p^3 M/F_1^2\right);\ k_x = K_X/K_Y;\ k_\varphi = K_\varphi K_Y/F_1^2;\\
&f_0 = F_0/F_1;\ n = N/F_1;\ q = K_Y Q/F_1 = \frac{l - x_c}{cos\,\varphi} - btg\varphi.
\end{aligned} \quad (2)$$

where τ is time; $F_0 = Mg$ is gravity force; $F_1 = K_Y Y(t)$; H_X, H_Y, H_φ are damping coefficients; K_X, K_Y, K_φ are stiffness coefficients, $K_X = K_{X_1} + K_{X_2} + K_{X_3} + K_{X_4}$, $K_Y = K_{Y_1} + K_{Y_2}$ (Fig.2); $X_{st}, Y_{st}, \varphi_{st}$ are coordinates of the static equilibrium position; N is normal force.

Modeling of parts alignment

Based on formed dynamic model of parts alignment and motion equations of part contacting with the base (Eq. 1), MATLAB code was written for peg-in-hole type parts alignment investigation. Geometrical contact conditions of the movably-based part and immovable base have been derived from equations of the lines through the points B_1B_2, B_2D_2 and B_1D_1 (Fig. 2), expressed via coordinates of these points, the coordinates of inertia centre C and φ angle, and taking into account geometry of the parts under alignment. Applying geometric contact conditions of the parts and stiffness and damping parameters of the movably based part and the base, reaction N, arising at contact point, was calculated. The characteristics of vibratory displacement and influence of different parameters on the alignment process were modeled varying the parameters of dynamic system and excitation.

By modeling results the dependencies of parts alignment duration on initial pressing force, the coefficient of friction, assembly clearance, on the parameter evaluating angular stiffness and also on excitation parameters were defined.

Under the marginal initial pressing force (<2) and small angular stiffness ($k_\varphi = 5...7$), directional displacement and turn of the movably based part runs more slowly (Fig. 3, a). Here δ is joining clearance, defined as:

$$\delta = \frac{L - A}{A}$$

where A is half-width of the insertable part; L is half-width of the slot (Fig. 2).

Increasing the initial pressing force, alignment duration diminishes. Under bigger values of the parameter k_φ ($k_\varphi = 10...20$) and marginal initial pressing force (<2), duration of the parts alignment diminishes. Further increasing the pressing force, alignment duration initially increases, but later diminishes.

The dependencies of duration of parts alignment on friction between the parts in contact under different values of the pressing force f_0, are presented in Fig.3, b. Having small values of the friction coefficient μ, alignment duration τ increases more rapidly in comparison with case when the coefficient has higher values.

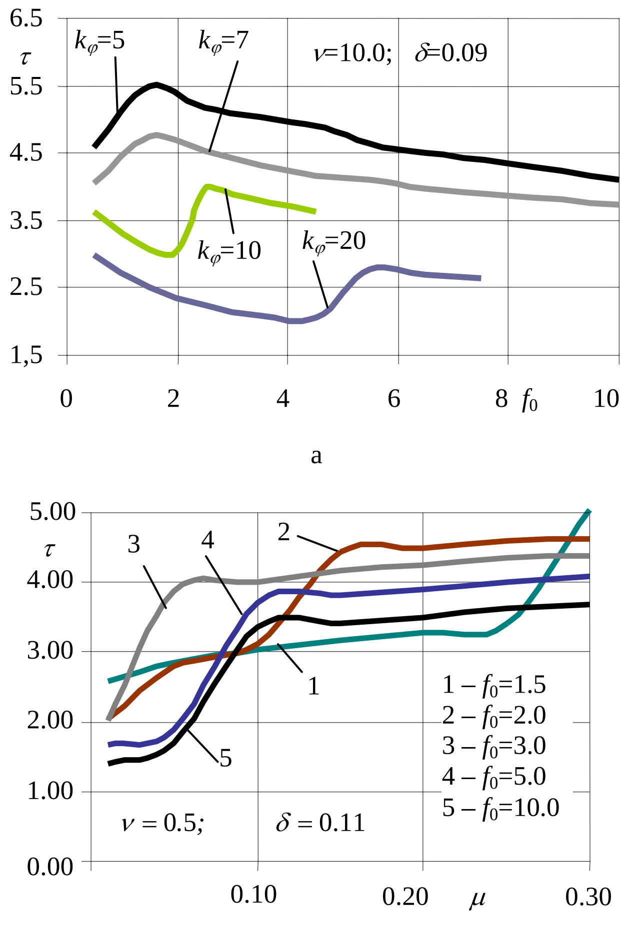
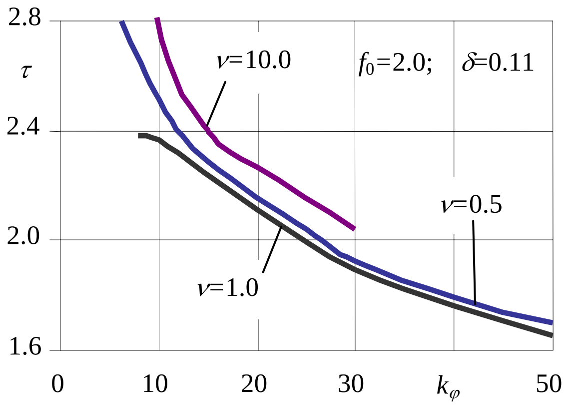
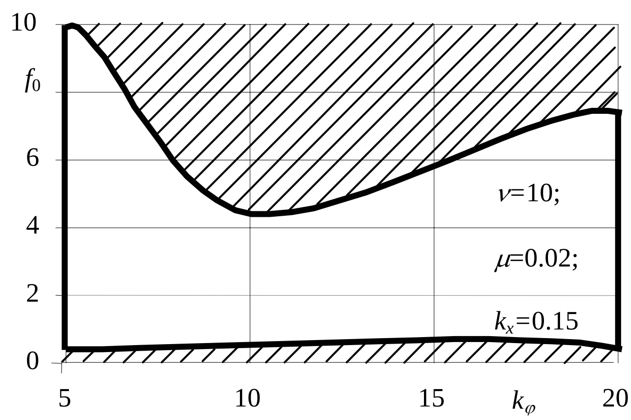


Fig. 3. Dependencies of parts alignment duration on: a – initial pressing force f_0; b – friction coefficient μ

Under acting pressing force f_0 of particular value and small values of angular stiffness parameter k_φ (Fig. 4, a), movably-based part is able to turn relative to the immovably-based part by such an angle that parts alignment does not occur. Under bigger values of parameter k_φ, the component has less possibility to turn. If the action, which causes directional displacement, overcomes the influence of friction and restoring elastic forces, matching of the components may occur. When the forces, those predetermine directional displacement and turn, are in equilibrium with resistance forces, matching becomes impossible. Kinematic excitation frequency ν has influence on the process of parts alignment. If $\nu \le 10$, reliable alignment of the parts takes place within a wider range of values of the angular stiffness parameter k_φ, than under higher frequency ($\nu > 10$). Based on modeling results an area (Fig. 4, b) of the stable alignment of the parts was defined. Properly chosen and matched parameters of dynamic system and excitation ensure reliable alignment of the parts.



a



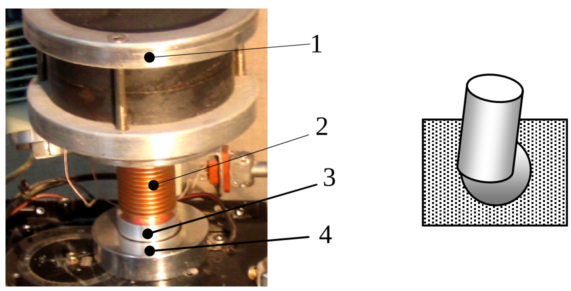
b

Fig. 4. Dependencies of parts alignment duration τ on parameter k_φ (a); defined area of stable alignment of the parts (unhatched) depending on parameters k_φ and f_0 (b)

Experimental investigation of parts alignment

Experiments were carried out with the objective to verify developed mathematical model of vibratory alignment [8]. To investigate parts alignment, experimental setup was made (Fig. 5), consisting of electromagnetic vibrator *1*, resilient element *2*, with cylindrical or rectangular cross-section part *3* attached. Mating part *4* was fixed in locating device, where a photodiode, used to fix start/end state of the components alignment, was mounted. The photodiode through a resistance was connected to oscilloscope, which transforms analog signal into a digital and displays it on computer screen. The experiments have been carried out performing vibratory alignment of cylindrical and rectangular cross-section chamferless parts under 1 mm assembly clearance. Pressing force F_0 was varied in the range 0.5…3 N, the amplitude A of excitation frequency varied within the range 0.5…1.5 mm, excitation frequency was 50…100 Hz; parts axial misalignment Δ was 0.5…2.5 mm.

Initially pressed towards the bushing by predetermined magnitude force the shaft is misaligned and due to resilient element is tilted relative to the bushing axis. In such way advantageous conditions are set for elastic restoring moment appearance and parts surfaces matching.



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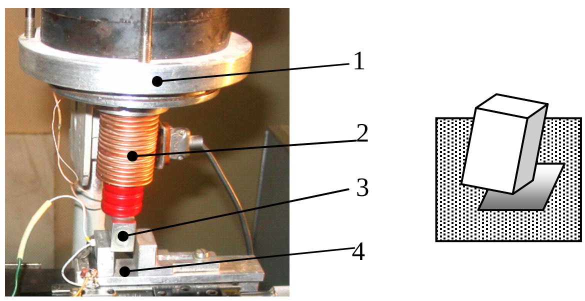

b

Fig. 5. Experimental setup for cylindrical (a) and rectangular cross-section (b) parts alignment

Within frequency range 50...60 Hz, the process of alignment is unstable (Fig. 6), has relatively long duration (~300 ms to 3 s). At excitation frequency 60…80 Hz, alignment is successful and is of short duration (70...100 ms). Similar character of the alignment was noticed investigating alignment of cylindrical parts. When excitation frequency is higher than 90 Hz, due to intensive vibrations of resilient element and the shaft attached, the duration of alignment significantly increases.

The turn angle of the movably-based part and also the alignment duration are predetermined by initial pressing force F_0, which must be selected so that could force the movably-based part to move towards the mating part. As

$F_0 = 1\ldots1.5$ N, alignment of the parts is stable and has short duration. When $F_0 > 2$ N, alignment process is unstable with repeated cases of alignment failure and significantly increased duration.

When axial misalignment of the components is Δ=1÷2 mm, alignment duration is very short and under different values of the initial pressing force F_0 differs negligibly, as axial misalignment further increases, alignment duration significantly increases.

The areas of parameter sets have been determined, where alignment of the parts goes reliable and stable (Fig. 7).

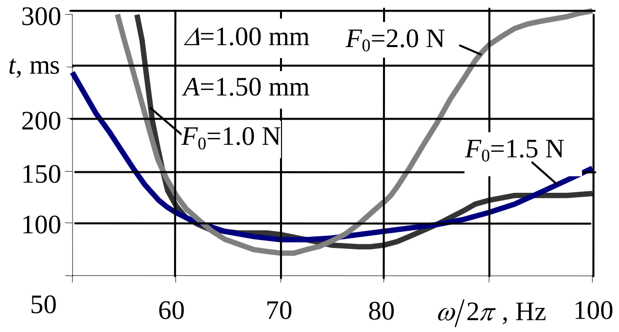

Fig. 6. Dependence of rectangular parts alignment duration t versus excitation frequency

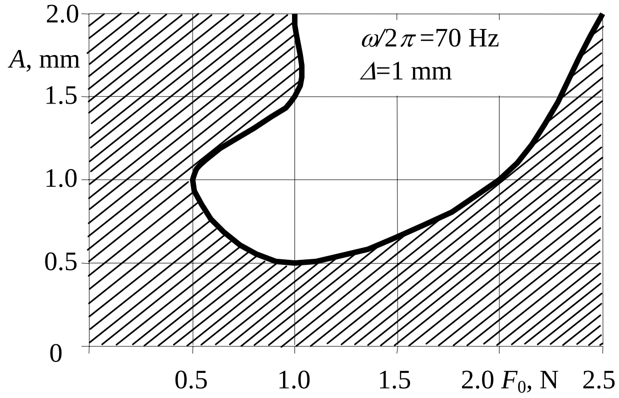

Fig. 7. Area of stable alignment of rectangular cross-section parts (unhatched) depending on excitation amplitude and initial pressing force

Properly matched system and excitation parameters enable reliable and fast alignment of the cylindrical and rectangular cross-section parts as positioning error is up to a few millimeters.

Conclusions

1. Modeling results revealed that more advantageous conditions for parts alignment are as initial pressing force $f_0 \le 10$, friction coefficient $\mu = 0.1...0.3$. The dependencies of alignment duration on assembly clearance under different friction coefficients are of similar character – increasing friction coefficient, assembly duration increases. The influence of angular stiffness on parts alignment also depends on the initial pressing force.

2. At smaller values of excitation frequency ν, alignment runs in a much wider range of values of angular stiffness k_φ. Increasing the excitation frequency, alignment duration also increases.

3. The areas of parameter sets have been determined, where vibratory alignment goes stable. The initial pressing force, angular stiffness and excitation frequency have major influence on stable alignment areas.

4. Performed experiments verified that properly matched parameters of dynamic system and excitation provide possibility for reliable peg-hole-type alignment of the parts during robotized assembly. Experimentally obtained alignment duration dependencies on excitation frequency, amplitude and initial pressing force provided qualitative verification of modeling results.

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