106. Vibratory positioning of automatically assembled parts

B. Bakšys, N. Puodžiūnienė
Kaunas University of Technology, Lithuania

The Journal was received on 15 June 2001 and was accepted for publication on 27 July 2001.

1. Introduction

Assembly is a final stage of product manufacturing. It has an influence on all technological process, starting from the production of bank part and finishing with the control tests of the product. On average the assembly takes about 53% of the production time and amounts to 10-30% of the total product manufacturing costs in the industry of agricultural mechanisms and telecommunications equipment [1]. To decrease total production costs, improve working conditions, improve efficiency, decrease product cost the new assembly methods and technologies are used. One of the more serious obstacles for assembly automation is that oftentimes products are not designed for assembly.

In assembly automation substantial attention must be devoted to product construction and manufacturing principles. Product construction, its degree of precision, weight, size of connecting parts will have an influence on design procedure of automatic assembly equipment. About 80% of manufacturing cost is determined at the stage of design, thus project design should be given an adequate attention. The project must be designed for the automatic assembly from the very beginning. The purpose of such design should be to simplify product manufacturing and assembly. Equipment and devices of automatic assembly perform main and auxiliary operations: preliminary orientation of connecting parts, part feeding into the assembly zone, fastening, transportation and removing. These operations are facilitated by part design for automatic assembly. This is an iterational design procedure, the purpose of which is to simplify assembly operations ensuring assembly efficiency and high product quality. Parts must be simply automatically oriented, stable and simply fastened and transported. Main principles of part design for assembly: to simplify feeding and to decrease re-orientation of the connecting parts. For this purpose the parts assembled are based movably, so they could orient themselves, chamfers are used, a number of movable parts of the assembly unit is decreased, and the similar parts are standartized.

The most important assembly problem is orientation of the connecting parts and directional matching of their surfaces before assembly. The process of assembly is dependent on surface matching. In the devices of the automatic assembly, when the classic matching methods are used, it is not always possible to ensure sufficiently precise matching. Using automatic vibrational assembly with correctly selected system and excitement parameters it is possible to reliably orient parts among themselves and to connect them without difficulties, even when parts are without chamfers. In this case connecting surfaces of the parts are matched due to vibrational displacement of the movably based part. This displacement is in the direction of diminution of the error of the interdependent position of the connecting parts. Application of the vibrational body displacement to the automatic assembly was examined in [2,3] publications.

2. Dynamic Model and Equations of Motion

The vibratory displacement of a body on an inclined plane as used in automatic assembling irrespective of the angular bend in respect of a rigidly based part is analysed in work [4]. This work is devoted to the vibratory displacement of a movingly based part by a plane movement in non - impact regime which entrusts the orientation of the assembled parts with respect to each other when a rigidly based part is excited in two perpendicular directions.

The dynamic model (Fig. 1), permitting to investigate the displacement and bend of a movingly based part consists of a body of mass M, with elastic and damping elements, representing the movingly based part, and an immovable support with a slit, representing a rigidly based part related to the system of co - ordinates XOY. The body is rectangular and its centre of inertia is in the point (X_C, Y_C). The co - ordinates of this point and the turn angle φ determine the position of the body in respect to the locating element.

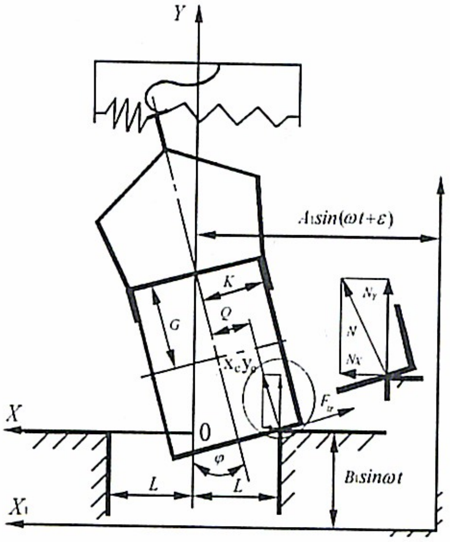

Fig. 1. Model of Dynamic Vibratory Displacement

Before connecting the parts, which are fastened in locating elements, are pressed to each other by a predetermined force. When in the position of assembling the axes of the parts do not coincide, in the process of pressing one part to the other elastic elements get deformed and the movingly based part turns by an angle in respect to the rigidly based part. In directions of axes X_1 and Y_1 perpendicular harmonic vibrations of the same frequency ω $X_1 = A_1 \sin(\omega t + \varepsilon)$ and $Y_1 = B_1 \sin \omega t$ are applied. Due to the vibratory excitement the body fulfils directional movement in the direction of X axes and turns in respect to locating element. Thus the connected parts are orientated in respect to each other. Having the aim to connect the parts without difficulties the condition $Q = L/\cos\varphi$ should be satisfied.

The equations of movement of a body of mass M contacting with the locating element

$$\left.\begin{aligned}
&M\ddot{X}_C + H_X\dot{X}_C + C_X(X_C - X_{st}) = -M\ddot{X}_1 + N\sin\varphi - F_{tr}\cos\varphi\\
&M\ddot{Y}_C + Hy\dot{Y}_C + Cy(Y_C - Y_{st}) = -M\ddot{Y}_1 + N\cos\varphi + F_{tr}\sin\varphi - P_0\\
&I\ddot{\varphi} + H_\varphi\dot{\varphi} + C_\varphi(\varphi - \varphi_{st}) = N(Q + Gf)
\end{aligned}\right\} \quad (1)$$

where X_{st}, Y_{st}, φ_{st} are co - ordinates of the position of static equilibrium; H_x, H_y, H_φ are damping coefficients; C_x, C_y, C_φ are stiffness coefficients; f is the rate of sliding friction; $\bullet = d/dt$; P_0 is gravity; N is the force of normal pressing of the body to the locating element.

The force of dry friction F_{tr} is expressed in the following dependencies

$$F_{tr} = \begin{cases} +fN, & \text{when } V < 0\\ -fN, & \text{when } V > 0\\ (-1,+1)fN, & \text{when } V = 0 \end{cases}$$

where $V = \dot{X}_C\cos\varphi + \dot{Y}_C\sin\varphi + G\dot{\varphi}$ is the speed of the body sliding on the support.

By substituting the meanings of $\ddot{X}_1$ and $\ddot{Y}_1$ into equations (1), we shall have

$$\left.\begin{aligned}
&M\ddot{X}_C + H_X\dot{X}_C + C_X X_C = MA_1\omega^2\sin(\omega t + \varepsilon) +\\
&+ N(\sin\varphi \mp f\cos\varphi) + C_x X_{st}\\
&M\ddot{Y}_C + H_Y\dot{Y}_C + C_Y Y_C = MB_1\omega^2\sin\omega t +\\
&+ N(\cos\varphi \mp f\sin\varphi) - P_0 + C_y Y_{st}\\
&I\ddot{\varphi} + H_\varphi\dot{\varphi} + C_\varphi\varphi = N(Q + Gf) + C_\varphi\varphi_{st}
\end{aligned}\right\} \quad (2)$$

where A_1 and B_1 are amplitudes of vibrations; ε is the phase of displacement between the components of perpendicular vibrations.

Under the regime of non - impact movement the body contacts with the support. Thus the co - ordinate of mass centre Y_C may slightly change only with the change of turn angle φ of body. As such an angle is small, the change of Y_C may be left without attention. The second equation of the system (2) is used for the calculation of normal force of pressure. Under the regime of non - impact movement the body contacts with the locating element. Thus the co - ordinate of mass centre Y_C may slightly change only with the change of turn angle φ of the body.

As such an angle is small, the change of Y_C may be neglected. The second equation of the system (2) is used for the calculation of normal pressing force.

$$N = \left(P_0 - C_Y Y_{st} - MB_1\omega^2\sin\omega t\right)/\left(\cos\varphi \mp f\sin\varphi\right) \quad (3)$$

By substituting the expression (3) into the equations one and three of system (2) we shall receive the equations of displacement of a body on locating element

$$\left.\begin{aligned}
&M\ddot{X}_C + H_X\dot{X}_C + C_X X_C = MA_1\omega^2\sin(\omega t + \varepsilon) +\\
&+ \left(P_0 - C_y Y_{st} - MB_1\omega^2\sin\omega t\right)\frac{\sin\varphi \mp f\cos\varphi}{\cos\varphi \mp f\sin\varphi} + C_x X_{st}\\
&I\ddot{\varphi} + H_\varphi\dot{\varphi} + C_\varphi\varphi = \left(P_0 - C_Y Y_{st} - MB_1\omega^2\sin\omega t\right)\times\\
&\times\frac{Q + Gf}{\cos\varphi \mp f\sin\varphi} + C_\varphi\varphi_{st}
\end{aligned}\right\} \quad (4)$$

The dimensionless quantities are substituted and the equations are written down in a dimensionless form

$$\nu = \frac{\omega}{p};\ \nu_x = \frac{C_x}{C_y};\ h_x = \frac{H_x}{\sqrt{C_y M}};\ a_1 = \frac{A_1 C_y}{P_0};\ b_1 = \frac{B_1 C_y}{P_0};$$

$$\mu_\varphi = \frac{I}{M}\left(\frac{C_y}{P_0}\right)^2; \quad h_\varphi = \frac{p^3 M}{P_0^{\,2}}H_\varphi; \quad \nu_\varphi = \frac{C_\varphi C_y}{P_0^{\,2}};$$

$$q = \frac{C_y}{P_0}Q = \frac{l + x_c}{\cos\varphi} - g\,tg\,\varphi; \quad l = \frac{C_y}{P_0}L; \quad g = \frac{C_y}{P_0}G$$

$$\left.\begin{aligned}
&x_c'' + h_x x' + \nu_x x_c = \nu^2 a_1\sin(\nu\tau + \varepsilon) +\\
&+ \left(1 - y_{st} - \nu^2 b_1^{\,2}\sin\nu\tau\right)\frac{\sin\varphi \mp f\cos\varphi}{\cos\varphi \mp f\sin\varphi} + \nu_x x_{st}\\
&\mu_\varphi\varphi'' + h_\varphi\varphi' + \nu_\varphi\varphi = \left(1 - y_{st} - \nu^2 b_1^{\,2}\sin\nu\tau\right)\times\\
&\times\frac{q + gf}{\cos\varphi \mp f\sin\varphi} + \nu_\varphi\varphi_{st}
\end{aligned}\right\} \quad (5)$$

The characteristics to describe non - impact vibratory displacement of a body by plane movement are set up by solving equations (5) by a numerical method.

3. Modeling the Vibratory Displacement of a Body

One of the most significant characteristics qualifying the automatic assembling process is time when elastically based part moves from an initial position to the position in which it is totally orientated in respect to the other part, their connecting surfaces are matched and the parts are connected without difficulties. The error of the interposition of connecting parts in the initial moment is determined by the co - ordinate x_C of the inertia centre of the body, which is usually negative. This co - ordinate and the angle φ of turn of the body change in the process of vibratory displacement (Fig. 2, 3). The character of their change is predetermined by the intensity of vibratory excitement, the rigidity of elastically based elements, initial pressing force.

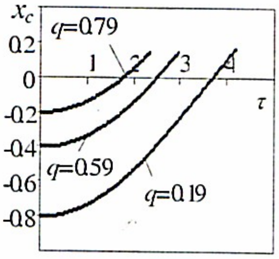

Fig. 2. Graphs $x_c(\tau)$

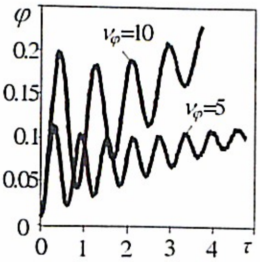

Fig. 3. Graphs $\varphi(\tau)$

Vibratory automatic assembly needs directional vibratory displacement and turning for the reason of which the connected parts are orientated in respect to each other and the error in their interposition in the position of assembling is eliminated. But under relevant parameters of the system and excitement the body vibrates about the state of static equilibrium and there is no directional vibratory displacement. Thus automatically the parts may be assembled when the error of their interposition is not more than the amplitude of vibrations of the body about the position of static equilibrium (Fig. 4).

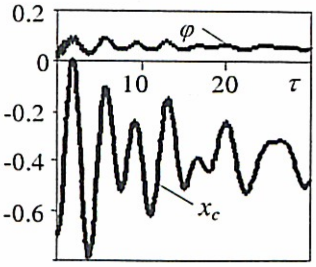

Fig. 4. Graphs $x_c(\tau)$ and $\varphi(\tau)$

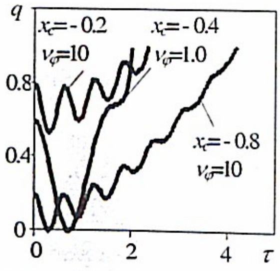

Fig. 5. Graphs $q(\tau)$

The position of contact point of the body and locating element in respect to the centre of inertia of the body is determined by the parameter q. As the body moves towards the matching direction, the parameter q grows. But when stiffness coefficient of turning is small, the parameter of displacement q at the beginning of displacement diminishes (Fig. 5). This means that the body at the beginning moves to the opposite direction as compared with matching direction of connected surfaces. Then a quick growth of the parameter q commences and reaches the set up value when the angle φ of turn of the body is big. In this position the connected surfaces may not be matched though the body has moved the set up distance. In modeling it was considered that the parts may be connected provided that the condition $q = {}^{1}\!/_{\cos\varphi}$ was followed.

The duration and character of the vibratory displacement depends on the frequency of excitement ν, the coefficients of elastic force of resistance and the moment ν_x, and ν_φ. The coefficients ν_x, and ν_φ depend on the rigidity of elastic elements of the locating element. With the growth of stiffness coefficient of turn the time of matching grows (Fig. 6). The range of change of turn angle of elastically based body in respect to the rigidly based part depends on the parameter ν_φ. When the values of the coefficient are small (ν_φ <5) elastically based body at the end of matching bends in respect to the support by a big angle (Fig. 7). Then the conditions for connecting become worse as it is impossible to insert into a hole the body, which is inclined with a big angle.

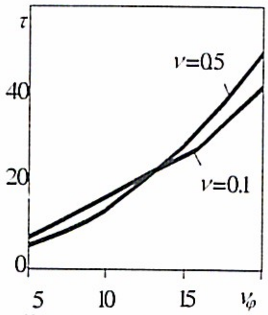

Fig. 6. Graphs $\tau(\nu_\varphi)$

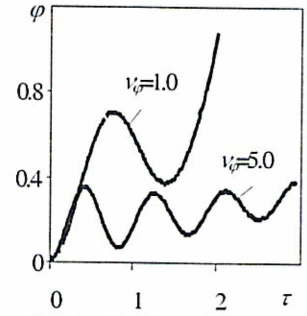

Fig. 7. Graphs $\varphi(\tau)$

As the parts are excited with higher frequency vibrations ν, the time of matching of the parts becomes shorter (Fig. 8). Then in their contact zones the frequency of the component of the motive force of normal pressing grows and the process of matching is more intensive. For shortening the time of the parts matching in case of higher rigidity of turn, the process of exciting should be achieved by the vibrations of higher frequency.

Due to increasing of the coefficient of the elastic resistance force ν_x, the time of matching grows (Fig. 9). When the coefficient ν_x, grows to such a level when the elastic force of resistance in the direction x exceeds the motive force, the connected surfaces of the parts may not be matched and automatic connection is impossible.

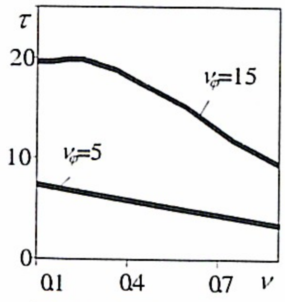

Fig. 8. Graphs $\tau(\nu)$

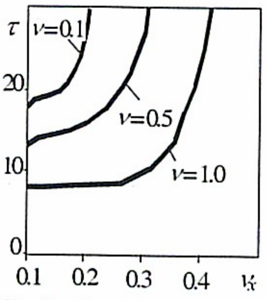

Fig. 9. Graphs $\tau(\nu_x)$

The value of friction coefficient f depends on the material of assembled parts and the quality of processing of their contact surfaces. The dependence of the duration of matching on friction coefficient f has a vividly expressed extreme (Fig. 10) the position of which in respect to f depends on stiffness coefficient of turn ν_φ. In design process of vibratory assembling devices the construction of elastic elements, having on influence on stiffness coefficient of turn, should be chosen to permit the shortest duration of matching.

The phase angle between the components of perpendicular vibrations characterize the turn of symmetrical axes of ellipsis trajectory in respect to co - ordinate axes. The influence of this angle on duration of the parts matching is shown in Fig. 11. When $\varepsilon = 0$, the parts are matched in the shortest period of time. In this case the ellipsis becomes a segment of the line inclined by the angle $\pi/4$ in respect to the axis x. In choosing bigger amplitude of the excitement of vibrations b_1, towards the direction y, you may shorten the time parts matching.

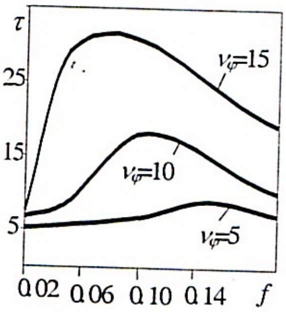

Fig. 10. Graphs $\tau(f)$

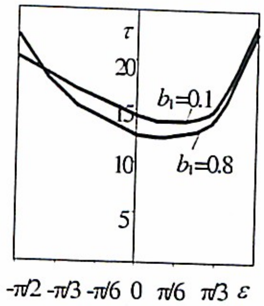

Fig. 11. Graphs $\tau(\varepsilon)$

Due to the increase of damping coefficient h_x the time of matching of the parts grows (Fig. 12).

For the movingly based part to move under the influence of vibrations an initial stretching-frame should be formed between connected parts – they must be pressed to each other by using a predetermined force. While pressing the parts the elastic locating elements are deformed and the movingly based part inclines and the centre of mass moves into the direction x. The initial pressing force is proportional to the parameter y_{st} and the initial turn and displacement is characterized by φ_{st} and x_{st}. With the growth of primary stretching-frame characterized by co - ordinate y_{st} the duration of assembling grows (Fig. 13).

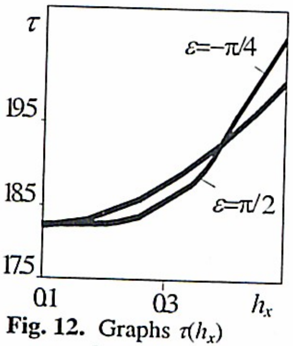

Fig. 12. Graphs $\tau(h_x)$

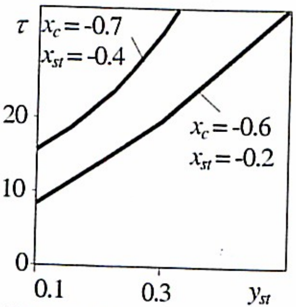

Fig. 13. Graphs $\tau(y_{st})$

The duration of matching of the surfaces of connected parts and vibratory assembling depends on average speed of displacement of the body and is calculated by the equation

$$\dot{\xi}_{vid} = \frac{l/\cos\varphi - q_{pr}}{\tau} \tag{6}$$

where l is the dimension of the slit of rigidly based part; q_{pr} is the initial meaning of the parameter setting up the position of the body and contact point of locating element in respect to the centre of inertia of the body displacement; τ is the time of matching of the parts.

Due to increase of the values of the parameter ν_x the average speed of displacement decreases and the duration of assembling grows (Fig. 14). The average speed grows when higher frequency vibrations are used for excitement (Fig. 15) and the values of stiffness coefficient of turn are lower.

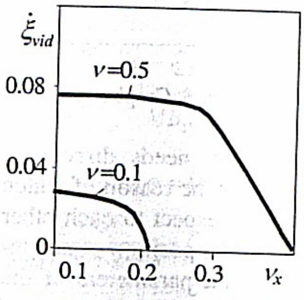

Fig. 14. Graphs $\dot{\xi}_{vid}(\nu_x)$

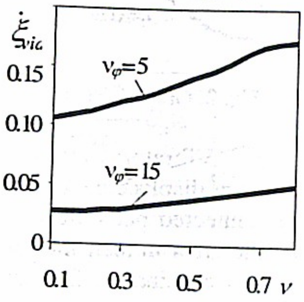

Fig. 15. Graphs $\dot{\xi}_{vid}(\nu)$

The influence of phase angle between the components of perpendicular vibrations on average speed is not big. In case of small amplitudes of vibrations in the direction x the average speed is almost constant. When the amplitude of vibrations $a_1 = 0.8$, the highest average speed will be achieved when $\varepsilon = \pi/2$. Then the axes of symmetry of the elliptical trajectory coincide with the axes of co - ordinates and the elliptical trajectory becomes a circle (Fig. 16).

The average speed is highly influenced by friction coefficient (Fig. 17). There the minimum of the function $\dot{\xi}_{vid}(f)$ exists. When the values of the parameter f are small, the change of average speed is quick. Beyond the point of minimum, in a relevant interval of change of f, the $\dot{\xi}_{vid}(f)$ will grow. Later on, with the growth of f the speed will fall down.

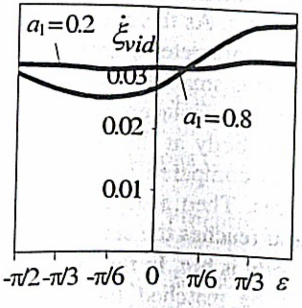

Fig. 16. Graphs $\dot{\xi}_{vid}(\varepsilon)$

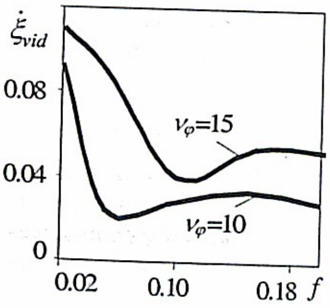

Fig. 17. Graphs $\dot{\xi}_{vid}(f)$

In the process of the investigation it was determined that the vibratory displacement takes place only under relevant combinations of the parameters of the system and excitement. The main spheres of the combinations of the system and excitement permit to choose the most rational construction and excitement parameters of a vibratory automatic assembling device. Fig. 18-21 (hatched) show the spheres of the most essential parameters when the vibratory displacement and assembling take place. The below graphs are drawn up when the values of parameters are as follows

Fig.18 - $x_{st} = -0.2$, $x_c = -0.5$, $f = 0.08$; Fig.19 - $x_{st} = -0.4$, $x_c = -0.7$, $f = 0.02$; Fig.20 - $x_{st} = -0.4$, $x_c = -0.7$, $f = 0.1$; Fig.21 - $x_{st} = -0.4$, $x_c = -0.7$.

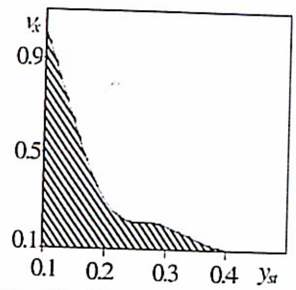

Fig. 18. The sphere of parameters ν_x -y_{st} combinations when vibrational displacement occurs

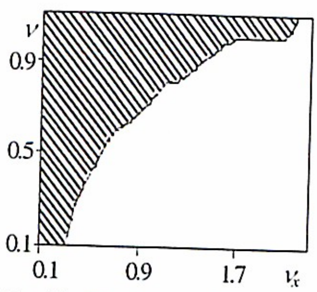

Fig. 19. The sphere of parameters ν-ν_x combinations when vibrational displacement occurs

When the values of combinations of the parameters are taken from non hatched sphere, the body vibrates about the position of static equilibrium or the vibratory displacement is not enough for matching of the connected surfaces and joining of the parts. In case of bigger values of the parameter of initial interference y_{st} the parts may be matched when the stiffness coefficient of locating element in the direction x is lower (Fig. 18). If you wish to assemble under a bigger stiffness coefficient, you must choose a higher frequency of excitement (Fig. 19). Similar is the dependence of parameters ν and y_{st} (Fig. 20). With the growth of friction coefficient and stiffness coefficient ν_x the sphere of combinations of these parameters, when it is still possible to match the parts, becomes more narrow (Fig. 21).

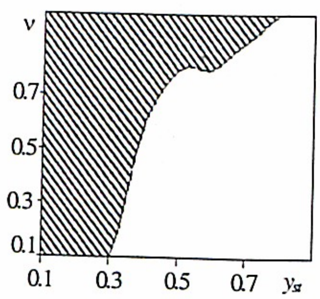

Fig. 20. The sphere of parameters ν-y_{st} combinations when vibrational displacement occurs

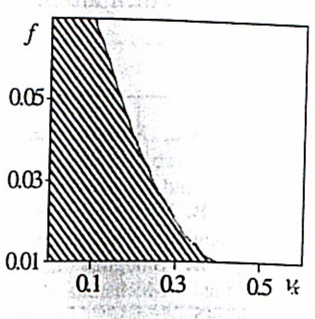

Fig. 21. The sphere of parameters f-ν_x combinations when vibrational displacement occurs

Graphs 2 and 5 are drawn up with the following values of the parameters

ν_x=0.1, ν= 0.1, ν_φ=10, f=0.1, x_{st}=-0.2 , a_l=0.2, b_l=0.1.
The values of the parameters in other graphs

$f = 0.1$, $\nu = 0.1$, $\nu_x = 0.1$, $\varepsilon = \pi/4$, $x_c = -0.7$, $x_{st} = -0.4$, $a_1 = 0.2$, $\nu_\varphi = 10$, $\varphi_{st} = 0.01$, $y_{st} = 0.1$.

4. Application of the vibrational displacement for automatic assembly

Automatic assembly cannot be analyzed separately from design of the product. A final product of the automatic assembly is an article or part thereof, a unit consisting of various parts, which might be of various forms, sizes, mass, and physical properties. Effectiveness of the vibrational automatic assembly is very dependent on design of the various parts, which are parts of the assembly unit. When designing automatic vibrational assembly devices it is necessary to take into account the suitability of the design of the parts for vibrational assembly.

The whole assembly process is dependent on the configuration of the connecting parts. The configuration determines the primary orientation in the connecting part feeding units, stable position in the basing devices and transportation devices. Mass determines selection of basing, transportation, feeding mechanisms and parameters of excitement. Physical mechanical properties influence vibrational excitement regimes. Non-metal parts made of fragile materials may be easily damaged by the vibrational excitement. Thus, the excitement amplitude must be carefully selected taking into account material, of which the connecting parts are made.

Reliability of the assembly is determined by the orientation of the connecting parts in relation to each other in the assembly position. Most frequent reasons of failure to assemble are wrong matching and fastening of parts. In case of automatic assembly, parts must have a possibility to take such an interdependent position, from which they would be connected without impediments insofar various parameters are within the limits of tolerance. Vibrational assembly devices based on the principle of autosearch provide one of the parts in the assembly position with the movement of the certain trajectory on the plane, which is perpendicular to the direction of connection between the parts. Their activity is of probabilistic nature. Thus, it is not always possible to avoid failure to assemble parts. There are good prospects for the vibrational assembly devices, in which part basing and interdependent position errors in the assembly position are compensated by directed movement of the movably based part. In this way an interdependent orientation of the parts is ensured, which is necessary for an unhindered assembly. Connecting parts are matched and fastened with required precision by means of working devices of the assembly mechanisms. Nature of working device depends on the type of connection and may be step-type, rotational, or helical.

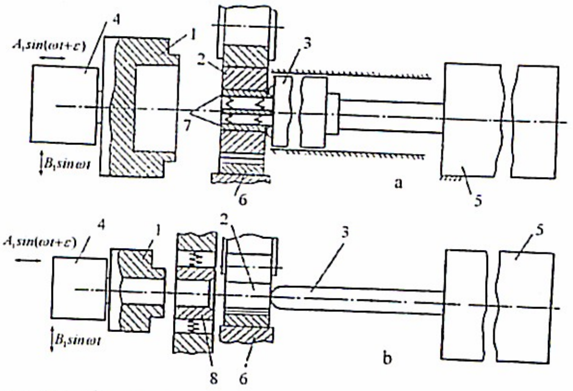

Fig. 20. Vibrational devices for assembly of cylindrical parts: a – for assembly of a bushing with body; b – for assembly of a shaft with a bushing.

Vibrational assembly devices with elastic compensators ensure centering of the connecting parts in relation to each other with necessary precision before the connecting begins. The part 2 connected to the body 1 is fed one by one from the feeder and is based on the prism 6. Pusher 3 (Figure 20) with springing plates 7 is given the movement by means of the drive 5. As pusher 3 moves to the left, the end of it goes into the hole of the part 2 and pushes it until contact with the body 1. Body 1 is exited in two perpendicular directions by means of the device 4. During excitement, cylindrical surface of the part 2 being connected is being centered in relation to the hole of the body 1.

Connecting parts can be centered using spring orientator 8 (Figure 20, b). First, shaft 2 is pushed into orientator 8 by means of the pusher 3. When axes of the surfaces connected do not coincide, the end of the shaft is pressed to the main part 1. After the contact between the connecting parts, the vibrator sets in. During the induction of the part 1, the connecting surfaces are matched in two perpendicular directions, and parts are connected without impediments.

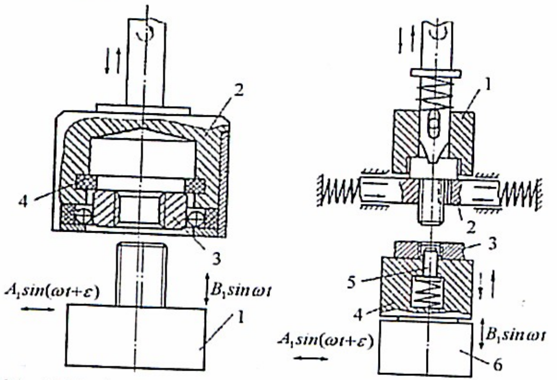

Fig. 21. Vibrational devices for connecting thread parts: a – for screwing a screw onto a bolt; b – for joining screw with the bushing.

A shift of axes of thread parts in starting assembly position is influenced by a clearance between thread surfaces, size of chamfers, thread profile depth, angle of turning of connecting parts and other factors.

When rigidly based part is exited in perpendicular directions (Figure 20, a), screw 3 is movably based in the head 2 and kept in place by springing balls. Screw edge leans onto the elastic ring 4. When axes of the thread surfaces do not coincide, end surfaces of bolt and screw lean onto each other. When bolt is exited in perpendicular directions movably based screw will move in the direction of decrease of error of relative position of the connecting parts and this way the screw will be screwed onto the bolt.

In the assembly unit (Figure 21, b) the screw is based by outside surface, springing prisms 2. Plate 3 is aligned by internal surface of a thread, catcher 5 and is based on the table 4. When table 4 is exited in perpendicular directions, thread surface of the table is centered in relation to the bushing hole and this way the thread is screwed into the thread hole of the plate.

5. Conclusions

1. The dynamic model of displacement by plane movement was created. By using the above model the displacement and turning of non - impact body representing a movingly based part when a rigidly based part is excited in two perpendicular directions was analyzed.

2. It was determined that the biggest influence on the duration of matching of the parts τ and on average speed displacement of a body $\dot{\xi}_{vid}$ was made by the frequency of excitement ν, the coefficients of elastic force of resistance and the moment ν_x and ν_φ and the friction coefficient f. When the values of turn stiffness coefficient are small (ν_φ<5), at the end of displacement the elastically based part is inclined in respect to the rigidly based part. Thus it is impossible to match the connected surfaces and to connect the parts automatically.

3. The essential spheres of combinations of parameters of the system and excitement when the vibratory assembling by using non - impact regime were set up. The biggest influence on the area of the sphere of existence of the vibratory assembling is the frequency of excitement ν and the coefficient of elastic resistance force ν_x.

4. Presented are examples of vibrational assembly mechanisms, which are based on the vibrational displacement.

References

1. **Ke-Lin Du, Xinhan Huang, MinWang and Jianyan Hu.** Assembly robotics research: A Survey. International Journal of Robotics and Automation. Vol.14, No.4, 1999.
2. **Bakšys B.** Vibracinis tampriai bazuojamojo kūno poslinkis. – Mechanika. – Kaunas: Technologija, 1995, Nr.1, p. 61-65.
3. **Bakšys B.** Smūginis tampriai bazuojamojo kūno poslinkio režimas. – Mechanika. – Kaunas: Technologija, 1996, Nr.1(4), p. 42-45.
4. **Bakšys B., Puodžiūnienė N.** Directional vibratory displacement of the automatically assembled parts. – Journal of Viroengineering.-Vilnius: Vibromechanika, 2000, No4(5), p. 61-67.