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Investigation of Soft Impacts in Elements of Pipe Robots

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1. Introduction

Investigation of dynamics of impact interactions in elements of robots is an important problem. Theoretical basis of various structures of robots are presented by V. A. Glazunov [1] and are developed by the scientists supervised by him. Vibratory drives and their use in robots are investigated in [2]. Vibrators of vibro impact type and their resonant zones are analysed in [3]. Nonlinear systems and their stabilisation are described in [4]. Dynamics of impacts in mechanical systems is investigated in [5]. Systems with impacts and their periodic orbits are analysed in [6]. Nonlinear impacts and vibrations are investigated in [7].

Soft impacts take place in various mechanical systems, including various types of machines and mechanisms. Among them their application in elements of manipulators and robots is especially important. Soft impacts take place in the process of motion of a pipe robot. Schematic representation of a pipe robot with soft impacts is presented in Fig. 1.

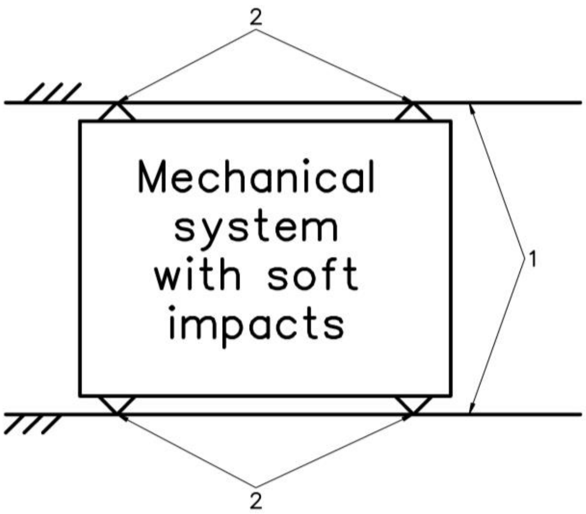


Fig. 1 Schematic representation of a pipe robot with soft impacts: *1* – the pipe; *2* – nonlinear supports

Vibrators with deformable impact support under harmonic excitation are especially useful in the case when their stationary regimes of motion are stable. This is useful in practice by applying those vibrators to single direction manipulators and various robots of space type.

For practical application it is necessary to reveal dynamical qualities of the system from where it would be possible to determine optimal regimes. For this purpose, investigations of dynamics of the system by numerical methods were performed.

In this paper dynamics of soft impacts in elements of manipulators and robots is investigated. The model of the investigated system is described. Numerical investigations for various parameters of the system are performed. Free and forced vibrations are investigated. This enables effective application of such systems in engineering.

2. Model of the vibro impact system with soft impacts

Schematic representation of soft impacts is presented in Fig. 2. In the figure m denotes the mass, C denotes the coefficient of stiffness and H denotes the coefficient of viscous friction. Also, C_0 denotes the coefficient of stiffness of the support and H_0 denotes the coefficient of viscous friction of the support. The amplitude of the harmonic exciting force acting to the mass is denoted as F.

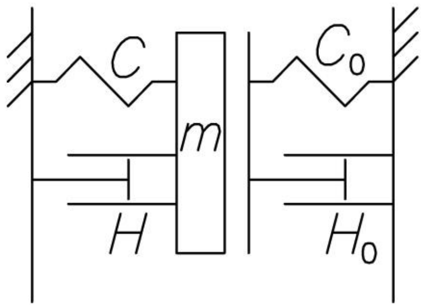


Fig. 2 Representation of dynamic model of soft impacts

Further the following notation is introduced:

$$h=\frac{H}{m},\ h_0=\frac{H_0}{m},\ p^2=\frac{C}{m},\ p_0^2=\frac{C_0}{m},\ f=\frac{F}{m}. \qquad (1)$$

Thus, h is the coefficient of viscous friction between the vibrating mass and the immovable wall divided by the mass; h_0 is the coefficient of viscous friction between the support and the immovable wall divided by the mass; p^2 is the coefficient of stiffness between the vibrating mass and the immovable wall divided by the mass; p_0^2 is the coefficient of stiffness between the support and the immovable wall divided by the mass; f is the amplitude of harmonic excitation acting to the mass divided by the mass.

Dynamics of the vibro impact system with soft impacts is described by the following differential equations:

$$\begin{aligned} &\ddot{x}+\left(h+h_0\right)\dot{x}+\left(p^2+p_0^2\right)x = f sin\omega t, \text{ when } x = x_0, \\ &\ddot{x}+h\dot{x}+p^2 x = f sin\omega t, \\ &h_0\dot{x}_0 + p_0^2 x_0 = 0, \text{ when } x < x_0, \end{aligned} \tag{2}$$

where: x is displacement of the investigated element; ω is frequency of excitation; t is the time variable; x_0 is displacement of the support and the upper dot denotes differentiation with respect to time.

Dynamics of the conservative vibro impact system with soft impacts is described by the following differential equations:

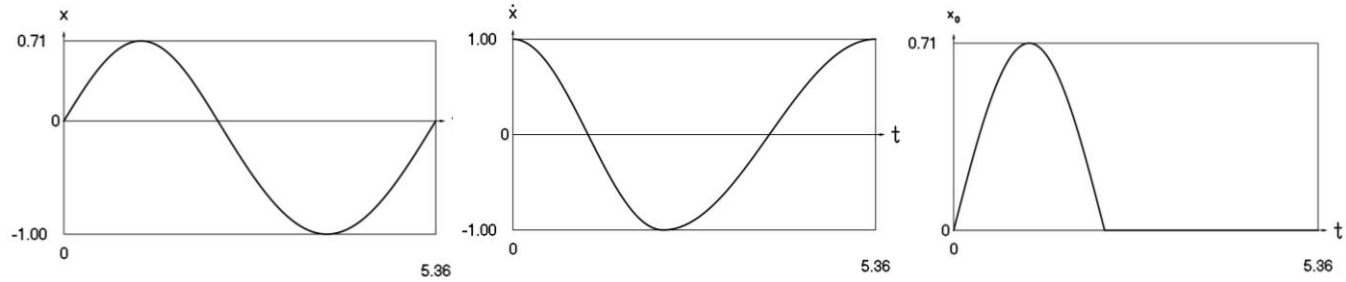
$$\begin{aligned} &\ddot{x}+\left(p^2+p_0^2\right)x = 0, \text{ when } x = x_0, \\ &\ddot{x}+p^2 x = 0, \\ &x_0 = 0, \text{ when } x < x_0. \end{aligned} \tag{3}$$

3. Investigation of the conservative system

The following initial conditions are assumed:

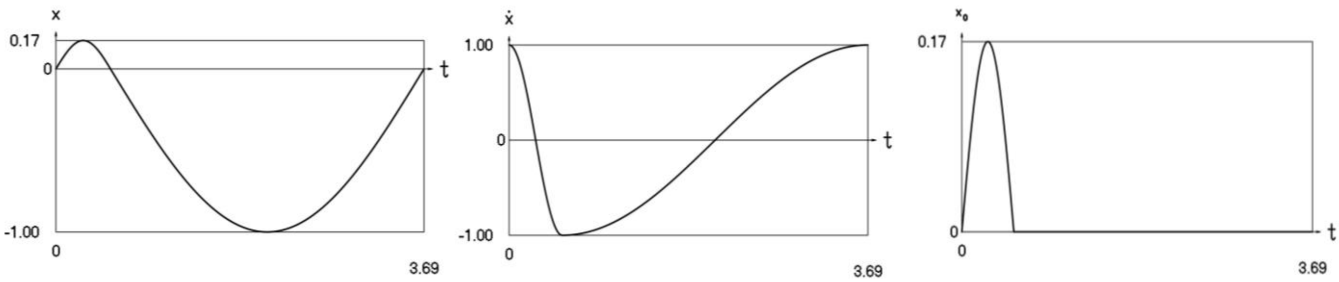
$$x(0)=0,\ \dot{x}(0)=1,\ x_0(0)=0. \tag{4}$$

It was assumed that p^2=1. Investigations for various values of p_0^2 were performed, increasing this value makes the support stiffer and behaviour of the system becomes closer to the system with ideal impacts. Here only some typical results are presented. Results for $p_0^2 = 1$ are presented in Fig. 3. Results for $p_0^2 = 32$ are presented in Fig. 4. Results for $p_0^2 = 64$ are presented in Fig. 5. Results for $p_0^2 = 128$ are presented in Fig. 6.



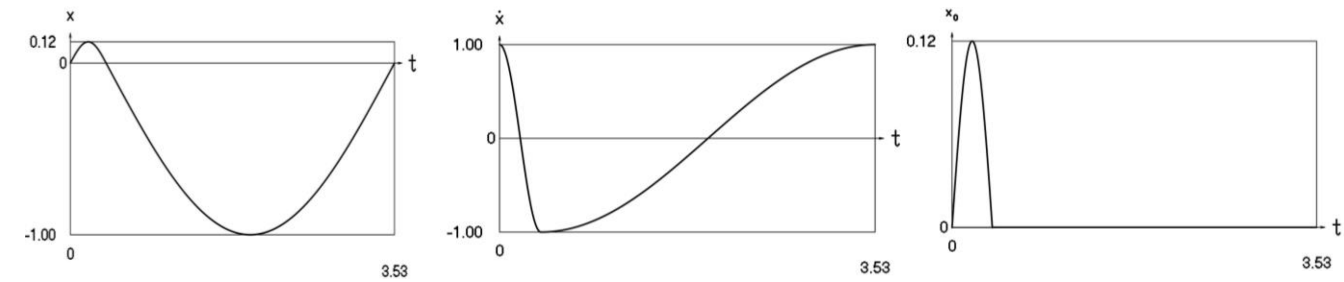
a) Displacement x as function of time t b) Velocity $\dot{x}$ as function of time t c) Displacement x_0 as function of time t

Fig. 3 Results for $p^2 = 1$ and $p_0^2 = 1$



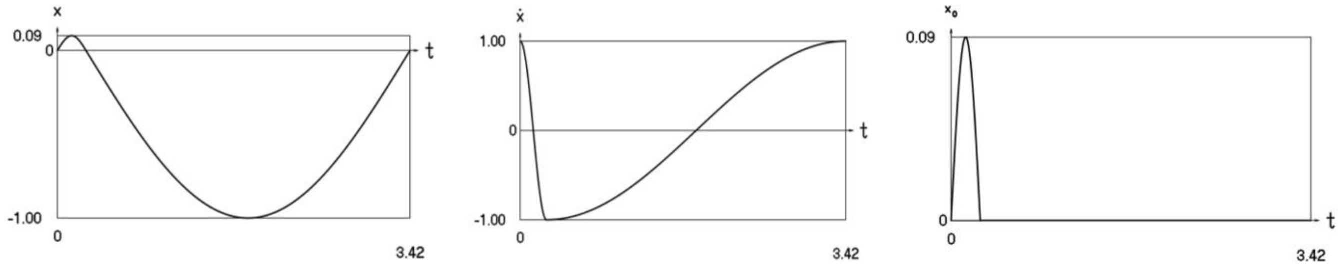
a) Displacement x as function of time t b) Velocity $\dot{x}$ as function of time t c) Displacement x_0 as function of time t

Fig. 4 Results for $p^2 = 1$ and $p_0^2 = 32$



a) Displacement x as function of time t b) Velocity $\dot{x}$ as function of time t c) Displacement x_0 as function of time t

Fig. 5 Results for $p^2 = 1$ and $p_0^2 = 64$



a) Displacement x as function of time t b) Velocity $\dot{x}$ as function of time t c) Displacement x_0 as function of time t

Fig. 6 Results for $p^2 = 1$ and $p_0^2 = 128$

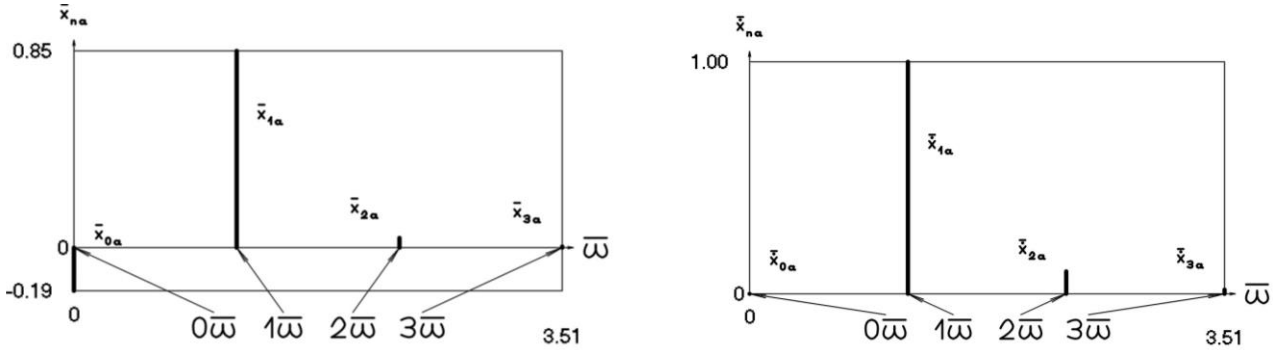
The presented results show the influence of the stiffness of the support to the dynamic behavior of the investigated vibro impact system with soft impacts. It is seen that with the increase of the coefficient of stiffness of the support period of free vibrations decreases.

Constant part and amplitudes of first three harmonics when p^2=1 for different values of p_0^2 are investigated. Increasing this value makes the support stiffer and behaviour of the system becomes closer to the system with ideal impacts. Results for $p_0^2 = 1$ are presented in Fig. 7. Results for $p_0^2 = 2$ are presented in Fig. 8. Results for $p_0^2 = 4$ are presented in Fig. 9. Results for $p_0^2 = 8$ are presented in Fig. 10. Results for $p_0^2 = 16$ are presented in Fig. 11. Results for $p_0^2 = 32$ are presented in Fig. 12. Results for $p_0^2 = 64$ are presented in Fig. 13. Results for $p_0^2 = 128$ are presented in Fig. 14.

The presented results show the influence of nonlinearity to the amplitude of the first harmonic as well as to the amplitudes of the higher harmonics. It is seen that with the increase of the coefficient of stiffness of the support frequencies of free vibrations increase, while amplitudes of the first harmonic decrese and amplitudes of the higher harmonics increase.

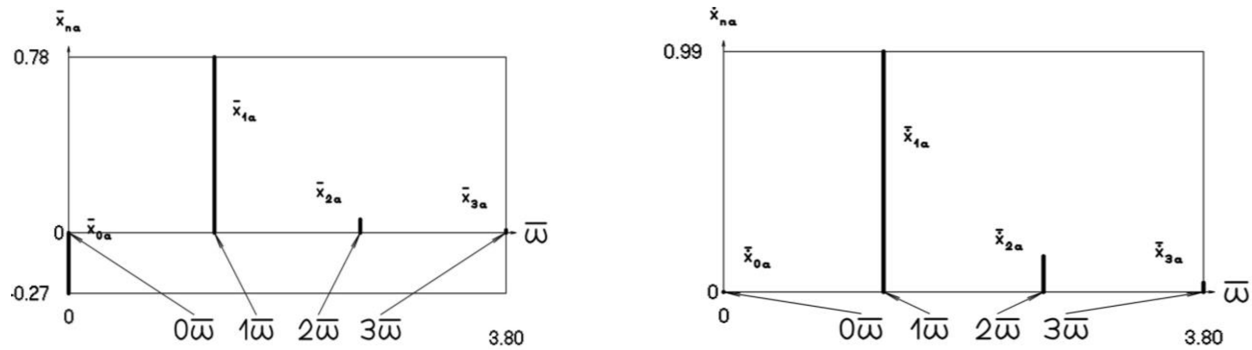
Dependence of the period of free vibrations T from the coefficient of stiffness p_0^2 when it is assumed that p^2=1 is presented in Fig. 15.

From the presented graphical relationship, it is seen that with the increase of the stiffness of the support the period of free vibrations decreases. This corresponds with the previously presented results for various definite values of the coefficient of stiffness of the support.



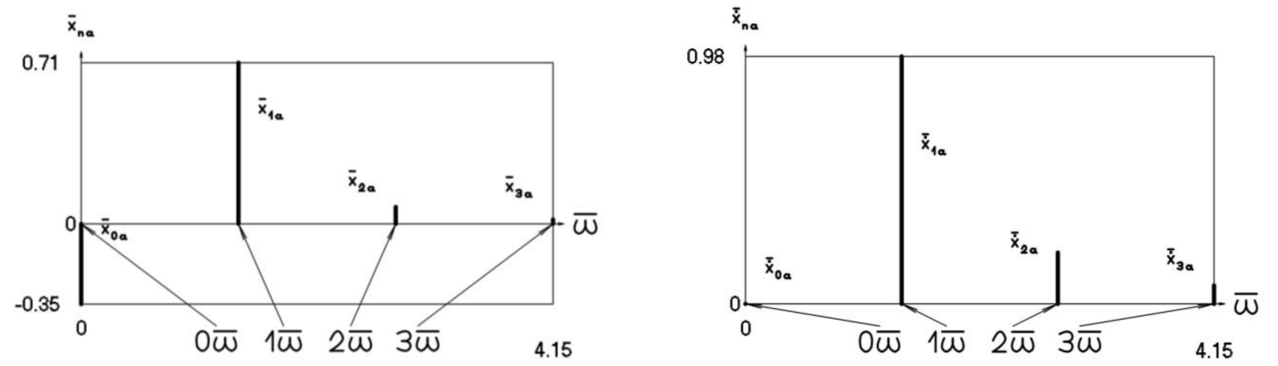
a) Displacement x b) Velocity $\dot{x}$

Fig. 7 Constant part and amplitudes of first three harmonics for $p^2 = 1$ and $p_0^2 = 1$



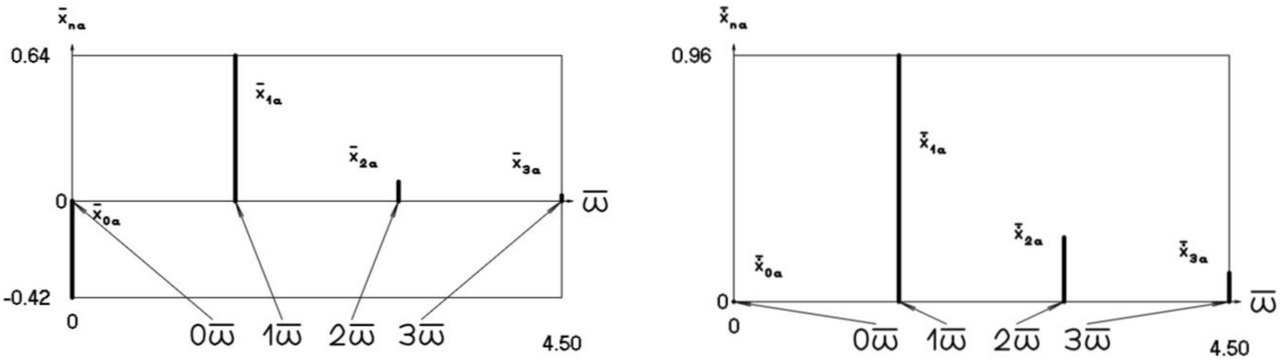
a) Displacement x b) Velocity $\dot{x}$

Fig. 8 Constant part and amplitudes of first three harmonics for $p^2 = 1$ and $p_0^2 = 2$



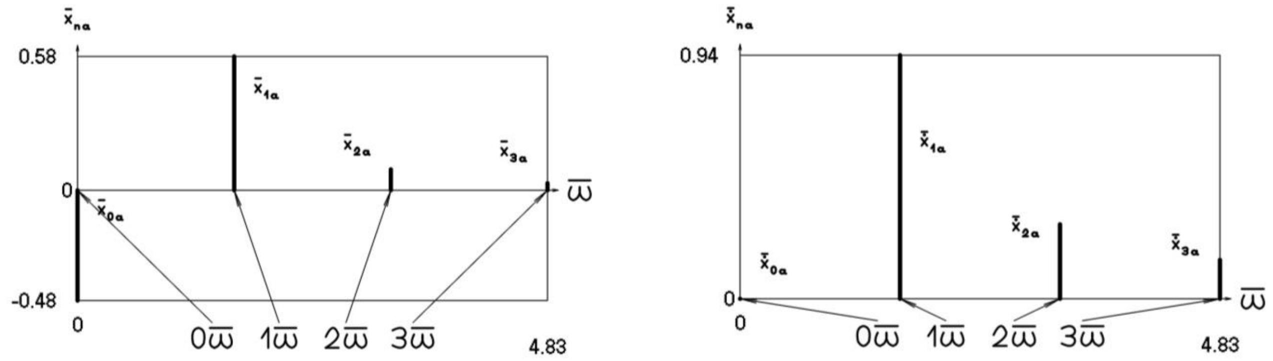
a) Displacement x b) Velocity $\dot{x}$

Fig. 9 Constant part and amplitudes of first three harmonics for $p^2 = 1$ and $p_0^2 = 4$



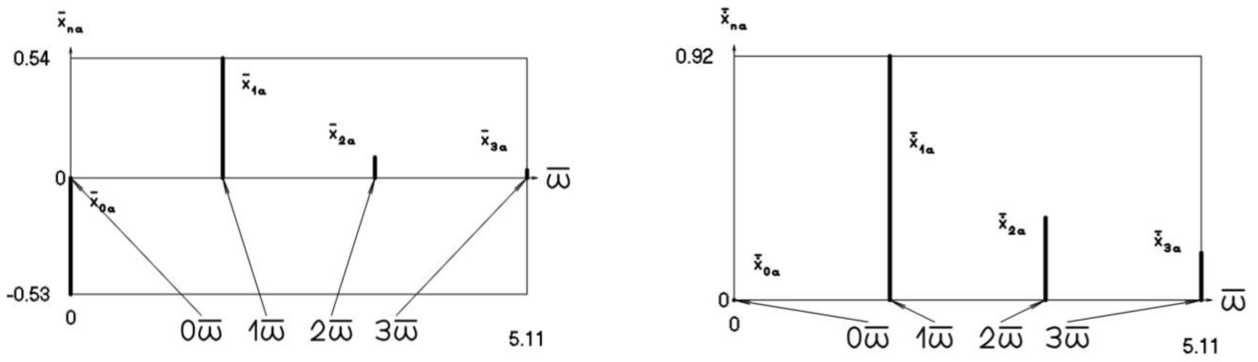
a) Displacement x b) Velocity $\dot{x}$

Fig. 10 Constant part and amplitudes of first three harmonics for $p^2 = 1$ and $p_0^2 = 8$



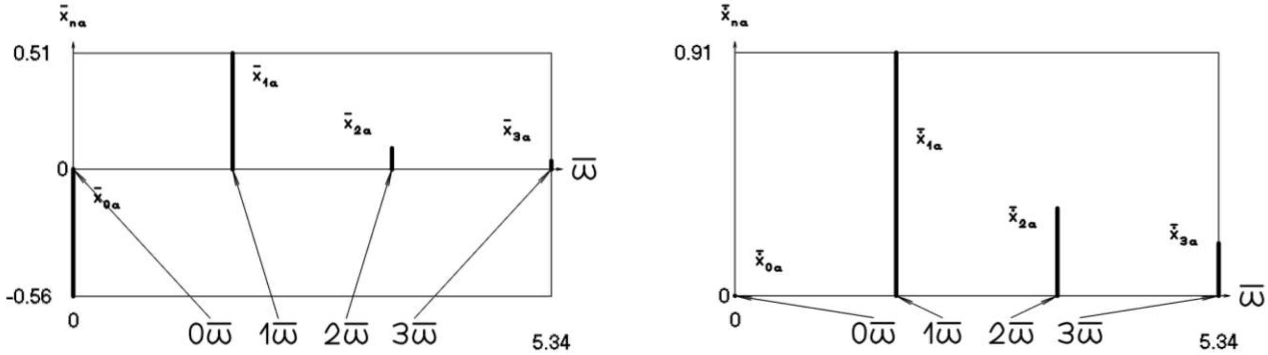
a) Displacement x b) Velocity $\dot{x}$

Fig. 11 Constant part and amplitudes of first three harmonics for $p^2 = 1$ and $p_0^2 = 16$



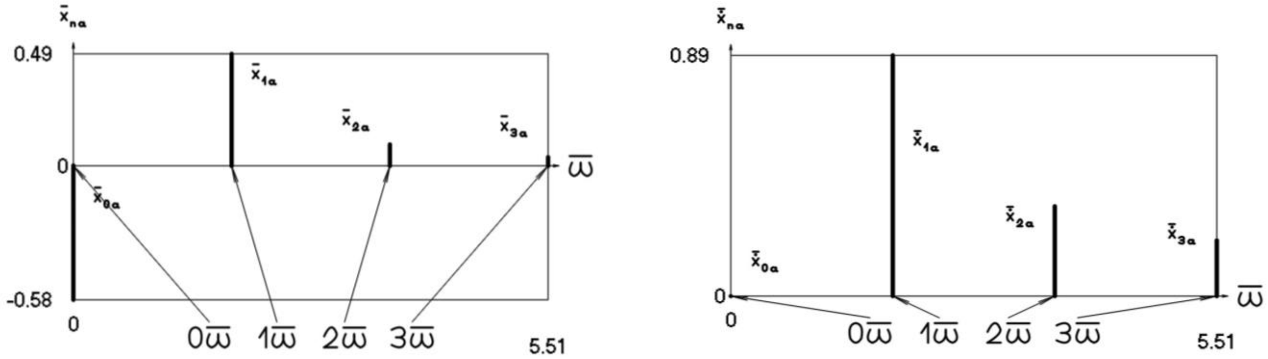
a) Displacement x b) Velocity $\dot{x}$

Fig. 12 Constant part and amplitudes of first three harmonics for $p^2 = 1$ and $p_0^2 = 32$



a) Displacement x b) Velocity $\dot{x}$

Fig. 13 Constant part and amplitudes of first three harmonics for $p^2 = 1$ and $p_0^2 = 64$



a) Displacement x b) Velocity $\dot{x}$

Fig. 14 Constant part and amplitudes of first three harmonics for $p^2 = 1$ and $p_0^2 = 128$

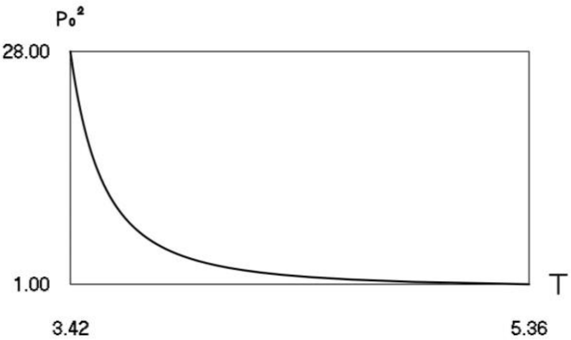


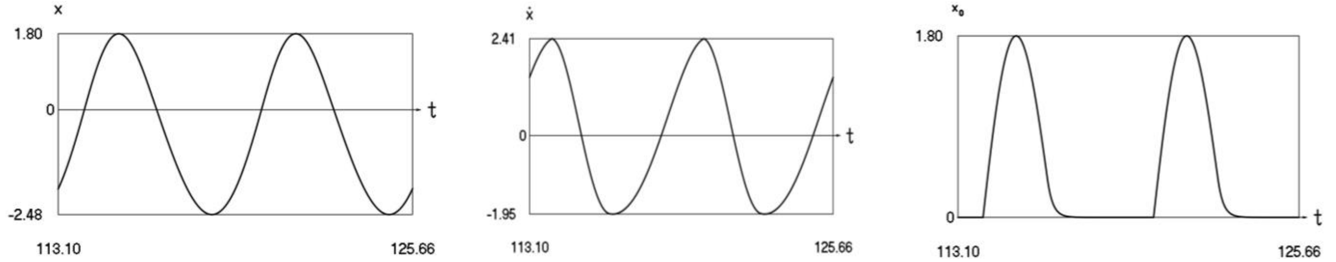
Fig. 15 Dependence of the period of free vibrations T from the coefficient of stiffness p_0^2 when $p^2 = 1$

4. Investigation of forced motions

Zero initial conditions are assumed. The following values of the parameters of the investigated vibro impact system with soft impacts were assumed: ω=1, f=1, h=0.2, h_0=0.2, p^2=1. Two periods of steady state motions are shown.

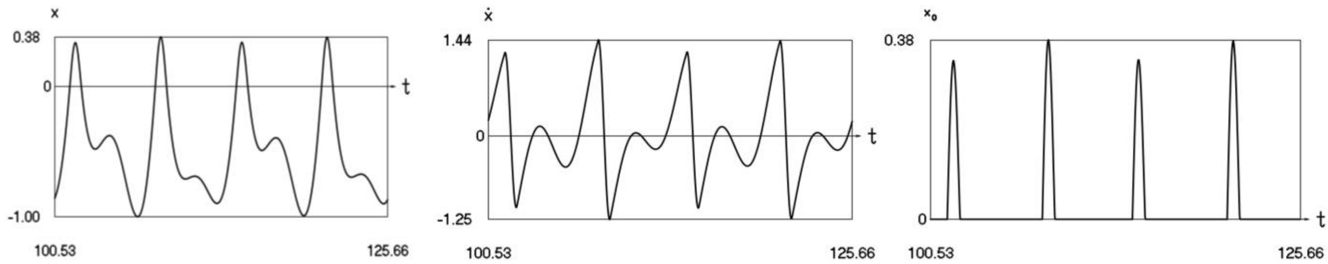
Investigations for various values of p_0^2 were performed, increasing this value makes the support stiffer and behaviour of the system becomes closer to the system with ideal impacts. Here only some typical results are presented. Results for $p_0^2 = 1$ are presented in Fig. 16. Results for $p_0^2 = 16$ are presented in Fig. 17. Results for $p_0^2 = 32$ are presented in Fig. 18.

From the presented results it can be noted that for the first value of the coefficient of stiffness of the support period of steady state motion coincides with the period of the exciting force, while for the last two values of the coefficient of stiffness of the support period of steady state motion is equal to two periods of the exciting force. Thus, it can be concluded that with the increase of the coefficient of stiffness of the support behavior of the investigated vibro impact system with soft impacts experiences essential changes.



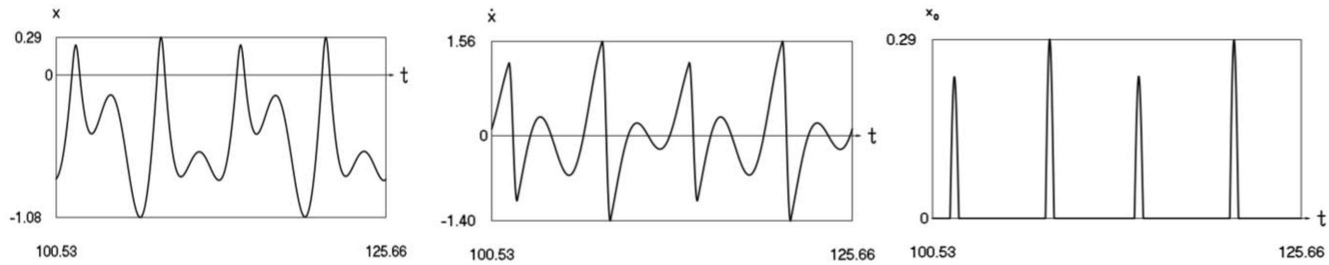
a) Displacement x as function of time t b) Velocity $\dot{x}$ as function of time t c) Displacement x_0 as function of time t

Fig. 16 Steady state motion for $\omega = 1,\ f = 1,\ h = 0.2,\ h_0 = 0.2,\ p^2 = 1$ and $p_0^2 = 1$



a) Displacement x as function of time t b) Velocity $\dot{x}$ as function of time t c) Displacement x_0 as function of time t

Fig. 17 Steady state motion for $\omega = 1,\ f = 1,\ h = 0.2,\ h_0 = 0.2,\ p^2 = 1$ and $p_0^2 = 16$



a) Displacement x as function of time t b) Velocity $\dot{x}$ as function of time t c) Displacement x_0 as function of time t

Fig. 18 Steady state motion for $\omega = 1,\ f = 1,\ h = 0.2,\ h_0 = 0.2,\ p^2 = 1$ and $p_0^2 = 32$

Main characteristics of steady state motion as functions of frequency of excitation are investigated. The following values of the parameters of the investigated vibro impact system with soft impacts were assumed: $f = 1,\ h = 0.1,\ h_0 = 0.1,\ p^2 = 1,\ p_0^2 = 128.$ Results are presented in Fig. 19, Fig. 20, and Fig. 21.

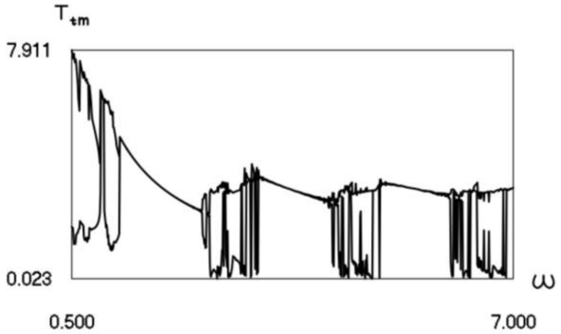


Fig. 19 Minimum and maximum inter impact intervals of steady state motion as functions of frequency of excitation in periodic regime for f=1, h=0.1, h_0=0.1, p^2=1, $p_0^2 = 128$

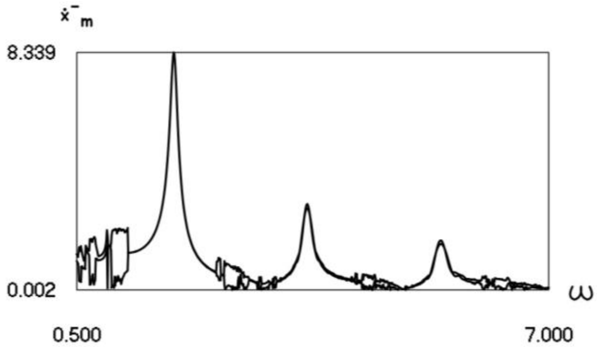


Fig. 20 Minimum and maximum velocities before impact of steady state motion as functions of frequency of excitation in periodic regime for f=1, h=0.1, h_0=0.1, p^2=1, $p_0^2 = 128$

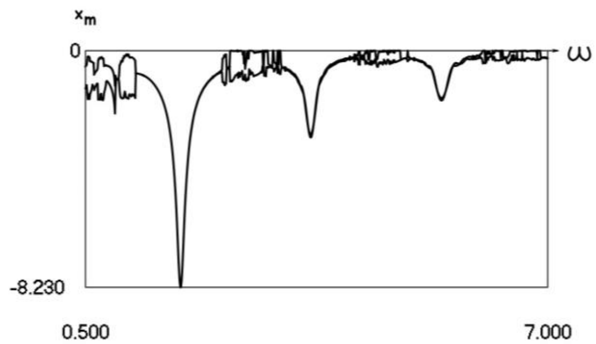


Fig. 21 Minimum and maximum minimum displacements in inter impact intervals of steady state motion as functions of frequency of excitation in periodic regime for f=1, h=0.1, h_0=0.1, p^2=1, $p_0^2 = 128$

From the results presented in the figures the minimum and maximum inter impact intervals as functions of frequency of excitation, minimum and maximum velocities before impact as functions of frequency of excitation, minimum and maximum minimum displacements in inter impact intervals as functions of frequency of excitation are seen. Three resonant zones of expected single valued motions are observed in the presented results. They correspond to optimal regions of operation of the vibro impact system with soft impacts.

5. Conclusions

Investigation of dynamics of impact interactions in elements of manipulators and robots is an important engineering problem. In this paper dynamics of soft impacts in elements of manipulators and robots is investigated. The model of the investigated system is described. Numerical investigations for various parameters of the system are performed. Free and forced vibrations are investigated.

From the presented results it can be noted that for the smaller values of the coefficient of stiffness of the support period of steady state motion coincides with the period of the exciting force, while for the higher values of the coefficient of stiffness of the support period of steady state motion is equal to two periods of the exciting force. Thus, it can be concluded that with the increase of the coefficient of stiffness of the support behavior of the investigated vibro impact system with soft impacts experiences essential changes.

Main characteristics of steady state motion as functions of frequency of excitation are investigated. From the obtained results the minimum and maximum inter impact intervals as functions of frequency of excitation, minimum and maximum velocities before impact as functions of frequency of excitation, minimum and maximum minimum displacements in inter impact intervals as functions of frequency of excitation are seen. Three resonant zones of expected single valued motions are observed in the presented results. They correspond to optimal regions of operation of the vibro impact system with soft impacts.

Results of the performed analysis of dynamic interactions with soft impacts in the elements of manipulators and robots are used in the process of design of pipe robots of advanced type.

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INVESTIGATION OF SOFT IMPACTS IN ELEMENTS OF PIPE ROBOTS

S u m m a r y

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For practical application it is necessary to reveal dynamical qualities of the system from where it would be possible to determine optimal regimes. For this purpose, investigations of dynamics of the system by numerical methods were performed.

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From the presented results it can be noted that for the smaller values of the coefficient of stiffness of the support period of steady state motion coincides with the period of the exciting force, while for the higher values of the coefficient of stiffness of the support period of steady state motion is equal to two periods of the exciting force. Thus, it is concluded that with the increase of the coefficient of stiffness of the support behavior of the investigated vibro impact system with soft impacts experiences essential changes.

Main characteristics of steady state motion as functions of frequency of excitation are investigated. From the presented results the minimum and maximum inter impact intervals as functions of frequency of excitation, minimum and maximum velocities before impact as functions of frequency of excitation, minimum and maximum minimum displacements in inter impact intervals as functions of frequency of excitation are seen. Three resonant zones of expected single valued motions are observed in the presented results. They correspond to optimal regions of operation of the vibro impact system with soft impacts.

Results of the performed analysis of dynamic interactions with soft impacts in the elements of manipulators and robots are used in the process of design of pipe robots of advanced type.

Keywords: soft impact, stable motions, eigenfrequencies and forced frequencies, optimal regimes in the vicinities of resonant vibrations.

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