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CRITERIA OF ESTIMATION OF ACTIVE VIBRATION ISOLATION SYSTEM IN HAND-HELD PERCUSSIVE TOOLS

SUMMARY

The first step for the assessment and choice of comfort parameters of an active vibration isolation system of hand-held percussive power tools is the construction of appropriate dynamical model of the operator–tool–base system. The interaction between the hand and handle is composed of the passive, dynamical reaction of the hand caused by the vibration signal and a slowly varying feed force by which the operator controls the tool operation. In the paper a complex model of human-operator was proposed. Visual and tactile feedback signals coming to human nervous system were assumed as basic components of control of percussive tool by operator. It was shown that vibration comfort and work efficiency of the percussive tool are contradictory notions. Some feedback signals responsible for the control of the tool operation are attenuated by the vibration isolation system and finally when vibration comfort increases the control of the tool and the work efficiency decrease. In the paper a criterion of assessment of work comfort with percussive tool was assumed. Simulation of the proposed model of operator-tool-base system was done applying MATLAB/Simulink. The influence of parameter values of the proposed active vibration isolation system on the assumed comfort criterion was analyzed. The obtained results were graphically presented.

Keywords: *man-machine***,** *human-operator, active vibration isolation, hand-tool*

KRYTERIA OCENY AKTYWNEGO UKŁADU WIBROIZOLACJI W RĘCZNYCH NARZĘDZIACH UDAROWYCH

Ocena i ustalenie warunków doboru właściwego układu wibroizolacji rękojeści w ręcznych narzędziach udarowych, wymaga zbudowania odpowiedniego modelu układu: „człowiek – narzędzie – podłoże”. Oddziaływanie człowieka-operatora na rękojeść narzędzia składa się z dynamicznej, biernej reakcji rąk, wywołanej sygnałem drganiowym, oraz wolnozmiennej siły nacisku, za pomocą której operator steruje pracą narzędzia. Zaproponowany w pracy model układu „człowiek – narzędzie – podłoże” jest złożonym układem, w którym występują wzrokowe i dotykowe sygnały zwrotne docierające do systemu nerwowego człowieka, na których podstawie realizuje on odpowiednie funkcje sterowania. Zastosowanie układu wibroizolacji rękojeści tworzy przeszkodę na drodze przepływu niektórych sygnałów zwrotnych. Podnosząc zatem komfort wibracyjny, możemy równocześnie obniżyć komfort ergonomiczny, polegający na łatwości sterowania pracą narzędzia. W związku z tym sformułowano odpowiednie kryteria oceny komfortu pracy. Za pomocą pakietu MATLAB/Simulink przeprowadzono symulację oraz przeanalizowano wpływ parametrów pewnego aktywnego układu wibroizolacji na wartości przyjętych wskaźników komfortu. Wyniki przedstawiono w postaci wykresów.

Słowa kluczowe: *człowiek-maszyna, człowiek-operator, aktywny układ wibroizolacji, narzędzie ręczne*

1. INTRODUCTION

The principle way of the reducing of hand-transmitted vibration acting on human operator is to isolate tool's handle by application of vibration isolation system (VIS). The use of the vibration isolation system increases the work comfort by lowering handle vibration levels, but at the same time it can provoke symptoms of discomfort of the operator, who may feel the tool more difficult to operate and control. This effect should be also taken into account at the stage of designing of active vibration isolation system (AVIS). Finally, a broader approach in AVIS designing is needed where both comfort factors, mentioned above, are considered.

2. PROBLEM DESCRIPTION

The basis of the designing of the simulation model used in the present paper is the block diagram of the system operator-tool-base shown in the Figure 1 [2–4]. The system operator-tool-base is considered here as man-machine system [8], and the handling operations with the tool are considered as manual control problem. The controlled variable of the problem is the efficiency of the chiselling process v (the rate at which the chisel penetrates into the base). In order to achieve the assumed efficiency v_z the operator acts on the handle with an appropriate pressure force F_h which in the presented block diagram is the only control function realized by the operator.

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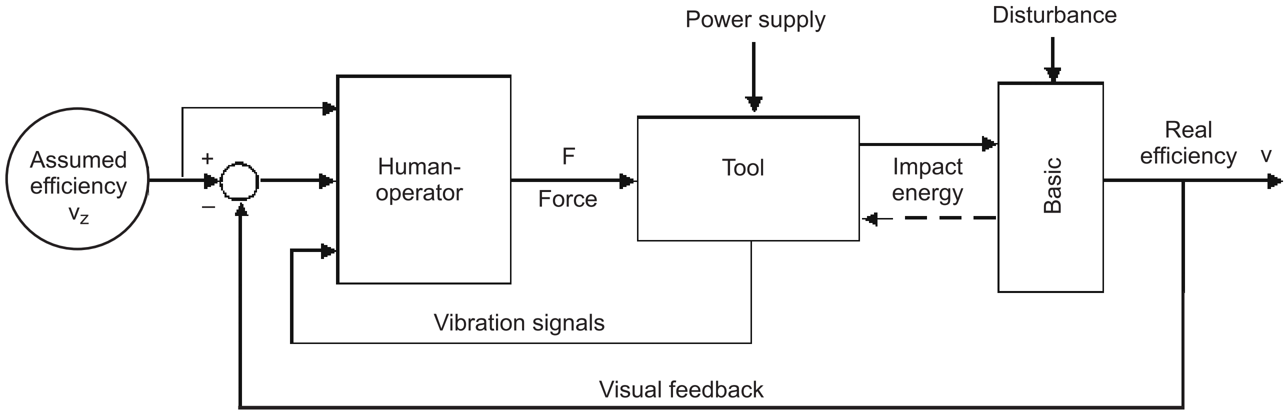

Fig. 1. Block diagram of the operator-tool-base system

The total force developed by operator $F(t)$ can be divided into two components: slowly variable component $F_h(t)$ which is considered as continuous push control force, and fast variable component $F_1(t)$ corresponding passive, dynamic reaction coming from handle vibration as it is shown by relation

$$F(t)=F_h(t)+F_1(t) \tag{1}$$

It was assumed, that forces $F_h(t)$ and $F_1(t)$ are independent and can be depicted by two independent models. The force $F_1(t)$ was depicted by mechanical, one-mass model proposed in [7]. Modelling of the reaction of human-operator, and in particular force $F_h(t)$, was the principal problem presented in the paper. The force $F_h(t)$ totally depends on physical and mental reaction of operator. The structure of the human model was assumed prior to some data taken from [6, 8] where the similar investigations concerning pilot steering stick took place. The target of simulation investigations of the adopted model was to estimate the influence of active, non-linear parameters of vibration isolation of the handle, on predefined indices of work comfort. The simulations were done using MATLAB/Simulink software.

3. MODEL OF THE TOOL-BASE SYSTEM

The percussive tool (pneumatic hammer, riveter, demolition hammer etc.) shown in the Figure 2 can be described as a transducer which changes the energy of the source into the vibro-impact process [1].

The driving force $U(t)$, realized by pneumatic, electric, hydraulic or electromagnetic engine. In order to transmit the energy of the source to the base and ensure the correct operation of the tool, it is necessary to exercise a required pressure force on the tool body, from within a range specified by its minimum and maximum value. The correct and most efficient operation of the tool takes place for the condition when there is one impact of the striker on the tool during each work cycle with period T. If a vibration isolation system is used, the operator who controls the tool acts with a pressure force $F_h(t)$ on the handle. The force with which the vibration isolation system acts on the tool body is equal to $P(t)$. This force consists of a fast periodic component $P_1(t)$ related to the vibro-impact process and a slowly-varying component $P_h(t)$, calculated as the following average

$$P_h(t)=\frac{1}{T}\int_{t-T}^{t} P(\tau)d\tau \tag{2}$$

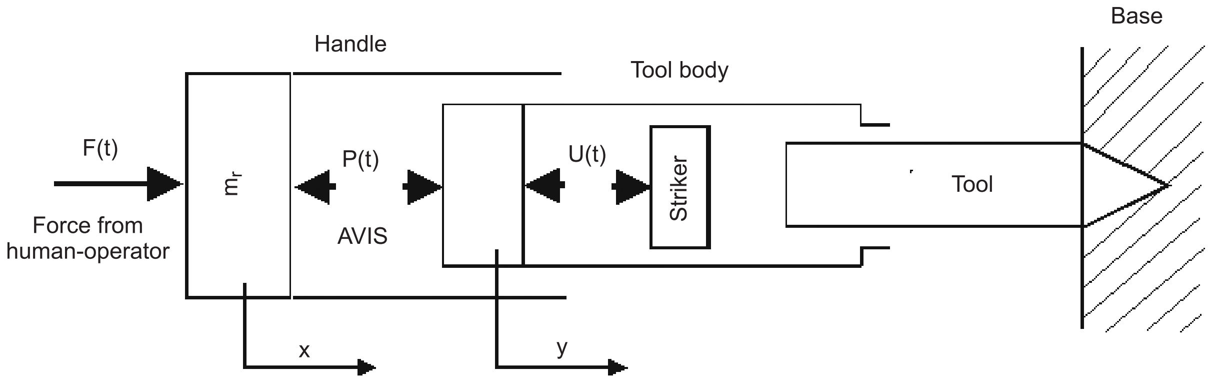

Fig. 2. Diagram of percussive tool with vibration isolated handle

The force $P_h(t)$ results from the action of the slowly-varying component of the operator force on the handle $F_h(t)$, which is the main tool operation control function. It has been shown in [1], that a percussive tool can be described as a discrete modulator, which changes the slowly-varying pressure force $P_h(t)$ acting on the tool body to a modulated sequence $I(nT)$ of the striker pulses on the tool

$$I(nT) \cong P_h(nT)T\sum_n \delta(t-nT) \tag{3}$$

where:

$\delta(t)$ – the Dirac delta function,
n – number of an impact.

The efficiency of the chiselling process defined as $v_n = b_n f$, where b_n is the penetration of the tool into the base during the n-th impact and $f = 1/T$ – the frequency of impacts, is expressed as in [1] in the form of the following relationship

$$v_n = G_n P_h(nT) \tag{4}$$

The coefficient G_n depends on the tool parameters and on the elastic-plastic properties of the base. Using the above developments, the process of imbedding of the tool into the base is approximated by a continuous function, by reducing the relation (4) to the form

$$v(t) = GP_h(t) \tag{5}$$

where coefficient G represents the tool-base system, which reacts with output $v(t)$ to the control signal $P_h(t)$. Throughout the paper a constant value of G will be used, however it is possible to account for the time dependence of this coefficient by considering such dependence as disturbances. When building the simulation model of the system operator-tool-base, the subsystem tool-base will therefore be reduced to relationship (5) and the periodic vibration of the tool handle $y(t)$ will be assumed as kinematic excitation. The chiselling efficiency $v(t)$ is proportional to force $P_h(t)$, so in simulation model of the system operator-tool-base, presented in the Figure 5, the force $P_h(t)$ can be considered as the backward signal instead of efficiency $v(t)$. The assumed input efficiency $v_z(t)$ can be substituted by the assumed pressure force $N_z(t)$. It was also assumed that the tool's body vibration did not contain the slow-varying component so in investigation of slow-varying processes of the operator-tool-base system one can assume that tool's body does not move.

4. ACTIVE VIBRATION ISOLATION SYSTEM OF HANDLE

Some producers of hand power tools have already done and presented some tests and prototypes of active vibration isolation systems of handle (ex. *Atlas Copco*). Due to economic reasons rather simple solutions, where the reaction force is controlled by relative displacement, are applied. Cushions with controlled air pressure are used as vibration isolation systems in pneumatically driven tools [2, 4]. Change of pressure is the result of inflow and outflow of air to and from elastic chamber and is controlled by relative displacement of handle and tool's body. Allowing some simplifications [2], model of such system can be described by the following relation

$$P = P_w + b\dot{w} + cw + c_n w^3 + \lambda\int w dt \tag{6}$$

where:

P – overall force with which the vibration isolation system acts on the tool handle and body,
P_w – force of pre-tension,
w – relative displacement of handle tool body relative,
b – coefficient of viscous resistance,
c – coefficient of stiffness,
c_n – coefficient of non-linear force characteristics,
λ – gain of active component of overall force.

Introduction of pre-tension allows for transmission through vibration isolation system of big pressure forces exerted on handle by operator. Each power tool has its specific range of forces within which regularity of impacts and normal work are assured. Human-operator, working with percussive tool, develops time-varying pressure force within that range. The pre-tension P_w can be assumed as the average value of force with optimal work of tool ensuring the highest efficiency. The value of pre-tension P_w can be also assumed as the mean value calculated from the registered time histories of random force $F_h(t)$ during the normal work with tool without vibration isolation system. Non-linear component of relation (6) was introduced to limit the relative displacements generated by variable pressure force. For $\lambda = 0$ one obtains passive vibration isolation system, which can be claimed to systems with constant force of acting. The considered system will work effectively in the range of displacements near $w = 0$. The "active" ($\lambda > 0$) component in relation (6) ensures that the system tends, independently on pressure force value, to position zero. In that case the pressure force applied by operator depends on aim of observed efficiency of work. In case $\lambda = 0$ the vibration isolation system will work correctly only in case when $F_h \approx P_w$. Such situation is very wearing for operator because he must all the time concentrate his attention on keeping, assumed *a priori*, constant pressure force. Handling of tool is in this case very limited.

5. HUMAN-OPERATOR MODEL

Simulation block-diagram of considered human-operator model is shown in the Figure 3. Two quantities are considered as inputs:

1) error $e = N_z - P_h$,
2) handle displacement x.

Output is the pressure force F_h exerted on handle by operator. Central nervous system is represented by Gain, Integrator and Transport Delay. In numerical calculations the following values were assumed: gain $K = 3$, time delay $\tau = 0.2$ s.

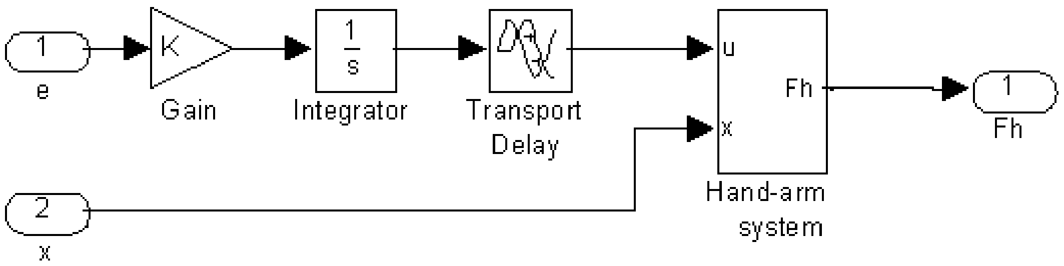

Fig. 3. Simulation block-diagram of human-operator

Hand-arm system, composed of nerves, muscles and bones are depicted by mechanical model shown in the Figure 4. It is modified version of model presented in [6] with data $m_h = 4$ kg – reduced mas of hand-arm system, $b_h = 35$ Ns/m, $k_h = 176$ N/m, $b_1/k_h = \tau_1 = 0.1$ s – coefficients of damping stiffness modelling properties of musculs system. Force $F_m(s)=1/(\tau_m s+1)$ is the reduced force generated in muscles by signal u coming from the operator's central nervous system trough the muscle activation block, with time of reaction $\tau_m = 0.05$ s. The pressure force on handle $F_h(s)$, controlled by operator can be written as follows

$$F_h(s) = \frac{1}{\tau_m s+1} u(s) - [H(s) - H_1(s)]x(s) \qquad (7)$$

where: $H(s) = m_h s^2 + b_h s + k_h$, $H_1(s) = k_h/(\tau_1 s + 1)$.

In the Figure 3, block "Hand-arm system" was introduced taking into account Eq. (7).

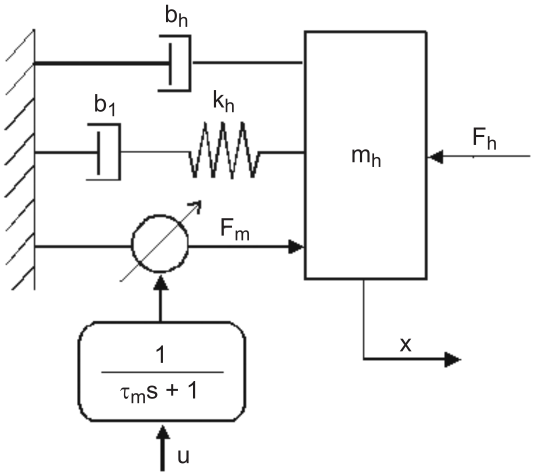

Fig. 4. Mechanical model of hand-arm system

6. SIMULATION DIAGRAM

The simulation model of the considered system operator-tool-base system was built in Simulink and shown in the Figure 5 according to the assumptions presented in section 2.

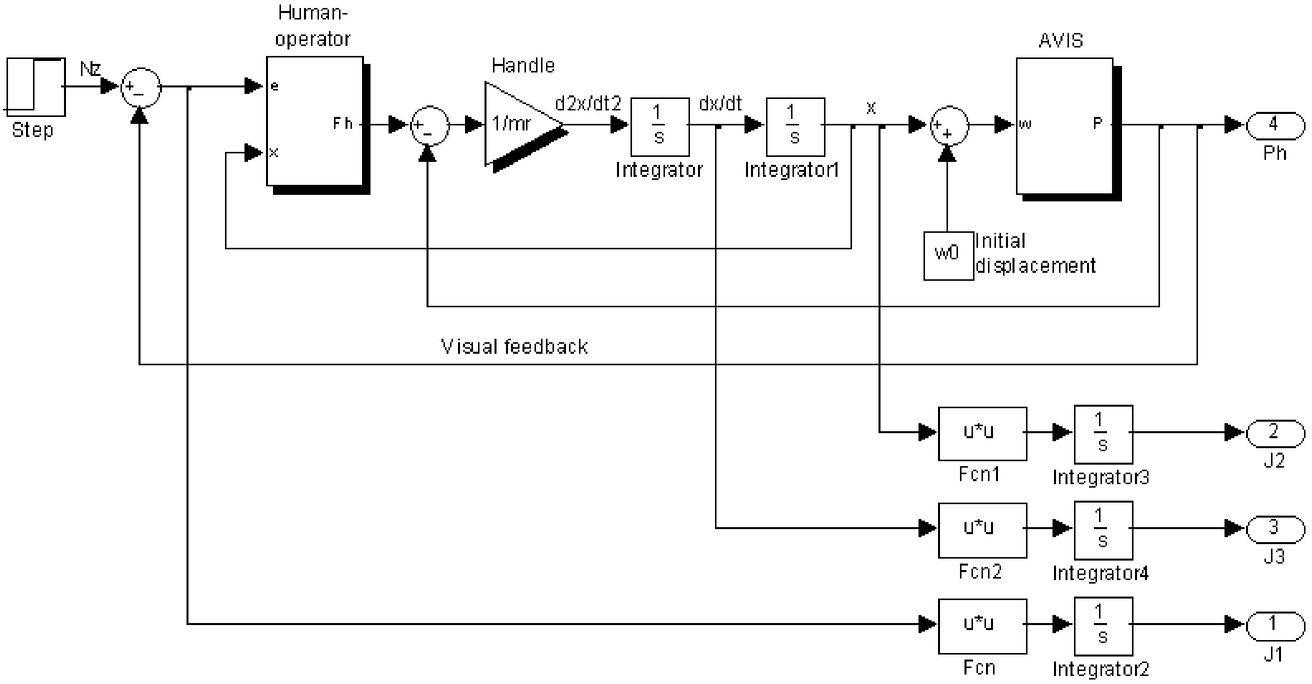

Fig. 5. Simulation model of the system operator-tool-base

The simulation model was used in simulation studies of the system behaviour, concerning the slow-varying processes during the work of tool controlled by operator. The system consists of two main subsystems: human-operator and active vibration isolation system (AVIS). The handle is represented as an amplifier with the gain $1/m_r$, where m_r is the mass of handle. Testing input signal, representing given pressure force N_z, was assumed in the form of step function. Such approach corresponds practically to character of continuous work with percussive tool which can be characterized by short (several or a dozen or so seconds), repeated periods of pulse trains of impacts. Each period begins with switching on the power and application to the handle, almost at the same time, early intended pressure force. The period ends with switching off the power and disengaging of pressure force by operator. During the work period the operator can correct (increase or decrease) the applied force by observing the process and work efficiency. In the paper, the simulation time t_k corresponds to the period of work described above. As it was shown in section 3 the work efficiency $v(t)$, quantity observed by visual feedback by the operator, can be substituted by force $P_h(t)$, transmitted through vibration isolation system to the tool's body. The visual feedback shown in block-diagram corresponds to output force $P_h(t)$. Outputs 1, 2 and 3 are used in calculation of defined below comfort indices J_1, J_2, J_3. Due to the pre-tension P_w in vibration isolation system the position of this system at the initial moment is described by displacement $w(0) = w_0 < 0$, which before each start of simulation is calculated from the following equation

$$c_n w_0^3 + c w_0 + P_w = 0 \tag{8}$$

Relation between the displacement in vibration isolation system w and displacement of handle x given by

$$w = x + w_0 \tag{9}$$

was taken into account in simulation block-diagram. At the initial position the integrator is switched off. It switches on at the moment of beginning of simulation. This corresponds to the moment of switching on the power in the active system.

7. COMFORT INDICES

In analysis of man – machine systems the problem of handling qualities [5] is one of the most important. Applying this kind of assessment to the control possibilities of the operator-tool-base system, three indices characterising the quality of the work process have been proposed. They can be considered as the decisive factors of work comfort feeling.

First index is defined by functional (10) as follows

$$J_1 = \int_0^{t_k} (N_z - P_h)^2\, dt \Big/ \int_0^{t_k} (N_z - F_{h0})^2\, dt \tag{10}$$

where $F_{h0}(t)$ is the corresponding time history of pressure force in situation when the handle is rigidly coupled with tool's body. In the considered case this signifies, that the handle is immobile and the pressure forces on handle and tool's body are equal. The functional (10) defines task performance.

Indices

$$J_2 = \frac{1}{t_k} \int_0^{t_k} x^2\, dt \tag{11}$$

and

$$J_3 = \frac{1}{t_k} \int_0^{t_k} \dot{x}^2\, dt \tag{12}$$

can describe either physical or mental workload of operator. The less values of these indices the bigger feeling of work comfort. In general, the handling qualities of tool can be characterized by the following performance index

$$J = q_1 J_1 + q_2 J_3 + q_3 J_3 \tag{13}$$

where q_i ($i = 1, 2, 3$) are arbitrarily chosen weighting coefficients.

The main index characterizing the efficiency of AVIS is degree of vibration reduction of handle. In the paper this index has been defined with some simplification. If we assume that tool's body is separated from handle by AVIS and its vibration is known having character of kinematic excitation, the index of vibration reduction will be defined as ratio of vibration levels of handle and tool's body. Vibration of percussive tools has periodic character. The most important is fundamental frequency corresponding to impact frequency. The tool body vibration $y(t)$ has been assumed in the form of a harmonic function with frequency $\omega_1 = 188{,}49$ 1/s , ($f = 30$ Hz). Presented below way of estimation of index of vibration reduction can be also applied to poly-harmonic excitation.

Absolute displacement of handle can be considered as sum of slow ($x(t)$) and fast ($x_1(t)$) varying components and written as follows

$$\tilde{x}(t) = x(t) + x_1(t) \tag{14}$$

Relative displacement can be presented in the analogous way

$$\tilde{w}(t) = w(t) + w_1(t) \tag{15}$$

where fast-varying component is given by

$$w_1(t) = x_1(t) + y(t) \tag{16}$$

Total force reaction of AVIS can be presented as follows

$$P(t) = P_h(t) + P_1(t) \tag{17}$$

Amplitudes of $w_1(t)$ are small in comparison with possible slow-varying displacements $w(t)$. Doing linearization of characteristics (6) for signal $w_1(t)$ in the vicinity of $w(t)$ we can describe force $P_1(t)$ in the form

$$P_1 \cong (c + 3c_n w^2) w_1 + b\dot{w}_1 \tag{18}$$

In this expression the last component of characteristic of VIS was omitted because within the considered range of frequency its influence is negligible as the integral component filters high frequencies. The dynamical characteristics of operator's hands are indispensable for estimation of handle displacement $x_1(t)$. In that case the model shown in the Figure 4 cannot be applied because in the range of considered frequencies dynamical properties of operator hands are different than frequencies of slow-varying processes. Taking into account one-mass hand model of Reynolds [7] transmissibility $X_1(s)/Y(s)$ can be presented in the form

$$W(s;w) = \frac{X_1(s)}{Y(s)} = \\ = \frac{bs + (c + 3c_n w^2)}{(m_r + m_R)s^2 + (b + b_R)s + (c + 3c_n w^2)} \tag{19}$$

where:

m_R = 0.103 kg,
b_R = 39.5 Ns/m,
c_R = $3.65 \cdot 10^3$ N/m,

are the parameters of model of hand.

Putting $s = i\omega_1$ into (19) the degree of vibration reduction can be presented as follows

$$K(w) = \left| W(i\omega_1; w) \right| \tag{20}$$

Index (20) is a function of slow-varying displacement $w(t)$. During one period of work t_k, in spite of existing transient process caused by sudden changes of applied pressure force, this index does not change. Finally, as a measure of efficiency of AVIS the following mean value was assumed

$$J_w = \frac{1}{t_k} \int_0^{t_k} K(w(t))dt \tag{21}$$

The values of indices (10)–(13) and (21) were calculated from simulation of the system operator-tool, shown in the Figure 5, in the range of time $[0, t_k]$, with assumptions that input is a step function and that excitation $y(t)$ is omitted. The general criterion of assessment of AVIS was considered in the form

$$Q = J_W + \alpha J \tag{22}$$

where parameter α was a chosen weighting multiplier.

8. SIMULATION RESULTS

Influence of parameters including nonlinear stiffness characteristic (6) on work of AVIS and, in particular on the work comfort indices defined above, was main target of calculation and simulation. All results were obtained for presented in section 5 values of parameters. Other constant values were taken as follows: mass of handle m_r = 2 kg, damping coefficient b = 20 Ns/m, coefficient c_n = 107 $\mathrm{N/m}_3$. In each case the simulation time was t_k =10 s.

In the Figure 6 time histories of force $P_h(t)$ transmitted to handle and displacement of handle $x(t)$ for input step force N_z = 100 N were shown.

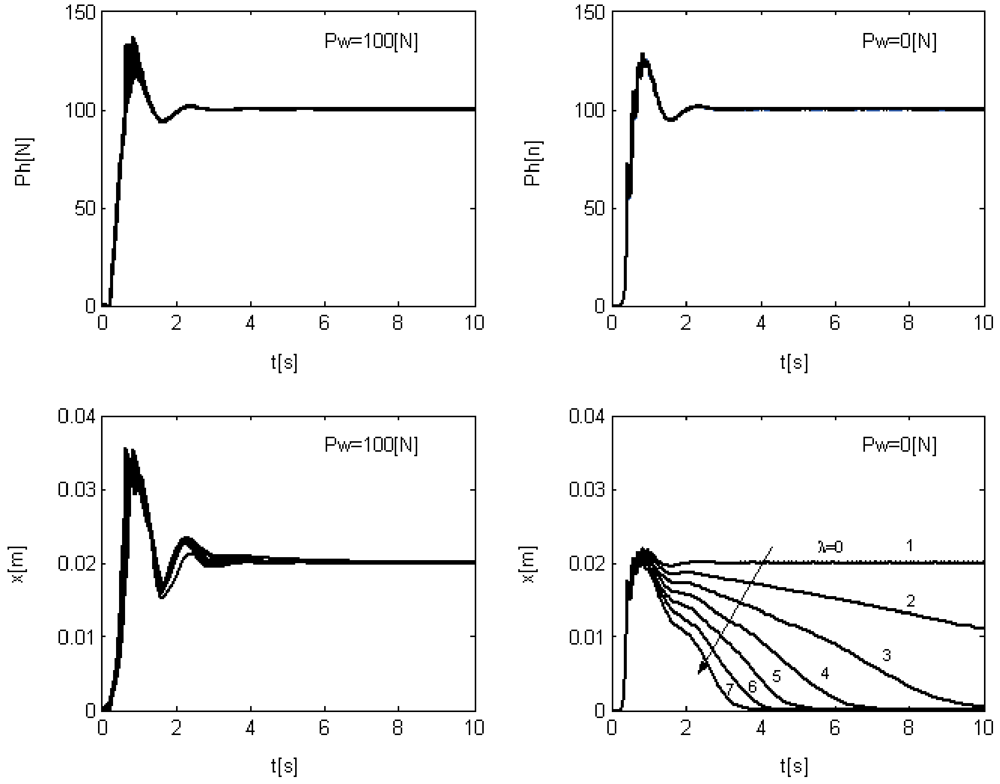

Fig. 6. Time histories of $P_h(t)$ and $x(t)$

The time histories with pre-tension P_w =100 N and without pre-tension P_w = 0 N are shown correspondingly on the left and on the right side of the Figure 6.

In this figure the influence of parameter λ from the formula (6) was also presented. Curves numbered i = 1, ..., 7 in lower, right side of Figure 6 were drawn for the values λ_i = = 500·(i–1) N/sm.

Influence of parameters c and λ, (with constant N_z = 100 N) on comfort indices J_1, J_2, J_3 and J_w was shown in the Figures 7 and 8 which illustrate correspondingly cases where P_w =100 N and P_w = 0 N.

Sensitivity of comfort indices on step value of N_z, for constant values of $c = 10^3$ N/m and P_w was shown in the Figures 9 and 10. In these figures the influence of parameter λ was also presented.

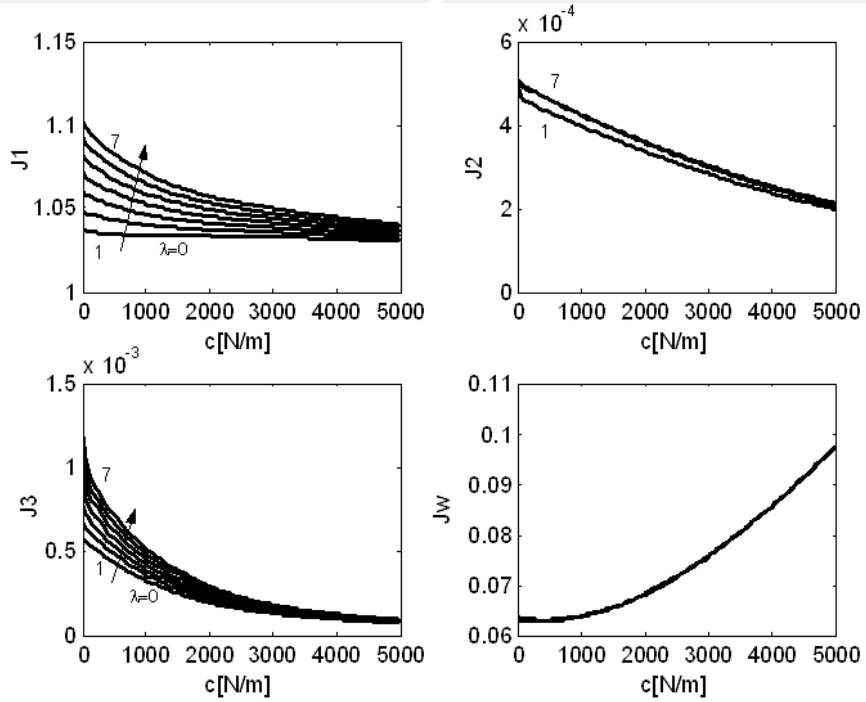

Fig. 7. Influence of stiffness c and parametr λ on comfort coefficients with P_w = 100 N

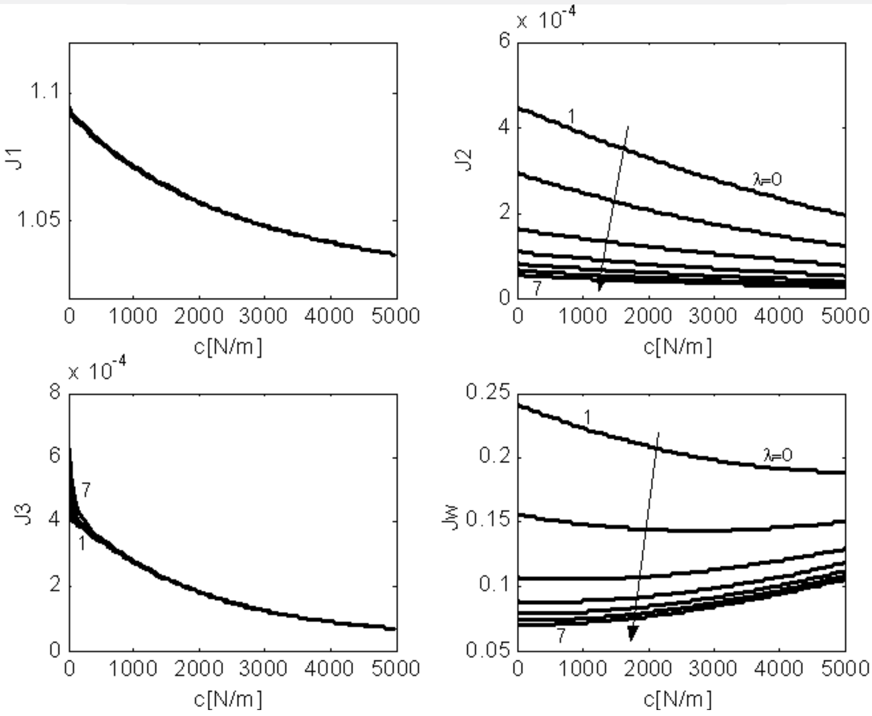

Fig. 8. Influence of stiffness c and parametr λ on comfort coefficients with P_w = 0 N

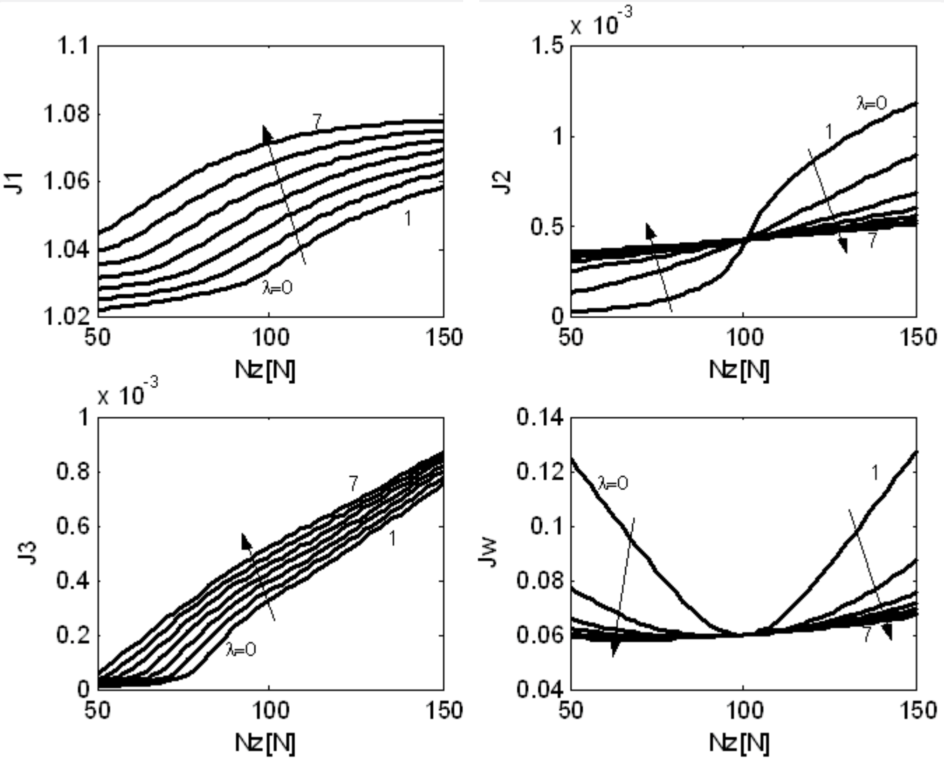

Fig. 9. Influence of value of N_z and parametr λ on comfort coefficients with P_w = 100 N

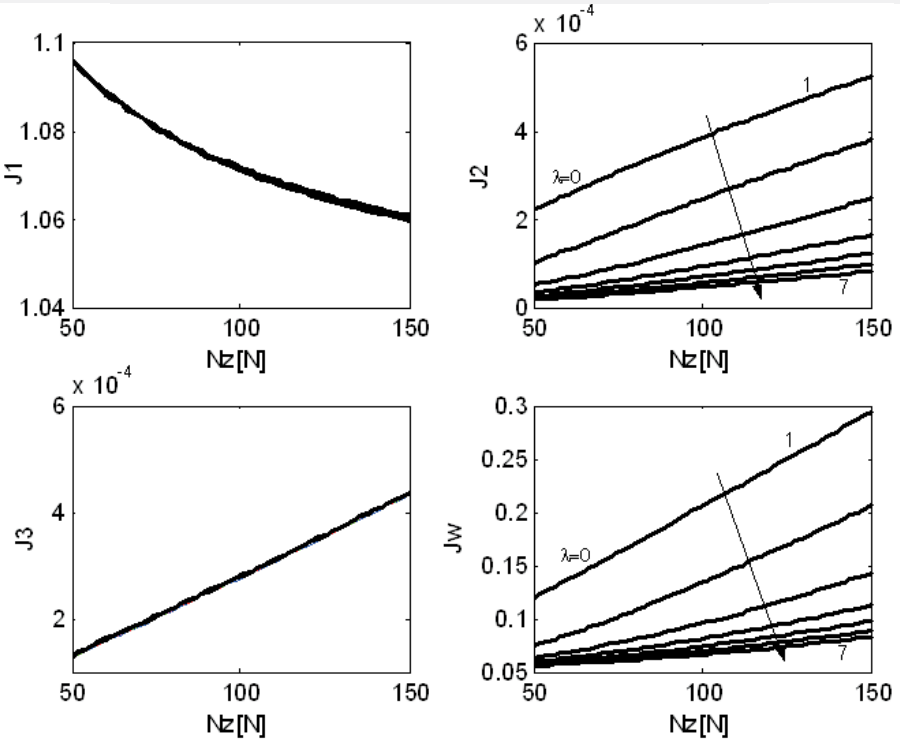

Fig. 10. Influence of value of N_z and parametr λ on comfort coefficients with P_w = 0 N

9. CONCLUDING REMARKS

The presented results confirmed the supposition that hand – tool operator should be modelled as a control system. Such approach allows for appropriate design of vibration isolation of handle. As it was shown in the Figure 7, for pre-tension case – P_w = 100 N, with increase of the value of the stiffness parameter c, indices J_1, J_2, J_3 decrease but vibration isolation index J_W increases. Little negative influence of the active element ($\lambda > 0$) can be observed on the indices J_1 and J_3. The influence of active element ($\lambda > 0$) on indices J_2 and J_W is negligible. In case when $P_w = 0$, shown in the Figure 8, quite different situation takes place. In this case one can observe big, advantageous influence of parameter λ on indices J_2 and J_W. There is no influence of parameter λ on indices J_1 and J_3. The Figure 9 shows changes of corresponding indices in case when the required pressure force N_z is different than the fixed value $P_w = 100$ N. With increase of the value of λ the sensitivity of indices J_2 and J_W, on difference between N_z and P_w, decreases. In case $P_w = 0$, shown in the Figure 10, increase of λ makes index J_2 and (what is the most important) index J_W more independent of force N_z, and simultaneously decrease values of these indices.

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