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A SEMI-ACTIVE PNEUMATIC SUSPENSION OF THE WORKING MACHINE SEAT

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Abstract: *The paper presents issues related to improving the vibro-isolating properties of the semi-active electro-pneumatic suspension of the working machine seat. A practical implementation of the system controlling the force of the pneumatic spring mounted in the seat suspension mass-produced was presented herein. An output function controlling the pressure valve of the pneumatic system supplying the bellow actuator was suggested. The developed solution made it possible to conduct dynamic tests over the pneumatic spring applied in relation to the semi-active suspension system.*

Keywords: Vibro- Isolation, Semi-Active Suspension Control, Bellows Actuator.

1. Introduction

Vibrations are transferred from the mechanical vibrating systems to humans and negatively affect the functioning of their various tissues, blood vessels and organs. A number of body disorders are found among humans exposed to continuous influence of mechanical vibrations, and as a consequence, persistent lesions in the form of vibration syndrome. It applies to many professional groups performing their work in a sitting position, i.e.: operators of construction machines, vehicle and tractor drivers (Guglielmino et al., 2008; Maciejewski and Krzyżyński, 2011; Mizuno, 2005).

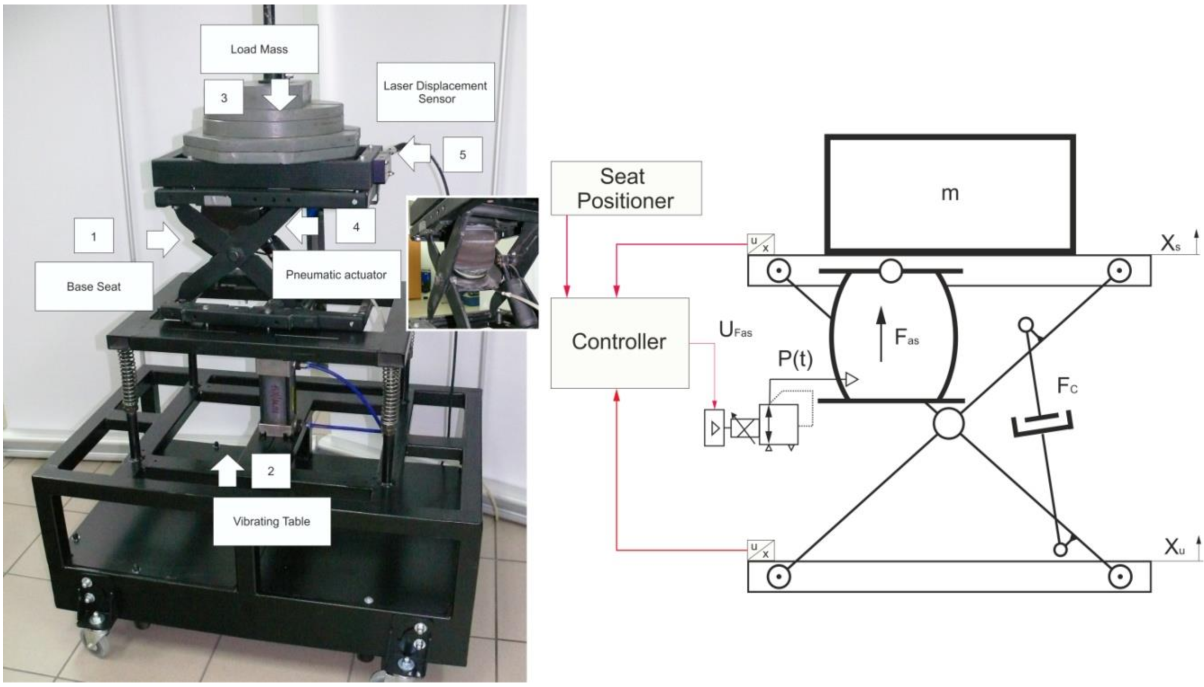

Fig. 1: General view of the experimental stand, a block diagram of the semi-active control system of the seat suspension.

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Many structures use solutions which make it possible to change the damping factor by the operator depending on the individual assessment of his weight and the working conditions. Effective damping can be obtained automatically or manually by setting the constant pressure value (pneumatic spring) or voltage (current) in the silencer with variable damping characteristics (magneto-rheological fluid). Semi-active systems with dampening or elasticity coefficients variable over time and determined by the control system constitute an extension of this method. The value of elasticity or damping coefficients changes continuously, and thus, it can be updated during the operation of the machine which is exposed to vibrations caused by the conditions of the road, or the vibrations themselves caused by the devices. The advantages of the semi-active systems include their low requirements as far as the power of an external energy source is concerned. That is why, such systems are often used in practice. They make it possible to reduce the seat vibrations with low frequency of excitation forces (up to 5 Hz), while maintaining good vibro-isolating properties at higher frequencies of excitation forces (Tora, 2013). The works in order to develop new constructions for seat suspensions with the use of active and semi-active and active vibration reduction systems are conducted in the Department of Manufacturing Engineering and Metrology at the Faculty of Mechatronics and Mechanical Engineering of the Kielce University of Technology. A design of a semi-active seat suspension with a controlled pneumatic bellow spring was developed. An experimental test stand to study the vibro-isolating properties of the working machine seat is shown in Fig. 1. The basic element thereof is a pneumatic-hydraulic vibro-isolator of the base of the working machine seat (1). The vibro-isolator is composed of a frame in the shape of a bi-link four-bar linkage which the seat of the machine operator is ultimately mounted to. A pneumatic bellow actuator and a hydraulic damper are connected with the rocking levers of the quadrangle (Woś et al., 2013).

2. Modelling the vibro-isolating properties of the test stand

A simplified model of the seat suspension includes system elastic force derived from pneumatic spring F_{as}, damping force F_c of the hydraulic damper and G-force of mass load F_g. A bellow actuator applied in the system has some specific physical properties. After filling it with compressed air, it may act as a pneumatic spring. If a charged bellow actuator is loaded with mass, the vibrating system will be received. Force F_{as} coming from the pneumatic spring and acting in the vertical direction on the object isolated from vibrations, was defined as the product of effective area A_{ef} and relative pressure p-p_0:

$$F_{as} = A_{ef} \cdot (p - p_0) \tag{1}$$

With an increase of pressure p, and thus, an increase of volume V, height h of the bellow increases and simultaneously its effective area A_{ef} is reduced.

Stiffness k of the pneumatic bellow is expressed with the ratio of load F_g compared to deflection h of bellow $k = dF_g / dh$, and the dependencies on deflection h and pressure p were specified in the following way (Dindorf, 2013):

$$k(h, p) = p \frac{dA_{ef}}{dh} + \frac{A_{ef}^2}{C_g(p)} \tag{2}$$

Where: C_q gas capacity of the bellow, $C_g = V/K_g$, K_g modulus of air elasticity, $K_g = \kappa\, p$, $\kappa = 1.4$ – adiabatic exponent.

The bellow force acting on the suspension system was defined in the following way:

$$F_{as}(h) = k(h)\left(h_0 - h\right) = \kappa \cdot p_0 \cdot A_{ef} \frac{h_0 - h}{h_0} \left(\frac{h_0}{h_0 - h}\right)^{\kappa+1} \tag{3}$$

Frequency f_o of the bellow vibrations amounts to:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{\kappa \cdot p_0 \cdot g}{h_0 \cdot p}} \tag{4}$$

An appropriate degree of vibro-isolations of the bellow actuator (pneumatic spring) is found in for frequency $f = 1.4\, f_0$. Fig. 2 shows the timeline of the vibro-isolating seat mass for rectangular extortion. The research was conducted with determined pressure values p. Fig. 3 shows the timelines of the vibro-isolating mass (72 kg) with extortion frequency of 2 Hz and a pressure change in the bellow. The system achieved the best vibro-isolating properties for the pressure ranging from 3.44 to 4.25 bar.

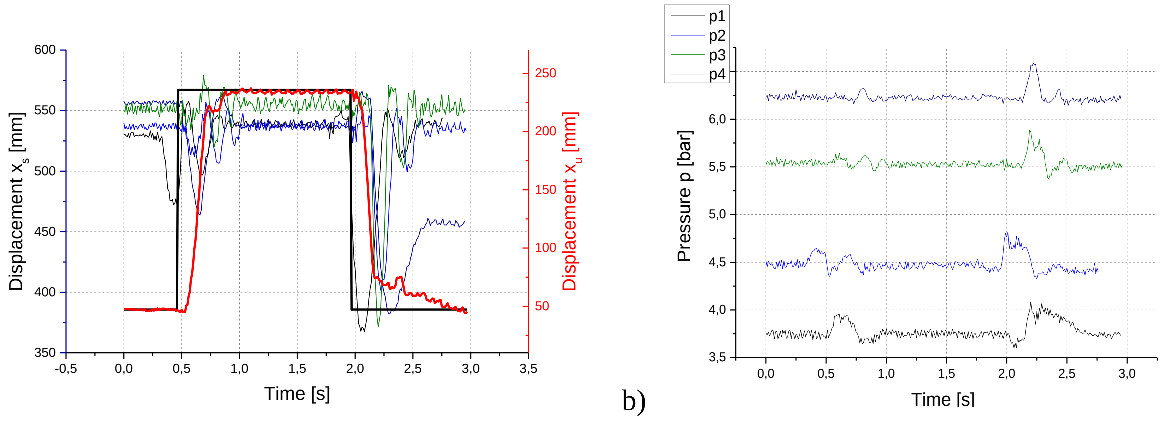


Fig. 2: Timelines of the displacements of vibro-isolating mass x_s and extortion x_u a) for various pressure values b).

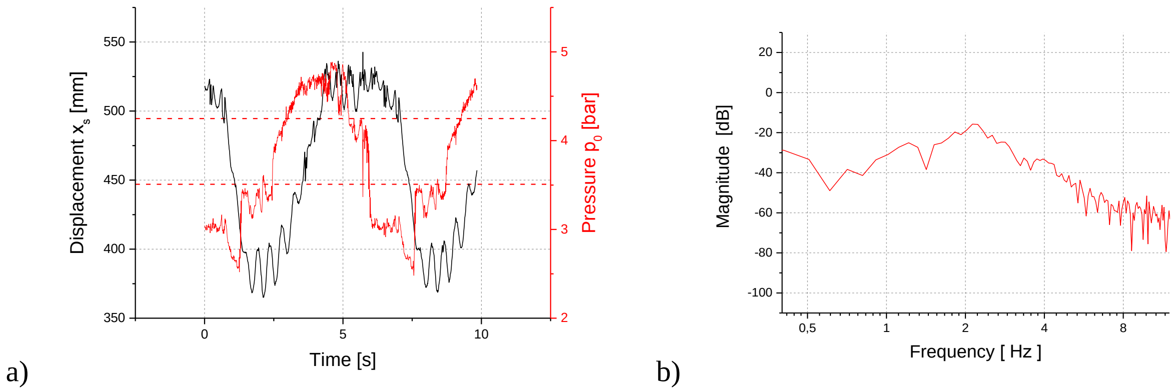


Fig. 3: Timelines of vibro-isolating mass displacements with pressure change p a) and frequency response of displacements of system vibrations b).

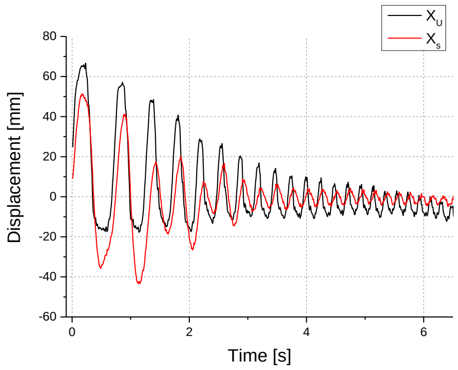
3. Control system

The primary objective of the seat control is to reduce the acceleration, which the driver is affected by. Controlling the suspension system (Fig. 1) is based on the measurements: the displacement of the working seat system with the mass, and the relative displacement of driver's seat (x_s) and substrate (x_u). The function of the controller is to tune the pre-determined pressure in the bellow actuator in such a way so that as the acceleration of the seat is minimized. The initial pressure determination in the bellow depends on the weight of the vibro-isolating mass. Force F_{as} generated in the semi-active system does not depend only on the control signal, but also on current seat deflection x_u, x_s. The value of the voltage controlling the pressure valve is calculated on the basis of the mass function:

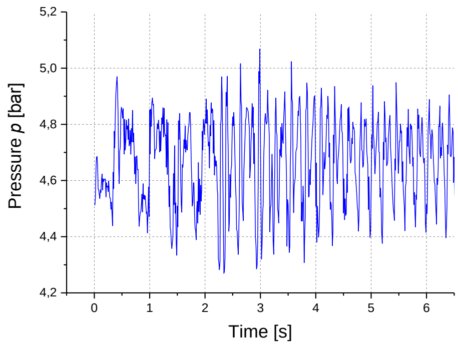
$$u_{F\,as} = u_{ref} + w \cdot \left(k_1 \cdot u_2(\dot{x}_u - \dot{x}_s) + k_2 \cdot u_2(x_u - x_s)\right) \tag{5}$$

where: $w = \left| \dfrac{x_u - x_s}{(x_u - x_s)_n} \right|$, $(x_u - x_s)_n$ - nominal value of the relative displacement of the suspension system, k_1, k_2 - coefficients of the controller reinforcements.

Fig. 4 presents the timelines of the displacements of vibro-isolating mass x_s and substrate x_u for extortions with a sinusoidal signal with the amplitude of 80 mm and modulated frequency ranging from 0.1 Hz to 6 Hz. As a result of the controller’s operation of the semi-active system with an adjustable stiffness of the pneumatic spring, the amplitude of the vibro-isolating mass response was decreased. For mass of 72 kg, bellow pressure of 4.6 bar and frequency of free vibrations of 2.2 Hz, the transmission of vibrations decreased by approximately 22 dB. At high frequencies (from 4 Hz), the change of dampening properties of the system with a pneumatic spring is almost unnoticeable.



a)



b)

Fig. 4: Timelines of the displacements of the vibro-isolating mass a) and adjustable pressure value b).

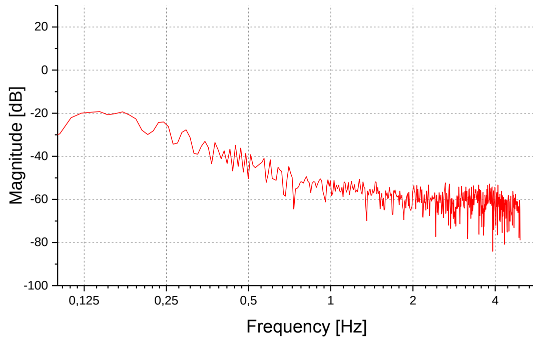


Fig. 5: Frequency response of semi-active vibro-isolation.

4. Conclusions

The solution of the seat vibro-isolation suggested herein is based on the existing construction solution of the passive suspension system applied commonly in working machines. Such systems are characterized by low effectiveness of vibration reduction as far as low frequencies of extortions are concerned, as there is an amplification of vibrations in the case of frequencies of free vibrations (1 – 2 Hz). Due to the control system applied to adjust the stiffness of the pneumatic spring, the vibro-isolating properties of the seat for a given range of extortion frequencies were improved. A significant advantage of the developed system is its low demand for power of the external energy source. The suggested system effectively reduces the values of the relative seat displacements, and hence, the comfort and safety at work might be improved in the future.

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