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A COMPARISON OF THE HUMAN BODY-SEAT MODEL RESPONSES TO SEVERAL TYPES OF IMPULSE EXCITATIONS

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The purpose of this paper is to present the response of a human body-seat model to the external disturbance in form of an impulse excitation. A 2-DOF Active Human Body Model with two distinct positions ("back-on" an "back-off") is used in the simulations. Additionally, two different seat types are considered: rigid and passive. Several types of impulse excitations are used ranging in shape, amplitude and disturbance time. A comparison of the results is made: the first on the assumption of equal excitation energy, and the second one for impulses of equal amplitudes but different duration.

Keywords: impulse excitation, vibroisolation, body-seat model

1. Introduction

The behaviour and response of a human body to sudden excitations and disturbances has become an important area of research, judging solely the amount of books and publications regarding the topic (Griffin, 1990; Fritz, 1999; Liang and Chiang, 2008; Książek, 2011; Nawayseh and Griffin, 2009). Numerous experiments and tests were performed (Cho and Yoon, 2001; Książek and Łuczko, 2007; Blood *et al.*, 2010), for the purpose of reducing the influence of such disturbances to a human body. In addition to these experiments and mostly thanks to them, several analytical human body models were designed (Kim*et al.*, 2005; Hinz *et al.*, 2010; Książek and Ziemiański, 2012) presenting further possibilities for research in this field.

In this paper, one of such models found in the literature is analysed (Książek, 1999). The primary purpose of this analysis is to determine the effect of several types of impulse excitations upon the human body – the seat model. These types of excitations differ in terms of shape, amplitude and length, which allows comparing responses of the models.

2. Description of the Active Human Body Model (AHBM)

The biomechanical model of a sitting human body used for the purpose of this analysis is taken from (Książek, 1999b). The characteristic feature of this model is the possibility to analyse two distinct human positions: "back-on", with the back of the body supported by a chair, and "back-off" without such a support. It was shown in an earlier research (Książek, 1999a) that the behaviour of the model subjected to harmonic excitation strongly differs depending on the position assumed by the passenger.

In Figs. 1a and 1b the 2-DOF model of the human body for two different type of seats is shown. The seat on the left is a rigid one, represented by a lumped mass m_0. The right seat is a passive one, consisting of a mass m_0, damper α_m and spring k_m. These additional elements make it possible for the seat to behave as a simple vibroisolation system (VIS).

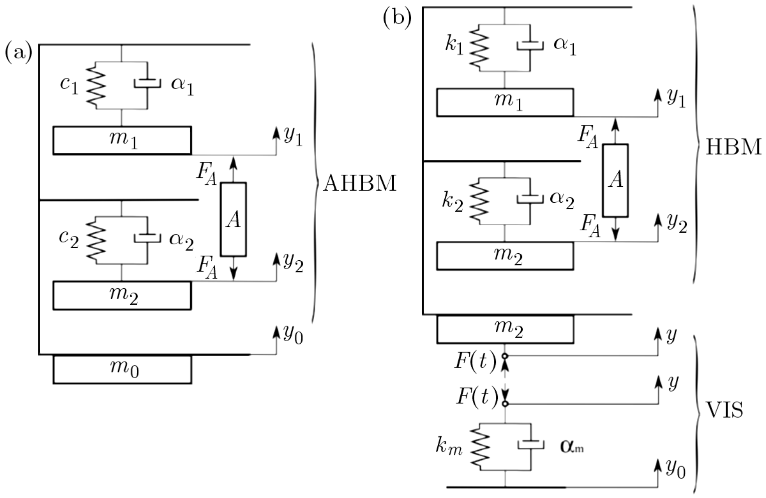

Fig. 1. Active human body model with rigid seat (a) and with passive (VIS) seat (b), Książek (1999b)

While the "back-on" and "back-off" body positions share the same model as shown in Fig. 1, they differ in terms of active control forces developed in the body as well as the values of separate parameters. The control forces for each model can be written using the following equations

$$
\begin{aligned}
F_{back-off} &= -k_{11}(y_1 - y_0) - k_{12}(\dot{y}_1 - \dot{y}_0) - k_{13}(y_2 + y_0) - k_{14}(\dot{y}_2 + \dot{y}_0) \\
F_{back-on} &= -k_{11}(y_1 + y_0) - k_{12}(\dot{y}_1 - \dot{y}_0) - k_{13}(y_2 + y_0) - k_{14}(\dot{y}_2 - \dot{y}_0)
\end{aligned}
\tag{2.1}
$$

The parameters on the other hand are calculated based on both these equations and the values obtained during the experimental phase. The parameters acquired for both positions, for the human body of mass 70.8 kg are provided in Table 1.

Table 1. Parameters for "back-off" and "back-on" position

	"back-off"	"back-on"
m_1 [kg]	9.1	66
k_1 [N/m]	11972.5557	51189.32
α_1 [Ns/m]	3251.9783	1704.17
m_2 [kg]	61.7	4.8
k_2 [N/m]	22456.7485	63335.50
α_2 [Ns/m]	519.044	1262.59
k_{11} [N/m]	97323.2354	123251.32
k_{12} [Ns/m]	-2226.0653	-1781.04
k_{13} [N/m]	-1960.5176	-104227.69
k_{14} [Ns/m]	1164.3525	759.69

By using the models shown in Fig. 1 and described by Eqs. (2.1), it is possible to obtain the transfer functions between both masses and the ground (H_{1g}, H_{2g}) for every presented combination of the position and seat type. These, in turn, after substitution of the parameters (Table 1) are used to obtain the response of the masses to an impulse excitation.

3. Response of the AHBM to impulse excitation

3.1. Choice of impulse types

The aim of the paper, as stated before, is to analyse the behaviour of the human body-seat model under an impulse excitation. In order to do so, the definition of such an excitation needs to be provided first. For this purpose, several types of impulse functions, differing in shape have been chosen. The list of functions is provided in Table 2 with the shapes presented in Fig. 2 and impulses defined by Eqs. (3.1)-(3.4), respectively.

Table 2. List of impulse excitations

Impulse type	Amplitude [–]
square	10
triangle	17.3205
half-sine	14.1421
spline	17.5158

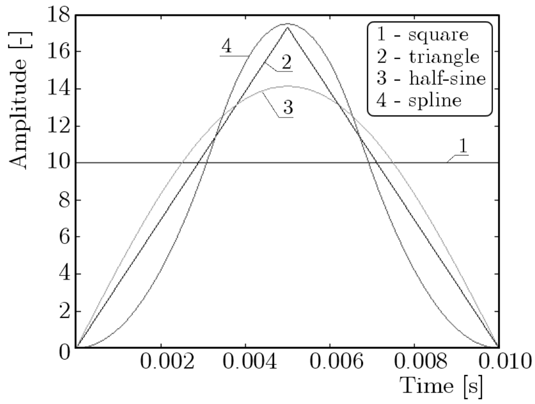

Fig. 2. Shapes of impulse excitations

The value of amplitude associated with each function has been calculated on the assumption of equal "signal energy" E_x and equal time Δt of the disturbances. This assumption has been made to ensure that the results obtained from the analysis for different impulse excitations are comparable. The energy E_x of each signal $x(t)$ can be calculated using Eq. (3.5). It should be noted that the energy obtained this way may have units other than [J], and depends on the unit of the signal used for the calculation.

While in Table 2 no physical unit is assigned to the amplitude, in this paper it is assumed that the excitation is in form of a sudden displacement (bump), and the units are given in centimeters. Using the previously found transfer functions between both masses of the model and the ground (H_{1g}, H_{2g}) it is possible to directly obtain the displacement. From these displacements, it is possible to calculate the acceleration and, in turn, the forces to which these masses might be subjected

$$x_{sq}(t) = A_{sq} \qquad t \in [0, \Delta t] \tag{3.1}$$

$$x_{tr}(t) = \begin{cases} \dfrac{A_{tr}}{\Delta t} t & \text{for} \quad t \in \Big[0, \dfrac{\Delta t}{2}\Big] \\ \dfrac{-A_{tr}}{\Delta t} t + 2A_{tr} & \text{for} \quad t \in \Big[\dfrac{\Delta t}{2}, \Delta t\Big] \end{cases} \tag{3.2}$$

$$x_{hs}(t) = A_{hs} \sin\Big(\frac{\pi}{\Delta t} t\Big) \qquad t \in [0, \Delta t] \tag{3.3}$$

$$x_{sp}(t) = \begin{cases} \dfrac{12A_{sp}}{\Delta t^2} t^2 & \text{for} \quad t \in \Big[0, \dfrac{\Delta t}{3}\Big] \\ \dfrac{12A_{sp}}{\Delta t^2} \Big[\dfrac{3}{4}\Big(\dfrac{\Delta t}{3}\Big)^2 - \Big(t - \dfrac{\Delta t}{2}\Big)^2\Big] & \text{for} \quad t \in \Big[\dfrac{\Delta t}{3}, \dfrac{2\Delta t}{3}\Big] \\ \dfrac{12A_{sp}}{\Delta t^2} (t - \Delta t)^2 & \text{for} \quad t \in \Big[\dfrac{2\Delta t}{3}, \Delta t\Big] \end{cases} \tag{3.4}$$

$$E_x = \int_0^{\Delta t} x^2(t)\, dt \tag{3.5}$$

3.2. Response to impulse excitation (equal energy)

The first series of tests have been performed for selected impulse excitations on the assumption of equal energy and equal time, as stated in the previous Subsection. While the shapes and amplitudes of the impulses are different by this assumption, the results proved to be almost identical with no regard to the type on the excitation. Therefore, the results for both masses and both types seats, are presented only for one type of the impulse.

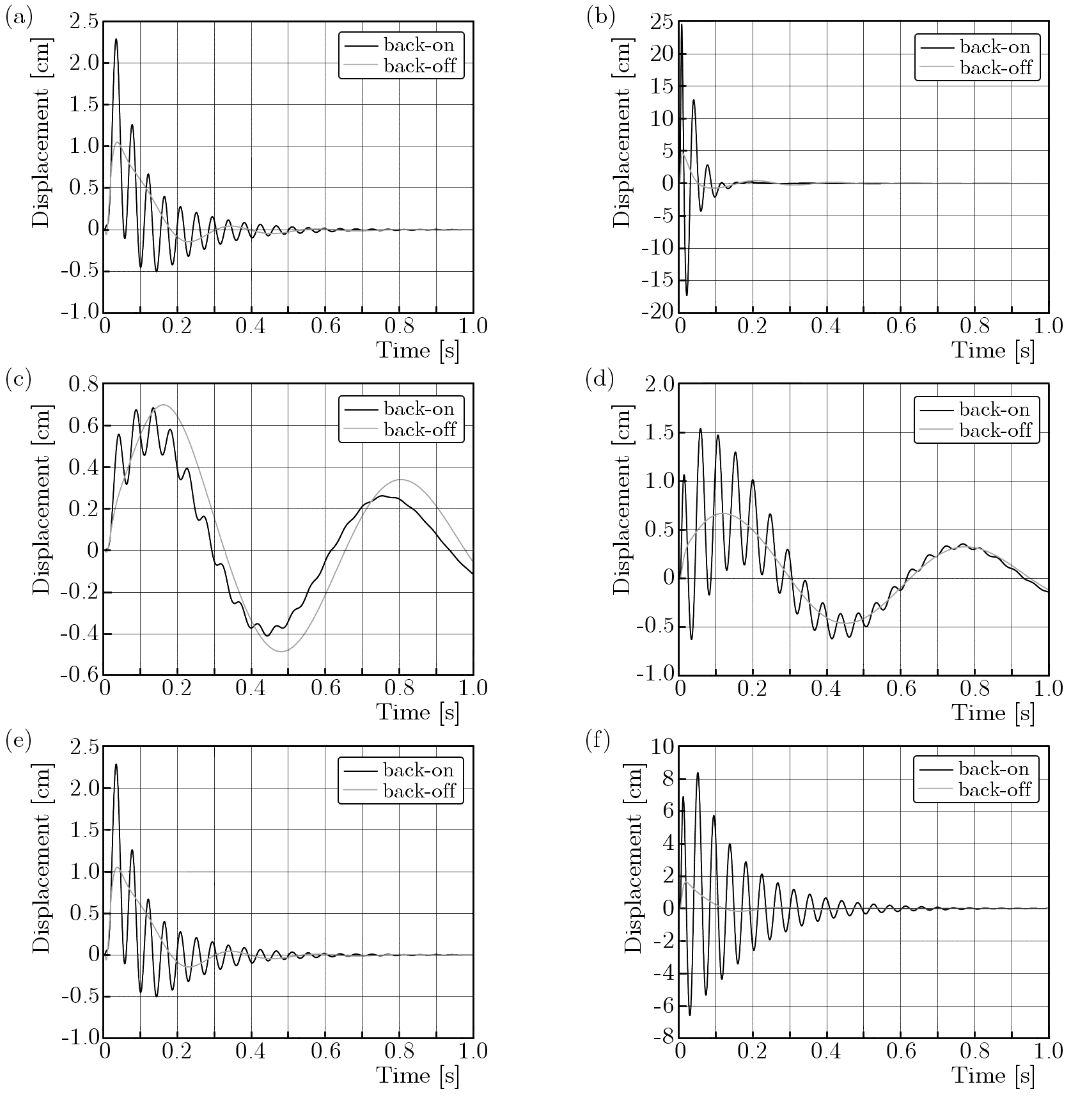

Fig. 3. Response of the human body-seat model to the impulse excitation for both "back-on" and "back-off" positions: (a) upper mass, rigid seat; (b) lower mass, rigid seat; (c) upper mass, passive seat ($\alpha = 260\,\mathrm{Ns/m}$); (d) lower mass, passive seat ($\alpha = 260\,\mathrm{Ns/m}$); (e) upper mass, passive seat ($\alpha = 2600\,\mathrm{Ns/m}$); (f) lower mass, passive seat ($\alpha = 2600\,\mathrm{Ns/m}$)

In Fig. 3, the response of the model to the considered impulse disturbance is presented. In the case of the model with the rigid seat (Figs. 3a,b), the displacement for both masses is quite high, especially for the "lower mass" m_2 in the "back-on" position, for which it reaches the value of 25 cm. In addition to that, the frequency of oscillations caused by the impulse is greater than that for the "back-off" position. By analysing both these factors (amplitude and frequency of oscillation), a conclusion can be drawn that in the case of the "back-on" position the accelerations caused by the impulse excitation and by extension forces, to which the "lower mass" is exposed, are much higher than in the other case ("back-off" position).

In Figs. 3c,d, the response to the same excitation but with the seat type changed to "passive" is shown. It can be seen that the simple vibroisolation system works as intended, and the amplitude of oscillations is much lower than for the model with the rigid seat. However, as before, it should be noted that the frequency of vibration for the "back-on" position is much higher than for the "back-off" position. Figures 3e,f used for the comparison show that the damper parameter α_m is ten times larger in this case. The frequency of oscillations is similar, but the amplitude in each case is much higher. This however is to be expected as the seat becomes more rigid with this modification. An additional confirmation of these observations can be obtained by analysing Bode plots of the models under consideration, see Fig. 4.

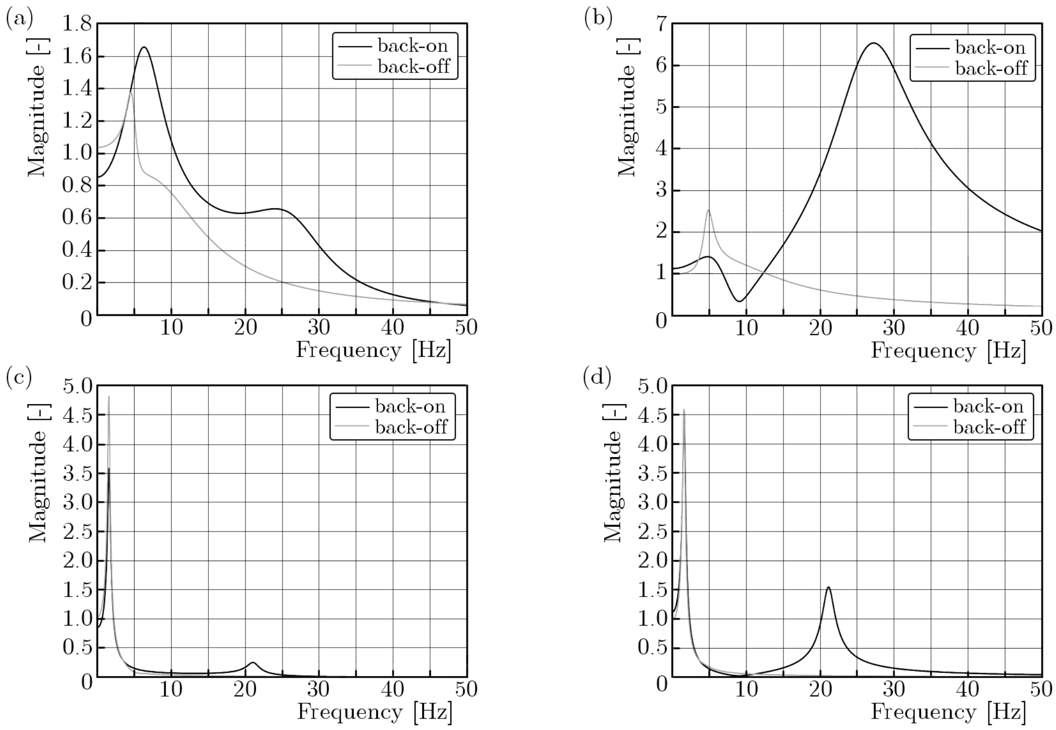

Fig. 4. Bode plot for both "back-on" and "back-off" positions in the range 0.1-50 Hz: (a) upper mass, rigid seat; (b) lower mass, rigid seat; (c) upper mass, passive seat $(\alpha = 260\,\mathrm{Ns/m})$; (d) lower mass, passive seat $(\alpha = 260\,\mathrm{Ns/m})$

3.3. Response to impulse excitation (velocity condition)

The second part of the analysis has been carried out on the assumption that the amplitude of the impulse excitation is constant, while the time in which this excitation occurrs vary. In the analysis, this could be interpreted as a model moving with a given velocity over a bump of a certain height and width. The faster the movement of the model, the shorter the time of the disturbance.

The shape of the impulse chosen for the purpose of this test is the "spline". The width of the bump considered in the analysis is $w = 0.5\,\mathrm{m}$, while the height h which corresponded to the amplitude of the impulse is equal to $0.1\,\mathrm{m}$. The values of velocity considered in the test are 5, 10 and $20\,\mathrm{m/s}$ with the impulse duration of 0.1, 0.05 and $0.025\,\mathrm{s}$, respectively. The results obtained for the passive seat with default parameters can be seen in Fig. 5.

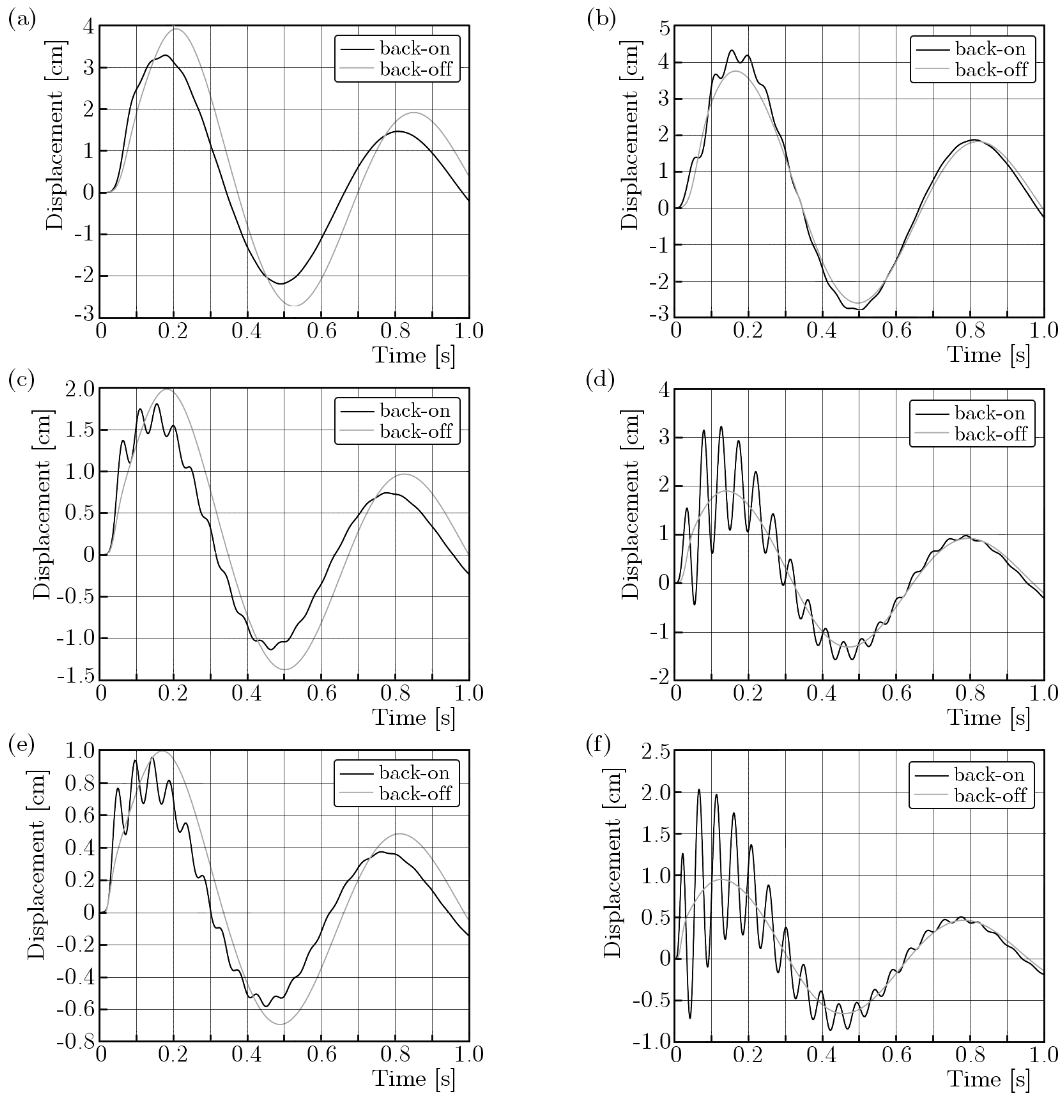

Fig. 5. Response of the human body-seat model with the passive seat to the impulse excitation of amplitude h equal to 10 cm but different time lengths Δt: (a) upper mass, $\Delta t = 0.1$ s; (b) lower mass, $\Delta t = 0.1$ s; (c) upper mass, $\Delta t = 0.05$ s; (d) lower mass $\Delta t = 0.05$ s; (e) upper mass, $\Delta t = 0.025$ s; (f) lower mass, $\Delta t = 0.025$ s

It can be noted in Fig. 5 that the response of the model is strongly dependent on the duration of the impulse. This is especially true in the case for the "back-on" position – the oscillation at velocity 20 m/s (0.025 s) is noticeably larger than that at 5 m/s (0.1 s). Worth noting is also the fact that the amplitude of the response is larger for longer impulse duration. This is related to the energy of excitation – with an increase in the impulse duration the energy is increased as well.

4. Conclusions

Several simulations and calculations have been performed in this paper in order to determine the response of the human body-seat model to an external excitation. The conclusions gathered from the results of these simulations can be written as follows:

- the "back-on" human body position is much more susceptible to an impulse excitation than the "back-off" one

- the response of the model is only slightly affected by the shape of the impulse; this is of course valid on the assumption of the equal signal energy and a short impulse duration
- depending on the velocity at which the obstacle (bump) is encountered, the response of the system changes; the shorter the duration (and therefore higher velocity), the stronger are high-frequency oscillations in the model; on the other hand the shorter time leads to a drop in the energy of the signal, and thus the amplitude of the response is lower.

Additional modifications are considered for the presented model and for further testing. The most important ones are the modification of AHBM equations to include non-linearities of the model and the addition of an active controller which along with the presented passive seat might improve the damping properties of the system, thus reducing the vibration to which the human body is subjected.

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