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Analysing the effect of helicopter pilot cushion on body vibrations through numerical and analytical investigation

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ABSTRACT

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Exposure to vibrations of certain frequencies can pose a risk to the pilot's body. During flight, the maneuvers performed by the pilot expose them to sudden and unfavorable accelerations, which can cause physical, physiological, and psychological problems. Researches indicate that the use of seat suspension systems is effective in reducing high-frequency vibrations. However, for small movements, which occur at low frequencies between 2 to 15 Hz, the cushion of the pilot's seat plays a more significant role. In this paper, we investigate the effect of the cushion on reducing vibrations in the pilot's body. At first, the results obtained from the biodynamic equations of the helicopter pilot's body have been compared and validated with the experimental results. Then, the biodynamic responses of the equations of motion using the finite element method have been compared with the experimental test results. Finally, the biodynamic responses of the pilot's body have been investigated by considering the cushion effect with two series and parallel models. The results show that the Kelvin model is much more accurate than the Comsol model.

Introduction

Helicopters are used in many military and civilian applications due to their unique capabilities. However, the high levels of vibration transmitted to the crew are the origin of many health problems such as fatigue and physical injuries to the crew over the long time. These vibrations are caused by the operation of the rotors, gearbox and engine, in addition to the structural vibrations caused by the unstable aerodynamics of the helicopter, they are usually transmitted to the body of the pilot and passengers through the cabin floor and seats [1]. One of the ways to reduce vibrations is to use an appropriate seat suspension system and cushion. The presence of dampers in the system reduces vibrations and increases the fatigue life of structural parts. In fact, high damping is one of the important factors in the design of machine components and industrial equipment. On the other hand, the type of materials used in the pilot's seat cushion is of particular importance. Of course, researches have shown that at low frequencies, the seat suspension system is not very useful in reducing the vibrations of the passenger's body, and the material of the cushion plays a more effective role in this regard [1].
The vibrations introduced to the body of the passengers and the helicopter pilot are usually in the low frequency range (usually below 10 Hz), while the natural frequency of the spine is between 4 and 8 Hz. Therefore, it increases the possibility of creating an escalation phenomenon in the spine [1]. This is an important factor in causing many injuries such as back pain, neck arthritis, etc. and has a serious impact on the health and performance

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of passengers. Therefore, removing the vibrations to the passenger and pilot of the helicopter has been an interesting subject in recent years.
Until now, for many cars, the vibration has been neutralized by using seat cushions or by inserting an energy absorber that works well against these frequencies in the low frequency absorption range, has been investigated [1].

Suleiman et al. use a control method to control the suspension system of a vehicle. In the presented model, the vehicle is modeled as 7 Degrees of Freedom (DOF). Also, in this research, a comparison between control strategies has been discussed [2]. Aksu et al., for road analysis, investigated the vehicle chassis, where the driver and passenger were modeled as a combination of mass and spring. In this analysis, the effects of the room and passengers in the stationary state have been omitted [3]. Kurdestani et al. performed a mathematical analysis of the sitting body model using a multi-degree-of-freedom system of masses, springs, and mechanical dampers, in which each of the masses contained one DOF in this model [5]. Panko et al., presented a new finite element model to estimate the internal force at the L3, and L4 vertebra. They assumed the beads to be rigid so that they could be analyzed better and faster with the software [6].
There are two types of models for the spine model of the human body. Continuous model and discrete model. In the continuous model, the spine is modeled as a rod that has an unlimited number of DOF. However, the continuous model is slightly different from the structure of the spine of the human body. In the discrete model, the structure of the spine is considered in the form of different anatomical elements of the body, such as vertebrae, discs, ligaments (robots and muscles), which are modeled separately. This model has many components and good coverage of the spine [7]. The first discrete model was presented by Ladam [8], based on the response of the human body during ejection from an airplane. One of the discrete models of the spine is presented by Yoshimura et al. [9].

In humans, brain, heart and lung lesions, rupture of abdominal membrane and chest cavities can vibrate. Although the whole-body acceleration contour is a function of frequency, significant data are not available for these cases. In one study, the exposure time of 15 minutes for 6 g vibration was reported, which causes gastrointestinal bleeding that lasts for several days [10]. Cardiovascular lesions may also occur during long periods of vibration. Epidemiological evidence states that people who were subjected to vibration had a higher risk of back pain, sciatica and lumbar disc compared to the control group who were not subjected to vibration. Also, the vibrations that occur in airplanes, ships and non-road vehicles increase the risk of heart problems [11]. Rakheja et al, showed that about 73% of the mass of the human body in a sitting position, when the feet are on the ground, is borne by the seat and the rest of the weight is borne by the feet [12]. Also, investigating the vibrations from the chair to the human body is very important

The leading standard in the field of Whole Body Vibration (WBV) is the ISO 2631-1 standard, which is used to evaluate the human body's tolerance against uniaxial vibrations. The ISO 2631-5 standard is used to evaluate the human body's tolerance against multiaxial vibrations. In fact, these two standards describe the measurements and analysis necessary to investigate the vibration transmitted to the human body through supporting surfaces such as legs, seat and back in standing, sitting and lying positions.
Most of the conducted researches are active regarding the suspension systems of the pilot's seat, as well as the modeling of several DOF of the human body, and not much has been studied about the effect of different cushions with different characteristics.

In this research, the effect of different cushions on the helicopter pilot's seat is investigated. There are vibrations. In the second part, due to the acceptable compatibility of the response of the biodynamic equations of motion in the 4 DOF model with the experimental results, in this research, this 4 DOF Boileau model has been used [12]. In the next part, the numerical modeling of the sitting human is done in the finite element software (Comsol) and the transmission capability is compared with two analytical and numerical solution methods, and in the final part, the effect of the seat cushion in two modes of analytical modeling of the model Kelvin-Woigt and Maxwell are investigated. One of the innovations of this research is the simultaneous comparison of pilot seat cushion modeling by Maxwell and Kelvin-Woigt methods, and also finding the most effective parameter related to the seat cushion material among the stiffness, damper and mass parameters of the cushion to find the greatest effect in reducing the vibrations of the pilot's body.

Biodynamic equations of motion

In the study of the biodynamic behavior of the body, three parameters are usually used in the study of the biodynamic behavior of the body, three parameters are usually used in the study of the biodynamic behavior of the body, three parameters are usually used in the study of the biodynamic behavior of the body, three parameters are usually used transmissibility, Driving point mechanical impedance and also the apparent mass. In equations 1 to 3 respectively the transmissibility of the seat to the head and resistance to mobility, as well as the apparent mass are shown. In these equations, STHT represents the seat to head transmissibility, DPMI represents mechanical impedance, and APM represents apparent mass, jω indicates the complex vector of the Fourier transform [13].

$$STHT(j\omega) = \frac{X_n(j\omega)}{X_1(j\omega)} \tag{1}$$

$$DPMI(j\omega) = \frac{F(j\omega)}{V(j\omega)} \tag{2}$$

$$APMS(j\omega) = \frac{F(j\omega)}{a(j\omega)} \tag{3}$$

Dynamic analysis of 4 DOF model

In order to obtain the response of the pilot's body to the vibrations coming from the seat, the models in which the human body is sitting on the seat should be examined. In this section, the 4 DOF model is modeled in which the pilot's body vibrates in the **Z** direction. Figure 4 shows the human body model, where the body parts are connected to each other by linear springs and linear dampers, which is in accordance with the 4 DOF model of Rakheja, the reason for choosing this 4 DOF model is the very good agreement of the results with Boileau's experimental model [12].

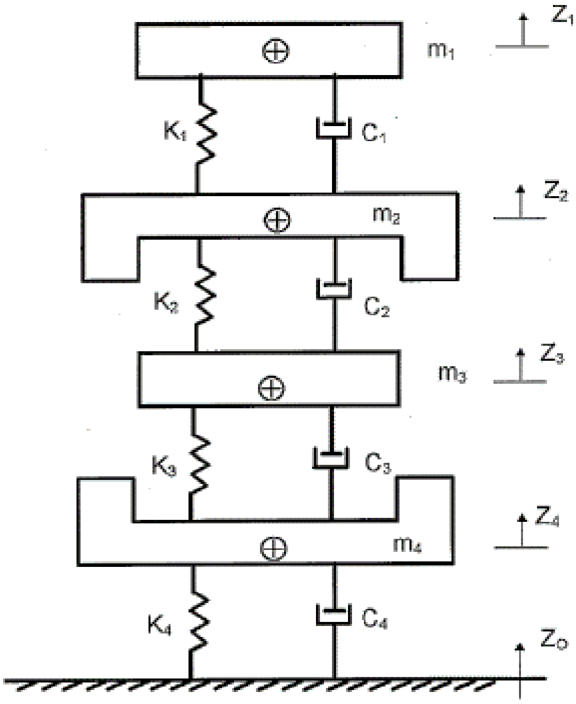

Fig. 1. The 4 DOF biodynamic model [12].

Model with specifications and the values related to the mass and stiffness of springs and damping are also given. (**m_1**) mass of head, (**m_2**) mass of upper body, (**m_3**) mass of abdominal cattle and (**m_4**) mass of seat and thigh, and **c** and **k** express the damping and stiffness between the masses.

Equations of motion

Equations 4 to 8 show the differential equations of the 4 DOF system of the pilot sitting on the seat. The differential equations related to each degree of freedom can be generally expressed as equation 4. In this equation, the matrices [M], [C], [K] and {P} are the mass matrix, damping matrix, stiffness matrix, and the external excitation forces matrix, respectively, and their size is 4 × 4 square.

$m_1 = 5.31$ kg, $K_1 = 310$ kN/m, $C_1 = 400$ Ns/m,
$m_2 = 28.49$ kg, $K_2 = 183$ kN/m, $C_2 = 4750$ Ns/m,
$m_3 = 8.62$ kg, $K_3 = 162.8$ kN/m, $C_3 = 4585$ Ns/m,
$m_4 = 12.78$ kg, $K_4 = 90$ kN/m, $C_4 = 2064$ Ns/m.

$$[M]\{\ddot{Z}\} + [C]\{\dot{Z}\} + [K]\{Z\} = \{P\} \quad (4)$$

In equations 5 to 8, $\ddot{\boldsymbol{z}}, \dot{\boldsymbol{z}}, \boldsymbol{z}$ represent acceleration, velocity, displacement vectors, respectively, $\mathbf{m_i}$ represents the mass, and $\mathbf{k_i}$ represents the stiffness of the spring and $\mathbf{C_i}$ represents the damping.

$$m_1\ddot{z}_1 + c_1\dot{z}_1 - c_1\dot{z}_2 + k_1 z_1 - k_1 z_2 = 0 \quad (5)$$

$$m_2\ddot{z}_2 - c_1\dot{z}_1 + c_1\dot{z}_2 + c_2\dot{z}_2 - c_2\dot{z}_3 - k_1 z_1 + k_1 z_2 + k_2 z_2 - k_2 z_3 = 0 \quad (6)$$

$$m_3\ddot{z}_3 - c_2 z_2 + c_2\dot{z}_3 + c_3\dot{z}_3 - c_3\dot{z}_4 - k_2 z_2 + k_2 z_3 + k_3 z_3 - k_4 z_4 = 0 \quad (7)$$

$$m_4\ddot{z}_4 - c_3\dot{z}_3 + c_3\dot{z}_4 + c_4\dot{z}_4 - k_3 z_3 + k_3 z_4 + k_4 z_4 = 0 \quad (8)$$

Verification

The comparison of the natural frequencies obtained by the analytical method with the experimental results of Boileau [12] is shown in Table 1. The first natural frequency is in the range of 5 Hz, and as can be seen, the experimental and analytical results agree with each other to an acceptable extent.

Table 1. Validation of results of analytical and experimental natural frequencies [12]

parameter	Experimental results	Analytical results
$f_1(Hz)$	4.9	4.98
$f_2(Hz)$	8	8.3

Finite element modeling

Comsol software is used to model the limited implementation. Figure 2 shows the model designed in finite element software of the pilot sitting on the seat. It should be noted that the weight of a sitting person is approximately 73% of the total body weight without considering the weight of the thigh down [14].

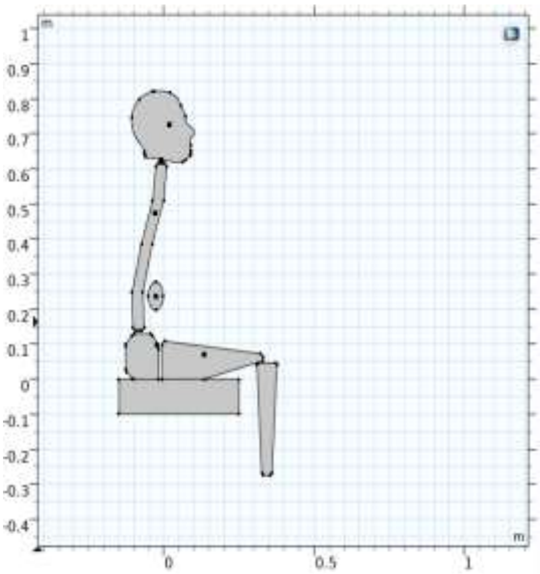

Fig. 2. Finite element modeling of the passenger sitting on the seat

Table 2 shows the characteristics of the mass, stiffness and damping of the model of the passenger sitting on the seat.

Table 2. Characteristics of the mass, stiffness and damping of the human body [12]

Parameter	Value	Description	Parameter	Value	Description
m_head	7.24[kg]	Mass of head	K_4	1.93[kN/m]	**Horizontal stiffness between the abdomen and Upper Torso**
m_torso	19.9[kg]	Mass off upper Torso	K_5	0.905[kN/m]	**Stiffness between** seat and cushion
m_pelvis	11.01[kg]	Mass of pelvis	C_1	0.066[kN/(m/s)]	**Damping between head and upper torso**
m_thigh	20.35[kg]	Mass of thigh	C_2	1.79[kN/(m/s)]	**Damping between the upper Torso and lower torso**
m_viscera	12.92[kg]	Mass of viscera	C_3	0.061[kN/(m/s)]	**Damping between the thigh and lower torso**
m_cushion	0.7[kg]	Mass of cushion	C_4	0.079[kN/(m/s)]	**Damping between viscera and upper torso**
k_1	113.7[kN/m]	Stiffness between head and upper Torso	C_5	0.015[kN/(m/s)]	**Damping between the lower torso and cushion**
K_2	0.299[kN/m]	Stiffness between upper Torso and seat			
K_3	6.40[kN/m]	Stiffness between thigh and seat			

The meshing of the designed model is shown in Figure 3. The mesh is Free Triangular and the size of the meshes is reduced as shown in Figure 4 until the results converge.

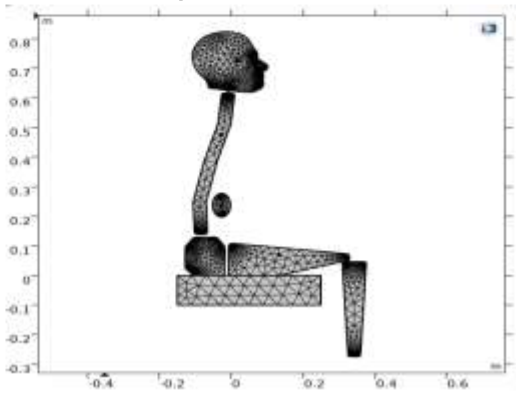

Fig. 3. Meshing model of the passenger sitting on the seat.

According to Figure 4, as mesh convergence, at 5 Hz frequency, the transmissibility is equal to 1.62, and by increasing the element more than 16230, there is no great effect on increasing the accuracy, so the outputs were extracted with the same number of elements.

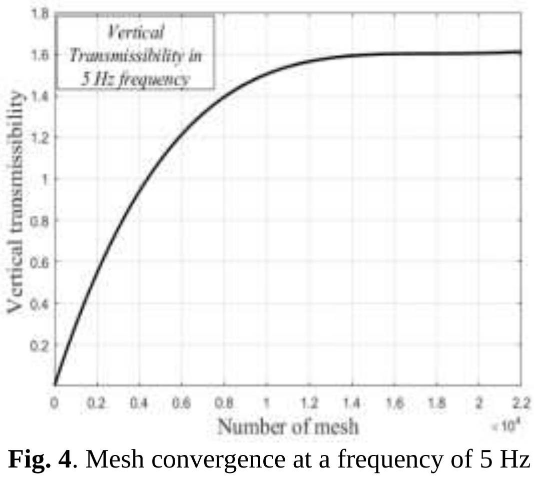

Fig. 4. Mesh convergence at a frequency of 5 Hz

Numerical solution results

Figure 5 shows the displacements in the second vibration mode. It can be seen that the end parts of the legs and head have the most movement.

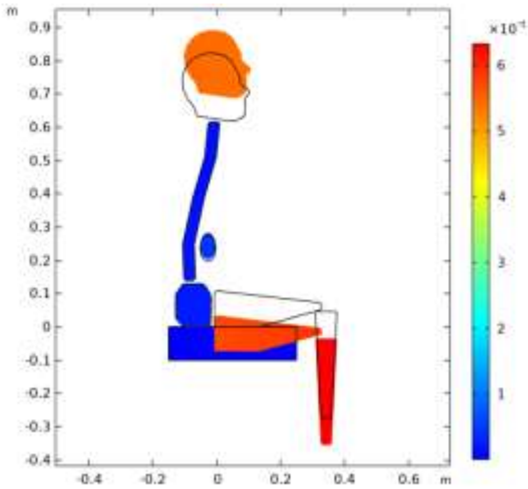

Fig. 5. Displacements in the second natural frequency of human seated

Figure 6 shows the third mode of vibrations of the pilot sitting on the seat. In this vibrating mode, the head and neck tend to move forward, and the stomach and seat are slightly tilted back.

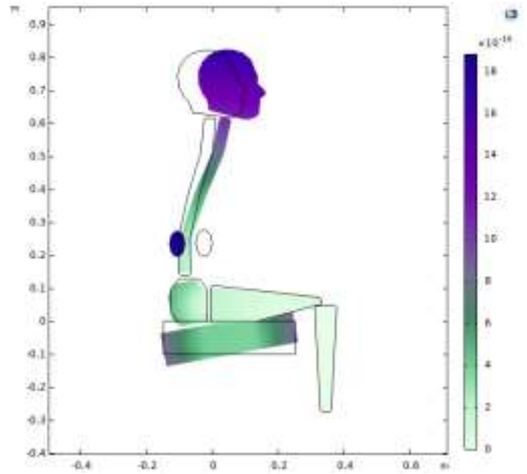

Fig. 6. Third mode shape of human seated

Figure 7 shows the diagram of the vertical seat to head transmissibility. The transmissibility at 5.5 Hz is 1.63.

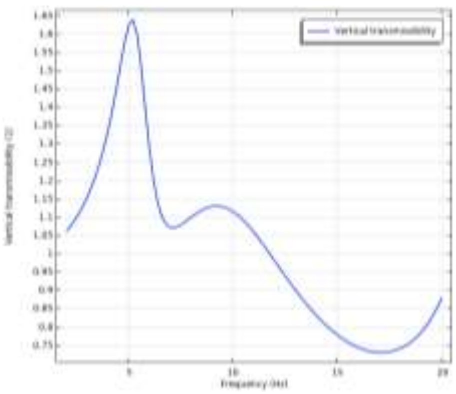

Fig. 7. Vertical seat to head transmissibility

Figure 8 shows the comparison of the vertical transmissibility between finite element modeling and 4 DOF analytical modeling. The peak of the transmissibility graph in the two modes is 1.6 to 1.7 and occurred at 5 to 6 Hz and is almost in good agreement with each other.

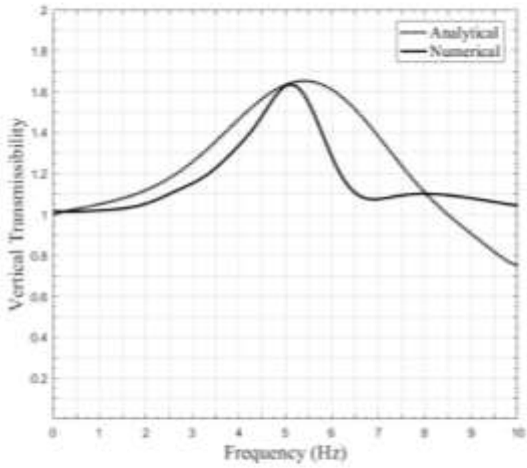

Fig. 8. Analytical and numerical Comparison of the Vertical seat to head transmissibility

Explanation of the Maxwell and Kelvin-Woigt model

In multi degree of freedom models of the mass-spring, if the spring and damper are placed in parallel, it is called the Kelvin-Woigt model, and if the spring and damper are connected along each other, it is called the Maxwell model. In the Kelvin-Woigt model, the strains are equal to each other and the tension in the spring and damper are different from each other, while in the Maxwell model, the strain created in the spring and damper is not the same, but the spring-damper system has almost the same tension.

Maxwell's model is meaningful considering the application of uniform stress on the material, that is, the module and its components receive a constant amount of stress. In the Kelvin-Woigt model, when an external load is applied, the sample undergoes a uniform strain, that is, the model and its components endure a similar strain.

Analytical solution of the 5 DOF model (Kelvin-Woigt model)

Figure 9 shows the 4 DOF model of the sitting human body along with the effect of the cushion as another degree of freedom that makes up 5 SOF in total.

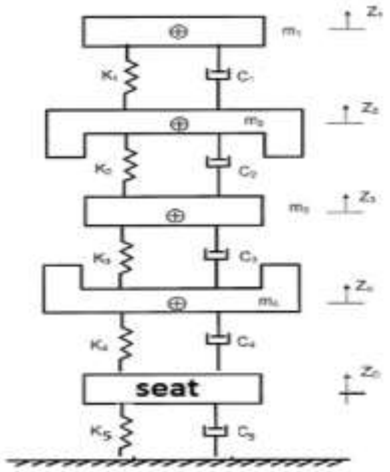

Fig. 9. The 5 DOF of human and cushion with Kelvin-Woigt model

Description of the model and Equations of motion

In this model, the mechanical characteristics of the cushion are designed and analysed as a parallel spring-damper combination (Kelvin-Woigt model).

In order to obtain the biodynamic response of the pilot's body to the incoming vibrations, the models of the human body sitting on the cushion should be examined. In this section, a 5 DOF model in which the pilot's body is assumed to be 4 DOF and the seat cushion is 1 DOF, in which the pilot's body vibrates in the vertical direction.

Equations 9 to 13 show the motion differential equations of the 5 DOF system of the pilot sitting on the seat.

$$m_1\ddot{z}_1 + c_1\dot{z}_1 - c_1\dot{z}_2 + k_1 z_1 - k_1 z_2 = 0 \quad (9)$$

$$m_2\ddot{z}_2 - c_1\dot{z}_1 + c_1\dot{z}_2 + c_2\dot{z}_2 - c_2\dot{z}_3 - k_1 z_1 + k_1 z_2 + k_2 z_2 - k_2 z_3 = 0 \quad (10)$$

$$m_3\ddot{z}_3 - c_2\dot{z}_2 + c_2\dot{z}_3 + c_3\dot{z}_3 - c_3\dot{z}_4 - k_2 z_2 + k_2 z_3 + k_3 z_3 - k_3 z_4 = 0 \quad (11)$$

$$m_4 z_4 - c_3\dot{z}_3 + c_3\dot{z}_4 + c_4\dot{z}_4 - c_4\dot{z}_5 - k_3 z_3 + k_3 z_4 + k_4 z_4 - k_4 z_5 = 0 \quad (12)$$

$$m_5\ddot{z}_1 - c_4\dot{z}_4 + c_4\dot{z}_5 + c_5\dot{z}_5 - k_4 z_4 + k_4 z_5 + k_5 z_5 = 0 \quad (13)$$

Figure 10 shows the seat to head transmissibility by considering the effect of different cushions with the same stiffness and mass and with different damping ratios based on the Kelvin-Woigt model. It can be seen that the analytical results in the case of ζ=0.04 are more consistent with the experimental results of Boileau [12].

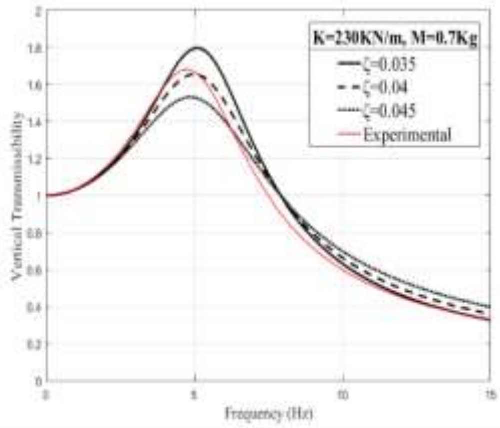

Fig. 10. Vertical seat to head transmissibility with a cushion effect and different damping ratios in the Kelvin-Woigt model

Figure 11 shows the seat to head transmissibility by considering the effect of different cushions with the same damping ratio and mass but with different hardness based on the Kelvin-Woigt model. It can be seen that the analytical results in the case of K=230KN/m are more compatible with the experimental results of Boileau [12].

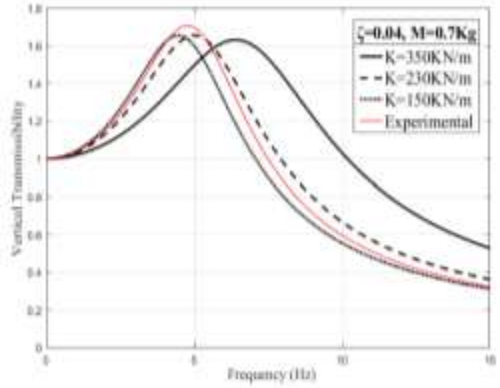

Fig. 11. Vertical seat to head transmissibility with a cushion effect and different stiffness in the Kelvin-Woigt model

Analytical solution of 5 DOF model (Maxwell model)

To get the response of the pilot's body, models in which the human body is sitting on a cushion should be examined. In this section, a 5 DOF model, in which the pilot's body vibrates in the Z direction, is examined according to Figure 12.

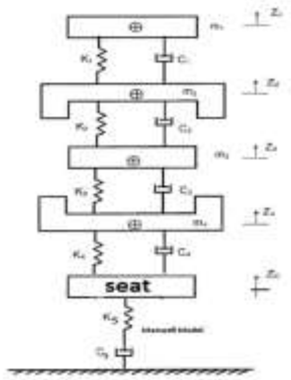

Fig. 12. The 5 DOF of human and cushion Maxwell model

Description of the model and Equations of motion

Figure 12 shows the used model based on the body parts of the human body, which are connected to each other by a Linear spring and a linear damper. In this model, the mechanical characteristics of the cushion are designed and analysed as a series spring-damper combination (Maxwell model).
Equations 14 to 18 show the motion differential equations of the 5 DOF system of the pilot sitting on the seat. In this modeling, the stiffness of the spring and damper are modeled in series.

$$m_1\ddot{z}_1 + c_1\dot{z}_1 - c_1\dot{z}_2 + k_1z_1 - k_1z_2 = 0 \quad (14)$$

$$m_2\ddot{z}_2 - c_1\dot{z}_1 + c_1\dot{z}_2 + c_2\dot{z}_2 - c_2\dot{z}_3 - k_1z_1 + k_1z_2 + k_2z_2 - k_2z_3 = 0 \quad (15)$$

$$m_3\ddot{z}_3 - c_2\dot{z}_2 + c_2\dot{z}_3 + c_3\dot{z}_3 - c_3\dot{z}_4 - k_2z_2 + k_2z_3 + k_3z_3 - k_4z_4 = 0 \quad (16)$$

$$m_4\ddot{z}_4 - c_3\dot{z}_3 + c_3\dot{z}_4 + c_4\dot{z}_4 - c_4\dot{z}_5 - k_3z_3 + k_3z_4 + k_4z_4 - k_4z_5 = 0 \quad (17)$$

$$m_5\ddot{z}_1 - c_4\dot{z}_4 + c_4\dot{z}_5 - k_4z_4 + k_4z_5 + k_5z_5 = 0 \quad (18)$$

Figure 13 shows the seat to head transmissibility by considering the effect of different cushions with the same damping ratio and mass, but with different stiffness based on Maxwell's model. It can be seen that the analytical results in the case of K=230KN/m are more consistent with the experimental results [12].

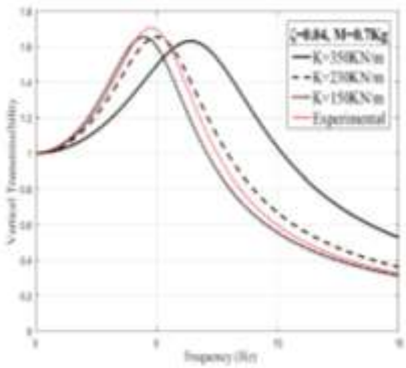

Fig. 13. Vertical seat to head transmissibility with a cushion effect and different stiffness in the Maxwell model

Figure 14 shows the seat to head transmissibility by considering the effect of different cushions with the same stiffness and mass but with different damping ratios based on Maxwell's model. It can be seen that the analytical results in the case of ζ=0.04 are more consistent with the experimental results [12].

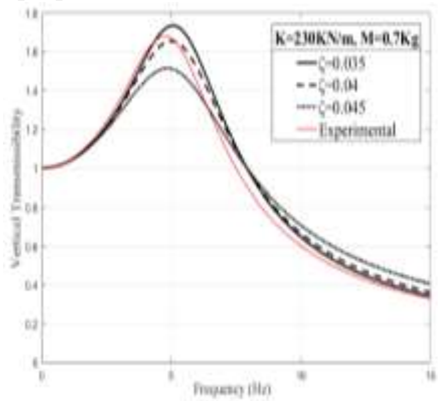

Fig. 14. Vertical seat to head transmissibility with a cushion effect and different damping ratios in the Maxwell model

Conclusion

In this research, the vibration effect of different cushions of the helicopter pilot's seat was investigated. First, the modeling of the 4 DOF of the sitting human body was done analytically and compared with the Boileau experimental results [12], In the next part, the numerical modeling of the sitting human was done in the finite element software (Comsol), and transmissibility was determined by two methods. Analytical and numerical solutions were compared with each other In the final part, the effect of seat cushion was investigated in two analytical models, the Kelvin-Woigt and Maxwell model, and the most important results obtained are as below.

1- Analytical results showed that the effect of the mass parameter on shifting the peak of frequency from the critical frequency range was much less than the effect of stiffness and damping parameters.

2- Comparison of the effect of cushions with different damping ratio showed that the effect of the cushion with the damping ratio ζ=.04 in the range of the first natural frequency is very consistent with the experimental results, and the cushion with the damping ratio less than 0.04 has a better effect in reducing the range of frequency and reducing the effects It has a physical disadvantage on the pilot's body, specially the spine, and by reducing the damping ratio, the transmissibility actually increases.

3- Comparing the effect of cushions with different stiffness, showed that the cushion with stiffness k=350KN/m, the peak of the graph is far away from the normal frequency range, so it has a better effect in reducing the adverse physical effects on the pilot's body.

4- Comparison of Kelvin-Woigt and Maxwell modeling showed that the response of the biodynamic equations of motion in chair cushion modeling with the Kelvin-Woigt method was more consistent with the experimental results [12].

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