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THEORETICAL CONSIDERATIONS CONCERNING THE HUMAN BODY BEHAVIOUR IN A VIBRATIONAL MEDIUM

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Abstract: Vibration is most simply defined as oscillating motion. It could be periodic or nonperiodic. Repeated loading of the lumbar spine occurs in activities of daily living like lifting and driving. The chronic exposure results in mechanical and chemical changes in the spinal components leading to spinal degeneration. These disorders in a person may lead to discomfort, loss in productivity, and an enormous increase in health care cost to society. In a chronic vibration environment, the prevalence of low-back problems is dependent on a host of factors including subject age, subject posture, magnitude of input vibration, and exposure time. It is imperative that efforts be made to understand the effects of wholebody vibration on the spine and how these can be prevented. This paper focuses on our contributions of the mathematical models in this area.

1. INTRODUCTION

Although the human body is a unified and complex active dynamic system, lumped parameter models are often used to capture and evaluate human dynamic properties. Lumped parameter models consisting of multiple lumped masses interconnectted by ideal springs and ideal dampers have proven to be effective in many applications, including those involving human exposure to whole-body vibration.

Figure 1 illustrates an example of a lumped parameter human model useful in the simulation of human response to vertical (longitudinal) vibration. The head, upper, center, and lower torsos, right and left arms, and right and left legs are modeled as lumped masses. The masses are connected together in the vertical direction by mass less springs and dampers that capture human viscoelastic properties.

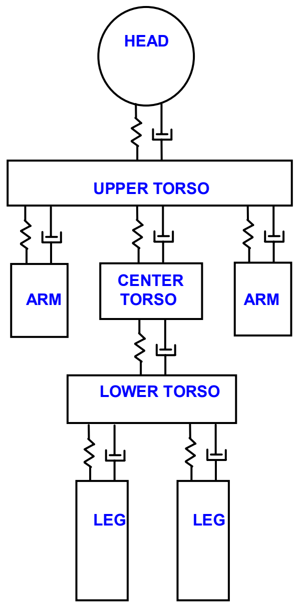


Figure 1. General lumped parameter human model

Four model categories are obtained using these criteria: vertical nonlinear models, multi-axis nonlinear models, vertical linear models, and multi-axis linear models.

1.1. Vertical Nonlinear Models

In 1960, Coermann [1] presented a 6-degree-of-freedom (DOF) model of a human (for standing and sitting postures) used to simulate human dynamic response to longitudinal vibration of very low frequencies. This model included masses for the head, the upper torso, the arm-shoulder, a simplified thorax-abdomen subsystem, the hips, and the legs. A nonlinear spring was connected between the upper torso and the hips in parallel with the thorax-abdomen subsystem to represent the elasticity of the spinal column. Model parameters for each element were estimated from measurements of the mechanical impedance.

The performance of the whole-body model was not published and is therefore difficult to assess. The characteristics of the spine and the thorax-abdomen subsystem, however, were evaluated in detail. Each was modeled with 1 DOF in the whole-body model. Damping was not included in the spine and the performance of the thorax-abdomen subsystem did not match the experimental data particularly well.

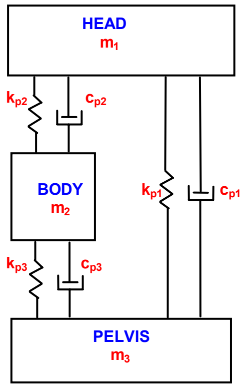


Figure 2. Vertical nonlinear Muksian and Nash model

In 1971, Hopkins [2] developed a 3-DOF model of a seated human consisting of the upper torso, viscera, and lower torso connected in series. Bilinear springs were used to connect the upper torso with the viscera and to connect the viscera with the lower torso. The vertebral column was represented by a linear spring connecting the upper and lower torsos. The model performance was compared with experimental impedance and transmission data. The model displayed the same number of resonant peaks as the experimental impedance data but had significantly different peak values. The model did not match the experimental transmissibility data, either in shape or in peak values. The model was used exclusively in the analysis of low-frequency vibration.

In 1974, Muksian and Nash [3] presented a 7-DOF nonlinear model dedicated to the analysis of vibration imposed on a seated human. The model included masses associated with the head, back, torso, thorax, diaphragm, abdomen, and pelvis. Linear springs and dampers were used between the head and the back, and between the back and the pelvis. Forces associated with the relative motion of the torso with respect to the back and muscle forces were included in the model as forces acting directly on the masses. The source of the stiffness values was not provided, but the values were similar to the experimental data obtained by Vogt et al. [7]. The damping coefficients were obtained from Coermann et al. [1] and Vogt et al. [7] (except that of abdomen-thorax viscera was an assumed value). The model performance was compared with the experimental data for acceleration ratio (for each mass relative to the input acceleration) given by Goldman and von Gierke [8] and Pradko et al. [9, 10]. At lower frequencies (1 to 10 Hz), the model matched the experimental data by Goldman and von Gierke [8] and Pradko et al. [10] well, but did not compare well with experimental data by Pradko et al. [9]. At higher frequencies, the model performance was significantly different than that observed experimentally.

In 1976, Muksian and Nash [11] presented a 3-DOF model of the human body in the sitting position that contained a parallel connection between the pelvis and the head. Figure 2 shows the model arrangement. It included masses associated with the head (m_1), body (m_2), and pelvis (m3) connected in series, very similar to the model given by Coermann et al. [1]. It neglected the arms and legs, and combined the mass of the upper torso and thorax-abdomen into that of the body. The model was based on the assumption that: (1) all springs (k_{p1}, k_{p2}, and k_{p3}) were linear in the frequency range between 1 and 30 Hz, (2) the damping between the head and body (c_{p2}) was zero, and (3) all other dampers ($c_{p1}$and c_{p3}) were linear between 1 and 6 Hz but nonlinear between 6 and 30 Hz. The values of the masses were obtained from Hertzberg and Clauser [4]. The spring stiffness and damping coefficients were determined by matching existing experimental data at corresponding input frequencies by Magid et al. [10] and Goldman and von Gierke [8]. Since two kinds of damper were used for different frequency ranges, the model performed well when compared with experimental data for single-frequency input. However, since the damping values depend on the input frequencies, analysis of the model performance is difficult to assess for conditions involving multiple-frequency input (i.e., random vibration).

1.2. Multi-Axis Nonlinear Models

In 1964, von Gierke described a two-axis, 7-mass model of a human in standing and sitting positions for longitudinal

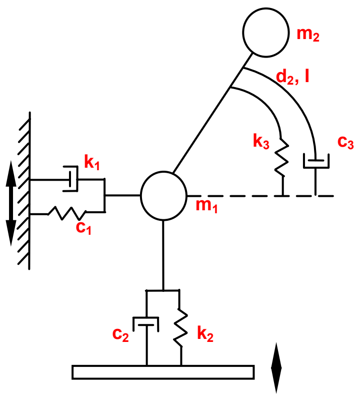


Figure 3. Multi-axis nonlinear Broman model

force application and pressures derived from the model presented by Coermann et al. [1].

The thorax-abdomen subsystem was extended to include one additional degree of freedom, the mass of the chest wall. A damper was added between the upper torso and the hips in parallel with the spine spring. Neither the values of the model parameters nor the model simulation performance were provided. This model was applied to the evaluation of motion of the abdominal wall, the diaphragm, and the lung and thorax.

In 1996, Broman et al. [12] described a 2-mass, 3-DOF model of a seated human (as shown in Fig. 3). It included a linear horizontal subsystem (k_1 and c_1), a vertical subsystem (k_2 and c_2), and a rotational subsystem (k_3 and c_3). The horizontal and vertical subsystems were used to represent the coupling between the human and the seat. The rotational subsystem was used to represent the rotation of the upper body relative to the lower body.

The model parameters were varied to match the experimental data from Pope et al. [13]. The parameter values are shown in Table 2. The model simulation yields results similar to that of a purely vertical subsystem (the horizontal subsystem spring (k_1) was assumed to have infinite stiffness in the simulation results). In the comparison, the model matched the experimental data very well; however, different values of the model parameters were used when matching the different experimental data, i.e., a single “average human” model was not developed.

1.3. Vertical Low-Amplitude Linear Models

Prior to the 1970s, most published models had nonlinear stiffness and damping characteristics to account for the nonlinear behavior observed in the relatively large deformation human tissue studies (necessary in an impact analysis). In 1978, Sandover [14] experimentally investigated the linearity of the human body response to vibration. Results from his investigation indicated that the human body could be modeled as linear when using a 2 m/s 2 rms broadband random vibration stimulus — typical of many transport situations.

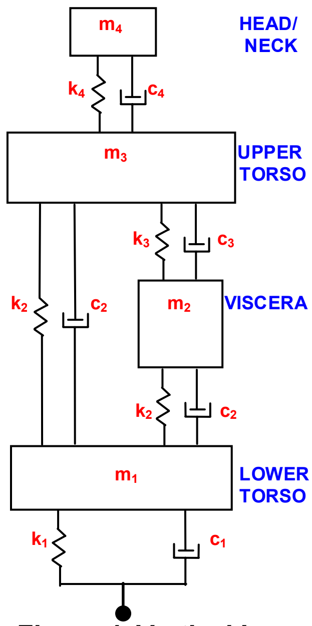


Figure 4. Vertical Low-amplitude Wan and Schimmels Linear Model

In 1981, the International Organization for Standardization (ISO) published a parallel 2-DOF model for both sitting and standing positions [15]. The model was developed to match a composite average driving-point impedance vs. frequency profile (magnitude and phase for the frequency range of 0.5 to 31.5 Hz) derived from existing experimental studies. Since the model had only two suspended masses, it was unable to match the phase response observed in existing experimental seat-to-head acceleration transmissibility studies at moderate to high frequencies [16] (phase angle of approximately 270°).

In 1987, ISO [16] published a 4-mass, 8-DOF model of a human for both sitting and standing positions. No correlation between the elements of the model and anatomical segments was established. Each springdamper set connecting masses included two springs and one damper (one spring parallel to the damper and the other in series). The model was developed to match a composite average seat-to-head acceleration transmissibility vs. frequency profile (amplitude and phase for the frequency range of 0.5 to 31.5 Hz) derived from existing experimental studies. The model matched the experimental data very well except for the transmissibility amplitude in the high-frequency range.

In 1987, Nigam and Malik [17] developed a 15-DOF undamped model for which only a standing posture was considered. It included masses for the head, neck, upper, central, and lower torso, upper and lower arms, upper and lower legs, and feet. The mass of each element was obtained from a previous anthropomorphic body segment study by Bartz and Gianotti [18]. The stiffness was obtained by combining the stiffness of adjacent segments. The model performance was compared with some experimental data such as resonance peaks from Goldman and von Gierke [8], and resonant frequencies for two modes from Greene and McMahon [19]. The natural frequencies of the model were in the range of the experimental resonant data but were relatively high. The leg stiffness was compared with the experimental values from Greene and McMahon [20]. The approximate value of the single leg was 15% larger than the experimental data. As damping was ignored in this study, the model is less realistic and general.

In 1995, Wan and Schimmels [21] developed a series/parallel 4-DOF human dynamic model designed to match the response of seated humans exposed to vertical vibration. Since the model was constructed for subsequent use in optimal seat-suspension design, model simplicity was highly desired. The topology of the 4-DOF model is illustrated in Fig. 4. The model consisted of head/neck (m_4), upper torso (m_3), viscera (m_2), and lower torso (m_1). The model parameters were obtained by comparing simulation results with the results of experimental tests on human subjects to determine: (1) the variation of seat-to-head acceleration transmissibility with frequency, (2) the variation of driving-point impedance with frequency, (3) acceleration ratio from Goldman and von Gierke [8], and (4) the published properties of the human body from Patil and Palanichamy [22].

2. PROPOSAL MODEL

2.1. Assumption to simplify the human body

In this paper we assumed that parts of the human body would only swing back and forth as well as move up and down. Because it was apparent that the human body would remain physically symmetry during exposure to vibration in a vertical direction.

Thus, in the physical vibration model, the transverse shaking of the human body is ignored. Therefore, we can assume that a two-dimensional model projected on the central plane, which is a midsagittal plane, of the human body would simulate the realistic vibration behavior of the human body.

As is noticed in figure 5, the structure is formed from the follow components: visual analyzer (eye); head; internal viscera; thorax; scapular belt; superior member; pelvis.

The dampers and the springs represent joints, tendons and another ale bindery organs modeling.

Is considered that the subject is submissive of a formal disturbances $F_p = F_0 \sin \omega t$ and is followed the analysis behavior of human organism (the precise maul of the seven parts of human organism) to this type of vertical vibrations.

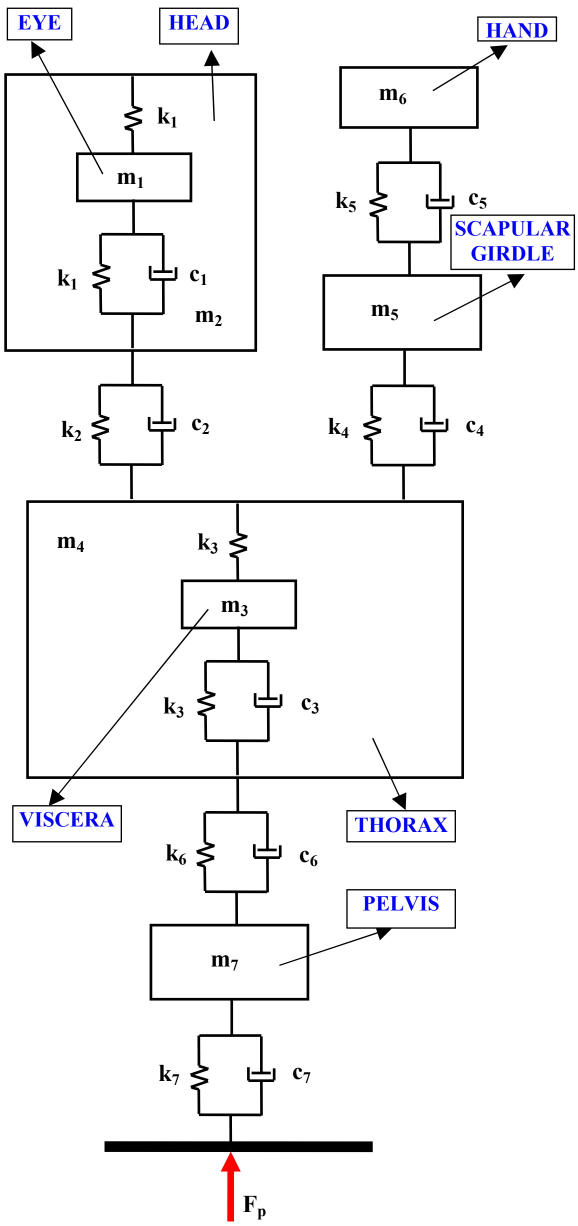


Fig. 5. Proposal Model

Additionally, to simplify the model of the human body further, the following conditions were assumed:
(1) It was assumed that the human body consists of visual analyzer (eye), head, internal viscera, thorax, scapular girdle, superior member and pelvis.. Each part of the human body has a mass and a rotating inertia at the centre of gravity (Fig. 5).
(2) The lower leg could be connected to the thigh and the thigh to the abdomen by a joint with an axis of rotation and generating a viscosity resistance moment. The resistance moment represents the passive resistance element of ligaments. The abdomen and chest are connected by a viscoelasticity element that consists of a spring and a damper and the thorax and head are connected in the same way.
(3) Only portions of the back of head, the back and the lower pelvis are exposed to the external force of the vibration.
(4) So that the head, trunk (chest, abdomen) and pelvis would never slip on the surface of the chair, there is sufficient frictional force at each point of contact.
Finally, we simplified the human body to a two-dimensional vibration model consisting of masses, rigid links, springs and dampers with nine degrees of freedom (Fig. 5).

2.2. Formulation of the equation of motion for the simplified human vibration model

In order to simplify the formulation of the equation of motion for the two-dimensional vibration model, we further assumed the following:
(1) Each part of the vibration model slightly vibrates around each static force equalizing position.
(2) The righting moment of springs and the attenuating force of dampers are in proportion to the displacement and the velocity, respectively.
(3) The saturation viscosity resistance moment is applied to the resistance moments between the lower leg and the thigh and between the thigh and the abdomen.

Finally, the equation of motion consists of the coefficient matrices illustrating the effects of the masses, rigid links, springs and dampers. The equation also has nine degrees of freedom, which were 3 rotations and 6 translations, which did not perpendicularly intersect each other.

$$\begin{cases} m_1\ddot{y}_1 + c_1\dot{y}_1 - c_1\dot{y}_2 + 2k_1y_1 - 2k_1y_2 = 0 \\ m_2\ddot{y}_2 + (c_2 + c_1)\dot{y}_2 - c_2\dot{y}_4 - c_1\dot{y}_1 + (k_2 + 2k_1)y_2 - k_2y_4 - 2k_1y_1 = 0 \\ m_3\ddot{y}_3 + c_3\dot{y}_3 - c_3\dot{y}_4 + 2k_3y_3 - 2k_3y_4 = 0 \\ m_4\ddot{y}_4 + (c_6 + c_3 + c_2 + c_4)\dot{y}_4 - c_6\dot{y}_7 - c_3\dot{y}_3 - c_2\dot{y}_2 - c_4\dot{y}_5 + \\ \quad + (k_6 + 2k_3 + k_2 + k_4)y_4 - k_6y_7 - 2k_3y_3 - k_2y_2 - k_4y_5 = 0 \\ m_5\ddot{y}_5 + (c_4 + c_5)\dot{y}_5 - c_4\dot{y}_4 - c_5\dot{y}_6 + (k_4 + k_5)y_5 - k_4y_4 - k_5y_6 = 0 \\ m_6\ddot{y}_6 + c_5\dot{y}_6 - c_5\dot{y}_5 + k_5y_6 - k_5y_5 = 0 \\ m_7\ddot{y}_7 + (c_7 + c_6)\dot{y}_7 - c_6\dot{y}_4 + (k_7 + k_6)y_7 - k_6y_4 = -F_p \end{cases}$$

in which: m_i - masses; c_i - amortizations; k_i - rigidities; y_i - displacements; $\dot{y}_i$ - velocities, $\ddot{y}_i$ - accelerations and F is a sinusoidal force.

3. RESULTS

3.1. The Own Vibrational Modes

The own pulsations and the forms of own modes (fig. 6) are obtained through the solution of the system of homogeneous equations for the free vibrations unamortized with next form:

$$[M]\{y\} + [K]\{y\} = \{0\}$$

3.2. The graphic representation of the system solutions

Each solution of the system can be writhed in the likeness of:

$$M_r\ddot{\xi}_r + C_r\dot{\xi}_r + K_r\xi_r = f_r$$

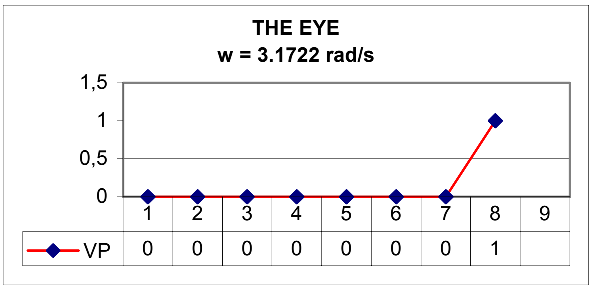
which describes the modulo of motion, characterized by the variation of main coordinate ξ_r .

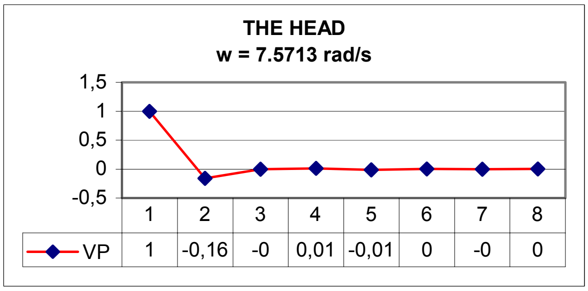
Each such equation can solved asunder, identically with the equation of constrained vibrations ale of the system with a degree of freedom and can be writhed like:

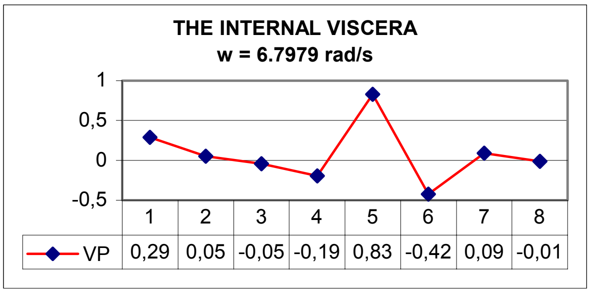
$$x = x_0 \cos pt + \frac{1}{p}\left(v_0 - \frac{q\omega}{p^2 - \omega^2}\right)\sin pt + \frac{q}{p^2 - \omega^2}\sin \omega t$$

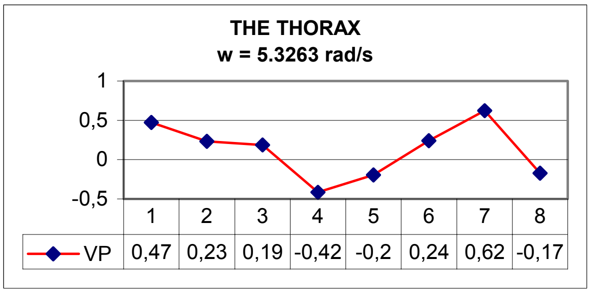
where: $p = \sqrt{k/m}$, $q = F_0/m$, $F_p = F_0 \sin \omega t$ and x_0, v_0 are initial displacements, respectively velocities.

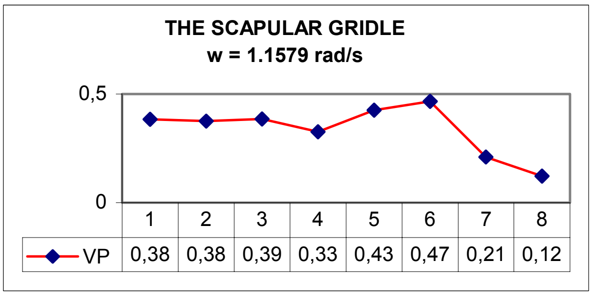
If $x_0 = 0$, $v_0 = \frac{q\omega}{p^2 - \omega^2}$, than $x = \frac{q}{p^2 - \omega^2}\sin \omega t$.

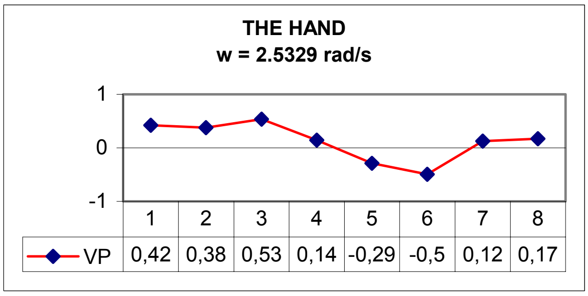












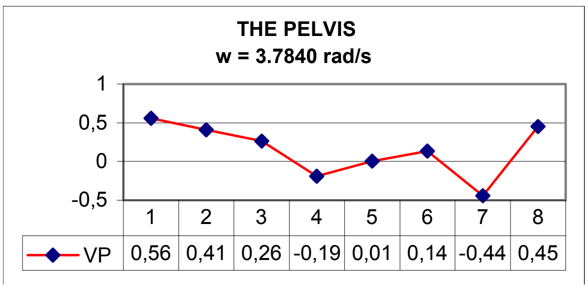


Fig. 6. The own modes of vibration

For the proposal model, we consider:

$$p = \sqrt{k_r/m_r}\ , \quad q = F_0/m_r\ , \quad F_p = F_0 \sin \omega t$$

Reduced masses are identically with the masses of the system's elements and the reduced rigidities are:

$$k_{r_1} = 2k_1, k_{r_2} = 2k_1 + k_2, k_{r_3} = 2k_3, k_{r_4} = k_2 + 2k_3 + k_4 + k_6, k_{r_5} = k_4 + k_5, k_{r_6} = k_5, k_{r_7} = k_6 + k_7$$

or
$$y(\omega, t) = \frac{F_0}{k - \omega^2 m} \sin \omega t$$

This is the expression of the system's movements. For $F_0 = 4 \cdots 60$ and $\omega = 6 \cdots 50 \quad rad/s$, we obtained the movements represented the charts:

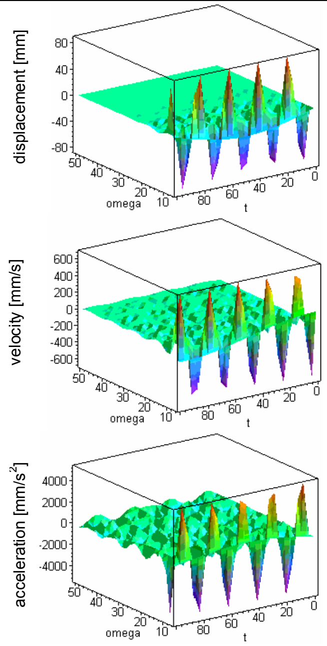


Fig. 7. Displacements, velocities and acceleration representation of the eye

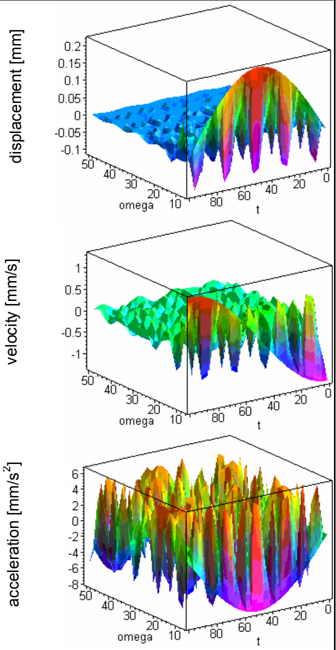


Fig. 8. Displacements, velocities and acceleration representation of the head

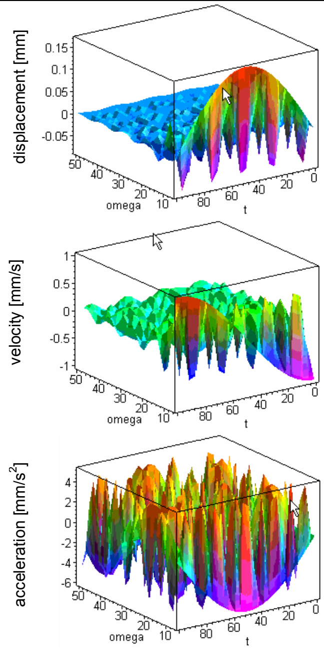


Fig. 9. Displacements, velocities and acceleration representation of the internal viscera

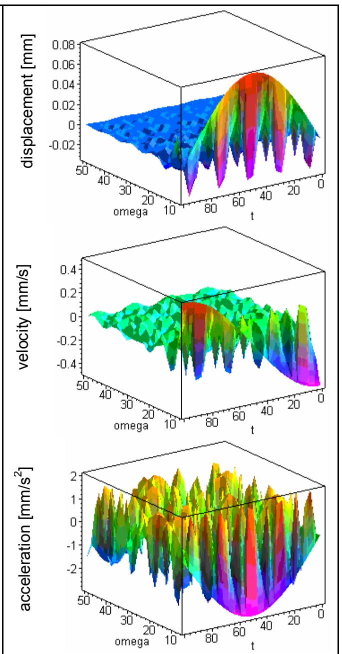


Fig. 10. Displacements, velocities and acceleration representation of the thorax

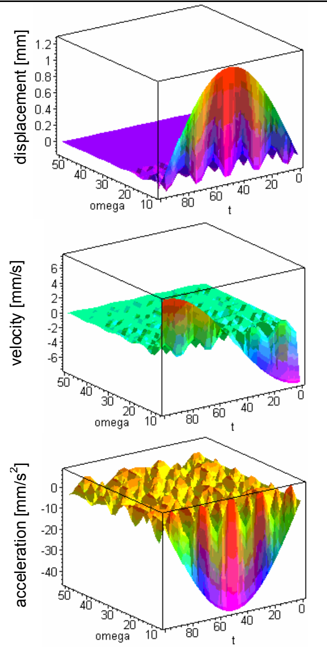


Fig. 11. Displacements, velocities and accelera-tion representation of the scapular gridle

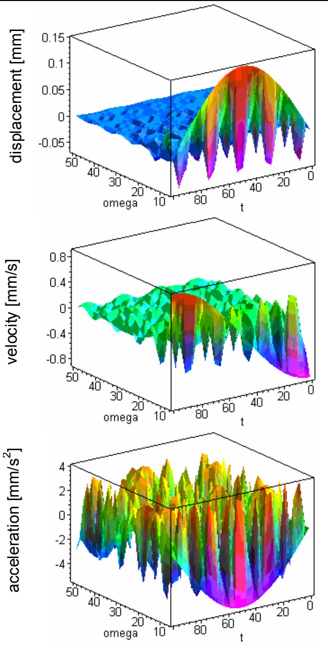


Fig. 12. Displacements, velocities and acceleration representation of the hand

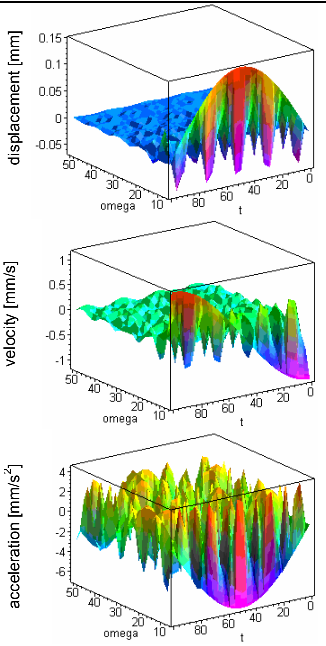


Fig. 13. Displacements, velocities and acceleration representation of the pelvis

4. CONCLUSIONS

In the previously figures we represented in MAPLE the variations of displacements, velocities and accelerations of the system for $\omega = 6..50$ rad/s, $t = 0..100$ s and $F_0 = 30$ N.

As per graphic the movement of the eye varies between 80 and 80 mm, with speeds contained between 600 and -600 mm/s and accelerations of -4000 to 4000 mm/s^2, what represents the very big values. Thence, such force solicits much eye and, by default, he steps in operable see.

Is can noticed from charts that the movements other systems are very little (don't exceed 2 mm, what means that applied force don't influences very many state of the systems. Also, the values of the speeds and the found accelerations are very little by-paths.

As a general conclusion, we can say that the human organism modeled as a system of table, springs and dampers is behaved like every mechanical systems. Most affected parts ale the organism are eye, head (the neurological systems) and the internal viscera. Law for which first sensations perceived by organisms to resonance is the sensation of bad (dizziness, sickness), as well as the disturbance of the sight and, here, he diminishes the orientation in space. The visual function is stricken, in fore rank, due to the fact that the visual analyzer is a sensory system, but and by reason of this orientation after a visual axis, carry temporally the vibration is earnest affected.

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