The Numerical Analyze of the Human Behavior in a Vibrational Medium

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Abstract: - The vibration environment is a common man-made artificial surrounding with which humans have a limited tolerance to cope due to their body dynamics. This paper studies the dynamic characteristics of a standing human body system in a vibration environment. The main result is a multi degrees of freedom lumped parameter model that synthesizes two basic dynamics. First consists in global human dynamics, the apparent mass phenomenon, including a systematic set of the model parameters for simulating various conditions like body posture, backrest, footrest, muscle tension, and vibration directions and the second in local human dynamics, represented by the human pelvis/vibrating seat contact, using a cushioning interface. The model provided an analytical tool for human body dynamics research. It also enabled a primary tool for seat and cushioning design. Combining the geometry and the mechanical characteristics of a structure under large deformation into a lumped parameter model enables successful analysis of the human/seat interface system and provides practical results for body protection in dynamic environment. This paper focuses on our contributions of the numerical and experimental models in this area.

Key-Words: - Human Body, Vibration, Modeling, Simulation, Experimental Research, Body Protection.

1. Introduction

Vibrations can be defined as oscillations of mass about a fixed point. When the body comes in contact with a mechanical source of vibration the tissues of the body become displaced from their resting position. In the work setting there are basically three types of vibration that are significant to the worker. These include whole body vibration, segmental vibration and resonance.

The most common form of whole body vibration is vehicular vibration. In this case vibration enters the body through the buttocks and the feet and to a lesser extent the hands. Segmental vibration is the result of mechanical vibration that comes in contact with body parts and the effect becomes localized. This form of vibration is transferred into the hands and arms when we use power tools.

All physical systems have their own natural frequency. When tissues of the body are exposed to sources of vibration corresponding to their natural frequency these tissues go into resonance. That is, the strength or amplitude of the vibrations exceeds that of the source. When the body comes is contact with mechanical vibration there is a direct adverse physiological effect on the body. The effect interferes with work efficiency and in some situations can put the worker at risk for injury. Any factor that has the potential to impair the worker's function is a significant issue in ergonomics and therefore must be eliminated or reduced to the greatest extent possible.

The human body is made up of organ systems composed of different tissues. When it comes in contact with a source of vibration it reacts as a set of linked masses. Each tissue mass has its own natural frequency. Smaller structures tend to resonate at higher frequencies and larger masses tend to resonate at lower frequencies. Biologically the situation is by no means simpler, especially when psychological effects are included. In considering the response of man to vibrations and shocks it is necessary, however, to take into account both mechanical and psychological effects.

Knowledge about comfort and fatigue-decreased proficiency is based on statistical data collected under practical and experimental conditions. Because experiments with human beings are difficult, time consuming and in extreme cases unesthetical, much of the knowledge about damaging effects has been obtained from experiments on animals. It is, of course, not always possible to "scale" results obtained from animal experiments to reactions expected from man, but nevertheless such experiments often result in valuable information.

Many people are exposed to whole-body vibration in vehicles: cars, buses, trains, ships and airplanes, on a daily basis. In some previous paper, it was confirmed that whole-body vibration caused a subject discomfort, fatigue and physical pains [4]. There are several reports describing how vibration interferes with people's working efficiency, safety and health [1]. Therefore many researchers have concentrated their efforts on reducing the amount of vibration from products and vehicles. There are many reports describing the measurement of the transmissibility of the human body under vibration [5], [7]. It has also measured the transmissibility of the whole body in sitting and lying posture exposed to vertical vibration [4]. The results of these reports indicated the resonance of the human body depended on various factors: the posture, the materials of the given seat surface, vibration magnitude and frequency. The measurements of the transmissibility of the body under various vibrations are inefficient, laborious, tedious and expensive. On the other hand, there are a few computer-automated procedures used to predict the human body's responses to vibration [3], [6], [8]. It is difficult to accurately estimate the behavior of the human body under vibration, because it is a complex active dynamic system. Further, it is most important to bear in mind that the complexity is not only due to physical characteristics but also due to psychological and physiological characteristics. However, no vibration model concerning the physiological and the psychological reactions of a person exposed to vibration environments has been found. Therefore, we considered that the construction of a vibration model that could reproduce the characteristics of the vibrating human riding on an automobile should be a research task. The vibration model should not only be able to reproduce the behavior of the physical human body but also predict the physiological and psychological reactions.

In constructing the vibration model, we would predict the characteristics of the physical reactions. In this paper the vibration model was constructed in accordance with the results of our research into the characteristics of the human exposed to a vertical sinusoidal wave force. 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 interconnected by ideal springs and ideal dampers have proven to be effective in many applications, including those involving human exposure to whole-body vibration.

The vibration environment is a common man-made artificial surrounding with which humans have a limited tolerance to cope due to their body dynamics. This paper studies the dynamic characteristics of a seated human body system in a vibration environment. The main result is a multi degrees of freedom lumped parameter model that synthesizes two basic dynamics. First consists in global human dynamics, the apparent mass phenomenon, including a systematic set of the model parameters for simulating various conditions like body posture, backrest, footrest, muscle tension, and vibration directions and the second in local human dynamics, represented by the human pelvis/vibrating seat contact, using a cushioning interface. The model provided an analytical tool for human body dynamics research. It also enabled a primary tool for seat and cushioning design. Combining the geometry and the mechanical characteristics of a structure under large deformation into a lumped parameter model enables successful analysis of the human/seat interface system and provides practical results for body protection in dynamic environment.

Considering first the human body as a mechanical system it may, at low frequencies and low vibration levels, be roughly approximated by a linear lumped parameter system of the type shown in Fig. 1. One of the most important parts of this system with respect to vibration and shock effect seems to be the part marked "thorax-abdomen system".

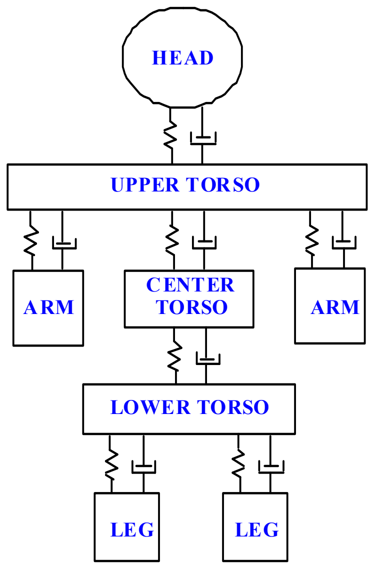

Fig. 1. General lumped parameter human model

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. 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 [10] 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.

In 1971, Hopkins [11] 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 [12] 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. [16]. The damping coefficients were obtained from Coermann et al. [11] and Vogt et al. [16] (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 [17] and Pradko et al. [18, 20]. At lower frequencies (1 to 10 Hz), the model matched the experimental data by Goldman and von Gierke [17] and Pradko et al. [20] well, but did not compare well with experimental data by Pradko et al. [18]. At higher frequencies, the model performance was significantly different than that observed experimentally.

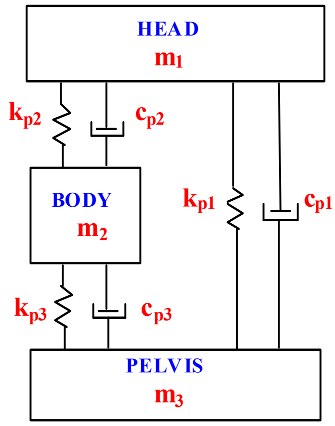

Fig. 2. Vertical nonlinear Muksian and Nash model

In 1976, Muksian and Nash [19] 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 (m_3) connected in series, very similar to the model given by Coermann et al. [10]. 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 [13]. The spring stiffness and damping coefficients were determined by matching existing experimental data at corresponding input frequencies by Magid et al. [19] and Goldman and von Gierke [17]. 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 force application and pressures derived from the model presented by Coermann et al. [10].

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. [21] 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.

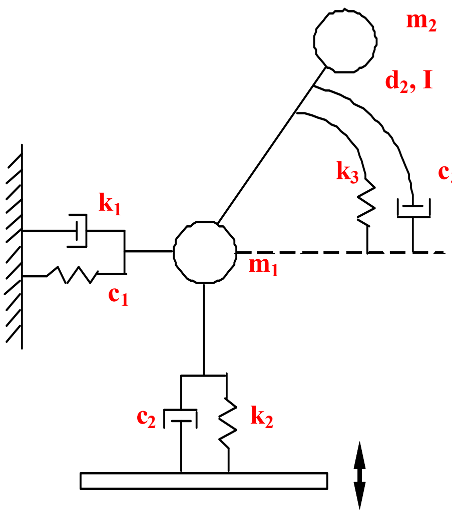

Fig. 3. Multi-axis nonlinear Broman model

The model parameters were varied to match the experimental data from Pope et al. [22]. 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 [23] 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.

In 1981, the International Organization for Standardization (ISO) published a parallel 2-DOF model for both sitting and standing positions [24]. 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 [25] (phase angle of approximately 270°).

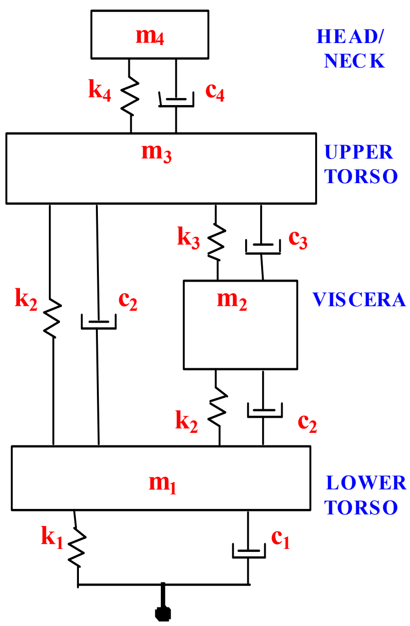

Fig. 4. Vertical Low-amplitude Wan and Schimmels Linear Model

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 [27]. 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 [28]. 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 [29]. 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 [30] 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 [17], and (4) the published properties of the human body from Patil and Palanichamy [31].

2. Proposal Model

2.1. Assumption to simplify the human body

Motion sickness results from exposure to frequencies below 1 Hz, more particularly those below 0.5 Hz. Symptoms are many and varied, but may include vomiting, nausea, sweating, spatial unease, drowsiness, and dizziness. While motion sickness is most common in children, and many fail to show signs of susceptibility in adulthood, it has been demonstrated that everyone may be made sick if the appropriate stimulus is used. Symptoms are most frequently observed in moving vehicles but there are a number of other environments where motion sickness may be initiated (e.g., fairground devices, simulators, microfiche readers, swimming) [1].

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.

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.

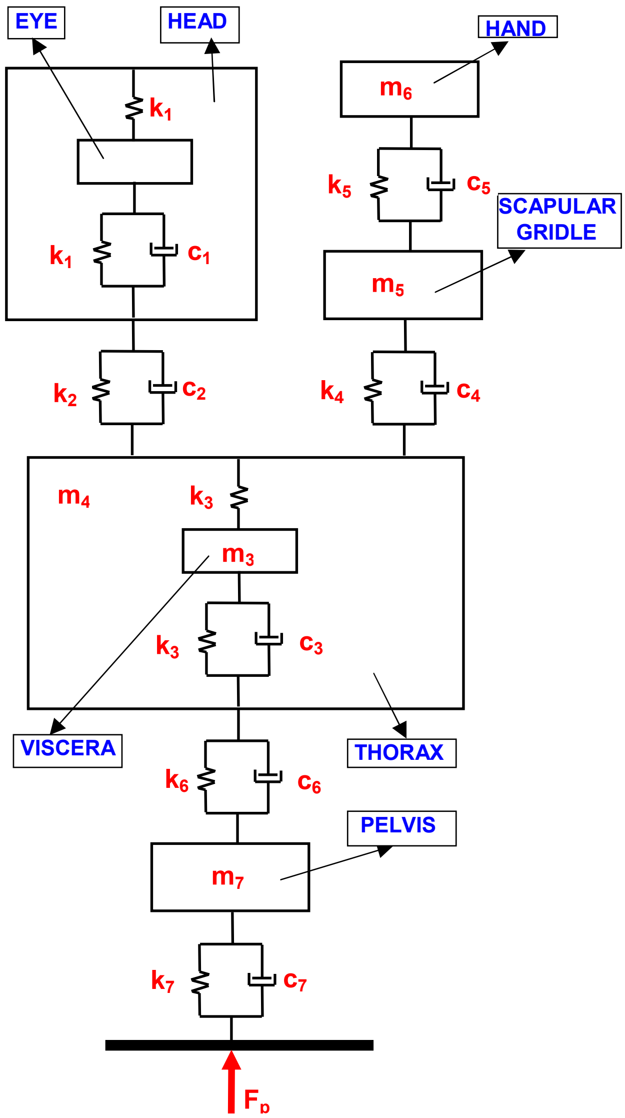

Fig. 5. Proposal Model

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.

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.

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

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

3. Numerical Results

3.1. The Eigen value modes

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

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

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 type 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:

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

and x_0, v_0 are initial displacements, respectively velocities.

If $\quad x_0 = 0, \quad v_0 = \dfrac{q\omega}{p^2-\omega^2},$

than $\quad x = \dfrac{q}{p^2-\omega^2}\sin \omega t.$

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 $F_0 = 4\cdots 60\,\mathrm{N}$ and $\omega = 6\cdots 50$ rad/s, we obtained the movements represented in the charts from fig. 7 - 13.

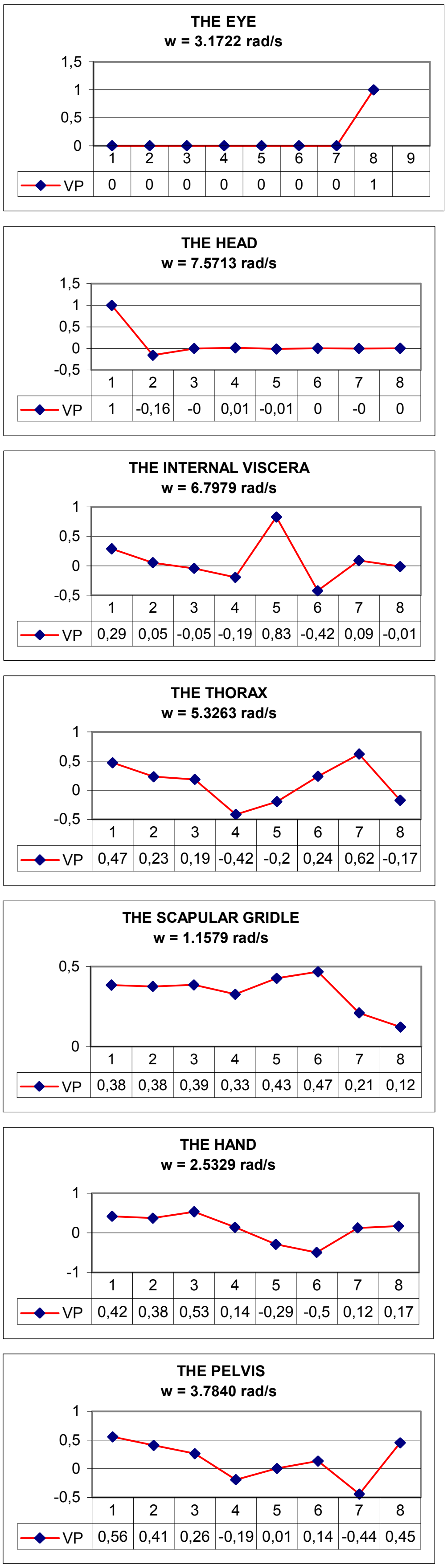

Fig. 6. The Eigen value of vibration

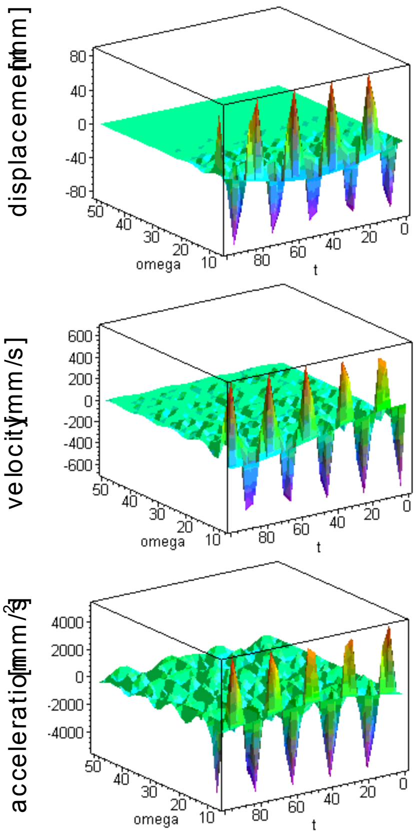

Fig. 7. Displacements, velocities and acceleration of the eye

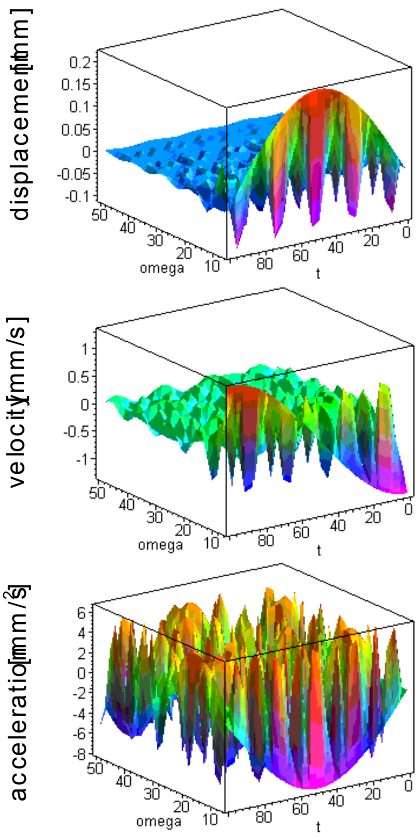

Fig. 8. Displacements, velocities and acceleration of the head

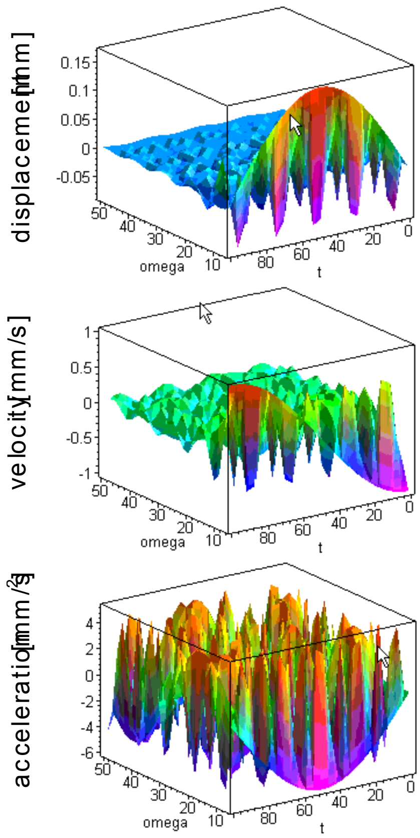

Fig. 9. Displacements, velocities and acceleration of the internal viscera

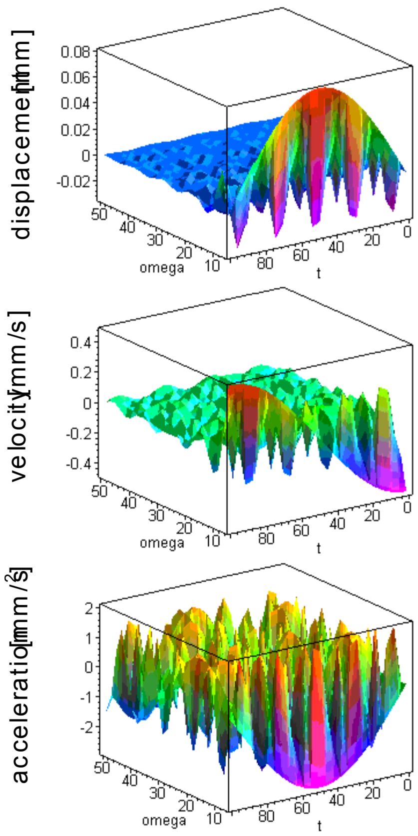

Fig. 10. Displacements, velocities and acceleration of the thorax

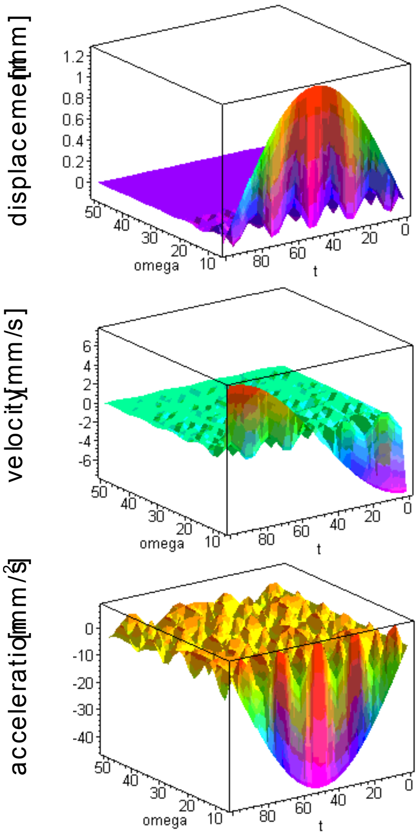

Fig. 11. Displacements, velocities and acceleration of the scapular gridle

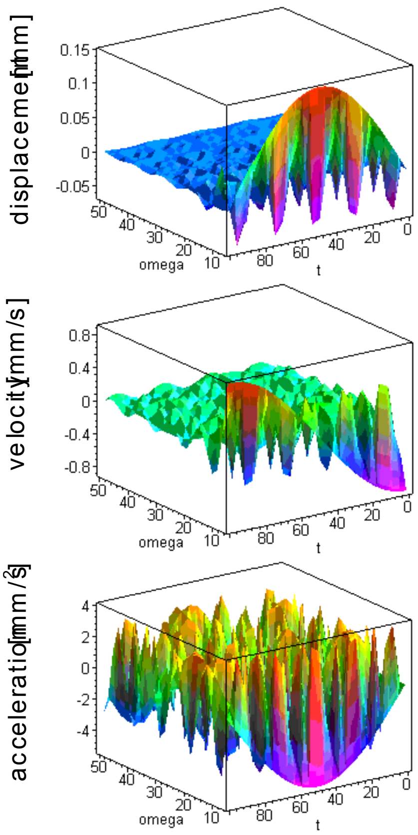

Fig. 12. Displacements, velocities and acceleration of the hand

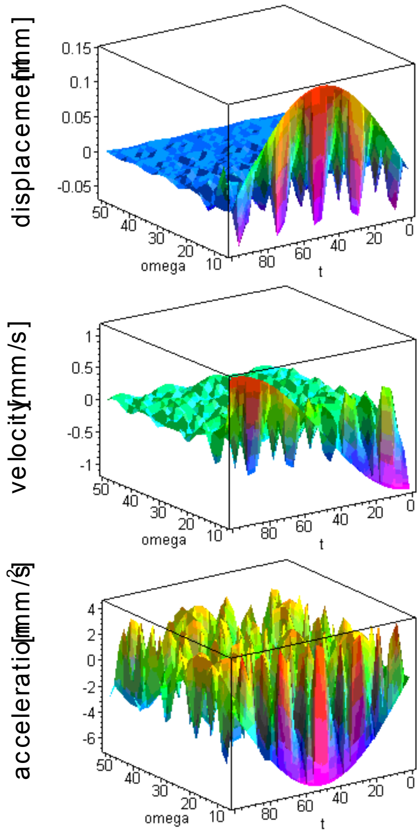

Fig. 13. Displacements, velocities and acceleration of the pelvis

4. Experimental consideration

To verify the validity of analytic previous model, we utilized a technical stand for the analysis behavior of human organism to shock and vibrations (fig. 14).

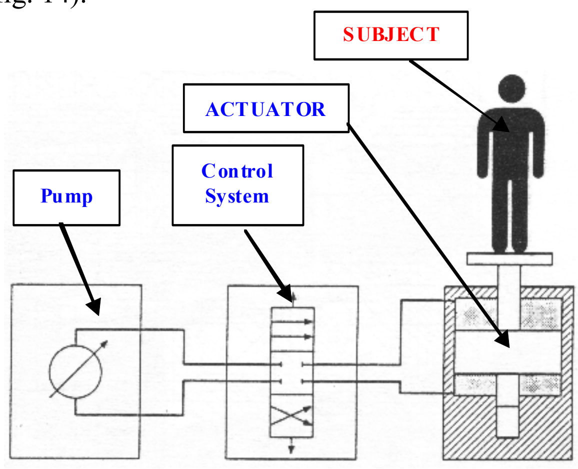

Fig. 14. Experimental stand for the analysis behavior to vibrations of human organism

The experimental stand analysis the behavior of the organism to vertical vibrations of small amplitude. On the vertical hydraulic cylinder is mounted a platform, which is put the subject, carry the visas a points from the field of vision (fig. 15). The control is achieved through the medium of the software specialized of the computer. The input data are by-path in his force movement, while frequent is variable.

Fig. 15. Subjective method to verify the behavior of the human organism to vibrations

For each input data the frequency is varied within the moment in which interfere the capable general modifications of the subject. Therefore, the method is subjective, because exists physiological neurological causes and, psychological what influences it. More, the results are modified from an individual to other, pursuant to the individual way in which reacts each organism fractionally. The conditions of average interfere and they through the state of comfort which can it generate.

5. Conclusions

In the previously figures (7…13) 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.

The experimental results were influenced by the follow parameters:

- The position of the subject – vertical or inclinable – in vertical position the subject touches giddap the frequents of resonance;
- The vertical position with the hands besides his bodies influences in the sustentation equilibrium;
- For subject to vibrations through this enlargement the time in organism interferes the state of lassitude, case in which the results can be wrong;
- The relaxation state of the organism - if the brawn are tensed, and the subject is not relaxed, the resonance frequency breeds; Is and the case in which the subject is in vertical position with the hands besides his body;
- The ocular refraction - the most important disturbances of the ocular refraction step in measurements through the fact that ammetropie influences an eye-sight, as well as the phenomenon of accommodation;
- The subject is putted on his shoes - the footwear interferes through his factor of amortization and by reason of the direct contact that has with the floor.

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