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PhD Thesis
–Abstract–

STUDY ON THE MECHANICAL VIBRATIONS ACTING UPON THE HUMAN BODY IN AN AUTO VEHICLE

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ABSTRACT

Keywords: Whole body vibration; vertical vibration; mechanical model of human body in seated posture; natural frequency; the biodynamic responses of a seated human body.

Whole body vibration is caused by the vibrations transmitted through the seat or the feet by machines at the workplace and vehicles. Exposure to high levels of whole-body vibrations can present risks to health and safety and are reported to cause or aggravate back injuries.

In a seated posture in an auto vehicle, humans are most sensitive to whole-body vibrations under low-frequency excitation. The effect of such exposure on the health depends on the nature of vibration of the body affected by vibration and duration of exposure to them.

STRUCTURE OF THE THESIS

The thesis is structured in three main parts: Part I - Documentary Study, Part II - Numerical Modelling and Part III - Experimental Research. The contents of the thesis are developed within 8 chapters, of which the last one is reserved to conclusions, original contributions and research directions. At the end of the thesis, there are the references and appendices. Bibliography includes a total of 156 titles, of which 27 belong to the author (3 single author papers, 21 first author papers and 2 papers co-author) 11 standards and 12 websites addresses issues related to the thesis.

Chapter 1. INTRODUCTION

The first chapter defines the work plan and organization of the thesis, starting from the fact that the proposed theme solution requires several steps, which link the mathematical modeling problems with the programming. It shows the importance of the topics addressed in this thesis; we state the objectives of the thesis and means to achieving them. Studied bibliographic documentation required knowledge in a wide range of areas, namely: mechanics, biomechanics, anthropometry, mechanical vibrations, mathematics, systems theory, modeling and simulation, and computer programming.

Chapter 2. THE WHOLE-BODY VIBRATION. GENERAL ASPECTS

This chapter presents aspects of the influence of the vibrations on the human body, emphasizing the application site classification according to their vibration and negative effects of functional and organic nature that they produce. It gives an overview of several biodynamic models with concentrated parameters associated with the human body in a sitting position.

Chapter 3. METHODS OF MEASUREMENT AND VIBRATION REDUCTION BY MEANS OF THE VEHICLE SEAT

This chapter brings into attention some aspects regarding methods of measurement, evaluation and reduction of human body vibration in sitting position in their vehicle seat. We also defined notions of comfort and data regarding discomfort in a vehicle seat. Static and dynamic properties are specified for the car seat. Constructive solutions for the reduction of vibrations are presented in comparison by designing different types of suspension seats.
Chapter 4. MECHANICAL SCHEMES IN MODELING, NATURAL FREQUENCY AND DAMPING

For this study, we defined a mechanical model of the human body in a sitting position. The model comprises four masses, coupled by linear elastic and damping elements. The four masses represent the following four body segments for a seated individual: the thighs and pelvis in contact with the seat – $M_2$ called pelvis, the chest and upper torso – $M_3$ called upper torso, viscera $M_4$, the head and neck – $M_5$ called head. This is a 4 DOF lumped parameter biodynamic linear model and was named RS (mechanical model of human body sitting on the rigid seat - RS). The mass due to lower legs and feet is not included in this representation, assuming that their contribution to the biodynamic response of the seated body is negligible. The model fitted with a seat cushion and an additional suspension, making it a model with 5 DOF, was named SCS (Seat – Cushion - Suspension). Differential equations were established for the mathematical models of mechanical systems attached. Their frequencies were determined on both systems without damping. Eigenvalues and natural frequencies of the masses which enable the proposed mechanical systems to oscillate freely were established for both damped systems RS and respectively SCS. The values obtained in the two cases were compared with each other. Damping ratios for the two models that SR and SCS were determined. For SCS mechanical system presented the study of stability in Lyapunov sense. The human body in a sitting posture can be modeled as a mechanical system that is composed of several rigid bodies interconnected by springs and dampers.

In developing this chapter, the following conclusions can be drawn:

- The human body is a highly complex dynamic system with continuous parameters, but with gaps between various organs or body systems (i.e. skeletal system, muscular system, circulatory system, etc.).
- From a dynamic point of view, the human body can be studied as a whole or in parts as any mechanical system composed of ideal elements: concentrated mass and elastic characteristics without damping, elastic element without mass and without damping characteristics, without mass damper and without elasticity.
- For the driver, mechanical model of a human sitting on the chair consists of four distinct elements: head, upper torso, viscera and pelvis.
- The mechanical model can be studied individually (only the human body - with 4 degrees of freedom to move vertically) or with the seat assembly which is placed to form a system with five degrees of freedom in the vertical direction.
- The individual body analyzed as a mechanical system with 4 masses and 4 DOF has its 4 own frequencies, corresponding to 4 distinct segments of the body, which are:

  \[
  f_4 = 2317 \text{ Hz for viscera} \\
  f_3 = 3597 \text{ Hz for upper body} \\
  f_2 = 8661 \text{ Hz for pelvis} \\
  f_5 = 34278 \text{ Hz for head.}
  \]

- Ensemble human body with seat car makes up the HB/S (or SCS) system. This system has 5 own frequencies:

  \[
  f_4 = 2.0854 \text{ Hz for viscera} \\
  f_3 = 3.5680 \text{ Hz for upper body} \\
  f_2 = 8.6838 \text{ Hz for pelvis} \\
  f_1 = 10.0174 \text{ Hz for the seat cushion} \\
  f_5 = 34.2960 \text{ Hz for head.}
  \]
Analyzing the frequency ranges of values of their corresponding 4 DOF system and 5 DOF, we find relatively close results, the frequency of 10.0174 Hz, being the seat cushion.

- For each of the two mechanical systems (4 DOF and 5 DOF) a damping ratio matrix is calculated. $\mathbf{Z}_{\text{diag}}$ matrices determined for each of the two mechanical systems have all non-zero elements (damping ratio), in the case of the subunit values, so for each segment taken separately the damping is subcritical, each running pseudo-damped oscillations.

- The stability of the 5DOF system can be characterized by the eigenvalues of the system, or by using Lyapunov function. The analysis of the system energy (potential and kinetic) shows that it can not grow, so the system is asymptotically stable.

Chapter 5. STUDY OF THE FREQUENCY BEHAVIOR OF THE SCS SYSTEM

This is an analysis of the mechanical system behavior that, in time, the initial conditions imposed at different vibration frequencies in range 0.5 to 80 Hz chosen from the field, frequently associated with the effects of WBV health, and comfort activities specified in ISO 2631-1. From time domain analysis in the frequency pass SCS system where, using frequency response function (FRF), we determine the transmissibility of vibration from the seat surface to the head, Seat to Head Transmissibility - STHT.

From the study of behavior over time at different excitation frequencies from 0.5 to 80 Hz range in the area, according to ISO 2631-1:2001, mechanical system with 5 DOF (SCS) we found that:

- At frequencies from 0 to 0.5 Hz between all segments of the body oscillating in phase and amplitude signal relatively equal initial excitation, the system behaved as a whole and can be represented as a single concentrated mass;
- At 4 Hz frequency, the four parts of the body do not move in the same phase and same amplitude. The most affected parts of the body at this frequency are viscera and upper torso, for which 4 Hz frequency is closer to their own values;
- At 6 Hz frequency, the upper torso and head are most affected, due to the excitation signal frequency approaching their inherent frequency;
- At 8 Hz frequency, the head and upper torso oscillate in phase with amplitude similar to the one in phase opposition to the original signal. The pelvis is strongly affected in this frequency, which is very close to its own frequency;
- At 10 Hz frequency, the movement has insignificant values for body health. The pelvis is the most affected, but its magnitude is relatively small ($2 \times 10^{-3}$);
- At 20 Hz frequency, after the transient stability, the upper torso, viscera and head dampen the vibrations through the seat cushion;
- In frequency range 40-80 Hz all segments of the human body present vibration in the transient stability, these are gradually damping in steady state. In this frequency range only the pelvis has an undamped oscillation, which stabilizes the steady harmonic oscillations at very small amplitude, which occurs continuously throughout the period considered and is due to the excitation signal is maintained throughout this period;
- System HB/S subjected to initial harmonic excitation amplitude $5 \times 10^{-3}$ m oscillations presents a response with smaller amplitudes than the original signal. They are displaying the excitation signal influenced by their frequencies near the body mass of the original signal frequency. At low frequencies, all the parts of the body are vibrating with harmonic oscillations, and they are maintained throughout the review.
- At frequencies between 40-80 Hz, vibration masses $M_3$, $M_4$ and $M_5$ of the human body damped after about 2 seconds.
The complex and complete analysis carried out in this chapter concludes that the assimilated driver’s body or vehicle occupant is not injured while moving, neither due to vibrations to which it is subjected, nor after the removal of the vibrations.

The analysis of the seat-to-head transmissibility vibration found that different parts of the body, as parts of a vibrating mechanical system, show a peak around each of the first natural body frequency - 2.063 Hz. Frequency response magnitude is reduced to a range of 9.379 to 80 Hz. Vibration in this frequency range does not affect humans.

**Chapter 6. STUDIES ON VERTICAL HARMONIC VIBRATION ACTION ON THE HUMAN BODY**

This chapter studies the RS system response to initially sinusoidal excitation signal, at a proposed frequency and then its behavior in the excitation signal with frequency equal to the natural frequencies of mechanical system masses. The analysis is extended to the SCS system for a given signal frequency excitation and natural frequencies of the SCS system, determined in Chapter 4. Both systems are studied in the gravitational field in the frequency range 0.5 to 80 Hz, defined to be important for health, comfort and perception in ISO 2631-1. This chapter also presents a comparative study of the variation of parameters in the cushion and additional suspensions and the effects they produce on SCS mechanical system during its vibration under the action of the initial excitation.

In the case of frequencies close to or within the range of 4-8 Hz, critical to the human body, the simulated version is very sensitive to the transmitted vertical vibrations. For higher frequencies (i.e. 34.278 Hz) oscillations masses M₃, M₄ and M₅ are dampened very quickly (within 2 sec). At frequencies analyzed, only pelvis varies during the entire period of 2 sec. and its movement is within normal limit oscillations in all the cases.

The results lead to the following conclusions:

- The most affected part of the human body is the viscera, where the amplitude of the vibration has the highest value in all analyzed cases. At different frequencies, different parts of the human body work and amplify vibrations in the period 0-2 sec;
- At frequencies above 20 Hz, the human body parts dampen output signal, i.e. their movements, after approx. 2 sec. The human body is most sensitive to whole-body vertical vibration at the frequency in the range 1-8 Hz;
- Using the same mechanical model of the human body and different values of parameters K and C of the suspension seat, we can reduce the body's response to vertical vibration. Parametric studies of the seat cushion lead to the conclusion that the studied model's mechanical performance can be improved in terms of ride comfort by reducing seat cushion stiffness. The properties have influence on comfort and additional suspension spring mounted on the seat are recommended;
- Parameters that describe characteristics of the human body assimilated to a mechanical system with 4 degrees of freedom related to a person weighing 75 kg. In reality, these parameters vary from one person to another, depending on their mass and muscle properties. These parameters cannot be subjected to optimization (in the sense of being improved), because we cannot change the conformation of the human body. Instead, to mitigate the vibration body in a sitting position, the parameters that define the properties of the seat cushion and the suspension can be further optimized.

**Chapter 7. MEASUREMENT OF WHOLE-BODY VIBRATION - WBV, IN A VEHICLE**
Throughout the elaboration period of the thesis we did a long line of vibration measurements that affect the human body while moving vehicle / vehicles. The measurements were performed using SVAN 958 Vibration Analyser, fitted with seat accelerometer SV 39A / L. Measurements were grouped into certain categories of factors that influence data vibration.

A number of external factors were established, which aided us to analyze the degree of their influence on human body vibration in the car seat.

Experimental research undertaken highlighted a number of issues:

- body vibration inside a vehicle, at the three directions of measurement are different in size at the same point of measurement and are perceived differently in different points of measurement at the same time;
- feet, although they are considered to have negligible mass, when studying the human body sitting behavior under the influence of vibrations, are continuously affected by the engine vibration through the car floor;
- engine vibration from the seat cushion are dampened, but are more strongly felt in the back, because of their transmission through the back;
- backrest inclination ensures comfort and relaxation to the body when the car is stationary and the vibration are lowered by the backrest, but only if not using a seat belt;
- while driving the vehicle, the use of seat belts leads to a seat back inclination of 15° from normal, and this generates the largest amplitude of vibration of the human body through the seat back;
- the speed of the vehicle, at the same area of tread, influences body vibration amplitude; at lower speeds higher amplitude vibrations occur in all three directions;
- driving on different runways (asphalt, country road) produces, as expected, vibrations of different amplitudes, which are transmitted from the seat through the body. However, if this phenomenon occurs from time to time, at a constant rate, on the long run it can cause lumbar spinal disorders without this being registered as an occupational disease.

Chapter 8. GENERAL CONCLUSIONS, PERSONAL CONTRIBUTIONS AND LINES OF RESEARCH

This paper highlighted the theoretical and experimental vibration acting on the human body in a vehicle with the engine running at idle, while moving in different ways of running or under the influence of various external factors.

Taking into account the research contained by the paper and the conclusions drawn at the end of each chapter, general conclusions can be drawn. The personal contributions refer to the physical and mathematical modeling of human body subjected to biodynamic vibrations, to verification and validation of models, as well as "in situ" measures of the transmission of vibrations on the human body in a vehicle in the case of different situations analyzed (displacement with and without seat belt, move the seat back inclination certain influence on the vibration speed of travel, travel on different runways, travel with different car).

The results of measurements of surface car seat are comparable to those obtained by integration of differential equations related to the mechanical model. In both cases, the frequencies that have a negative effect on the health of the human operator – vertical vibrations are included in the range of 2-8 Hz range and were determined as a part of the body’s own frequencies, related to HB mechanical model. In the case of frequency range between 1 and 20 Hz, the vertical vibration amplitudes are largest. It is known that low frequency vibrations (1-20 Hz) cause back pain, herniated disc, diseases that may occur after a certain time of exposure to vibrations. Regardless of the existence of certain unforeseen external factors, it appears that exposure to vibrations transmitted to the human body in vertical plane in the range 20-80 Hz does not affect its health.