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Modeling a sitting human body/chair system in a vibration environment

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ABSTRACT: The scope of the present research is to study the global dynamic characteristics of a seated human body/chair system in a vibration environment, in order to protect the body by using specially designed cushions.

The main result is a mathematical-numerical multi D.O.F lumped parameter model, which describes the apparent mass phenomena, and the contact human pelvis/vibrating seat using a cushion interface. The model is based on experimental data and yields guide-lines for composite cushion design. By a proper selection of the geometry and materials of the composite cushion and applying the newly developed principle of quasi-uniform contact force distribution, the resonance frequency band of the system was adjusted and the energy absorbed by the human body minimized. The parameters of the model were obtained using a complex set of experiments and contact stress analysis.

The new approach of combining both the geometry and the mechanical characteristic of deformable structures in a lumped parameter model has enabled a successful analysis of some delicate contact problems in Biomechanics and practical results in Human Body Dynamics.

1. INTRODUCTION

Evolution is a very long and slow process, if the human life-span is taken as a scale unit. Change created by modern technology makes faster progresses with which evolution partly fails to cope. Man-made artificial environments have exposed the human body to conditions which are much more extreme in their characteristics, when compared to those of the natural environment. Thus, special consideration has to be given in order to protect the human body in these man-made artificial environments. Part of them, which is the scope of the present study, is the vibration environment which is commonly created by all means of transportation on sea, on land or in the air.

Two areas have been established for studying the biomechanical dynamic characteristics of the human body in a vibration environment: the global human body dynamics and the human body/seat contact force distribution. Both experimental and numerical approaches have been applied in those two areas. Experimental data from studies concerning the global human body dynamics prior to 1970 were brought together in the international standard I.S.O. 5982 (1981). The recent experimental work was done by Fairley and Griffin (1989, 1990), studying posture effects. Several experimental devices have been developed to measure the contact stress distribution at human body/seat interface in both static and dynamic condition (Arcan and Brull 1980, Arcan 1982, 1990, Prutchi 1988, Zanger 1989, Brosh 1990, Prutchi and Arcan 1990, 1993) Numerical studies have been mainly addressed to study the global human body dynamics. Multi DOF lumped parameter models were developed corresponding with the experimental data (Muksian et al. 1974, 1978, Patil et al. 1978, I.S.O. 5982 1981-E, I.S.O. 7962 1987-E, Nigam et al. 1987, Amirouche 1988, Fairley and Griffin 1989). Most of the experimental and numerical studies focused on vibration effects on the human body in a seated posture along the vertical axis. Special studies concerning the delicate interface between the human body soft tissues and stiff seat plate or flexible cushion, described the phenomena in *static* conditions only by using the finite element method (Brosh 1990, Comisioneru 1991).

In most cases, involving high performance vehicles, the people occupying them are not passive passengers, but rather active elements, who control the global system. The human tolerance and ability to perform in a vibration environment may limit the capability of the total system, thus a proper chair design is essential. The part of the chair which comes into contact with the soft tissue of the human body is the cushion. The cushion accomplishes two main requirements. From a dynamic point of view, the cushion serves as a filter between the human body and the vibration environment. Due to both static and dynamic considerations, the cushion creates a certain contact pressure distribution at the interface between itself and the soft tissue. The contact interface is highly irregular, from both geometrical and mechanical points of view.

In the absence of dynamic numerical models describing the interface of the human body/flexible seat, the cushion design for dynamic conditions uses experimental techniques. Since the problem in its nature is a trial and error one, the developing procedure becomes complicated and requires a long time for analyzing the data. A numerical model, which runs on a computer, by using a simulation program, will serve as a powerful tool, and will make the design procedure much shorter in time, and less complicated in nature.

It was in the scope of the present research, to study the global dynamics of a seated human body/chair system in a vibration environment, in order to protect the human body by using specially designed cushions. A mathematical-numerical approach, and the ACSL computer simulation program were used as basic tools.

The first step, in achieving the aim, was to develop a lumped parameter model which would describe the apparent mass of a seated human body in all three main vibration direction (X,Y,Z), and to represent, through model, various sitting posture and environmental characteristics, as well as their effects on the apparent mass phenomena.

The following parameters were examined:

- Sitting posture with and without backrest
- Five conventional degrees of muscle tension characterizing the sitting posture
- Footrest relative height
- Selected vibration spectra as the main environment characteristics

The second step was to develop a simplified 2-D lumped parameter model of the human pelvic structure coming in contact with the vibrating seat. The model represented the substructure both from a geometrical and from a mechanical point of view. In addition, the model described the vertical contact forces created at the interface between them.

The third step was to study and define basic guide-lines for the design of composite cushions, that should act as mechanical filtering systems protecting the human body in a specific vibration environment.

2. SEATED HUMAN BODY APPARENT MASS MODELING

2.1 *Experimental data base*

The experimental data base of the apparent mass modeling is the systematically experimental work of Fairley and Griffin (1989,1990), which is the latest experimental study investigating most of the factors influencing the apparent mass in the three basic vibrations axis. All the experimental work was done by using the same experimental methods on the same subjects and for that reason their study offers the ideal base line for a comparison between experimental data and numerical models.

2.2 *The apparent mass definition*

Although the human body is a completely unified organic system, it can not be treated simply as a single lumped mass. The human body exhibits a complex dynamic behavior. The apparent mass describes the mechanical characteristics of the human body when exposed to mechanical vibration.

The apparent mass of a seated human body is represented by the complex frequency function:

$$M(f) = \frac{F(f)}{A(f)} \qquad (1)$$

where: M(f)-apparent mass; F(f)-force transmitted at the human body/seat interface; A(f)-acceleration at the human body/seat interface; f-frequency.

2.3 *Lumped parameter model*

The linear lumped parameter model (Fig. 1) represents the apparent mass of the human body, in a sitting posture, on a stiff seat plate, in three vibration directions : vertical (Z), for and aft (X), and side to side (Y). On each axis the apparent mass is defined by a 2 D.O.F. model which is independent from the other two axes. One may note that the masses, to be used in the model, with m1, m3 (upper body and feet) moving in respect to the seat plate, and m2 (lower body) not moving at all in respect to the same plate; similarly the stiffness coefficient (Kb, Kf) and the damping ones (Cb, Cf) are, as the masses, connected to their direction (X, Y, Z). In cases where a footrest is used, a redundancy of the model is made by not using the mass element m3, since there is no relative movement between the footrest and the seat plate. The stiff seat plate moves in a sinusoidal motion with a constant acceleration spectrum which has a magnitude of 1 m/sec, and a frequency range of 0.25 - 20 Hz. Such input characteristics are the same as those used by Fairley and Griffin (1989, 1990) in their experiments.

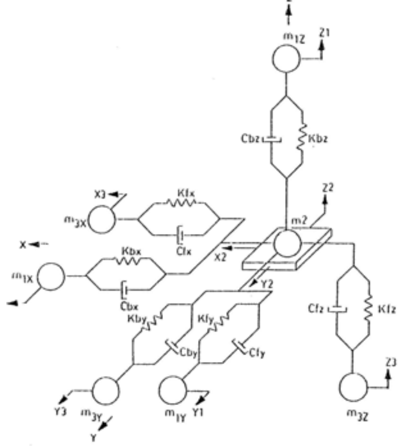

Fig. 1 : Lumped parameter model of a seated human body which represents the apparent mass phenomena on three separate axes.

2.4 *Parameter optimization - Guide lines*

In order to achieve the best representation of the experimental result by a numerical model, several basic guide lines had to be established for optimal selection of the model's parameters. The mass components of the model were considered to be non-variant parameters, whereas the viscoelastic elements were defined as variant parameters. The lumped parameter model degrees of freedom (1 D.O.F. or 2 D.O.F.) were determined based on vibration modes number of the apparent mass experimental results.

By a proper selection of the stiffness coefficients (Kb, Kf) and of the damping coefficients (Cb, Cf) the numerical apparent mass values and the resonance frequency peaks were fit to the experimental data.

2.5 *Normal sitting posture - Experimental versus model results.*

The body position was defined by Fairley and Griffin (1989,1990) as sitting on the stiff seat platform in a comfortable upright posture with normal muscle tension. The feet were supported by a footrest which moves with the stiff seat platform. The lower legs were vertical, and the hands rested in a lap position.

A representation of the experimental results by the model (Fig 1) was achieved by a proper selection the model parameters (Table 1)

Parameters	X Axis	Y Axis	Z Axis
m1	22.8	22.8	45.6
m2	6.0	6.0	6.0
m3	22.8	22.8	0.0
Kb	506.3	506.3	45005.3
Cb	51.3	75.2	1360.0
Kf	508.5	567.2	/
Cf	5625.6	3600.4	/

m [Kg] ; K [N/m] ; C [N*s/m]

Table 1: Reference posture - model parameters

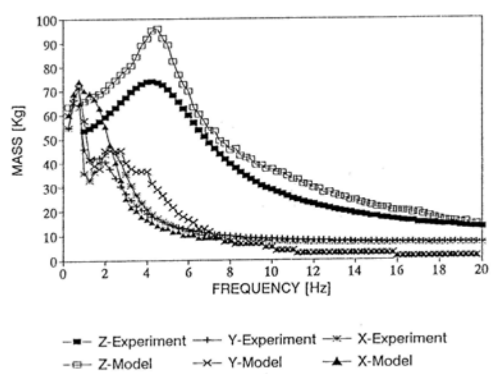

Fig 2: Apparent mass modulus of the reference posture - Experimental and numerical model results

The seated body presented two heavily damped modes of vibration in both X and Y direction. The first mode appeared to arise from a motion of the whole upper body. The second mode of vibration presumably arose from the horizontal response of the musculo-skeletal system of the body, buttocks and the hips which were out of phase with the shoulders. The apparent mass in the Z axis had one main resonance (Fairly and Griffin 1989, 1990)

From a comparison between the experimental data and the numerical model results (Fig. 2) a good representation of the experimental data was achieved by the model in both the global and the local range of frequencies (at the resonance frequencies).

3. DYNAMIC CONTACT MODELING: HUMAN BODY/STIFF OR FLEXIBLE SEAT SYSTEM

3.1 *Experimental data base*

The Contact Pressure Display (C.P.D.) technique (Arcan and Brull, 1976, 1980, Arcan, 1982) was used for experimental measurements of contact stresses between a seated subject and a flat stiff area (Brosh 1990). Since the C.P.D. approach is limited to contact pressure occurring between soft to stiff bodies, a sensor presented by Prutchi and Arcan (1990, 1993) was later developed for soft to soft systems which can comply to displacements occurring during sitting on a soft cushion.

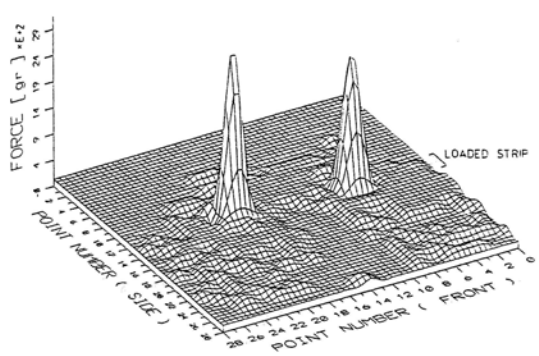

Fig. 3: 3-D space C.P.D meshed plot of the sitting area

A typical experimental result of the contact force between the human body and a stiff seat plate measured, using the C.P.D technique is presented in Fig 3. A 48 mm lateral strip (Fig. 3) including the two maximum local peaks produced by the *Ischial Tuberosities* (*loaded strip*), was able to characterize the total body/stiff seat plate contact.

3.2 *Model development stages and optimal overall behavior guide lines*

The lumped parameter model combined two dynamic phenomena : the apparent mass effect, and the vertical contact force distribution resulting from the interaction between the buttock soft tissue and a vibrating stiff seat platform. The 2-D model development procedure was divided into two phases. The first phase focused on the geometry and the mechanical representation of the pelvic structure coming in contact with a stiff vibrating seat platform. The second phase considered the influence on the vertical contact force distribution of various composite cushions with different mechanical and geometrical characteristics in a dynamic environment

The design of a cushion protecting against vibrations involved the use of composite structures. This cushion take advantage of the variable structural geometry, and nonlinear viscoelastic composite behavior. Three aims had to be achieved by using the selected cushion:

- Uniform contact stress distribution
- Minimal total force transmitted to the human body
- Justify the resonance frequency band

3.3 *Lumped parameter model*

The non-linear two dimensional (2-D), multi degree of freedom (M-D.O.F) lumped parameter model (Fig 4) is composed of two half symmetric sub-systems, interacting with each other: human pelvis above the load strip, and two layer composite flexible cushion. Each VOIGT element column represented contact area of 12 mm x 16 mm. The contour of the soft tissue represented by Ti and Di were measured from a X-ray photograph of the human pelvis cross section geometry.

The apparent mass of the human body (Mls) is represented by the model developed in section 2. The masses of the cushion (m1,...,m26) were represented in the model by lumped masses. Theoretically, 26 different material characteristics could be used in order to define the cushion. In the present study, the cushion was composed of only 3 different commercial cushion materials, which was the reasonable choice from a manufacturing point of view. The model input was the same as defined in section 2.3.

The elastic components of VOIGT element characteristics were based on measured data. The mathematical formulations are as follow: for human body soft tissue - Eq. 2, and for the cushion matherials - Eq. 3. The viscosity components are represented mathematically by Eq. 4

$$F_{ki} = F_{0i}\left(\left(\frac{1}{1-\Delta z_i / T_i^0}\right)^r - 1\right) \quad \text{for } i = 1 \ldots 13 \qquad (2)$$

$$N_{ki} = f_{mat(j)}(\Delta z_i) \quad \text{for } i = 1 \ldots 26,\ j = 1,2,3 \qquad (3)$$

$$F_{ci} = N_{ci} = C_i \Delta \dot{z} \quad \text{for } i = 1 \ldots 26 \qquad (4)$$

Where: F_{ki}, F_{ci} - Elastic and viscosity forces of the soft tissue; N_{ki}, N_{ci} - Elastic and viscosity forces of the cushion material; Δz_i - Material relative displacement; $\Delta \dot{z}_i$ - Material relative velocity; T_i^0 - Soft tissue thickness (unloaded); $f_{mat\,(i)}$ - cushion elastic force deflection function of the j material; F_{0i}, r, C_i - constants; i - Element index; j - Material index

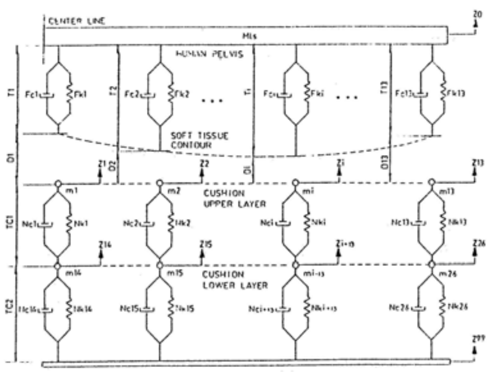

Fig 4: A lumped parameter 27 D.O.F. model of the human pelvis interacting with a two layer composite cushion.

3.4 *Model results*

The contact force distribution of human body/seat interface was studied for different cushions characterized by shapes and materials , e.g., stiff seat plate, flat and shaped homogenous cushions, flat and shaped heterogeneous cushions (Fig 5)

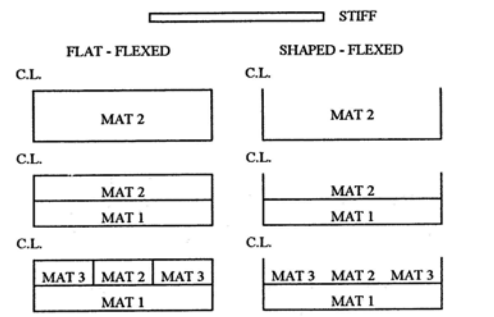

Fig 5. Cushion configurations - Schematic representation of half cushions (C.L.-Center Line).

The maximum vertical contact force distribution, produced by the interaction between the human pelvis and the composite flexible cushion during the steady state condition for each input frequency motion, was plotted. For static condition see Fig 6, and for dynamic condition see Fig 7.

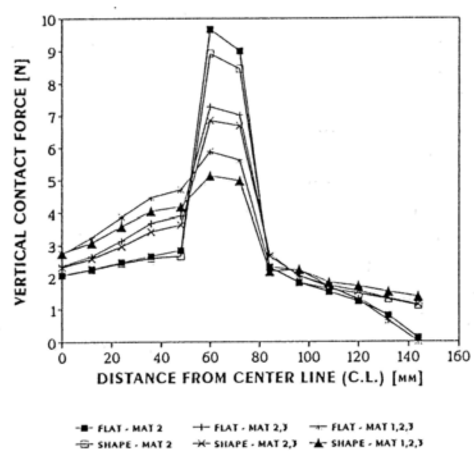

Fig 6: The static vertical contact force distribution of the human pelvis interacting with various configurations of flexible cushions.

The best result was achieved by using a shaped cushion built of three materials. The material under the *Ischial Tuberosities,* where the peak zones of the vertical contact forces were created, had the lowest stiffness out of the three materials (MAT2). The other zones of the upper layer of the cushion were constructed from the material which has the highest stiffness (MAT1). For the lower layer of the cushion a material (MAT3), whose stiffness value was in between the two (MAT1, MAT2) ,was used.

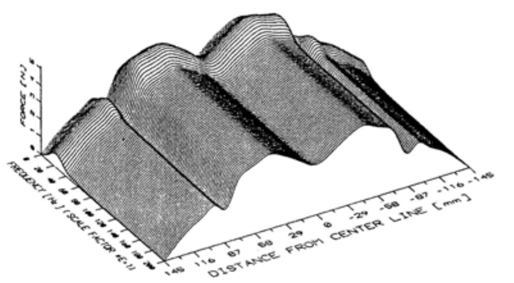

Fig 7: The dynamic vertical contact force distribution of the human pelvis interacting with a composite two layer flexible flat cushion.

4. CONCLUSIONS

A 2 D.O.F lumped parameter model proved to be able to represent the experimentally obtained apparent mass data, and to describe the apparent mass phenomena in the sitting posture and the environmental characteristics by a proper selection of masses and viscoelastic coefficients.

A new approach was developed to represent the contact forces (stresses) between two deformable structures by using multi D.O.F lumped parameter models with series of non-linear VOIGT. The number of those elements determines the model's resolution. This model can use as a basic tool for cushion design in vibrational environment.

A very good correspondence between the experimental data base and the model behavior was achieved

A basic consideration for this development was the principle that uniform contact map may drastically reduce the forces transmitted to the human body in vibrational environment.

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