Upon modeling and testing of hand-arm system vibrations in the view of professional diseases prevention. A systematic approach

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Abstract: - The paper presents the systematic approach regarding the modeling and testing methods used for hand-arm system vibrations in the view of professional diseases prevention. It aims to evaluating preventive strategies to reduce worker exposures to hand-arm transmitted vibration and to decrease the occurrence of Hand-Arm Vibration Syndrome (HAVS) in workers. Special emphasis is given to preventive measures and to the transfer of knowledge from the research results to tool manufacturers, and occupational health physicians in fields related to medical, ergonomic, testing, engineering and legal aspects of HAVS. Due to the importance of the subject, the European Directive 2002/44/EC has been implemented into the national legislation of Member States.

Key-Words: - hand-arm vibrations, occupational health, daily exposure assessment, modeling and simulation.

1 Introduction

The occupational diseases due to vibrations represent nowadays one of the great concerns in the labour medicine. Workers from exposed fields of activity (Table 1) accuse symptoms on a large scale that could be associated to the vibration cause [1].

Table 1. Fields of activity with high risk from the vibration exposure point of view [1]

Field of activity	**Vibr. Type**	**Vibration source**
Agriculture	WBV	Tractors driving
Constructions	WBV	Vehicles with heavy equipment
	HAV	Pneumatic drilling machines, pneumatic hammers, etc.
Forestry	WBV	Forestry vehicles (tractors) driving
	HAV	Chain saw
Mining	WBV	Mining vehicles driving
	HAV	Rock drill hammer
Metal cutting	HAV	Machine tools
Shipyard	HAV	Pneumatic hand tools
Textile	HAV	Sewing machines, looms
Transport	WBV	Vehicle driving

It is still a problem for medicine to state that an identified disease is caused, to a great extent, by vibrations, since the contributing factors are usually several and interrelated. However, due to the problem complexity, presently there is a lot of research carried on by joint teams of engineering and medical researchers, at international level. Consequently, the vibrations influence can be clearly systematized in two distinct categories: whole body vibrations – with significant effects in the entire human body; vibrations on different sections of the body – that transmit significant accelerations and displacements only in some sections, such as the hand-arm system.

In the literature, the first category is referred to as WBV (***W**hole **B**ody **V**ibrations*), and the second one as HAV (***H**and **A**rm **V**ibrations*). An overview of the state of the art in human body protection against vibrations, both at national and international level, is presented in [2].

Due to the research carried on in this field, presently the critical frequencies that affect the human body are known [1]. Moreover, the research results led to several standards and regulations imposed both to the manufacturers of vibration generator equipment and to the employers whose employees are exposed to vibrations during the work. The most recent demonstration of the overall concern related to this subject is the European Parliament and the Europe Council Directive 2002/44/CE from July 25, 2002, regarding the security and health minimum requirements related to the workers exposure to the physical agents (vibrations) generating risks.

2 Health effects of HAV exposure

Within the area of vibration transmitted to the human body, hand-arm vibration is the second large problem, different from whole-body vibration in the type of problems it gives rise to. Whereas vibration transmitted into the standing or seated body normally generates problems of a general nature – motion sickness, discomfort, reduced-working efficiency, low-back pain etc., vibration applied to the hand-arm may produce physical damage locally if the level and exposure times are sufficiently high [1].

Several tests have proved that vibration levels encountered in many commonly used power tools are sufficiently high to cause damage when operated for durations common in industry. Typical of these power tools are chipping hammers, power grinders, hammer drills, and chain saws, found in widespread use in the mining, construction, manufacturing and forestry industries (see Table 1). Vibration may be transmitted into the body from a vibrating tool or hand-held workpiece via one or both arms simultaneously, causing, at lower levels, discomfort and reduced working efficiency: reduced grip strength, pain in arms and shoulders. Those can further lead, for example, to sleep disturbance and inability to do fine work. At higher levels and longer exposure periods, diseases affecting the blood vessels, joints and circulation occur. Severe exposure leads to a progressive circulation disorder in the part of the body suffering the highest level of vibration, usually the fingers or hand where hand-held tools are concerned. This is variously known as “dead hand”, vibration-induced “white finger”, or Raynaud's disease (Fig. 1). In extreme cases this leads to permanent damage or gangrene.

Fig. 1 Hand aspect in “white finger” disease [3]

The medical research revealed hand-arm vibrations as possible cause for Carpal Tunnel Syndrome, too. It usually occurs when the median nerve, which runs from the forearm into the hand, becomes pressed or squeezed at the wrist. The median nerve controls sensations to the palm side of the thumb and fingers (although not the little finger), as well as impulses to some small muscles in the hand that allow the fingers and thumb to move. Fig. 2 shows (coloured in grey) the palm area affected by this syndrome.

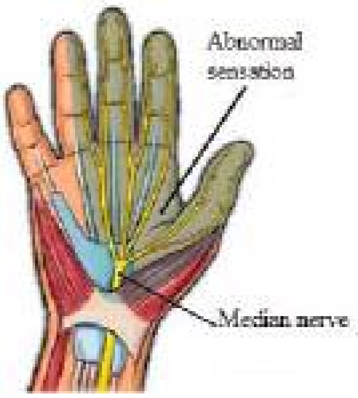

Fig. 2 Palm area affected by Carpal Tunnel Syndrome [4]

A special attention should be given to the medical entity named Hand-Arm Syndrome, caused by vibrations. The syndrome incidence is not known at the population sector that works in high risk environment; however, the studies related to this subject appreciate that this affection is underestimated and usually wrongly diagnosed as carpal channel disease [5]. Therefore the difference should be done between the Hand-Arm Syndrome and the occupational Raynaud Syndrome described above. Whereas the second one strictly refers to the vascular disorders at hand (finger) level, the first one includes vascular, neurological and muscle-skeleton disorders produced as a consequence of vibration exposure. The HAV syndrome was described for the first time in 1986 by the Stockholm working group, who also conceived an evaluation scale [6]. Aiding this scale, both the vascular and neurological components can be assessed, by ranking from 0 to 4. The 3 stage (vascular or neurological), according to the Stockholm scale, contraindicates the subject exposure and to continue to work in the vibration environment. The disease severity increases together with the exposure period. The medium exposure time that causes the HAV syndrome varies in terms of epidemiological studies, from 9.1 to 23.3 years); this variation is probably due to the heterogenic study batches [7].

The most exposed occupational groups are related to activities in which vibratory machines and tools are manipulated: forestry workers, farmers, workers in mining industry, machine building industry, constructions, dental technicians. The clinical panel is described in the literature [5]. The physiological-pathological mechanisms the HAV syndrome is based on are not completely known, however it can be surely stated that following changes are present: vasospasm at vascular level, organic micro-angiopathy with the vascular wall hypertrophy and endothelial cells alteration, occlusive arterial thrombosis, diffused neuropathy that affects the Pacini corpuscles (the mecano-receptors at fingers level) [5].

These diseases, their cause and consequences, together with prevention solutions are currently being extensively investigated both by medical and engineering researchers [2]. On the other hand, according to the regulations in force, measuring and assessing the hand-arm vibration levels has to be done by the manufacturers of the power tools - to label their tool - as well as by the end user – who need to check the vibrations for their workers in order to limit the daily exposure.

3 Methods for HAV assessment

Discussion upon HAV assessment methods involves the specific descriptors definition, presentation of different evaluation approaches as well as measurement equipment description.

3.1 Specific descriptors

In order to asses the human vibrations the specific descriptors have to be known, since they represent the output of the measurement testing:

– PEAK value, positive or negative, is the highest absolute value of the instantaneous vibration signal (acceleration, velocity or displacement) within one second time period;
– RMS value (root mean square) of the frequency weighted accelerations, on x, y, and z orthogonal axes (eq. 1, fig. 3).

$$a_{hv} = \left[\frac{1}{T}\int_0^T a_{hv}^2(t)dt\right]^{\frac{1}{2}}, \qquad (1)$$

where T is the duration of measurement and *a*w is the frequency weighted acceleration.

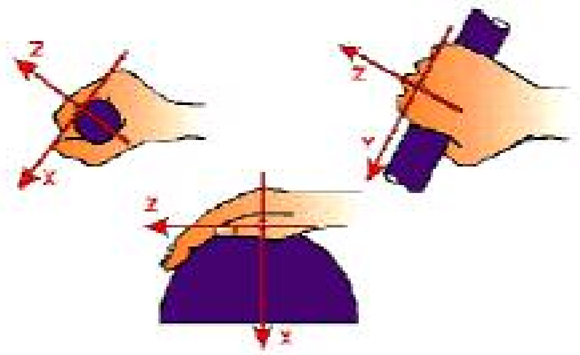

Fig. 3 Orthogonal axes for hand-arm vibration measurement. [8]

– CREST factor is the ratio between the PEAK value and RMS value for the specific vibration (human vibration, acceleration, velocity or displacement) within one second time period (eq. 2):

$$CREST = \frac{PEAK}{RMS} \ . \qquad (2)$$

It is dimensionless; it is used for indicating the peak values of a vibration signal; for a sine signal, crest factor is 1.41.

– VDV (vibration dose value) is defined in BS6472: 1992 standard, as:

$$VDV = \left[\int_{t=0}^{t=T} a^4(t)dt\right]^{\frac{1}{4}} . \qquad (3)$$

For easy calculations, an estimated vibration dose value for a given time period (i.e. 16 hrs/day) can be determined, using the relation:

$$eVDV = 1.4 \times a(rms) \times t^{0.25}, \quad (4)$$

where *eVDV* is the *VDV* estimate in $[\mathrm{m/s}^{1.75}]$, *a(rms)* is the RMS acceleration (denoted also with a_{hv}), in [m/s^2], t is the total expusure time, in [s].

3.2 Different approaches for descriptors calculation

According to ISO 5349-1:2001 standard, the frequency weighted RMS is measured is measured on each of the three orthogonal directions (Fig. 3), resulting the values: a_{hvx}, a_{hvy}, a_{hvz}. For assessing the vibration exposure an overall value is calculated, combining the influences on the three axes:

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \qquad (5)$$

The daily vibration exposure A(8) is based on the vibrations magnitude and the exposure time, being expressed in [m/s^2], according to equation (6):

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \quad , \qquad (6)$$

where a_{hv} is the measured vibration, in m/s^2; T is the exposure time corresponding to the viration a_{hv} ; T_0 is the reference time for a working day (i.e. 8 hours). If the employee is exposed, during one working day, to several vibration sources (for example if he/she uses more tools in the same day), the *partial vibration exposure* is calculated, ased on the viration magnitude and the exposure time of each process. These values are then combinated, thus resulting the daily exposure:

$$A(8) = \sqrt{A_1(8)^2 + A_2(8)^2 + A_3(8)^2 + \ldots} \quad (7)$$

where $A_1(8)$, $A_2(8)$, ..., $A_n(8)$ are the partial exposure values for the different vibration sources acting on the same person during the working day.

The exposure level assessment can be obtained either from information provided by the different tools manufacturers (regarding the vibration levels of the working equipment) or by measurements. However, the exposure time – as key issue in calculating the daily exposure, depends on several factors and may significantly influence the measurement accuracy. Among these factors are:

– the time measurement accuracy;
– the estimated exposure time, provided by the human operater subjected to vibrations – who usualy would overevaluate the exposure time;
– estimation of working cycles for a working day.

Since the mathematical relations for descriptors calculation are quite complicated, there have been developed literature different methods that allow for a rapid assessment of the daily vibration exposure [9], [10].

3.2.1 Daily exposure graph

The graph gives an alternative method for daily exposures or partial vibration exposures monitoring (more details in [10]). A simple look is needed on the graph for the $A(8)$ line at or just above where the vibration magnitude value and exposure time lines meet. The green area in indicates exposures likely to below the exposure action value. These exposures must not be assumed to be “safe”. There may be a risk of hand-arm vibration injury for exposures below the exposure action value, and so some exposures within the green area may cause vibration injury in some workers, especially after many years of exposure.

3.2.2 Daily exposure nomogram

The nomogram provides an alternative method for obtaining daily vibration exposures (more details in [10]). The determination consists of the following operations: 1-Draw a line from a point on the left hand scale (representing the vibration magnitude) to a point on the right hand scale (representing the exposure time); 2-Read off the partial exposures where the lines cross the central scale; 3-Square each partial vibration exposure value; 4-Add the squared values together; 5-Take the square root of the result to give the overall $A(8)$ daily vibration exposure value.

3.2.3 Exposure points system

Hand-arm vibration exposure management can be simplified by using an exposure “points” system (more details in [10]). For any tool or process, the number of exposure points accumulated in an hour (denoted $P_{E,1h}$ in points/ hour) can be obtained from the vibration magnitude a_{hv} in m/s² using the following relation:

$$P_{E,1h} = 2a_{hv}^2 . \qquad (8)$$

Exposure points are added together, so one can set a maximum number of exposure points for any person in one day. The exposure scores corresponding to the exposure action and limit values are:

– exposure action value (2.5 m/s²) = 100 points;
– exposure limit value (5 m/s²) = 400 points.

The number of the exposure points is defined by relation (9):

$$P_E = \left(\frac{a_{hv}}{2.5m/s^2}\right)^2 \cdot \frac{T}{8ore} \cdot 100 , \qquad (9)$$

where a_{hv} is the vibration value, in m/s^2 and T is the exposure time, in hours.

The daily exposure yields by applying relation (10):

$$A(8) = 2.5m/s^2 \sqrt{\frac{P_E}{100}} . \qquad (10)$$

3.2.4 Traffic light system

Another simple method consists in using the indications of a “traffic light” system, where each tool is clearly marked with a hand-arm vibration color coding, dependent on the expected in-use vibration magnitude of each machine (more details in [10]). The success of the traffic light system is dependent on the quality of data used to determine the color rating of each machine. The green area indicates exposures likely to below the exposure action or limit value. These exposures must not be assumed to be “safe”. There may be a risk of hand-arm vibration injury for exposures below the exposure action value and other management controls must be used to ensure that workers are trained to understand and operate the system correctly, that the systems are actually correctly used and that workers at risk do not develop symptoms of hand-arm vibration syndrome.

3.3 HAV Measurement Equipment

Several manufacturers provide nowadays equipment for human vibration measurement. What one should keep in mind is that for ensuring correct measurements, the measurement procedure should obey the standard regulations. They are listed below, as reference:

- ISO5349 – Mechanical vibration – Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration;
- ISO1683 – Acoustics – Preferred reference quantities for acoustic levels
- ISO5347 – Methods for the calibration of vibration and shock pick-ups
- ISO5348 – Mechanical vibration and shock – Mechanical mounting of accelerometers
- ISO5808 – Mechanical vibration and shock affecting man – Vocabulary
- ISO8041 – Human response to vibration – Measuring instrumentation;

As a general rule, a HAV testing equipment should consist of: data acquisition frontend, data processing software, triaxial accelerometer to provide information upon vibrations transmitted on the three orthogonal directions. Fig. 4 presents the experimental set-up used for hand-arm vibration study at Transilvania University of Brasov, within the framework of a research project on this topic.

Fig. 4 Example of HAV experimental set-up at Transilvania University of Brasov

The results consist of weighted magnitude of vibration both in linear and dB) for the 3 directions of the accelerometer. The maximum acceleration is the one to be taken into consideration. In addition, if required for some types of tools, the following results can be provided: RMS acceleration levels a_h, weighted acceleration levels a_h, W, acceleration level in dB La_h (reference acceleration of 1μm/s2).

The HVB analyzer determines the daily vibration exposure in the four study cases, as presented in Figure 5. For each case the following parameters are available: RMS Sum – see relation (1), and CREST factor (relation 2).

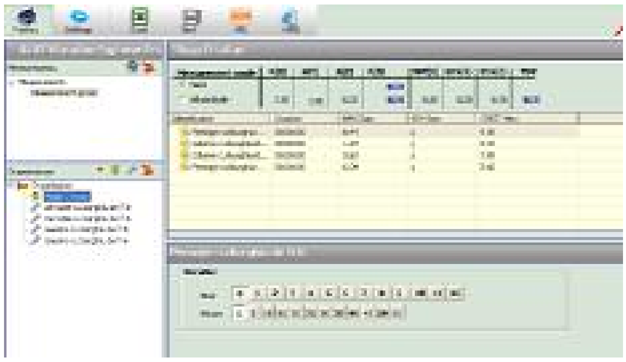

Fig. 5 Example of study cases results

The data from the analyzer can be further transferred on a PC (through USB port) and different files can be generated for data processing. In this case, the data have been processed from an Excel file. The results are presented in Table 2.

Table 2. Experimental results

Id.	RMS sum	CREST max
1	8.49	9.36
2	6.04	5.82
3	3.52	7.89
4	1.23	6.27

Taking into account the admissible value foreseen in the regulation documents, it can be easily observed the percussion operation generates vibrations above the limits ($5m/s^2$). The use of borers with higher diameters will also lead to increased vibrations, which may affect the worker, on long term. The type of measurement results presented in Table 2 represent input data for the database further used by the medical specialists for identifying the occupational diseases caused by vibrations.

4 Prevention Ways and Measures

The ultimate aim of the research performed in HAVs field is to identify prevention ways and measures that would decrease the vibrations influence on human health. This issue involves not only tool design problems but also medical, social and legal aspects.

From legal point of view, the European Directive 2002/44/EC of the European Parliament and of the Council lays down minimum requirements for the protection of workers from risks to their health and safety arising or likely to arise from exposure to mechanical vibration [11]. According to this document, each member state has developed systems for health surveillance for the workers exposed to vibrations. From medical point of view, this would result in implementing programs, by occupational physicians, for educating and training people to be

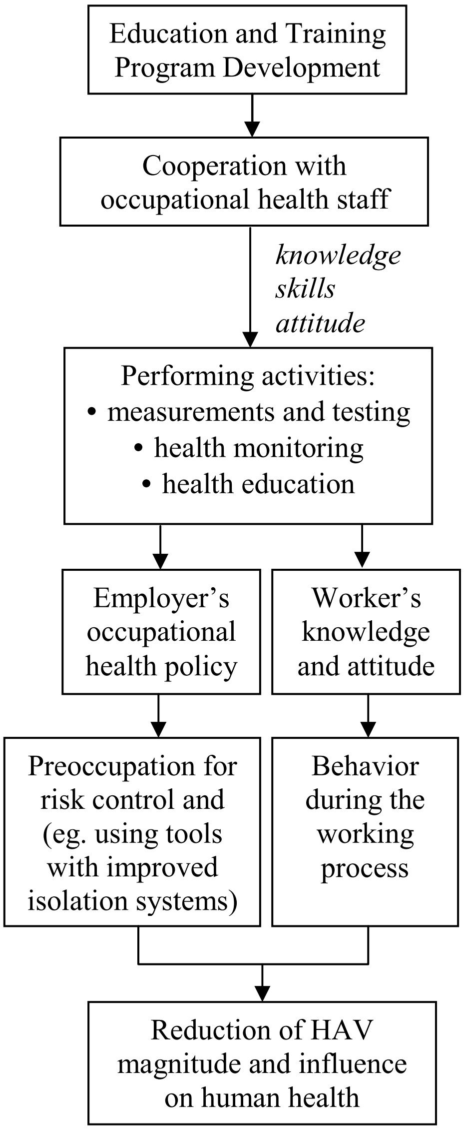

Fig. 6 Program scheme for education and training in HAVs field

aware of the risk and to act for reducing its consequences (including periodic tests and health monitoring). A possible scheme of such programs is presented in Fig. 6.

As for the engineers, the research is directed towards identifying advanced isolation systems for human body protection to vibrations. One starting point in this task is to develop hand-arm system models, allowing for simulation of its dynamic behavior in a vibration environment. The analytical models are compared with test results and improved according to measurement data, so that to become reliable tools for further analysis and behavior prediction.

Different approached in modeling and simulation of hand-arm system are discussed in the following paragraph.

5 Hand-Arm System Modeling and Simulation

5.1 Dynamic model

The dynamic model represents the problem in a schematic way; in most of the cases it resumes a simplified approach by accepting a set of assumptions. According to this definition, some observations related to dynamic model use may occur:

– even if it leads to calculation volume reduction, too many simplifying assumptions may yield to results with no practical confirmation;
– on the other hand, tending to solve the problems of dynamics in a too complex way may introduce difficult and time consuming calculations, even for the nowadays sophisticated computers.

Therefore the engineer is the one to decide upon the model complexity degree, the nature and number of simplifying assumptions, and afterwards to interpret the results for

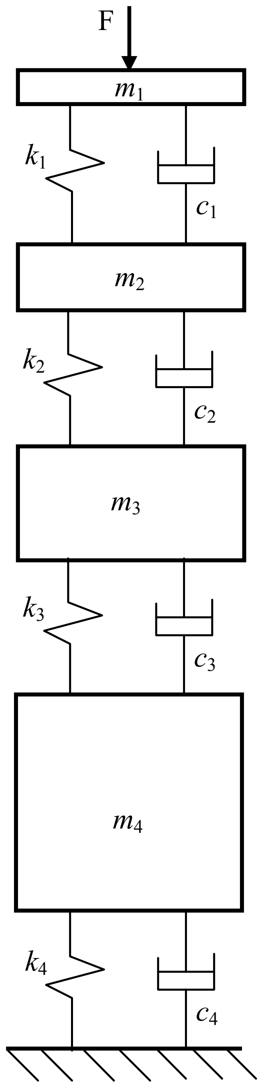

Fig. 7 Biodynamic model of hand-arm system [12]

practical use. Whatever the assumptions, a correct dynamic model should ensure, at least for a certain domain of inputs, the same outputs as the initial system (unaffected by simplifying assumptions).

In the hand-arm dynamic investigation the biodynamic model proposed by Harris [12] is used (Fig. 7). The analysis involves the writing of the equations of motion for the 4 d.o.f. model. This results in the following matrix equation:

$$[M]\{\ddot{y}(t)\} + [C]\{\dot{y}(t)\} + [K]\{y(t)\} = \{F(t)\} \qquad (11)$$

where *F(t)* is the input force; $y(t),\ \dot{y}(t),\ \ddot{y}(t)$ are the outputs (displacement, velocity or acceleration);

$$[M] = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix}$$ is the mass matrix;

$$[C] = \begin{bmatrix} c_1 & -c_1 & 0 & 0 \\ -c_1 & c_1 + c_2 & -c_2 & 0 \\ 0 & -c_2 & c_2 + c_3 & -c_3 \\ 0 & 0 & -c_3 & c_3 + c_4 \end{bmatrix}$$ represents the damping matrix, and

$$[K] = \begin{bmatrix} k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2 + k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 + k_4 \end{bmatrix}$$ is the stiffness matrix.

By applying Laplace transform in zero initial conditions, the following equation results:

$$\left(p^2[M] + p[C] + [K]\right)\{Y(p)\} = \{F(p)\} \qquad (12)$$

where $p^2[M] + p[C] + [K] = [Z(p)]$ is the dynamic stiffness, and the inverse of transfer matrix [H(p)]. For solving this problem, it has to be transformed in an eigenvalue problem, according to equation (13):

$$(p[A] + [B])\{Y'\} = \{F'\}\ , \qquad (13)$$

where: $[A] = \begin{bmatrix} [0] & [M] \\ [M] & [C] \end{bmatrix}$, $[B] = \begin{bmatrix} -[M] & [0] \\ [0] & [K] \end{bmatrix}$,

$\{Y\} = \begin{Bmatrix} p\{Y\} \\ \{Y\} \end{Bmatrix}$, $\{F\} = \begin{Bmatrix} \{0\} \\ \{F\} \end{Bmatrix}$.

Thus the eigenvalue equation is obtained:

$$|\lambda[A] + [B]| = 0\ , \qquad (14)$$

which generates 8 complex eigenvalues, in complex conjugates pairs. The solutions of equation (14), $\lambda_i, \lambda_i^*, i = 1...4, \lambda_i, \lambda_i^* = \sigma_i \pm j\omega_i$, give also the system natural frequencies and the corresponding modeshapes

5.2 Finite Element Model

Another approach in HAV modeling and simulation is related to the development of the FE model [13]. The model is obtained with CAD tools and analysed using the finite elements method (Fig. 8).

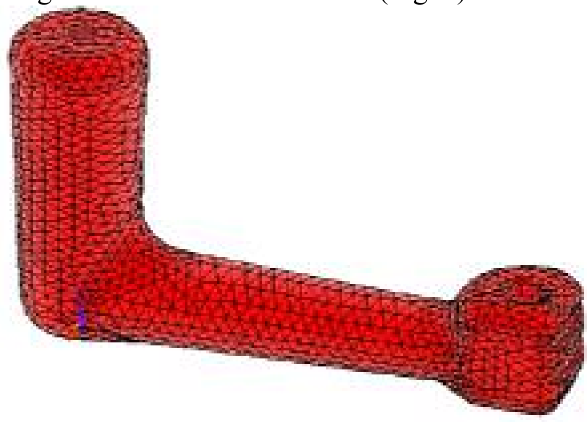

Fig. 8 The hand-arm finite element model

For the analysis an orthotropic material has been considered, with the following characteristics:

- The E modulus varies in terms of density; therefore a non-homogenous material is used. It has a greater value on axial direction (between 17 and 26.5 GPa) than on the transversal (8.51 – 19.4 GPa) and longitudinal (6.91 – 18.1) direction.
- Poisson ratio for the bone has been chosen as follows: $\nu_x = 0.31$; $\nu_y = 0.18$; $\nu_z = 0.18$.
- The G modulus for the human bone varies between 2.41 - 7.22 GPa on axial direction, between 3.28 - 8.65 GPa on transversal direction, between 3.28 - 8.67 GPa on longitudinal direction.
- The density varies for the human bones: it decreases along the years, having different values in terms of age, race and gender. For the present analysis it has been chosen a value specific for a white male, between 20 and 30, which is 1050 mg/cm^3 = 1050 kg/m^3.

The modal analysis performed on the model yields to the results are listed in Table 3 (for the first 20 eigenmodes extracted). The first 6 natural frequencies are close to zero, representing the rigid body motion; this result proves the model is correct and it can be used for further type of analysis (including the effect of different excitation levels on the hand-arm system). Just to have an idea about the analysis outputs, Figure 9 illustrates one of the 20th mode shapes.

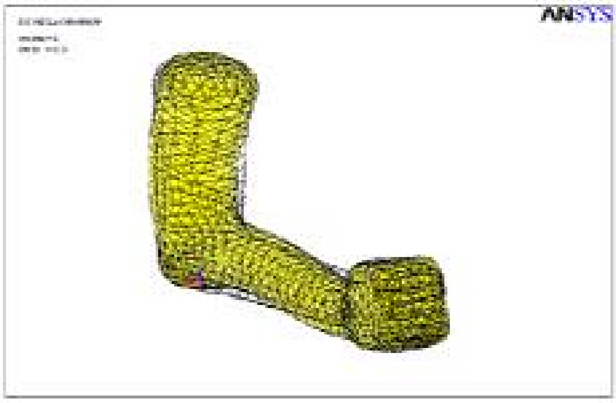

Fig. 9 Mode shape 13, f = 0.96949E-01Hz

Table 3 The results of the modal analysis performed for the hand-arm model.

Set	Natural frequency [Hz]
1	0.0000
2	0.33689E-08
3	0.10200E-07
4	0.11151E-07
5	0.20224E-07
6	0.29441E-07
7	0.18775E-01
8	0.31633E-01
9	0.34489E-01
10	0.51135E-01
11	0.63372E-01
12	0.86455E-01
13	0.96949E-01
14	0.10600
15	0.11725
16	0.12730
17	0.15547
18	0.16530
19	0.17985
20	0.19362

5.3 Finite Element Model Updating

Basically two approaches may be used for studying HAV structure: an analytical approach, based on a finite element model, and an experimental one, based on the experimental modal analysis. Since it is plausible to see the two approaches as complementary to each other, numerous attempts of combining them have been undertaken. The analysis of the dynamic behavior is however not straightforward. Modal parameters are determined either by experimental or by numerical methods. Results of both investigations are expected to correlate closely. Experimental measurements give information about the system in the configuration of test only. Finite element models allow to predict the system dynamic behavior structure under various loading and boundary conditions, but the reliability of the finite element models is often not guaranteed. Model updating techniques verify and correct these finite element models by means of experimental data. The result of a model updating analysis is a finite element model that is reliable for further predictions. The biomechanical system is analyzed using both the finite element and experimental approach and the updating procedure is performed in order to correct the analytical model based on the experimental data. The updating method is based on the calculus of sensitivity mass and stiffness matrices with respect to the updating parameters. Practically, the new, high performance analytical model is obtained by a redistribution of mass and stiffness inside the system. The updating is based on the minimization of frequency response functions residues, on one hand, and the minimization of the natural frequencies residues, on the other hand. This optimization problem is achieved by the least square method.The model updating procedure program [14] is conceived by six modules: 1) – universal file interface; 2) – Finite element code interface; 3) – correlation module between the theoretical (analytical) and experimental models; 4) – updating parameters selection module; 5) – updating criteria selection module; 6) – correction module.

5.3.1 Universal file interface

The experimental data are transferred to the updating program through the universal file interface. The interface reads the experimental model geometry, the coordinates and codes of the measurement points, the experimental modal shapes and experimental frequency response functions.

5.3.2 Finite Element code interface

The finite element code interface transfers the analytical model to the updating program. The program communicates with the finite element code, both in the initial stage of the initial model transfer and for intermediate calculus needed for the updating procedure. The interface launches the finite element code through an input file and it calculates the reduced mass and stiffness matrices by Guyan method. These matrices are described by a binary file. The updating program reads the matrices together with the geometrical model of the structure (i.e. the nodal coordinates ant the nodal codes). Further the frequency range is introduced and an input file is created for the modal analysis calculus. Then the program calls the finite element code and reads the resonance frequencies and the analytical mode shapes from the binary file.

5.3.3 Correlation module between the theoretical and experimental models

The module starts by determining the topological correlations between the two models: for each experimental measurement point the corresponding analytical node is identified. The tolerance of the correlation calculus is given by the radius of the sphere with the center in the measurement point. Thus, only the analytical nodes within the sphere are considered. When more then one node is identified within the sphere, for correlation it is chosen the closest node to the measurement point. Error appears if no node is identified within the sphere or if only one node is identified for two measurement points.

After the topological correlation between the analytical and experimental model the modal assurance criterion (MAC) values are calculated. The resulting MAC matrix is used for automatic pairing of analytical and experimental vibration modes. Each experimental mode is matched with the analytical mode that has the highest MAC value with respect to the experimental mode. If an automatic modes pairing is not optimal, one can use the manual pairing.

For the all pairs of modes the frequency resonance difference is calculated and, finally, the global mass of the finite element model is determined and compared to the real structure global mass.

5.3.4 Selection module of updating parameters

The updating parameters selection module consists of five sub-modules: 1-survey of the potential updating parameters, 2-updating parameters selection, 3-updating parameters implementation, 4-survey of the selected updating parameters, 5-deleting of current selection.

The first sub-module gives a list of the whole parameters that could be selected for updating; they are material properties or element properties and they are located in the finite element input file (see 5.3.2). The second sub-module generates the updating parameters, allowing any combination of the parameters listed by sub-module 1. The third sub-module reads the selected parameters from an ASCII file. The fourth sub-module generates a list of the overall list for all updating parameters and the last module deletes the current selection.

5.3.5 Updating criteria selection module

The updating criteria [15] selection module assembles the updating equations and defines the residues to be minimized. Therefore two different updating criteria can be combined: minimization of frequency response functions residues and minimization of resonance frequencies residues. If the first criterion is chosen, the updating frequencies have to be selected for each set of experimental frequency response functions. The selection can be achieved manually, by introducing the data aiding the keyboard, or graphically, aiding a cursor. For the second criterion the experimental resonance frequencies must be selected for their correlation with the analytical resonance frequencies.

For example, considering as updating criterion the minimization of resonance frequencies residues, the initial correlation between the analytical and experimental models is achieved by calculating the relative difference between the analytical and experimental natural frequencies, given by the following relations:

$$\varepsilon_{\omega_r} = \frac{\omega_r^a - \omega_r^x}{\omega_r^x} \quad (15)$$

$$\frac{\partial \varepsilon_{\omega_r}}{\partial u_i} = \frac{1}{\omega_r^x} \cdot \frac{\partial \omega_r^a}{\partial u_i} \quad (16)$$

$$\frac{\partial \omega_r^a}{\partial u_i} = \frac{1}{2m_r} \cdot \{\Psi\}_r^{a\,t} \cdot \left(\frac{\partial [K]}{\partial u_i} - {\omega_r^a}^2 \cdot \frac{\partial [M]}{\partial u_i} \right) \cdot \{\Psi\}_r^a \quad (17)$$

where: ω_r^a [Hz] is the analytical natural frequency, ω_r^x [Hz] is the experimental natural frequency, ε_{ω_r} [%] is the relative difference and u_i is the updating parameter i.

5.3.6 Correction module

The correction module calculates the new values of the updating parameters that have been set up in the previous stage. The only input value required is the number of iterations. Each iteration step starts with the calculus of sensitivity mass and stiffness matrices with respect to the updating parameters (1), (3) and an input file for the finite element code is created. The finite element code is run, the updating program reads the resulting mass and stiffness matrices and the corresponding sensitivities are estimated.

The next step consists of individual equations generation, according to the updating criteria (see 5.3.5). If the minimization of indirect frequency response functions residues is chosen as updating criterion, this involves the calculation of the analytical frequency response functions and the reduced dynamic stiffness for each updating frequency. Further, the equations obtained as a result of different updating criteria are assembled in a unique minimization problem, which is solved using the least square method. An input file for the finite element code is generated, which contains the updated finite element model, and then the finite element code is run having that as input file. The updated mass and stiffness matrices are read, so are the updated mode shapes. New MAC values are computed and a new matching of analytical and experimental modes is performed.

The last step is related to the convergence verifying: if the parameters are converging, which means the change is smaller then 0.1%, or if the maximum iteration number is reached, the procedure stops.

6 Conclusion

This paper intends to provide a systematic approach upon hand arm vibrations. The subject involves complex investigation both from medical and engineering point of view. Therefore, in the first part the health effect of HAVs have been briefly presented, together with the methods used for HAVs assessment and, consequently, the prevention measures. The second part deals with the engineering side of the subject, emphasizing on different methods for developing hand-arm models for dynamic analysis. As the final aim of the theoretical modeling is to provide reliable models corresponding to the real structural behavior, a model updating procedure is proposed; this allows the optimization of the finite element model in terms of test data, resulting in a model closer to reality, able to be used for further analyses.

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