DESIGNING SYSTEMS FOR PREVENTION OF OCCUPATIONAL DISEASES CAUSED BY HUMAN BODY VIBRATION

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Abstract: This paper presents some results of the research carried on within a research project financed by the Romanian Council for Research in Higher Education, that has as main aim to develop technics, specifications and methodologies for thoroughly study the mechanical vibration phenomenon the human body is subjected to during practising a profession, potential source of occupational diseases. Discussion is focused on designing solutions for active control of hand-arm vibrations caused by small sized tools, as research on dental technicians, for example, proved they represent a category subjected to such occupational disease.

Key words: hand-arm vibration, vibration control, damping, microsystem - MEMS.

1. INTRODUCTION

Several occupational diseases identified vibrations as main cause. Statistical studies put into evidence two main categories: diseases related to whole body vibration, with significant effects in the entire human body (e.g. law back pain, spine disturbances, etc.) and diseases related to hand-arm vibrations, that transmit significant accelerations and displacements only in some sections, such as the hand-arm system (e.g. Raynaud’s disease or White finger disease, Carpal tunnel, HAV Syndrome, etc.). As a consequence, the European Directive 2002/44/EC has been developed and implemented into the national legislation of Member States. It sets the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) [1].

A research group from Transilvania University of Brasov, Romania, is currently working on a project financed by the Romanian Council for Research in Higher Education, aiming to develop techniques, specifications and methodologies for thoroughly study the mechanical vibration phenomenon the human body is subjected to during practicing a profession, potential source of occupational diseases. Studying the state of the art in the field, the first conclusion came out: the whole body vibration (addressing mainly the profession of driver - driver of trucks, vehicles (for intra-factory transport), tractors (agricultural, forest), excavators, bulldozers, concrete platforms, or workers around fixed machines that transmit vibrations through the floor) is covered by a great number of studies and research results that ultimately may lead to solutions for part design in the view of vibration level reduction. Less research results are available for hand-arm vibrations (exposed occupations are all that use vibratory machines and tools, acting on the hand-arm system: miners – pneumatic hammers for rock boring, hydro-electric power plants, railways, etc.; workers form machine building – riveting, cast parts cleaning, etc.), although the medical studies draw the attention upon this category, as well.

The progress in studying HAVS and identifying the ways for professional disease prevention is directly linked the dynamic behaviour investigation of the hand-arm system. The hand-arm system is considered a deformable, spatial structure, with a certain complexity when it comes to
geometry, elastic properties and subjected loads. Although several experimental research have been carried on, theoretical studies are rare and limited to lumped-parameter studies in which distributed masses are reduced to concentrated mass connected to each others via springs and dampers in series or parallel consisting a multiple-degree-of-freedom vibratory system. The reason is maybe linked to the fact that the modelling of human body or part of it is not straightforward, maybe complexities are associated with this type of analysis: it is not possible to consider a single element of body and deal with as if it was isolated; nearly all human body elements have extremely difficult geometries not easily described in terms of simple geometrical shapes; biomaterials do exhibit complicated non-linear viscous-elastic behaviour and linear vibration theory fails to succeed in description of such a complex behaviour [2]. Nevertheless, a solution for reducing vibrations consists of using anti-vibration gloves: they absorb the vibration energy but can get some impairment of dexterity that may prevent the worker of wearing them. That is the reason why nowadays manufacturers search for alternative solutions in redesigning the parts of the machine or tool so that to diminish the vibration level. For example, the antivibe hammer offers 500% improved vibration damping over the professional hammers.

2. PROBLEM FORMULATION

2.1 Hand-arm vibrations induced by small size tools
A special category of workers subjected to hand-arm vibrations are the ones working with vibrating tools of small dimensions, for whom neither the gloves or the anti-vibe systems are of and use, due to the precision required and the small size tools. For example, dental technicians are exposed to hand-arm vibrations while working with various appliances and tools. Although the literature data are scarce, it seems that long term exposure may result in white finger disease. A study of 374 women with diagnosed hand–arm vibration syndrome in Sweden included many dental technicians. On average, the first symptoms appeared after seven years of exposure and the first visit to a doctor occurred after 11 years [3]. In a Czech study there were 9% of dental technicians with deteriorated plethysmographic curve and 11% with pathological motor conduction in nervus medianus [4].

2.2 Damping active control
Having the above figures as starting point, to which the attention drawn by the statistics at local and regional level is added, the research team from Brasov proposes a solution for reducing vibrations levels when using small size vibrating tools: the use of a micro-electro-mechanical system (MEMS) based on magneto-rheologic fluid as damping controller.

The active damping system is provided with a wide-band actuator capable of controlling the damping in the full bandwidth, as shown in Fig. 1 [5].

![Diagram](attachment:image.png)

Fig. 1. a) - Operating equipment generating a disturbance force \( f_d \), b) - Equipment subjected to a support excitation \( x_d \), c) - Active isolation device. The passive isolation system involves a spring and a damper, the system transmissibility being defined as:
\[
\frac{X_c(s)}{X_d(s)} = \frac{1 + 2\xi_s/\omega_n}{1 + 2\xi_s/\omega_n + s^2/\omega_n^2}
\]  
(1)

As it is presented in Fig. 2, the amplitude diagram yields to the following observations:

- for \( \omega < \sqrt{2}\omega_n \), all the curves are larger than 1 and become smaller than 1 for \( \omega > \sqrt{2}\omega_n \); the critical frequency \( \sqrt{2}\omega_n \) delimits the isolator attenuation and amplification domains;
- for \( \xi = 0 \), the high frequency decay rate is \( 1/s^2 \), while very large amplitudes occur near \( \omega_n \) (the natural frequency of the spring-mass system);
- the damping reduces the amplitude at resonance and tends to reduce the effectiveness at high frequency; the high frequency decay rate becomes \( 1/s \).

Fig. 2. FRF of passive isolator transmissibility for different values of the damping \[^{[5]}\]

The above observations lead to the conclusion that the design of a passive isolator involves a ‘trade-off’ between the resonance amplification and the high frequency attenuation. The ideal isolator should have a frequency dependent damping, which is high for values below critical frequency \( \sqrt{2}\omega_n \) - to reduce the amplification peak, and low for values above \( \sqrt{2}\omega_n \) - to improve the decay rate.

As a consequence, the objective of the active isolation system can be formulated: to achieve no amplification below \( \omega_n \) and an appropriate decay rate at high frequency.

3. APPROACH OF MICROSYSTEM DESIGN

3.1 Specific features in MEMS design

Designing a microsystem to be attached to the vibrating tool of small dimensions in order to actively control the damping by magneto-rheologic fluid represents a challenging objective, taking into account all the specific features induced by minimization and by the fact that a MEMS integrates mechanical, electrical and electronic components in a single chip. Therefore, the design requires some different description and detail levels: in the first place, the documentation regarding the microsystem specific features and needs has to be achieved, together with the assessment of different microfabrication possibilities \[^{[6]}\]. The following steps have to be performed for each proposed version of the designed device: the system division in components, materials choice, operations sequence set-up for each component, assembly methods set-up and product compact packaging.

It is emphasize that, due to the prototypes high cost, the analytical model development – for simulations – is strongly recommended. Thus the research and development cost is significantly reduced.

Microsystems modelling and analysis is a very complex issue. Modelling is present at different levels and uses a large variety of formulations, depending on the level. Four design levels are identified: system level, device or component level, physical level and process level. Among these levels there is a bilateral information exchange.

On the top there is the system level, described by the bloc diagrams and the distributed systems models, each of them leading to ordinary differential equations for system dynamic behaviour description. The state-space formulation is usually used, the equations system being transformed in first order coupled differential equations (state-space
equations). On the other extremity it is the process level, which includes the manufacturing operations sequence and the photo masks fabrication techniques. At this level the numerical modelling is sophisticated, that is the reason why several commercial CAD tools have been developed, named as ‘CAD Technologies’ or simply ‘TCAD’. For MEMS designers the TCAD tools importance consists mainly in the possibility of determining in advance the microsystem geometry in terms of the mask it will be used and in terms of the manufacturing operations sequence that can be achieved. The physical level deals with the real microsystem behaviour in the 3D space. The governing equations are mostly differential partial derivative equations. That is why, at this level, the simulation is done by numerical methods, for example the finite element method, the boundary element method, the finite difference method, etc. Although the microsystem behaviour representation at physical level by partial derivative equations is useful, it becomes too complicated when it refers to the overall system (including the components and the links between them). This is the reason why the next level has been introduced, which is the device or component level. At this stage the reduced order models are developed: they preserve the main features regarding the dynamic behaviour at physical level of each microsystem component, being, at the same time, compatible with the system level description.

3.2 Modelling and simulation
By applying the modelling concepts presented in the previous paragraph there can be designed the microsystem for position closed loop control, represented in Fig. 1. The modelling has been performed aiding Matlab – Simulink. The main objective of the designed microsystem is to apply an external force to an object so that the object moves in a position that coincides with the desired position. The desired position is given by the input value 1, called in the block diagram as ‘Desired position’. In order to achieve this objective the obtained position (the real position) is detected with a position sensor. Since all the measurements involve noise, they cannot be neglected in microsystem modelling and they are represented by input 3. The noise and the obtained position are the inputs of the position sensor. The sensor output is a signal representing the measured position of the sensor, probably altered by the noise or the sensor calibration errors. The measured value of the obtained position is subtracted from the desired position value, their difference representing the position error. This is the input for a controller that amplifies it and converts it in a time varying external force that makes the object move to that desired position by diminishing the error toward zero. A specific feature of microsystems is that the whole closed loop control described above takes place in the presence of some undesired movement sources, called ‘perturbations’. An example in this sense is the object subjected to a force due to the vibration of the microsystem support. Block diagram modelling by using Simulink is very efficient and widely spread nowadays. However, problems may occur when, according to the concept of microsystem (MEMS), connections between electrical and mechanical components have to be modelled. In this
situation it is recommended the mechanical model to be replaced by the electrical equivalent model. By adopting this model the entire microsystem (as a set of subsystems) can be modelled aiding the same program both for the mechanical and electrical components.

The next modelling level, the component level, identifies the specific values for mass, stiffness and damping, based on the information about the geometric features of the structure and the material properties.

4. HAND-ARM VIBRATION ASSESSMENT PROCEDURE

Hand-arm vibration assessment is achieved by using the following the system configuration [7]:

- Software: Pimento FFT Analyzer P-4000-NP; Pimento Octave Analyzer P-4040-NP;
- Hardware: Pimento Frame with 1 Slot and 4 channels P101DT4;
- Sensors: Tri-axial miniature accelerometer (type PCB 356B21).

This equipment set-up is used in order to evaluate the influence of tool vibrations on the human health, before and after implementing the vibration control system. As reference, ISO5349 – Mechanical vibration – Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration is used. The different Weighting Factors Kj are listed as specified in the ISO standard.

The experimental setup is presented in Fig. 4: a 3-axial accelerometer is mounted on the handle of the tool, according to the ISO5349 standards. Calibration values are entered directly from the calibration sheet of the transducer.

When running the calibration routine, the transducer sensitivities are calculated by the system and filled in automatically. The measurement is manually started and stopped. During the measurement, the time signal of the accelerometer is measured and displayed (Fig. 5). After measurement, the acceleration is calculated in 1/3-octave bands between 6.3Hz and 1250Hz (ISO 5349 standard) for each of the 3 directions of acceleration (Fig. 6). The experimental results (weighted magnitude of vibration both in linear and dB) for the 3 directions of the accelerometer are indicated.
The maximum acceleration is indicated in bold. In addition, the following results per 1/3-octave band and per accelerometer direction are listed (Fig. 7):
- RMS acceleration levels $a_{h}$;
- Weighted acceleration levels $a_{h,W}$;
- Acceleration level in dB $L_{a,h}$ (reference acceleration of $1\mu m/s^2$).

<table>
<thead>
<tr>
<th>Weighted magnitude of vibration</th>
<th>C1 (IA1): hand X</th>
<th>0.912</th>
<th>139.9</th>
<th>m/s²</th>
<th>dB (ref $10^{-6}$ m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2 (IA2): hand Y</td>
<td>8.281</td>
<td>138.4</td>
<td>m/s²</td>
<td>dB (ref $10^{-6}$ m/s²)</td>
<td></td>
</tr>
<tr>
<td>C3 (IA3): hand Z</td>
<td>0.001</td>
<td>50.3</td>
<td>m/s²</td>
<td>dB (ref $10^{-6}$ m/s²)</td>
<td></td>
</tr>
</tbody>
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Fig. 7. Results report for HAV assessment procedure.

For validation of the solution proposed for vibration active control that could decrease the vibration values and its influence on the hand-arm system, the measurement is applied during the entire working day, on a lot of workers. It takes some time until the first results can be collected, since the human subjects have to be monitored in time during a long period, before and after using the system.

5. CONCLUSION

Within the occupational diseases due to vibrations, one special attention should be given to hand-arm vibrations caused by small sized tools.

The vibration control system needs specific design, due to minimization, therefore the use of a magneto-rheologic fluid actuator is proposed for active damping control.

Even if it is fully acknowledged the role of experiment in confirming the design assumptions, due to the prototypes high cost, one can fully make use of the advantages of numerical modelling and simulation before developing the experimental model of the microsystem.

The proposed solution validation takes a long time, since HAV assessment has to be repeated on the human subjects, in years, before and after using the damping system; only this way can be clearly demonstrated that using the vibration control system may lead to decreasing the incidence of occupational diseases.

6. ACKNOWLEDGMENT

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7. REFERENCES


