A Review of Hand-Arm Vibration Simulation Approaches

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Summary
Hand-arm vibrations denote the interaction of a vibrating device with the hand touching it and consequently propagation from the hand on through the arm. Simulating the process, several aspects have to be considered and it has to be evaluated whether to approximate, to omit or to reflect them in detail in the model. Several different approaches have been suggested in literature. Some reflect the approximated geometry of the hand and the arm, while others simulate the hand and the arm as a mass-spring-damper system. Some works represent the anatomy in varying depth of detail. To use those models, the excitation of the hand-arm system, i.e. the vibration induced to the hand, has to be known. The effect of the coupling between the device and the hand-arm system on the respective excitation and hence the perception of the vibration, has yet to be investigated. As more and more aspects of devices are optimized, such as the sound and the appearance, other aspects like low vibrations that have been less prominent so far will receive more attention. In order to design and evaluate not only the acoustical and the visual aspects of a product, but also the vibration, the models as well as measurement procedures have to take the coupling into account.

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1. Introduction

For over 40 years, different models have been developed in order to assess hand-arm vibrations. Several different approaches have been used, partially based on standards that mostly have been worked up in the context of occupational safety. Several aspects have impeded the progress of models: the great variance in human physiology, in characteristics of the vibration excitation as well as in circumstances of occurrence and in operation of the respective tools. Studies on measurements of hand-arm vibrations (HAV) show a lack in knowledge or disagreements on factors and their influence under the respective conditions. In this work several types of models are compared regarding their featuring of factors that are known to have an effect on hand-arm vibrations.

2. Models

There are several approaches to model hand-arm vibrations. In [1] the models are grouped into distributed- and lumped-parameter-models. The latter are split into the subgroups single- or multiple-degrees-of-freedom models (single- or multiple-DoF), a beam model and grip-force dependent models.

The distributed-parameter model [2] uses the mass per unit of length, the stiffness, the damping and the effective length of the bones in order to describe the hand-arm system.

The single-DoF model [4] described in ref. [1] uses three uncoupled single-DoF mass-excited mechanical models to describe the biodynamic response along three orthogonal axes of the hand-arm system, when it is subjected to vibration in the range of 20-500 Hz. For each of the axes it applies a two-stage piecewise linear single-DoF model with two sets of parameters suited for two different frequency ranges. The authors in [6] proposed a single-DoF dynamic model in order to predict the biodynamic response to impulsive torque reaction forces such as those produced by rotating spindle power hand tools. In ref. [1] a mass-excited two-degrees-of-freedom model [5] is also described, for which the parameters were determined from the measured driving-point mechanical impedance response und vibration along the compression and shear axes in a frequency range of 10-1000 Hz at a fixed grip-force.

There are multiple three-DoF models presented in [1]. The model described in [7] is based on measurements on the influence of the grip-force on driving-point mechanical impedance characteristics of the human

hand-arm system and consists of semi-definite models with three DoFs for two axes and a three-DoF model with fixed support for the third axis. The others ([8], [9], [10], [11]) are identical only to the part of the model suggested for the third axis. Despite the agreement of the different models, their parameters differ substantially. The linear three-DoF model presented in ISO 10068 [11] is based on a study [12] on the most probable values of driving-point mechanical impedance of the human hand and arm by synthesizing previous reported data. Several four-DoF models that are similarly structured as the three-DoF models have also been proposed ([13], [11],[14]). There are studies in which the attempt has been made to link some parameters of the models to the physical visco-elastic behavior of the human hand-arm system (c.f. [1]).
The beam model, as presented in ISO 10068 [11] can be considered as a beam that is supported at its two ends and hinged at a point within its span.
The authors in [3] proposed a model that is closest to the beam model. The humerus bone was modeled as a cylinder with two hemispheres with different radii at its ends and used various clamping conditions

3. Influencing Factors

Various factors have been identified as influences on hand-arm vibrations. Those can be grouped into vibration characteristics, anthropology, position and others.

3.1. Vibration Characteristics

The characteristics of the vibration excitation affect their influence and the transmission to the hand-arm system. The frequencies contained in the vibration are an influencing factor ([3], [15], [18], [22]), as well as the amplitude ([19], [20], [21]) and the type of signal ([15], [18], [19], [22]). Further parameters that need to be considered are the duration [19] and the direction of the vibration [19]. Similar to human hearing not all frequencies have the same effect at the same sound pressure level.

3.2. Anthropology

Measurements have shown that physical measures ([19],[20]) of the hand-arm system affect the respective eigenfrequencies [3] and the transmission.
Aside from that, the rigidity, the mass moment of inertia, the static strength [6], the mechanical impedance [16] and the apparent mass [18] are influencing parameters of the biomechanical system regarding the transmissibility [18] of the vibrations.

3.3. Position

The angulation of the joints ([6], [20]) factors into the rigidity of the human hand-arm system and hence into the transmission of the vibrations. The stiffness of joints varies and depends on the angulation.
Additionally, several studies have shown that the hand position ([6], [18], [22]), the handle itself, as well as how the hand is positioned relative to the handle [22] have an effect on the vibration transmission to the hand and arm.

3.4. Others

Moreover, there are factors which influence implicitly or show interaction among themselves. High level noise decreases skin temperature, the reduction of which in turn leads to an increase in the grip force [21]. But it is not an unilateral dependence among the lateral two. A gain in grip force causes a reduction of the temperature in the fingers. The grip force or coupling force is the most named of the three ([17], [18], [19], [20], [21]), which is most likely due to the fact that it is the only one influencing the transmission of the vibrations directly.

3.5. Factors in models

As also stated in [1] there is a lack in quantitative knowledge on the vibration properties of the human hand-arm system. Studies such as [16], [18], [19], [20] and [22], as well as the standard ISO 10068 [11] each deal with one or more of those properties.
The above mentioned factors are known to have an influence on hand-arm vibrations, but the extend still has to be quantified or investigated further in many cases.
Since the vibration is used as the input signal, the vibration characteristics are included into the models, although it is unlikely that their respective effects are comprised to the full extend as studies such as [15] show that there is still need for further analysis.
Depending on the model anthropological factors are included for example by means of the mass or the effective lengths of the bones. In most cases the physical quantities of the hand are not comprised or simplified. The position of the handle and the entire hand-arm system do not seem to be included in the models directly, but only implicitly due to the conditions during measurements on the data of which the models were based.
Only a few models take the grip-force into account ([7], [9], [10], [13]). None of the considered models are known to have included the temperature of the skin or the surrounding noise level.
But not only the factors that are included in the models and how this is done are of influence on the model and the results it generates, also those that are omitted in the model or not controlled in the measurements on which the model is based affect it. As the differences in parameters in the three-DoF models show it is critical how those are determined, since differing conditions in the measurements to the data of which the parameters are fitted are of great influence, as

well as the variability among the subject who participated in the studies. Additionally the method applied to determine the parameters to represent the hand-arm system has an effect, hence is stated in [1] that a set of identified parameters is not a unique solution.

4. CONCLUSIONS

Most models are validated for specific conditions, such as specific grip forces, vibration types or hand-arm positions. It is very likely that their general validity can be improved by including more of the influencing factors. In order to incorporate them it is neccessary to quantify their impact, a qualitative assessment is therefor insufficient. This knowledge is not only useful for the progression of existing models, but both the knowledge and the further developed models will be needed, when hand-arm vibrations are to be analyzed in more detail than harmfull or -less or regarding their comfort [23]. Furthermore, the results in [16] showed that fixation points and applied methods for measurements cause a large variability in data and that the driving-point mechanical impedance does not represent the data dispersion in measurements. Hence differences in gaining the data on which the models are based may be one of the main causes limiting the general applicability of the current models. It can be concluded that all simulation approaches are still limited in their usability and that the lack of quantitative knowledge on several of the influencing factors hinders the progress in the development of the models.

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