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A model for simulating vibration responses of grinding machine-workpiece-hand-arm systems

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ABSTRACT

The objective of this study was to develop a vibration model of a grinding machine-workpiece-hand-arm system. A lumped-parameter model structure of the system was proposed, and its major parameters were determined using the mechanical impedance measured at the grinding point of a typical workpiece (golf club head) held by two hands and referenced to the vibration transmissibility spectra measured at the wrist and on the upper arm of human subjects. The model reasonably predicted the vibration transmissibility spectra measured on the club head and the driving-point response function when the grinding contact stiffness was below a certain value. This suggests that the model is acceptable not only to enhance the understanding of the system responses, but also to explore some engineering methods for controlling vibration exposures during the grinding process. The identified model parameters reveal that the major resonance of the handheld workpiece depends primarily on its mass and grinding contact stiffness. The feed force applied in the grinding process can substantially affect the grinding contact stiffness; as a result, it can significantly influence the resonance. Vibration-reducing gloves can marginally increase the workpiece resonance, but these gloves can reduce some vibration transmitted to the hand-arm system. This study also clarified an important mechanism for the prediction errors of linear human vibration models, which is useful to further improve human vibration modeling.

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1. Introduction

Grinding and polishing of handheld workpieces are manual processes used in the fabrication or repair of some components of sports equipment, tools, furniture, and dentures [1–3]. Significant vibration may be generated during such processes, and the vibration may be effectively transmitted to the fingers or hands of the workers holding the workpieces. Such vibration exposure may cause vibration-induced white finger (VWF), a form of Raynaud's Syndrome, and a significant cause of morbidity [4]. A recent study found a significant prevalence (>12%) of VWF among workers performing the fine grinding of

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golf club heads in some sports equipment factories [3]. Effective methods are required to reduce the vibration exposure to control this occupational disease among workers.

As part of the efforts towards controlling the vibration exposure of workers performing the grinding and polishing of golf club heads, an experimental study has been conducted to identify the basic vibration characteristics of the handheld workpieces made at a sports equipment manufacturer [5]. The study confirmed that the vibration of a handheld workpiece generally resulted from two types of vibration sources: (i) the vibration generated on the machine and transmitted to the workpiece; and (ii) the grinding vibration generated at the grinding interface. The machine vibration is highly correlated with the frequency-weighted vibration of the club head [5], which is required for assessing the risk of the vibration exposure in the standard method [4]. The grinding force generated at the grinding interface can result in substantial high-frequency vibration, which can also be effectively transmitted to the hands holding the club head during the grinding process. Many studies suggested that such high-frequency vibration should not be ignored for assessing the risk of VWF [6–11]. Therefore, both frequency-weighted and unweighted vibrations should be controlled in the grinding operations. While several engineering methods have been proposed to control the exposure, they have not been sufficiently evaluated. A systematic analysis of these methods requires a valid model of the grinding machine-workpiece-hand-arm system, but the literature search towards this study did not find such a model.

In principle, the required model can be constructed by combining a grinding machine model, a workpiece model, and a hand-arm-system model [12], similar to those used to simulate the vibration response of a tool-handle-hand-arm system [13–16]. While it is extremely difficult to analyze all the potential methods using a single model, the current study will focus on the development of the model for analyzing the engineering controlling methods associated with the vibration responses of the workpiece-hand-arm system. This avoids the need to simulate the detailed machine structure and grinding mechanisms. Then, the machine can be crudely simulated as a lumped-parametric structure, and the machine vibration can be generalized as a random-excitation input to the interface between the machine and workpiece.

The detailed biodynamic responses, such as the vibration stresses and strains of the hand-arm system, are not essential information for the analysis of the vibration control methods, but the overall vibration of the workpiece and that transmitted to the hand-arm system are critical for the evaluation of these methods. For this reason, it is not necessary to simulate the detailed responses of the hand-arm system, but its impedance or mechanical-equivalent model can be used to simulate the effect of the system on the workpiece response, similar to that used to analyze the tool responses [12,15,16]. Many such models are available [12–19], but they cannot be directly used in the current study, because their parameters were determined based on the biodynamic response functions of the hand-arm system with some specific arm postures and hand-handle coupling conditions that are largely different from those used in the grinding of handheld workpieces. The required model parameters should be determined based on the response functions of the dual hands-arms system with representative arm postures and hand-workpiece coupling conditions used in the grinding process [19,20]. The experiment required for the measurement has been conducted in our previous study [21].

Based on this background, the specific aims of the current study are to develop a model of the grinding machine-workpiece-hand-arm system using the available experimental data and to enhance the understanding of the vibration responses of the system. Some additional experiments are also conducted in the current study to evaluate the validity and usefulness of the model proposed and calibrated in this study. Based on the knowledge developed in this study, a few strategic approaches for reducing the vibration exposure in the grinding of handheld workpieces are also proposed and discussed.

2. Method

An inverse dynamic method based on frequency response functions was used to develop the model of the grinding machine-workpiece-hand-arm system. A previous study proposed a set of validation criteria for the development of human vibration models using this approach [20]. Those criteria were used as a general guide for the model development performed in this study.

2.1. General considerations and basic model structure

Belt grinding machines are widely used in the fine grinding of many handheld workpieces, and they are considered in this study. Fig. 1(a) shows such a machine used to grind a typical handheld workpiece – a golf club head. A schematic of its basic mechanism of operation is shown in Fig. 1(b). The grinding process is usually conducted on the drive wheel on the machine. The drive wheel is equipped with a rubber tread with inclined strips or teeth, which provides sufficient frictional force to drive the grinding belt subjected to tangential grinding force. The rubber tread is replaced with a new one when its strips are worn out by the grinding belt. The rubber tread also provides a certain cushion to avoid impacts during the grinding contact so that the fine grinding can be stable and smooth to achieve the desired quality of the product.

In the previous experimental study [5], the vibrations in three orthogonal directions (3-D) on two grinding machines and two handheld workpieces were measured. It was found that the vibration spectra in the three directions on each machine were highly correlated ($r > 0.90$, $p < 0.001$). The three axial vibration spectra measured on each workpiece were also highly correlated. These similarities suggest that the vibrations in the three directions resulted from the same excitations, and the basic mechanisms of the vibration transmission and system responses in all the directions were similar. Therefore, it is not necessary to simulate the coupled 3-D vibration responses of the system if the purposes of the modeling are to help