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Research paper

An improved model for dynamic analysis of a double-helical gear reduction unit by hybrid user-defined elements: Experimental and numerical validation

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ABSTRACT

This paper introduces an improved model generated by hybrid user-defined element method (HUELM) for dynamic analysis of a double-helical gear reduction unit. Based on theories of structural dynamics and system dynamics, the model consists of four developed elements to respectively simulate the gear pair, bearings, flexible shafts and the housing. A closed-loop test rig is constructed to validate the model: an encoder-based method is applied to measure vibration acceleration of the gear pair, and accelerometer-based measurement systems are employed to obtain the dynamic responses of the housing. Furthermore, two additional models by the finite element method (FEM) and the lumped mass method (LMM) are constructed for numerical comparison to illustrate the HUELM's substantial advantages. Compared with the LMM, the HUELM is of capacity to investigate the interaction among the subsystems; moreover, it is more efficient than the FEM primarily because of the integrated tooth contact analysis method and loaded tooth contact analysis method. It is demonstrated that the predictions by the HUELM match well with the experimental data in terms of meshing frequencies and vibration responses. It is also concluded from the numerical comparison that the HUELM is appropriate for dynamic analysis, particularly of large complex transmission equipment.

1. Introduction

As common power propulsion device in mechanical equipment, the double-helical gear reduction unit has been widely employed in many industrial applications. As shown in Fig. 1 [1], one typical reduction unit generally integrates many components, such as gear pairs, flexible shafts, bearings, a support box and attachments. In addition, this highly complicated system involves intricate contact relationships between its different parts.

It is well known that the dynamic behavior of the system substantially affects the vibration noise and durability characteristics of the machine of which it is a part. Magnified forces acting on gears may cause larger loads and stresses under dynamic conditions, which even result in damage to or the failure of gears. Therefore, dynamic analysis of the reduction unit is significant to theory expansion and engineering practice.

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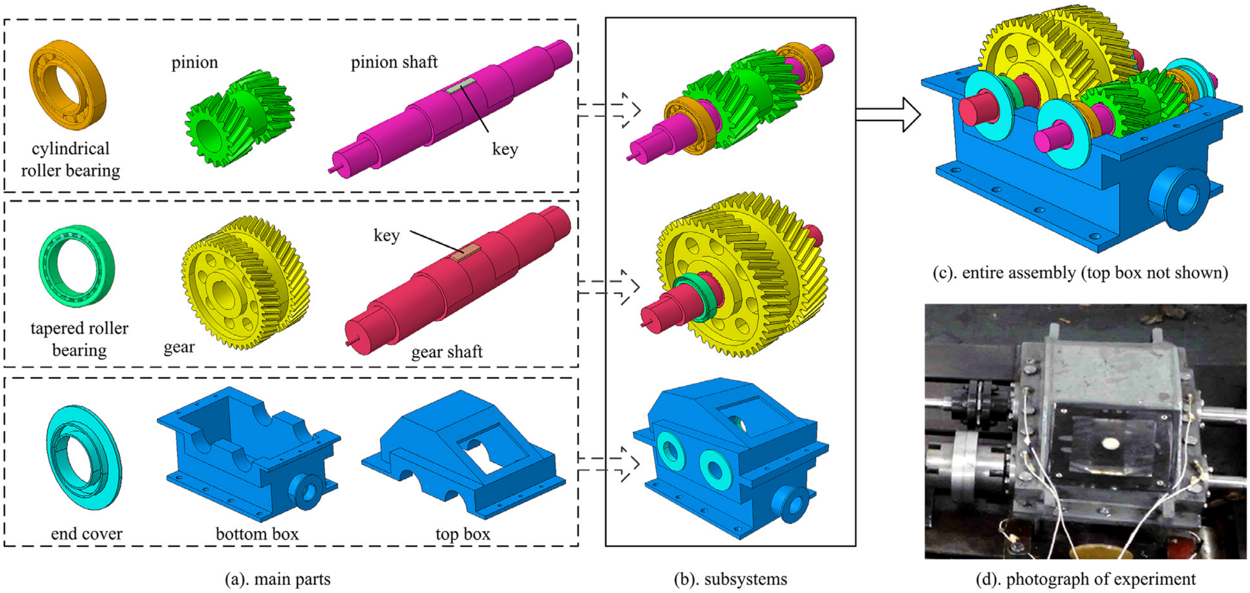

Fig. 1. Assembly relationship of a typical double-helical gear reduction unit: (a) main parts; (b) subsystems; (c) entire assembly (top box not shown); (d) photograph of experiment.

Over the past half-century, researchers [2–5] have investigated the dynamic characteristics of cylindrical gear systems by experimentation. The static transmission error (STE), loaded transmission error (LTE) and dynamic transmission error (DTE) of a gear system could be obtained through vibration measurement to evaluate dynamic performance. However, in the measurement, it is difficult to obtain the universal law of the dynamic behavior; moreover, experimental method generally requires substantial labor and material and financial resources. Therefore, numerical method is becoming more and more important for the dynamic analysis of the gear system.

Most numerical models have been based primarily on system dynamics theory. Tuplin [6,7] proposed a mass-spring model coupled with equivalent mesh stiffness to describe gear interaction, which forms the basis for modeling a gear pair. A group of studies [8–11] on gear pair present various models that use the lumped mass method (LMM). These models consider various vibration types, such as bending and rotational motions. In such simplified models, the LMM exhibits relatively high computational efficiency. However, simplification can also bring in modeling error, which decreases the model's calculation accuracy. For instance, flexible shafts are generally ignored during the modeling process. However, it is demonstrated that the shafts also have a substantial impact on the dynamic behavior of gear systems [12]. Because discrete lumped mass and stiffness are used to simulate the continuous shafts, modeling error is almost unavoidable. Most importantly, it is nearly impossible for the LMM to include the influence of a support box on the dynamic characteristics of a gear reduction unit. Particularly for a planetary gear train, the interaction between the structural subsystem and the transmission subsystem is generally ignored because a torque frame assembled with a carrier is difficult to be considered using the LMM.

The finite element method (FEM), which is based on theory of structural dynamics, is receiving increasing research attention, and there are many published papers that use this method to model gear systems [13–16]. Most often, a 3D solid element with a contact control method is employed for simulation analysis of the gear pair [17,18]. Alternatively, specific elements are developed for a special modeling purpose. For example, Lee [19] developed a flexible shaft element for vibration characteristics of automotive transmission. Due to its relatively accurate representation of complex geometric configurations, particularly the tooth surface, the FEM generally has higher calculation accuracy than the LMM. Moreover, response results of the support box of a gear reduction unit can be obtained through the FEM because the contribution of such a complicated structural subsystem is already considered during the dynamic analysis, which is difficult to achieve through the LMM. However, a considerable number of elements is required during FEM analysis to decrease modeling error. The complex finite element contact algorithm also requires numerous calculations, consuming substantial computing resources during analysis. These problems result in lower computational efficiency, limiting the broad application of the FEM. Therefore, a new dynamic model of the gear reduction unit is required that not only simulates the effect of structural subsystems offered by the FEM but also has the sufficient modeling accuracy and computational efficiency of the LMM.

A novel numerical model of a double-helical gear reduction unit integrating structural dynamics and system dynamics theories is proposed in this paper. The model employs a hybrid user-defined element method (HUELM) and adopts four specific elements to respectively simulate the gear pair, the flexible shafts, the bearing subsystems and structural subsystems (such as the support box). Therefore, this new model is of capacity to investigate interactions among main subsystems. First, the four elements, developed separately based on Abaqus secondary development technology and parametric modeling