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The effect of contact interface on dynamic characteristics of composite structures

James Shih-Shyn Wu [a,*], Jyh-Cheng Chang [a], Jui-Pin Hung [b]

[a] Institute of Mechanical Engineering, National Chung-Hsing University, Taichung, Taiwan 40227, ROC
[b] Department of Mechanical Engineering, National Chin-Yi Institute of Technology, Tai-Ping, Taichung, Taiwan 320, ROC

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Abstract

In this project, nonlinear characteristics on the rolling interface of a linear guide were studied by the finite element analysis and experimental verification. Contact of the ball/surface rolling interface in the rolling guides was simulated as a three-dimensional membrane element without thickness. By introducing Hertzian contact theory and applying proper normal/shear stiffness to such contact elements in the overall finite element model, dynamic behaviors of linear guides affected by preload were thus investigated. In the finite element procedure, three contact models, 1D point-to-point, 2D point-to-point and 3D surface-to-surface, were sequentially introduced for purpose of verification with experiments. As a validation in this project, vibrational experiments on linear guides with different preloads were conducted and related frequency spectrums were derived. Both the finite element and the experimental results reveal that the natural frequency of a linear guide increases with the increment of the preload. In addition, the dynamic characteristics predicted by finite element analysis agree well with those measured from instrumental experiments. The proposal of current study may provide an alternate and reliable way for understanding of the dynamic characteristic of the rolling contact components in machine design field.

Keywords: Linear guide; Hertz theory; Contact element

1. Introduction

Following the development in scientific technology, the requirement of the high-precision machine has been increasing steadily. In order to achieve the high-speed and high-precision positioning, the static/dynamic behaviors of transmission systems must be sufficiently understood in the design stage for a precision machine. The linear guide system with rolling balls is the more popular and effective transmission system because of the low wear and friction force induced at ball grooves when compared to the conventional guide with sliding contact interface. For the analysis of the static/dynamic behaviors, a linear spring was usually used to simulate the contact characteristics of the ball between the carriage and guideway (Ohta [10]). It is well known from Hertz's contact theory that the elastic deformation between the carriage and rolling ball or between balls and the rail behaves a nonlinear way with the contact force. Therefore, the nonlinear simulation of the contact interface of a linear guide system is worthy for investigation.

* Corresponding author. Tel.: +886 4 22870195x304; fax: +886 4 22877170.
E-mail address: sswu@dragon.nchu.edu.tw (J.S.-S. Wu).

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Applications of the Hertz's contact theory have been published in many earlier studies. Hagiu and Gafitanu [3] applied Hertz's theory to derive the relation between the normal force and the deformation of the ball bearing, and obtained the dynamic characteristic of the machine tools. Perret-Liaudet [11,12] described a shooting method to solve for the resonance of the sphere-plan contact. Yeh and Liou [14] showed the concept and estimation of virtual spring elements. Moreover, Lynagh et al. [7] and Hernot et al. [4] employed the nonlinear Hertz's contact theory to discuss the vibration and the stiffness matrix of the ball bearings. Recently, Monsak Pimsarn and Kazem Kazerounian [13] presented a PISE (pseudo-interference stiffness estimation) method to evaluate the equivalent mesh stiffness quickly. Concerning the studies relating to linear guide system, Ohta [10] employed the energy balance and Lagrange's method to derive the natural frequency of the carriage block in a linear rolling guide, and proved that the main peaks of the spectra were caused by lower rolling, yawing, pitching, vertical and higher rolling of the natural vibration modes. Later on, Ohta and Hayashi [9] proved that the linear guide system could be progressively analyzed by the finite element method. Different vibration modes including the lower rolling, yawing, pitching, vertical, first flexural, second flexural, and third flexural natural frequency were found in such a rolling contact mechanism. Meanwhile, it was noted that in Ohta and Hayashi's work, the contact stiffness was simulated by a single spring element only in normal contact direction, which might be referred to an one-dimensional point-to-point contact mode. So far, no study related to the surface-to-surface contact nonlinear model has been reported. This is a notable shortcoming because the surface-to-surface contact model is considered to be able to simulate the real contact behaviors.

In the study, finite element models to simulate the contact characteristic of the rolling interfaces were developed and discuss how the dynamic characteristic of the linear guide system was affected by the stiffness of the contact interface and the equivalent stiffness and the nonlinear responses were evaluated based on Hertzian elastic contact theory. In the beginning of this report, through Lagrange's approach, the difference of frequencies were discussed between the 1D point contact model presented in relevant literatures and 2D point-to-point contact model proposed in this study (Egert [1]). Moreover, Hertzian interface idea was adopted in the contact model between the rolling ball and carriage/rail for deriving the stiffness of the contact element to understand the dynamic behaviors of the linear guide system. The rolling track was also simulated in a realistic way by incorporating the finite element analysis with the surface-surface contact model. As a validation, relevant experimental modal tests were carried out on linear guideways with different preloads. Finally, comparisons and discussions on the results obtained from numerical predictions and experimental measurements were made and suggestions for further studies on the factors affecting the vibrations characteristics of rolling guides were supplied at the end of this report.

2. Contact stiffness of rolling interface

The linear guideway system is essentially designed with a Gothic arc groove, as shown in Fig. 1, which enables the rolling ball to contact with carriage and rail simultaneously and can be considered as a Hertzian contact mode here. According to the Hertzian elastic contact deformation theory, there is a nonlinear relationship between the local deformation at the contact point and the applied load acted on the contact components. For a linear guideway, the deformation of the raceway groove will increase with the applied load on the ball and enable the contact stiffness of the rolling interface to rise in a nonlinear way. Such a variation in contact stiffness may affect the dynamic behavior of this mechanism to a different extent. Therefore, in order to obtain correct vibration characteristics of a guideway, the contact stiffness must be suitably defined, see Johnson [6] and Goldsmith [2]

Fig. 1 shows the geometry of the ball in contact with the groove of carriage and rail at the contact angle of β, forming a two-point contact state. When a compression force F is applied, the contact boundary of contacting objects will deform a small amount of α and form an area contact of the shape of an ellipse with the major axis $2a$ and minor axis $2b$. The relationship between local contact force F and elastic deformation α can be written as follows:

$$F = k_h \alpha^{3/2} \tag{1}$$

$$k_h = \frac{4}{3} \frac{q_k}{(\delta_1 + \delta_2)\sqrt{A+B}} \tag{2}$$

$$\delta_i = \frac{1-\mu_i^2}{\pi E_i} \tag{3}$$