Journal of Sound and Vibration 393 (2017) 374–387

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Finite element algorithm reproducing hip squeak measured in experiment

Jaeyoung Kang

Dept. of Mechanical Design Engineering, Kongju National University, Cheonan City, South Korea

A R T I C L E I N F O

Article history:
Received 13 June 2016
Received in revised form
14 October 2016
Accepted 9 January 2017
Handling Editor: L. G. Tham
Available online 13 January 2017

Keywords:
Hip squeak
Finite element
Friction damping
Hertz contact
Nonlinear transient analysis
Stick-slip

A B S T R A C T

In this study, the frequency spectrum of squeak noise in hip joint system is measured in experiment. The numerical reproduction of hip squeak signal involves the formulation of the finite element geometry, the analytical contact kinematics such as Hertz theory and Coulomb's law and the mode-discretization. For general approach, the contact kinematics are analytically modeled to easily adjust the contact location, the contact area, the rotation direction, the pressure distribution, the friction law, and so on. Furthermore the friction stress vectors act on the 3-dimensional spherical contact surfaces where they can be divided into the steady-sliding and its transverse slip directions.

Numerical calculations for the various contact parameters are conducted to investigate the possibility of hip squeak occurrence and the nonlinear oscillations after the onset of squeak are also solved. In the transient analysis, the periodic limit cycle of hip squeaking is shown to be the stick-slip type oscillation. Then the numerical frequency spectrum is qualitatively compared with hip squeak signal measured in experiment. The stick-slip oscillation during hip squeaking and its contact behavior will be also discussed over the contact area within one period.

1. Introduction

Squeaking noise after total hip arthroplasty has been broadly reported [1–3]. A number of tests have been conducted for finding the causes of this sound [4–13]. The peak frequencies of hip squeak noise ranging from 550–4350 Hz were summarized in [14]. Squeaking always occurred after the onset of wear scar in lubricated edge loading tests [4]. No squeak was produced without third body particles under the lubricated edge loading condition [8]. Hip squeaking was readily reproduced in normal gait without lubrication, but, squeaking occurred only under the material transfer condition with lubrication [7]. Elevated friction is a common factor causing hip squeaking [10,13]. In the concentric articulation, hip squeak frequencies notably appeared as the tilting angle of contact zone was increased [11]. All vibration motions were elliptical during hip squeaking for the detected range of different kinematic configurations in the contact zone [12].

Some authors tried to reproduce the squeak frequencies of hip joint by performing the complex eigenvalue analysis based on the commercial finite element (FE) software such as ANSYS and ABAQUS [14–18]. The FE method linearizes the nonlinear characteristics of the friction-engaged system at equilibrium and estimates the unstable frequencies induced by the mode-coupling mechanism. However, experimental validation suggested that the conventional numerical simulation is still not able to reproduce the squeak frequencies of in-vitro test precisely [14, 17]. One of the technical difficulties in the FE

E-mail address: jkang@kongju.ac.kr

http://dx.doi.org/10.1016/j.jsv.2017.01.015

numerical simulation is that the system parameters related to the contact kinematics and geometry is too many to be considered. It is not possible to make the FE model with the variable contact parameters by the commercial FE software.

In reality, friction-noise is quite sensitive to the contact kinematics and geometry. In order to improve the accuracy of the numerical simulation, the contact geometry between the ball and socket should be precisely modeled. The small real contact area between the ball and socket has been estimated by the theoretical Hertz contact theory. The real contact area has been calculated in the concentric loading case [19] and the edge-loading condition [20]. The series of Kang's articles [21–23] introduced the non-conformal contact based on theoretical derivation with more precise contact kinematics in hip squeak analysis. It revealed that the size of the real contact area influences the hip squeak propensity in the presence of the negative friction-velocity slope [21,22], and it also explained the mode-coupling mechanism with a constant friction coefficient in the absence of damping effects [23]. However, the previous mathematical models are not adequate for the estimation of an actual hip squeak vibrations due to the over-simplified geometry and linearized derivations.

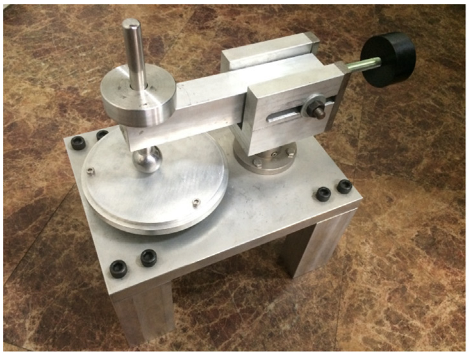
This work focuses on the development of the FE algorithm reproducing the hip squeak signal measured in the hip squeak test. The proposed model is constructed with the FE model geometry and the analytical contact kinematics allowing the variation of contact parameters such as clearance, rotation direction, acetabular orientation, loading direction, and so on, without any FE model changes. In this study, an axis-symmetric stem is chosen for the simplification of the model configuration and experiment. The suggested FE algorithm can be applied to any shapes of femoral stems by switching their FE modal data. The previous analytical hip squeak model [21–23] provides the theoretical background on the newly proposed FE algorithm. It will be shown that the proposed model can qualitatively reproduce the frequency spectrum of an actual squeak signal measured in experiment.

2. Analytical derivations

Hip joint tests are conducted in two categories (Fig. 1). First, friction coefficient is measured by using the pin-on-disk (Fig. 1a) in order to find out the negative slope character on dry contact between the ball and the socket. Later, hip squeak vibration is measured by using an accelerometer (Fig. 1b). In this analysis, the steel stem with 20 mm diameter and 200 mm length, the steel ball with 31.75 mm diameter and the aluminum socket with 31.95 mm diameter are used. The material of the disk is same as the socket in the pin-on-disk test. Before the tests, all specimen are finished by grinding process and cleaned in acetone. From the linear variation of the rotation speed of the disk (Fig. 2a), the friction coefficient is measured with respect to the sliding speed. It is found that the slope in friction-velocity curve is not negative (Fig. 2b). Then, the squeak test (Fig. 1b) is performed by reciprocating the stem directly by hand where squeak noise is clearly and easily reproducible as conducted by Currier et al. [24]. Fig. 3 demonstrates that the fundamental frequency f_1 and its higher harmonics are clearly produced during the squeak test. The other fundamental frequencies (f_2 and f_3) are also observed in the frequency spectrum. The results of these experiments reveal that the negative slope mechanism is not involved in the generation of squeaking, as opposed to the results of the previous theoretical models [21,22].

Conventional FE simulation failed to reproduce the squeak frequencies of this model configuration without the negative friction-velocity slope by using the commercial FE software in all times. The gap between the FE numerical simulation and the squeak test exists obviously as mentioned in the previous literature [14,17]. Therefore, the new FE algorism is suggested to reproduce the squeak frequency spectrum of this simple hip joint system as a starting point for the development of the accurate hip squeak modeling.

In order to do this task, the modeling methodology for a squeaking hip joint with variable contact parameters is newly introduced by using the analytical contact theory with an actual geometry (Fig. 4). The ball part of the hip joint slides over the hemispherical cup when it rotates with any combination of the components in the rotating speeds, Ω_1, Ω_2 and Ω_3. It is noted that the non-conformal contact area is formed over the ball under the tilted pressing load N_0 due to the clearance


(a)

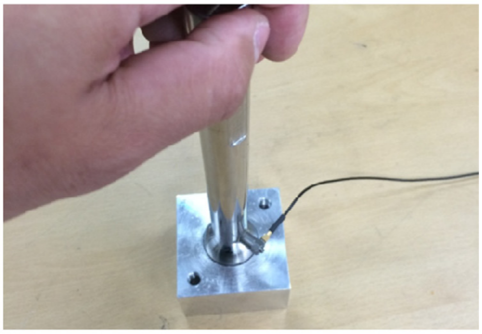

(b)

Fig. 1. Test apparatus for the measurement of (a) friction-velocity curve in a pin-on-disk system, and (b) hip squeak.