Medical Engineering & Physics 32 (2010) 604–609

Contents lists available at ScienceDirect

Medical Engineering & Physics

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

Squeak in hip endoprosthesis systems: An experimental study and a numerical technique to analyze design variants

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ARTICLE INFO

Article history:
Received 2 March 2009
Received in revised form
23 December 2009
Accepted 11 February 2010

Keywords:
Squeaking
Hip endoprosthesis
Complex eigenvalue
Sliding instability

ABSTRACT

Hip endoprosthesis systems are analyzed with respect to their susceptibility to self-excited vibrations and sound or noise generation. Experimental studies reveal that certain configurations can become unstable causing exponentially growing regular high-frequency oscillations that asymptotically approach a limit-cycle with considerable amplitude. Ultimately the vibrations do also lead to the emission of sound that is perceived as squeaking or squeal. To identify dominant influence factors and critical parameters, stability analyses were conducted on the basis of finite-element modeling. The resulting numerical approach, based on the determination of complex eigenvalues and eigenvectors, is shown to be an effective tool to analyze and show differences between endoprosthesis designs with respect to their susceptibility to develop squeaking phenomenons.

1. Introduction

Al_2O_3 ceramic components are widely used as articulation partners in total hip endoprosthesis systems. Ceramic-on-ceramic (CoC) couples show a high wear resistance and good biocompatibility [18,4,16]. However, squeaking of such hip implants was reported as a rather new phenomenon during the last years with a prevalence rate from under 1% to nearly 10%. Although squeaking is presently reported more often in clinical studies, the root causes for the sound generation are still poorly understood: Squeaking has been associated with mismatched ceramic materials [12], malpositioning of the components or fracture [19,20,7]. Also the role of wear and locally increased surface roughness of the interface has been debated [9,5]. Squeaking is sometimes also reported without obviously plausible reasons [19,8,20]. Experimentally squeaking has been reproduced by a number of groups for different in vitro conditions, cf. e.g. [2,15]. The results of these studies suggest that an interruption of the lubrication layer in the joint causing partially boundary lubrication might favor squeaking [23], even so other authors also report squeaking under lubricated conditions. From a dynamics perspective, stick-slip effects have been conjectured to take place, and sound generation might be triggered by these stick-slip effects similar to the tonal noises emitted by a fluid-filled wine-glass when a finger is moved along its rim [21,10]. Overall the phenomenon of squeaking in hip endoprosthesis systems has still to be considered to be only poorly understood: Experimental evidence is far from complete and numerical modeling to assess questions with respect to properties that are hard to access experimentally, is only starting. The debate about prime influence factors and root causes suffers strongly from the lack of fundamental dynamical understanding of the phenomenon itself. The purpose of the present study is therefore: (1) to contribute to a better understanding of the dynamical phenomena of squeaking in hip endoprosthesis systems, and (2) to support the development of computer-based methods that might ultimately serve to develop systems with no or acceptable squeaking propensity.

2. Materials and methods

The present study is comprised by an experimental and a numerical part. For the experimental study a laboratory test-rig was designed to reproduce squeaking of hip endoprosthesis systems in the lab. Complete systems were used for all tests (ceramic ball mounted on a stem and a acetabular liner inserted into a socket). The femoral component was clamped in a hydraulic press and a spinning motion together with a small joint load were applied to the acetabular components. Loading and boundary conditions were varied in wide ranges and dry as well as lubricated conditions were investigated. To analyze the squeaking from a dynamics point of view, surface velocities of a number of selected points on differ-

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doi:10.1016/j.medengphy.2010.02.006

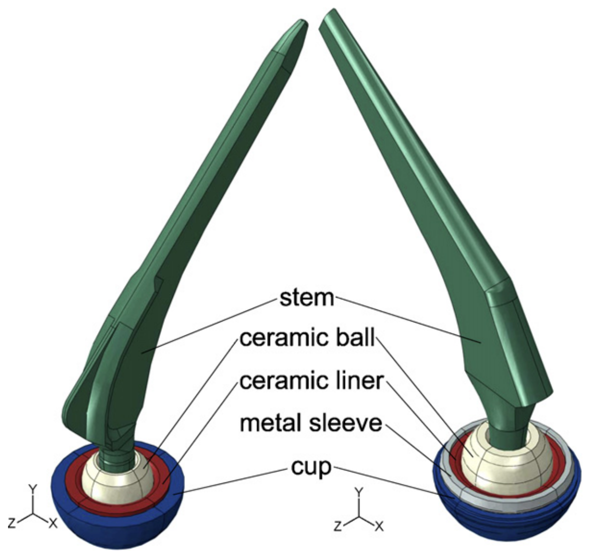

Fig. 1. Two total hip endoprosthesis systems under investigation. (left) System A with four components. (right) System B with five components.

ent components of the endoprosthesis systems were determined by laser-based Doppler velocimetry.

For the numerical analysis similar systems as used for the experiments were modeled using a commercial finite element analysis software (ABAQUS from Dassault Systemes Simulia Corp., Providence, USA). The two systems Fig. 1, on which the analysis focused, differ in geometry and material. While one system consists of four parts (metal stem and shell, ceramic ball and liner), the other system consists of five parts since in addition the ceramic liner is encapsulated in a metal sleeve.

Since, as will be shown subsequently from the experimental findings, the generation of vibrations is caused by an instability of the relative motion of the components with respect to each other, an eigenvalue analysis of the instantaneous working point is conducted. The resulting (complex) eigenvalues provide the vibration frequencies and the growth or decay rates of the natural vibration modes. This approach is used in a number of engineering disciplines, like aeroelastics or friction-induced vibrations [14,1]. The present application involves a rather specific methodological approach requiring more detailed explanation, since it partially differs from the realization of complex-eigenvalue analysis in other fields: The analysis consists of the following steps:

(1) A non-linear static analysis is used to apply forces and a kinematically specified movement to the system. This step generates the contributions of the non-conservative friction forces to the stiffness- and damping-matrices.
(2) A complex eigenvalue analysis (based on a standard subspace approach) is conducted that incorporates the effects of frictional coupling of the parts being in relative motion. A more detailed explanation of the eigenvalue extraction technique is given elsewhere [13,17,14,1,6].

The following loading parameters, kinematics and boundary conditions were chosen:

(i) *Loading and kinematics.* For the non-linear static analysis the stem is loaded with a force of 100 N applied to the top of the stem's taper pointing directly into the direction of the axis of rotation. This force corresponds to joint forces close to full extension of the hip, at which instant squeaking has frequently been observed ([3]). Forces of this magnitude have also been used in other laboratory experiments. Then the femoral side with stem and ball is set into a rotating motion at 1 rad/s around the ceramic part's symmetry axis with a particular value of the friction coefficient μ. This motion pattern corresponds only in part with the flexion-extension motions taking place in vivo (cf. e.g. [3]). The present choice has been motivated by two observations: First, the calculations to be described later and other investigations with a numerical setup where the axis of rotation and load vector are not parallel (cf. [22]) have shown that the rotational motion component dominates the stability properties and instabilities. Second, also in vivo observations with patients have suggested that squeaking seems to be generated mostly in those gait phases, in which the rotational component of the contact-velocity-field is strong. The full motion pattern will have to be explored in the future.
(ii) *Boundary conditions.* Two strategies seem plausible: one strategy would be to mimick as closely as possible the boundary conditions as they can be found in vivo. Due to the complexity of the system, this is a rather complicated task requiring infor-

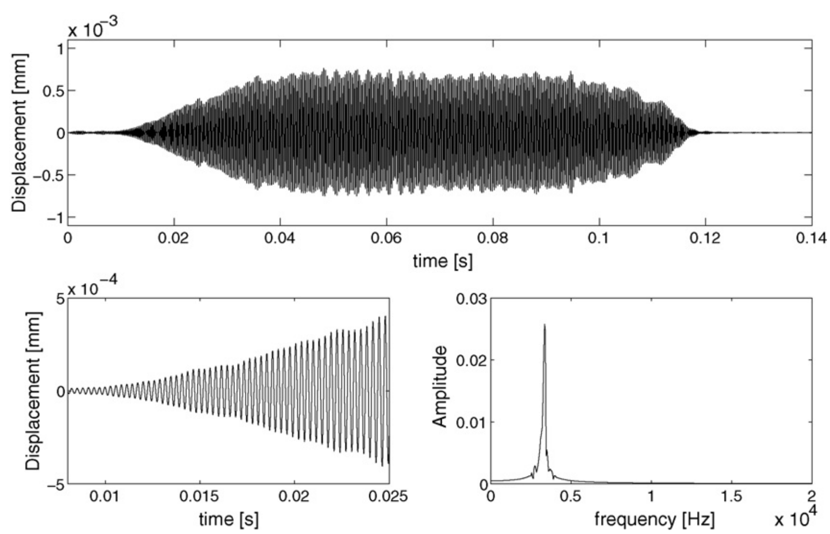

Fig. 2. (top) Typical result of a vibration measurement. Depicted is the displacement measured in vitro on the ceramic ball. (bottom left) Detailed view of the first 25 ms, during which the amplitude is increasing exponentially. (bottom right) Amplitude spectrum of the measured vibration with a sharp peak at 3350 Hz, the frequency of the squeak.