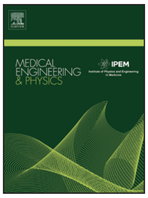
Medical Engineering and Physics 000 (2018) 1–9

Contents lists available at ScienceDirect

Medical Engineering and Physics

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



Modal frequency and shape curvature as a measure of implant fixation: A computer study on the acetabular cup

Petr Henyš[a,*], Steven Leuridan[b], Quentin Goossens[b], Michiel Mulier[b], Leonard Pastrav[b], Wim Desmet[b], Jos Vander Sloten[b], Kathleen Denis[b], Lukáš Čapek[a]

[a] *Department of Technologies and Structures, Technical University of Liberec, Studentská 1402/2, Liberec 461 17, Czechia*
[b] *Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300C, Leuven 3001, Belgium*

ARTICLE INFO

Article history:
Received 5 October 2017
Revised 24 June 2018
Accepted 15 July 2018
Available online xxx

Keywords:
Acetabular cup
Initial fixation
Finite element method
Modal shapes
Damage index

ABSTRACT

Modal parameters are often investigated in order to assess the initial fixation of an implant. Most of studies are focused on the natural frequencies and frequency response function. Usually the femoral stem is tested although the acetabular cup fixation is important as well. The results of implant stability assessment are inconsistent and seem to suggest that frequency as a stability indicator is not sufficiently sensitive. In this study the sensitivity of the modal properties to changes in the bone-implant interface was investigated with the help of the finite element method (FEM). A novel fixation index based on modal shape curvature was investigated as a potential measure of the implant fixation. Modal frequencies are sensitive to interface changes in some manner, but suffer from insensitivity to local changes at bone-implant interface. The sensitivity up to 44% of natural frequencies to stiffness change due insertion steps was observed. The tested damage indicators are able to detect localized small changes in peripheral stiffness (5% stiffness reduction) with 95% confidence under the noise up to 1%. The modal shapes and their curvatures have a great potential to be a robust fixation indicator.

1. Introduction

It is generally known that insufficient initial fixation of press-fitted acetabular implants leads to an excessive implant movement and consequent fibrous layer formation [44], which can cause aseptic loosening of the implant [15,16]. On the other hand, excessive mechanical press-fit fixation leads to an inadequate stress load in the peripheral bone. This may result in damage to the surrounding bone and subsequent implant failure [7]. Achieving the optimal fixation level is a fundamental factor for the long term outcome of the implant longevity. Initial implant fixation assessment is often based on destructive mechanical tests. Implant fixation can be measured by pull-out [38], lever-out [28] or torsional [10] tests, which are all unfortunately restricted to be used in an in vitro setting. Alternatively, medical imaging techniques can provide qualitative information about the implant state, but cannot quantify the amount of the initial fixation. Other major drawbacks of imaging techniques are; the emission of harmful rays, cumbersome to be used per-operatively and diffraction phenomena due to presence of metal materials [17]. Alternative concepts to assess implant fixation based on vibrational methods have been widely investigated by many authors (changes in natural frequencies or changes in the magnitude of frequency response functions (FRF) [6,12,22]). An instrumented impact hammer for measuring the implant stability has been developed and extensively tested. The impact hammer benefits from time-domain feature from force cell mounted on the hammer while does not require the response from bone itself [4,27,32,34,35]. Most of these studies are mainly concerned about the hip stem, although acetabular component failure rates are similar or even slightly higher. Moreover the qualitative assessment of the initial stability by auditory or other cues is more difficult than for the stem [23,25,39]. The monitoring of initial implant fixation by tracking frequency resonance shifts works well for dental implant [29–31], however the clinical implementation in total hip replacement (THR) is still a challenge. Monitoring of initial fixation has shown promising results on artificial and cadaveric bones and even on limited per operative trials on patients [12,13,19,33,34,43]. Challenges are still abundant however; patient-specific or operational factors may thwart the interpretation of changes in the FRFs. Additionally there is still no consistent opinion whether the lower or higher frequency band is more sensitive to initial fixation.

To investigate isolated parameters that influence the vibrational behavior of the bone-implant system, FEM models have

---

[*] Corresponding author.
E-mail address: petr.henys@tul.cz (P. Henyš).

https://doi.org/10.1016/j.medengphy.2018.07.003
1350-4533/

Please cite this article as: P. Henyš et al., Modal frequency and shape curvature as a measure of implant fixation: A computer study on the acetabular cup, Medical Engineering and Physics (2018), https://doi.org/10.1016/j.medengphy.2018.07.003

been developed. Pastrav et al. investigated the influence of contact conditions on the resonance frequencies of a hip stem by FEM. They found that change at contact area correlates with frequency shifts and more complex modes are more sensitive to changes in contact area [22,41]. The higher sensitivity of more complex modes has been supported by Qi et al. [45].

Modal analysis is the most widely used method to assess implant fixation, but only the natural frequencies are commonly studied despite the fact that they are rather global and would not reflect adequately local changes in the bone-implant interface. Corresponding mode shapes are more interesting because of their spatial dependence which potentially is more influenced by local changes in the bone-implant interface. Moreover, the curvature of mode shape is often used in industrial engineering to localize and quantify structural damage [8,40,57]. A curvature-based damage index (DI) can be calculated based on the difference or ratio of two states, a healthy and damaged state. The DI approximates the strain energy changes due to local changes in structural stiffness. Since the initial fixation of an implant is directly related to the interface stiffness, characterizing the implant stability using a form of this DI could be of interest. Based on the state-of-the art knowledge of the current methods dealing with monitoring of implant fixation, this study aims to investigate computationally the sensitivity of the frequencies, mode shapes and their curvatures to bone-acetabular implant interface changes. To the best of our knowledge, such study has never been published and brings a fresh look to the usability of a vibration approach in monitoring the fixation of implants

2. Materials and methods

2.1. FE models

The numerical model was composed of a validated finite element of an artificial pelvic bone. The finite element model of the bone was validated with respect to its modal properties. The material properties of the model were optimized based on the experimental modal analysis and large scale gradient based optimization scheme with accuracy error below 1% [18]. The implant model was based on a type SF-58 acetabular implant (Beznoska, Czech Republic). An isotropic, homogeneous material model was assumed for the implant with a Young's modulus of 110 [GPa] (TI6Al4V), a Poisson's ratio of 0.3 [-] and a density of 4500 $\mathrm{kg} \cdot \mathrm{m}^{-3}$. The bone-implant interface was modelled with simple interface conditions without friction or contact definitions. The bone and implant were kinematically constrained in order to prevent relative movement between them. The change at the interface was generated by different shared contact areas (SCA) at different implantation depths. The depth of reamed cavity was varied from 4.2 to −2.3 mm and was defined as a polar gap (Fig. 1). The range was carefully set-up so that at the lowest value the implant does not go through the medial wall while at the same time the implant only made contact with completely uncovered trabecular bone. The highest range 4.2 mm was selected so that the cortical contact area was more than 1000 mm^2. No Dirichlet boundary conditions were assumed to ensure no influence of boundary conditions. The hemispherical cup was positioned at 45° abduction and 25° anteversion [52]. The following simplifications are taken into account:

- Simplified interface model was described by changing of contact area without relative displacement between the bone and implant.
- No friction or stiffening effects were considered in the model.
- No damping properties were taken into account.

2.2. Modal analysis

A Krylov–Schur based method for solving the generalized eigenvalue problem was used from the library SLEPc [20]. Thirty-five eigenvalues and corresponding mode shapes were computed in a frequency range of 0–8 kHz by a spectral shift-invert approach. The factorization solver used in the transformation was of a MUMPS type [2]. The full numerical scheme was implemented in Python/C with parallel execution of assembling and solving the eigenvalue problem using the PETSc/SLEPc library [3]. The convergence of eigenvalues was verified on a parametrized mesh according to [18]. A mesh convergence analysis was carried out on the implant mesh. The maximum difference between eigenvalues was set to 5%. This threshold was satisfied by an average element size of 1 mm. Displacement field was approximated by a piecewise quadratic shape function. The mesh was created using the CGAL-3D library [54].

In order to compare two mode shapes quantitatively, the Modal Assurance Criterion (MAC) was used. The MAC is a standard similarity criterion commonly used in experimental and numerical modal analysis to match two mode shapes [1,49]. The MAC is defined as:

$$MAC(\psi_1, \psi_2) = \frac{\left|\psi_1^T \psi_2\right|^2}{\psi_1^T \psi_1 \psi_2^T \psi_2} \tag{1}$$

where $\cdot^T$ stands for the transpose and ψ_1, ψ_2 the real mass normalized mode shape vectors. To take into account the minor changes of the mesh for every insertion step, the mode shape vectors were interpolated on a template mesh with radial basis interpolation method [58]. The interpolation error was established by testing different mesh densities. The interpolation error was set to 10^{-6} and the MAC error to 1%. These criteria were satisfied with average element size 1 mm obtained from convergence analysis.

2.3. Damage indices

With all mode shapes computed, a curvature based method commonly used in structural health monitoring for damage identification was applied in order to quantify the changes of mode shapes for points at the bone-implant peripheral interface. The curvature was measured on the peripheral rim of acetabular implant at finite element nodes (Figs. 1 and 2). The curvature κ of the i^{th} mode shape ψ_i defined as second order derivation of ψ with respect to spatial coordinates:

$$\kappa_i = \frac{\partial^2 \psi_i}{\partial \mathbf{x}^2}, \mathbf{x} = \{x, y, z\} \tag{2}$$

was computed with second order forward differentiation. Three Damage Indices (DI-A, DI-B and DI-C) were used. The damage indices were sensitive to stiffness changes commonly occurring as a result from damage of a structure. Due to the reduced stiffness of a damaged object, the local curvature of the mode shape increases. The damage indices compare quantities derived from the mode shapes of the bone-implant construct between different states of the bone-implant construct. The undamaged state of the bone-implant construct was defined as configuration with the implant at an insertion level with depth −2.3 mm. This state represents the ideal fixation level of the implant. The damaged states of the bone-implant constructs were defined as the rest of the insertion levels. The *damaged* and *undamaged* states are indicated by superscripts $\cdot^d$, $\cdot^u$ respectively. The curvatures κ are expressed as a function of peripheral angle ϕ defined in Fig. 2. The variable N introduces the number of modal shapes used to compute the DI and has value 10 unless otherwise specified.

The first damage indicator (DI-A) [5] was defined as the difference between the mode shape curvatures κ of a *damaged* and

Please cite this article as: P. Henyš et al., Modal frequency and shape curvature as a measure of implant fixation: A computer study on the acetabular cup, Medical Engineering and Physics (2018), https://doi.org/10.1016/j.medengphy.2018.07.003