Finite Element Analysis into Eigenfrequencies of a Total Hip Stem with Different Levels of Loosening

Thomas Bender*[1], Martin Sass[1], Wolfram Mittelmeier[1], Rainer Bader[1], Daniel Kluess[1]
[1]University Medicine Rostock, Department of Orthopedics
Research Laboratory for Biomechanics and Implant Technology (FORBIOMIT)
*Doberaner Strasse 142, D-18057 Rostock, Germany, thomas.bender@med.uni-rostock.de

Abstract: A finite element model of a total hip replacement (THR) has been developed from the approach of modal analysis. The model is capable of determining the first 15 Eigenmodes of a THR with an artificial bone model. The model was equipped with several different defects to simulate a loosening of THR and to enforce a shifting of the frequency spectrum of the system's Eigenfrequencies.

Using the preliminary findings from the shifting of the frequency spectrum a classification of defects is to be created to get knowledge and experience of the level of loosening.

Keywords: Total hip replacements, Aseptic implant loosening, Resonance frequency analysis, Eigenfrequency analysis.

1. Introduction

Loosening of total hip replacements (THR) is still the main reason for revision [1]. Approximately 36,000 revisions are necessary in Germany each year [2]. Due to suboptimal sensitivity of currently applied diagnostic methods, e.g. radiographs, the loosening status is often identified late [3]. To optimize the accuracy, an acoustic method was tested in an animal experiment using rabbits [4]. Thereby, small implants with integrated magnetic balls were inserted in the femoral condyles. The implants were excited externally using a coil to produce an impingement of the ball and thus perform a sound analysis. Promising results encourage the transfer of this principle to total hip stems. In order to identify adequate evaluation parameters, the acoustic behavior was investigated by finite element analysis.

2. Use of COMSOL Multiphysics

In this paper the Eigenfrequency analysis is simulated in COMSOL (COMSOL Multiphysics 5.0, COMSOL Inc., Burlington MA). The assembly of the finite element model consists of a straight hip stem (Z-Stem, Merete Medical GmbH, Berlin, Germany) and a SAWBONE rigid foam cylinder 10pcf (Sawbones Europe AB, Malmö, Sweden) with gaps and aluminum pads as sensor mountings. Additional sensors are added as a rigid element with a defined mass (Figure 1).

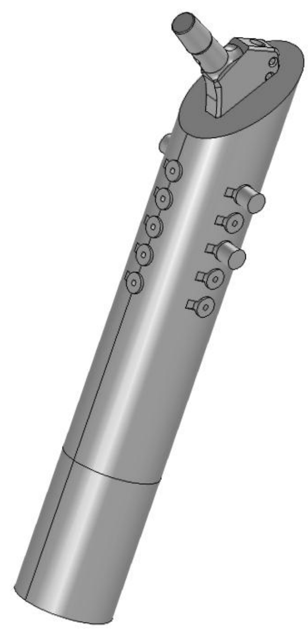

Figure 1: Total hip stem, artificial bone assembly with sensor mounting plates and vibration sensor.

A fixing of the THR is provided on the distal region of the SAWBONE cylinder. In additional studies, the THR was loaded with a body mass and the change in the Eigenfrequency has been determined.

2.1 Materials and Methods

The SAWBONE cylinder was equipped with different defects representing various states of loosening (Figure 5 and Table 1). For simulation three different states of loosening were created and analyzed in an Eigenfrequency FEM study.

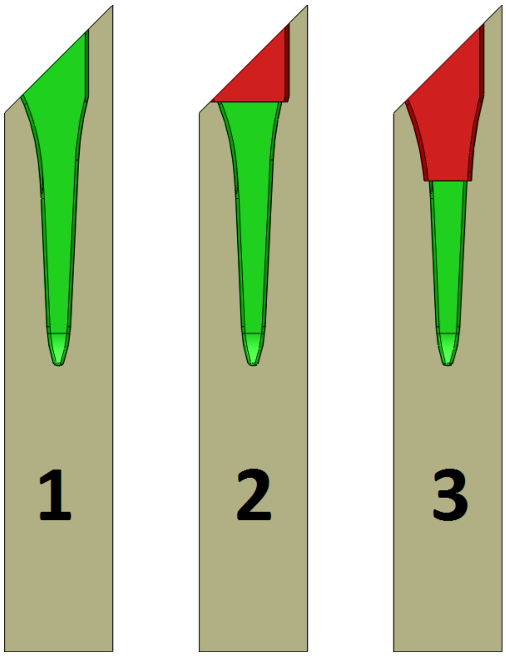

Figure 2: SAWBONE rigid form cylinder with partly different prepared bone defect (highlighted in red).

Table 1: Defect specification

No.	specification	defect area
1	pressfit	0 cm²
2	small defect	1.1cm²
3	larger defect	3.3cm²

At this point it is important to mention that the material of the artificial bone replacement has homogeneous foam (solid rigid polyurethane foam) structure and so represents a simplification of a human femoral bone.
For the titanium Z-Stem the material parameters of titanium Ti6Al4V were used (Table 2). The pads as sensor mounting plates are made of aluminum.

Table 2: Material properties

Domain	Density [kg/m³]	Poisson ratio [1]	Youngs modulus [MPa]
SAWBONE	160	0.3	86
Z-Stem	4430	0.342	113800
Aluminum pads	2700	0.33	70000

The sensor domains are defined as a solid with a fixed size and a constant density. The values of the Poisson ratio and Young's modulus were adopted from aluminum which makes up the largest part of the sensor. In addition, the senor domains are set as rigid object.

2.2 Modal analysis

With an Eigenfrequency study node the eigenvalue problem for a set of Eigenmodes and associated Eigenfrequencies are solved [5]. In the modal analysis a vibration of test specimen under a dynamic excitation is computed. The Eigenvalues are used to determine the Eigenfrequencies (or Eigenmodes) of vibration. Modal analysis helps in calculating the values of these mechanical resonant vibration frequencies of the specimen.

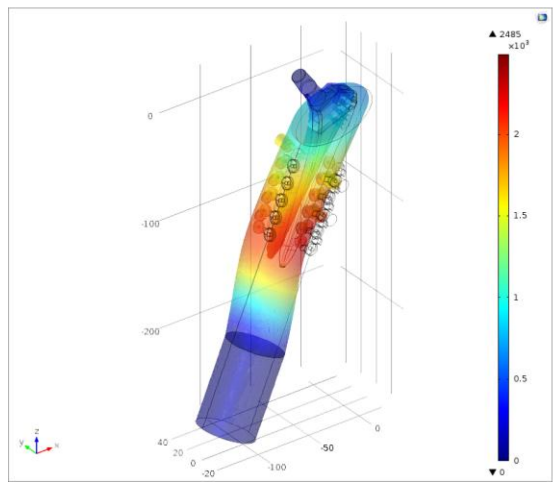

Figure 3: Mode 1, Eigenfrequency=424.42

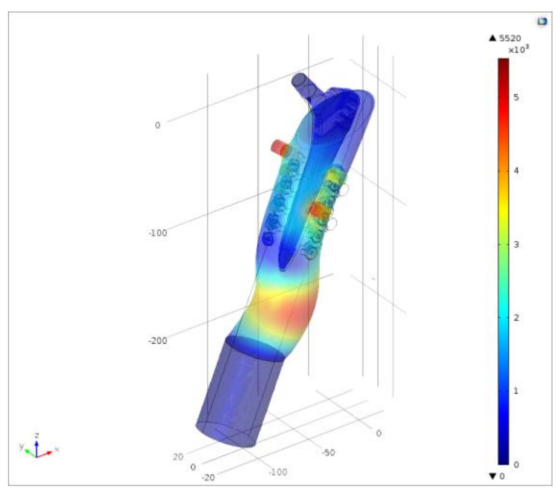

Figure 4: Mode 8 Eigenfrequency=2193.2

In Figure 3 and Figure 4 individual modes of the THR system are shown. This includes bending, compressions and torsions modes each corresponding with a higher order harmonics of the fundamental frequency.

2.3 Results

The results of the modal analysis (Figure 5) show a decrease of the Eigenfrequencies with larger loosening state and also a decrease with higher human body mass (Figure 6).

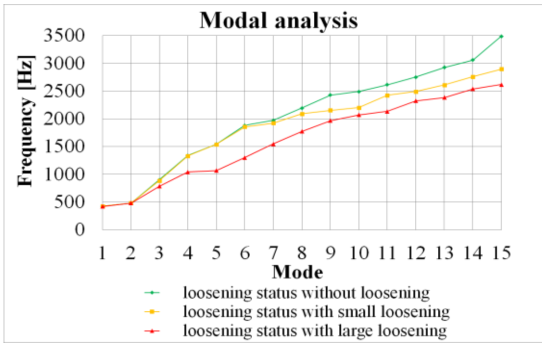

Figure 5: Results of a modal analysis with the first 15 Eigenmodes

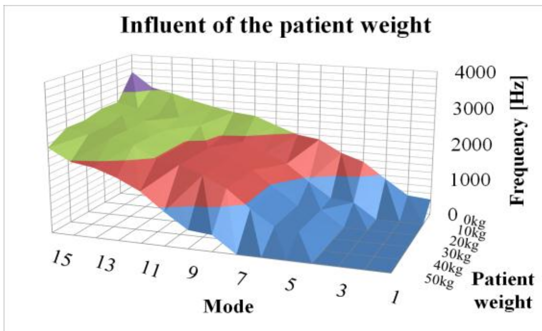

Figure 6: Influence of patient weight

3. Conclusions

A 3D model of a THR is created which has properties similar to those of a human femur. Three different states of loosening were provided to determine the corresponding Eigenfrequencies. In the present study, numerical investigations of a novel acoustic approach to diagnose loosening of total hip stems were carried out. Comparable with the results of [6], an increase of the hip stem-bone interface results in increasing Eigenfrequencies. With the aid of the frequency spectrum of the Eigenfrequencies a classification of loosening conditions could be created.

This model provides an initial overview of the behavior of Eigenfrequencies depending on the level of loosening under consideration of the patient weight.

4. Outlook

In future, these obtained results are validated by experiments. Therefore some measurements are already recorded. These are still different from the simulated results. One way of optimization lies in the adaption of the material data and in addition the geometry can be further optimized. The differences could also be caused by the experimental test setup. Superposition of different oscillations could have an influence as well as other coupled behavior with the environment. Furthermore no information about the amplitudes of the individual Eigenmodes is obtained from the modal analysis.

Another way of determining the level of loosening is an attenuation analysis of forced vibration of the system. This would require a time depending study in which the attenuated oscillations of a forced vibration are investigated. Unfortunately, there are currently no precise damping parameters available for SAWBONE (solid rigid polyurethane foam).

5. References

[1] Malchau, H. et al. The Swedish total hip replacement register. *The Journal of Bone & Joint Surgery*, **84(suppl 2)**, S2-S20 (2002)

[2] Statistical Federal Office Germany, Fallpauschalenbezogene Krankenhausstatistik (DRG-Statistik) Operationen und Prozeduren der vollstationären Patientinnen und Patienten der Krankenhäuser. *DRG-Statistik* 2010

[3] Temmerman, O. P. et al. Diagnostic accuracy and interobserver variability of plain radiography, subtraction arthrography, nuclear arthrography, and bone scintigraphy in the assessment of aseptic femoral component loosening. *Archives of orthopaedic and trauma surgery*, **126(5),** 316-323 (2006)

[4] Ruther, C. et al. Investigation of an acoustic-mechanical method to detect implant loosening. *Medical engineering & physics*, **35(11)**, 1669-1675 (2013).

[5] COMSOL AB, Eigenfrequency, *COMSOL Multiphysics Reference Guide*, **4.3a**, 292-293 (2012)
[6] Qi, G. et al. How much can a vibrational diagnostic tool reveal in total hip arthroplasty loosening? *Clinical Biomechanics*, ***18*(5)**, 444-458 (2003)

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7. Affiliations

Thomas Bender, M. Eng.
University Medicine Rostock
Department of Orthopedics
Doberaner Straße 142, 18057 Rostock
Email: thomas.bender@med.uni-rostock.de