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Rapid identification of elastic modulus of the interface tissue on dental implants surfaces using reduced-basis method and a neural network

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ABSTRACT

This paper proposes a rapid inverse analysis approach based on the reduced-basis method (RBM) and neural network (NN) to identify the "unknown" elastic modulus (Young's modulus) of the interfacial tissue between a dental implant and the surrounding bones. In the present RBM–NN approach, a RBM model is first built to compute displacement responses of dental implant-bone structures subjected to a harmonic loading for a set of "assumed" Young's moduli. The RBM model is then used to train a NN model that is used for actual inverse analysis in real-time. Actual experimental measurements of displacement responses are fed into the trained NN model to inversely determine the "true" elastic modulus of the interfacial tissue. As an example, a physical model of dental implant-bone structure is built and inverse analysis is conducted to verify the present RBM–NN approach. Based on numerical simulation and actual experiments, it is confirmed that the identified results are very accurate, reliable, and the computational saving is very significant. The present RBM–NN approach is found robust and efficient for inverse material characterizations in noninvasive and/or nondestructive evaluations.

1. Introduction

Osseointegration is the structural and functional connection between the living bone and dental implant surface (Bränemark et al., 1985; Friberg et al., 1991; Brunski, 1992). In the osseointegration process, conditions of implant-bone interfacial tissues influence significantly adaptive bone remodelling (Cowin, 1986) and material properties of interfacial tissues determine biomechanical responses and stability of implant-bone structures.

Several research works have been carried out to predict bone properties of implant-bone structure with in-vitro or in-vivo studies (Cowin, 2001). Examples are traditional mechanical testing, nanoindentation, imaging procedures or ultrasonic techniques (Cowin, 2001). A technique of resonance frequency analysis (RFA) (Meredith et al., 1996; Sennerby et al., 2005) has also been developed to detect implant stability. However, no precise method has been developed to determine noninvasively the material properties of implant-bone interfacial tissues after dental implant operations due to technical difficulties. It is, however, invaluable to develop a systematic and efficient inverse approach to identify material properties of interfacial tissues. In the area of nondestructive evaluation (NDE), two pieces of very important techniques have been made available. One is advanced inverse analysis techniques (Liu and Han, 2003) that allow systematic means to identify system parameters from properly designed measurable outputs. Another one is the so-called real-time computation methods that allow rapid computation of the outputs for a set of assumed inputs. These two pieces of techniques are applicable to identify material properties of dental implant systems.

Currently, the finite element method (FEM) is widely employed to evaluate the behavior of an implant-bone structure (Geng et al., 2001; Deng et al., 2008a b). A FEM analysis is, however, very time-consuming because of the complexity of implant-bone structures demanding a large amount of elements. In an inverse analysis, thousands and even hundreds of thousands of such "forward" analyses may be required. Thus, the total CPU-time for an inverse analysis can be unacceptably long. A fast forward solver is therefore critical in order to avoid very long CPU-time in inverse analyses.

A reduced-basis method (RBM) (http://augustine.mit.edu) is a fast computational technique which can solve forward problems rapidly with desired accuracy. RBMs with error estimation were employed to solve different kinds of partial differential equations. The detailed procedures for reduced-basis method for parametrized parabolic partial differential equations can be found in the work of Nguyen (2005); Grepl and Patera (2005). Applications of the reduced-basis method and its *rigorous* error

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estimation can be found in Veroy and Patera (2005), Rozza and Veroy (2007) for Navier–Stokes equation, in Patera and Rønquist (2007) for Boltzmann equation and in Huynh and Patera (2006) for stress intensity factor analysis. Recently, Liu et al. (2008a) developed a SGP_RBM method, for elasticity problems, based on a smoothed Galerkin projection (Liu, 2008), which can provide an upper bound to the *exact* solution while the original reduced-basis method provides a lower bound to the *exact* solution. The computational efficiency of such a RBM is found significantly higher compared to that of the FEM, and hence has been applied to inverse analyses of complicated engineering systems to reduce computational cost (Liu et al., 2005).

In the NDE for material and structural systems, inverse searching methodologies (Liu and Han, 2003) including direct search algorithm, gradient-base algorithm, genetic algorithms (GAs) and the neural network (NN), are commonly adopted. Applications of the GAs in inverse analyses can be found in work of Han et al. (2002) and Liu et al. (2002a, 2008b). In additions, the NN has found its applications in inverse problems of elastic wave propagation (Sribar, 1994), material characterizations (Huber and Tsakmakis, 1999) of functionally graded material (FGM) (Han and Liu, 2003; Han et al., 2003; Liu et al., 2001a, b, 2002b), material characterizations of implant-bone structure (Deng et al., 2004, 2008c), and optimal design problems (Sumpter and Noid, 1996). From these earlier studies, it is noted that the NN possesses unique computing features for identification of structural parameters which are non-linearly related to dynamic responses of the structure in a complicated manner. A RBM–NN approach in which a RBM model is developed as a "teacher" to train a NN is proposed in order to make use of the high computational efficiency of the RBM and the efficiency of the NN in performing inverse analyses.

A 3D FEM model is firstly constructed for a dental implant-bone system, and a fast RBM model is developed. The RBM model is then used to generate the displacement responses of the dental implant-bone structure to train a NN model. The trained NN model is next applied to inversely identify elastic moduli of interfacial tissues in the dental implant system by feeding with experimental measurements of the actual physical model of the dental implant system.

2. Construction of RBM model

2.1. Problem statement

A dental implant-bone problem is considered, and a sectional view of the problem is displayed in Fig. 1. The dental implant-bone system consists of four regions of the outermost cortical bone Ω_1 the cancellous bone Ω_2 the region of interfacial tissue Ω_3 and the aluminium rod of dental implant Ω_4:$\Omega = \cup_{i=1}^{4}\Omega_i$ Material properties of each region are listed in Table 1. A harmonic force of angular frequency ω is applied to the aluminium rod, and Dirichilet boundary condition is specified in Γ_D as shown in Fig. 1.

The purpose of our work is to identify inversely the elastic Young's modulus E of the interfacial tissue between the surface of aluminium rod and the cancellous bone from "measured" displacement responses of the dental bone structure to excitation forces of different frequency ω. Our analysis procedure consists of two parts: forward analysis and inverse analysis. The forward analysis determines the response of the system to a set of input of system parameter for which we need to build a RBM model. The inverse analysis determines the Young's modulus E from a given measurement of response of the dental system when it is excited. In the forward analysis, input parameters μ for our forward analyses are defined by E and the frequency $\omega : \mu = (E, \omega) \in \mathscr{D}$ where $\mathscr{D} = [1.0 \times 10^9, 4.5 \times 10^9]\,\mathrm{Pa} \times [500, 3500]\,\mathrm{Hz} \subset \mathbb{R}^{P=2}$. Based

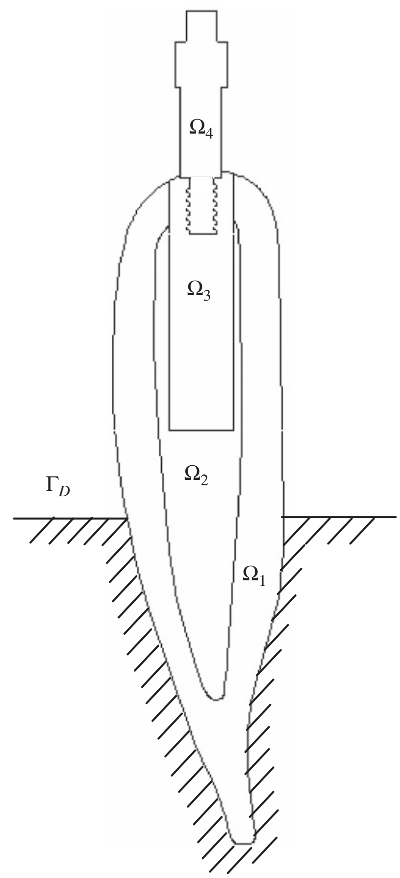

Fig. 1. Diagram of a dental implant-bone structure with four regions.

on the standare weakform of elasticity, for a given $\mu \in \mathscr{D}$, the *exact* solution of the *exact* problem satisfies (see, e.g., Grepl et al., 2007; Nguyen, 2005)

$$a(u^e(\mu), \upsilon; \mu) = f(\upsilon; \mu), \forall \upsilon \in \mathbb{S}, \quad (1)$$

where $\mathbb{S}$ is a proper Hilbert space and the output of interest is determined as

$$s^e(\mu) = \ell(u^e(\mu)), \quad (2)$$

where $s^e(\mu)$ is the *exact* output, $u^e(\mu)$ is the *exact* displacement, $a(,)$ is bilinear form and ℓ is linear functional.

The bilinear form $a(,)$ is now transformed into the parametric bilinear form as (Prud'homme et al., 2002)

$$a(w, \upsilon; \mu) = \sum_{q=1}^{Q} \Theta^q(\mu) a^q(w, \upsilon), \quad (3)$$

where $a^q(w, \upsilon)$ is μ-independent bilinear form and $\Theta^q(\mu)$ are the coefficient for affine function. This parametric bilinear form is crucial in formulating the reduced-basis method.

2.1.1. Experimental setting

A block of bovine rib of a mature specimen, obtained commercially from a butcher, is used as a physical model for the edentulous human mandible. The experiment procedure strictly abided with the National Advisory Committee for Laboratory Animal Research Guidelines and the General Laboratory Safety Procedure of National University of Singapore.

A 4×13 mm implant socket is prepared using drills according to the actual surgery protocol suggested by the manufacturer. To simulate the changes in stiffness of interfacial tissue during the