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Inverse structural modifications of a geared rotor-bearing system for frequency assignment using measured receptances

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ABSTRACT

Inverse structural modifications have been studied in theory but rarely implemented in practice. In this paper, the inverse structural modification theory based on receptances is further developed. The receptances of a modified structure are expressed in terms of the receptances of the original structure and the modifications to be made, which allows measured receptances to be used instead of system matrices or a modal model (and thus a theoretical model of the structure is not needed). The method proposed in this paper can be applied to assignments of several different kinds of dynamical properties such as natural frequencies, antiresonant frequencies and receptances, and to make pole-zero cancellation.

To address the lack of experimental validation to inverse structural modification problems in published papers, a geared rotor-bearing system is manufactured and tested to validate the method and provide experimental insights. Experimental results show that more than one natural frequency or antiresonant frequency can be assigned within acceptable accuracy and the sensitivity of modifications is crucial for the solutions of modifications cast as an optimization problem. An additional application for determining the optimal locations for given modifications to achieve the highest first natural frequency is also presented. The experimental results obtained prove the effectiveness and the ease of use of this proposed method. This work should help make inverse structural modification a popular means of passive vibration control to improve the dynamical behaviour of real structures.

1. Introduction

Nowadays, the energy density of a machine has significantly increased because such a machine tends to transfer a great amount of power or operate more efficiently than before. From a structural dynamics point of view, optimizing its design is a useful and fundamental way to achieve better dynamic performance. For an existing structure, it is often more useful to modify its structural properties (such as mass and stiffness, occasionally damping) to obtain certain desirable dynamic properties, which is usually referred to as structural modification. There are two complementary approaches to address structural modification problems: one is direct/forward structural modification approach and the other is inverse structural modification approach. The forward structural modification aims to predict the exact change to the structure's dynamic properties

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when known modifications are made at a given location while the inverse structural modification determines what modifications should be made so that the modified structure can have the prescribed dynamic characteristics [1].

Early studies of forward structural modification, which is also known as re-analysis, were reviewed and summarized by Baldwin and Hutton [2]. They classified the techniques into three groups based on the assumptions of the form of modifications: techniques based on small modifications, techniques based on localized modifications, and techniques based on modal approximation. Several approaches such as Rayleigh quotient [3], sensitivity analysis [4], and perturbation approach [5] were used to address forward modification problems without a complete reanalysis of the whole structure. However, compared with direct structural modification, inverse structural modification is more intuitive and time-efficient, which later on has been a more active area of research in the last decades. Part of the relevant literature is summarized as follows.

The solution for an inverse structural modification problem can be exactly obtained if a complete set of modal data is available. However, it is extremely difficult to identify most of a modal data set from an experimental point of view, which would later result in a truncation error problem. Many early studies [6–8] were focused on minimizing/circumventing the effect to achieve sufficiently accurate solutions. Other than modal information, system matrices, i.e. mass/damping/stiffness matrices, can also be used for the purpose of inverse structural modifications. Methods related to the usage of system matrices and sensitivity analysis were proposed in [9,10]. Among many techniques for solving the problem, receptance method recently has received considerable attention since it does not require a theoretical model to find the solution. That is to say, one can deal with a complex structure even though a realistic finite element model is very difficult to construct. Modal truncation error that can occur when using a spatial model or modal model can be avoided by the receptance method within a frequency range. The receptance method can be further divided into two groups based on the implementation: one is structural modification by passive elements (such as masses, springs, or beams), and the other is active vibration control using sensors and actuators.

Passive structural modification offers several advantages over active control. For example, the modified system is guaranteed to be stable, it does not require additional sensors, actuators or power suppliers, and it is able to deliver large modification to the system [11]. Among early studies, Tsuei and Yee [12] proposed a method for inverse structural modification based on the FRFs of an undamped vibrating system. The method could determine the required mass or stiffness modification value to give a system an assigned natural frequency with only a few computations. Later on, the same idea was extended to assign a damped natural frequency of a damped structure [13] by the same authors. Both studies considered changing only the mass matrix or stiffness matrix separately. A method of simultaneous mass and stiffness modification on lumped systems was presented in a book by Maia [14] in which a coefficient matrix and predetermined mass/stiffness ratios were introduced in the modification matrices instead of their absolute values. Methods for assigning an antiresonant frequency for spring-mass system were also covered in the book.

The most basic form of modification, rank-one modification, for pole or zero assignment has been well studied and summarized in a review paper by Mottershead [15]. Exact numerical solutions are available for rank-one modifications, which include point mass modification, grounded spring modification, or springs connected between two coordinates, if a solution exists. Cakar [16] extended the rank-one modifications to the case when some natural frequencies were kept the same after one or more mass modifications and addition of a grounded spring. For a rank-one modification, it is also possible to fix antiresonant frequencies while shifting natural frequencies since the zeros of a cross-receptance or a point receptance are not affected by the modification made at one of the coordinates of the receptance concerned. Mottershead and Lallement [17] studied pole-zero cancellation in which the assigned pole possessed the same frequency as the antiresonant frequency, and a vibration node could be created. A similar approach for assigning nodes was presented by Mottershead et al. [18].

Kyprianou et al. [19] showed that up to two natural frequencies could be assigned through an addition of a single degree-of-freedom (DoF) spring-mass oscillator. It was also shown that the effect of attaching an oscillator can be included in the system dynamic stiffness matrix without expanding its total number of DoFs. Zhu et al. [20] proposed a similar procedure to assign receptances at particular frequencies by using one or more simple spring-mass oscillators. This provided an alternative way to reduce vibration response of a system. Kyprianou et al. [11] managed to assign the natural frequencies and antiresonant frequencies of a continuous frame structure. The modification involved a 3×3 receptance matrix that covers two translational DoFs and more importantly one rotational DoF at the modification location. This study showed that the methodology based on receptance method still works even if the assigned frequency and mode shape are much different from the original ones.

A different approach was made by Richiedei et al. [21] and Ouyang et al. [22] in which the inverse problem was transformed into a multi-variable optimization problem. Both eigenvalues and corresponding eigenvectors could be assigned through minimizing an objective function, and the required mass and stiffness modifications could be computed simultaneously; additionally, for the specific case in which the function is proved to be convex, the solution is guaranteed to be a global minimum and is not affected by initial guess. This study and that in [6] motivated the work of Liu et al. [23] about eigenstructure assignment through placing multiple spring-mass oscillators.

Although inverse structural modification has been studied for many years, it is worthwhile mentioning that there are still several problems to be addressed. One of the problems which is usually referred to as partial eigenvalue or partial eigenstructure assignment problem recently has received much attention. Partial eigenvalue assignment aims to overcome the frequency spill-over, a phenomenon in which unassigned natural frequencies are also shifted after the assignment of a subset of natural frequencies. This phenomenon could result in an unfavorable situation in which an unassigned frequency is