RESPONSE SURFACE METHODOLOGY FOR DAMAGE DETECTION USING FREQUENCY AND MODE SHAPES

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DEDICATION

To Mak and Bapa who constantly encouraged and supported their daughter

To Dyana, Luqman and Ida who believed in their sister's ability

To Dylla who kept up her Titiq's spirits

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ABSTRACT

The model updating method is one popular method in vibration-based damage detection. However, the conventional model updating method requires a finite element (FE) model for sensitive computation during the iteration process, which leads to the problem of slow convergence and high time consumption. Therefore, the response surface methodology (RSM) has emerged as an alternative tool in FE model updating due to easy implementation and time-efficient processing where the computationally expensive analytical FE model is replaced by the simple and inexpensive response surface (RS) model. A recent RSM application in structural damage detection employs frequency as the sole response feature, limiting its ability to localise the existence of damage due to the inability of the frequency to ascertain damage in a symmetric structure. Therefore, a better RSM employing frequency and mode shapes as the response features is proposed in this study, as both parameters are proven sensitive to damage location. The implementation of the proposed method involves a three-phase procedure; (i) sampling, (ii) RS modelling and (iii) model updating. In order to develop the best RS model, two major parameters in the sampling stage, design of experiments (DOEs) and design spaces are carefully assessed through a series of sensitivity studies based on their damage detectability. The applicability of the technique is applied to detect simulated damage in numerical models of simply supported beam and steel frame structures as well as a laboratory tested steel portal frame. The results from sensitivity studies show that central composite design (CCD) with more sampling points in a small design space has better performance in detecting damages due to dense population of data which adequately represents the design space. The results from numerical study demonstrated that the proposed RSM method has a good ability to detect damage due to noise free data while results from experimental study depicted some false detections. It is concluded that the proposed method is reliable in damage detection provided that the data has good precision. Nevertheless, the presence of noise and errors in real practice are inevitable, thus pollute the measured data. Therefore, it is suggested to incorporate the effect of uncertainties in the proposed RSM to improve its applicability in real practice.

ABSTRAK

Kaedah mengemaskini model merupakan salah satu kaedah yang popular dalam mengesan kerosakan berasaskan getaran. Walau bagaimanapun, kaedah konvensional mengemaskini model memerlukan model unsur terhingga (finite element, FE) bagi pengiraan sensitif semasa proses lelaran yang menyebabkan masalah penumpuan perlahan dan penggunaan masa yang tinggi. Oleh itu, kaedah permukaan tindak balas (response surface methodology, RSM) telah muncul sebagai alternatif dalam mengemaskini model FE kerana pelaksanaan yang mudah dan proses yang efisyen di mana pengiraan analisis model FE yang mahal digantikan dengan permukaan tindak balas (response surface, RS) yang mudah dan murah. Applikasi terbaru RSM dalam mengesan kerosakan struktur menggunakan frekuensi sebagai ciri tindak balas tunggal, telah menghadkan keupayaannya dalam mengenalpasti lokasi kerosakan disebabkan ketidakupayaan frekuensi dalam mengenalpasti kerosakan dalam struktur yang simetri. Oleh itu, RSM yang lebih baik dengan menggunakan frequensi dan mod bentuk sebagai ciri tindak balas dicadangkan dalam kajian ini kerana kedua-dua parameter ini terbukti sensitif terhadap lokasi kerosakan. Pelaksanaan kaedah yang dicadangkan melibatkan prosedur tiga fasa; (i) persampelan, (ii) permodelan RS dan (iii) mengemaskini model. Bagi membina model RS terbaik, dua parameter utama di fasa persampelan iaitu rekabentuk eksperimen (design of experiments, DOEs) dan ruang rekabentuk, dinilai dengan teliti melalui satu siri kajian sensitiviti berdasarkan keupayan mengesan kerosakan. Kebolehgunaan teknik ini diaplikasikan untuk mengesan kerosakan simulasi dalam model berangka bagi struktur rasuk sokong mudah dan kerangka keluli serta kerangka portal keluli yang diuji di makmal. Hasil kajian sensitiviti menunjukkan bahawa rekabentuk komposit pusat (central composite design, CCD) dengan titik persampelan yang lebih banyak dalam ruang rekabentuk yang kecil mempunyai prestasi yang lebih baik dalam mengesan kerosakan disebabkan oleh populasi data yang padat yang mewakili ruang rekabentuk secukupnya. Hasil kajian berangka menunjukkan bahawa kaedah RSM yang dicadangkan mempunyai keupayaan yang baik untuk mengesan kerosakan yang disebabkan oleh data bebas gangguan manakala hasil kajian eksperimen menunjukkan beberapa pengesanan palsu. Disimpulkan bahawa kaedah yang dicadangkan boleh dipercayai untuk mengesan kerosakan dengan syarat bahawa data yang digunakan mempunyai ketepatan yang baik. Walau bagaimanapun, kewujudan gangguan dan ralat dalam amalan sebenar tidak dapat dielakkan, lantas mencemarkan data diukur. Oleh itu, adalah dicadangkan untuk menggabungkan kesan ketidakpastian dalam RSM yang dicadangkan untuk meningkatkan kebolehgunaan dalam amalan sebenar.

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LIST OF SYMBOLS

$\boldsymbol{M}$	Mass matrix
$\boldsymbol{C}$	Damping matrix
$\boldsymbol{K}$	Stiffness matrix
$\ddot{x}$	Vectors of acceleration
$\dot{x}$	Vectors of velocity
x	Vectors of displacement
ω_i	i^{th} modal natural angular frequency
$\emptyset_i$	i^{th} mode shapes
x	Input parameters
y	Response features
f	Approximation function
k	Number of input variables / number of elements
ε	Error
σ^2	Variance
N	Number of total points
n_c	Number of centre points
±1	Factorial points
±α	Axial points
D	Determinant
β	Regression coefficients
$\boldsymbol{Y}$	Matrix of actual response
$\widehat{\boldsymbol{Y}}$	Matrix of estimated response
n_r	Number of response feature
λ	Modal frequencies
$\emptyset$	Mode shapes
m	Number of considered mode

n	Number of considered node
R^2	R-square
$R^2{}_{adj}$	Adjusted R-square
$R^2{}_{pred}$	Predicted R-square
SS_R	Sum of squares regression
SS_T	Total sum of squares
$PRESS$	Predicted residual error sum of squares.
ω	Weight vector used to control the attainment factor of the goals
γ	Slack element used as a dummy in the optimisation
lb, ub	Lower and upper bounds of design parameters
E_0	Young's modulus in the undamaged state / initial state
E'	Young's modulus in the damaged state
E'_0	Young's modulus of the reference state
I	Moment inertia
D	Density
ρ	Poisson's ratio

LIST OF ABBREVIATIONS

ANN	Artificial neural networks
AR	Auto Regressive
ARMA	Auto Regressive Moving Average
ARX	Auto Regressive with exogenous input
BBD	Box–Behnken design
CCC	Circumscribed central composite
CCD	Central composite design
CCD_{64}	1/64 fractional factorial design
CCD_{MRV}	Minimum-run resolution V design
COMAC	Co-ordinate Modal Assurance Criterion
DOE	Design of experiment
DOFs	Degrees of freedom
DS	Damage state
DSF	Damage sensitive features
F	Reference state based on the first 4 frequencies only
FBDD	Frequency-based damage detection
FCC	Face-centred composite
FD	Factorial design
FE	Finite element
FFT	Fast Fourier Transform
FMS1	Reference state based on the first 4 frequencies and mode shapes
FMS2	Reference state based on modes 2 to 4 of the frequencies and mode shapes
FRF	Frequency response function
ICA	Independent component analysis
ICC	Inscribed central composite
MAC	Modal Assurance Criterion

MBDD	Mode shapes-based damage detection
MDLAC	Multiple damage location assurance criterion
NDT	Non-destructive tests
PCA	Principal component analysis
POM	Proper orthogonal modes
RC	Reinforced concrete
RS	Response surface
RS10	RS model derived from design space of E_0 - 0.1E_0
RS30	RS model derived from design space of E_0 - 0.3E_0
RS60	RS model derived from design space of E_0 - 0.6E_0
RS-F	RS model constructed from reference state F
RS-FMS1	RS model constructed from reference state FMS1
RS-FMS2	RS model constructed from reference state FMS2
RSM	Response surface methodology
SHM	Structural Health Monitoring
SRF	Stiffness reduction factor
UD	Uniform design

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CHAPTER 1

INTRODUCTION

1.0 Introduction

Many civil structures such as buildings and bridges are built to provide essential welfare in communities. These valuable assets are normally designed to be in service for a long lifespan. However, throughout their service time, the structures suffer from deterioration due to usage, environmental effects and accidental events such as earthquake. All these factors lead to local or global damage to the structures such as cracks, corrosion, delamination, disintegration and others that affect the integrity of structures. At worst, consequences like catastrophic failure might occur, which results in injuries, loss of human life and long term impacts on social and economic factors.

Several incidents have been reported due to loss of integrity of in-service structures. For example, the sudden collapse of the I-35W bridge over the Mississippi River in Minneapolis, Minnesota, on 01 August 2007 was due to improper structural design of the gusset plates used in the truss structures (Hao, 2010). An incident involving a building was the eight-storey Rana Plaza factory building in Savar, Bangladesh, where the warning to evacuate the building when cracks appeared a day before the collapse of the building on 24 April 2013 had been ignored. This incident resulted in about 2500 injured people and a death toll of more than 1000, and is thus considered as the deadliest structural failure incident (BBC News, 2013). Another building collapse incident reported on 27 September 2013 in Mumbai, India involved a five-story residential building, killing 61 due to improper renovation and illegal removal of a central wall and supporting beams (Cook, Yan and Udas, 2013). Recently, shoddy renovations and construction were blamed for the collapse of Gyeongju Mauna Resort Gymnasium in Korea (The Star, 2014) and Military Training Center barracks in Omsk, in the south of Russia (Steward, 2105). The occurrences of the aforementioned incidents have shown that an efficient method is vital in inspection and monitoring the safety conditions of the structures. This can be achieved by Structural Health Monitoring (SHM), a tool to diagnose the state of the structure. The application of SHM prolongs the life of structures through early detection of damage, thus minimising the potential for catastrophes.

1.1 Background of problem

SHM can be categorised into local and global methods. In the local method, visual inspection or non-destructive tests (NDT) such as ultrasonic waves, magnetic field, radio-frequency, eddy-current, thermal field and fibre optic are applied to assess the structure. However, the methods are labour-intensive and require clues to the damaged area. Therefore, the global method, namely vibration-based damage detection, has been explored by civil engineers over the past three decades due to its ability to diagnose structures as a whole (Cawley and Adams, 1979). Unlike the NDT local methods, this non-destructive global method is useful for SHM because it does not require prior knowledge of the damage location. Vibration-based methods utilise the fact that the presence of damage will reduce the stiffness and mass properties of the structure and subsequently change its dynamic behaviour. The vibration parameters are categorised into time, frequency and modal domains. The modal domain, which includes the frequency, mode shapes and damping ratio, is commonly employed as damage indicator because it is easier to determine and interpret than the other two domains (Doebling *et al.*, 1996). By knowing the differences in these parameters between the undamaged and damaged states, damage location and severity information can be obtained.

Abundant research has been performed to develop vibration-based damage detection methods. One method that has received attention is the model updating method. This method adjusts the mass, stiffness and damping parameters of numerical models for better agreement between the numerical model and test model. Model updating methods are categorised into non-iterative and iterative methods. Non-iterative methods directly update the stiffness and mass matrices of the numerical model through a closed-form direct solution. However, such methods leads to the loss of structural connectivity, and the suggested corrections are not always physically meaningful (Jaishi and Ren, 2006). On the other hand, iterative methods require sensitivity matrices to guide iteration in minimising the objective function. However, the sensitivity-based method seems not practical to be applied to structures with high degrees of freedom (DOFs) as it results in a time-consuming process due to the increase in DOFs. In addition, it also has problems of ill-conditioning and slow convergence due to dependency on the evaluation of the finite element (FE) model in every iteration process.

Therefore, an alternative method has recently been proposed to provide a fast running process by replacing the computationally expensive analytical FE model with a metamodel or surrogate model. A statistical-based surrogate model approach called response surface methodology (RSM) has been used considerably in model updating due to simplicity, and allows fast optimisation because of smooth gradients, thus lessening the convergence problem. The applicability and potential of RSM in reducing computation time and effort in the model updating process in the structural dynamic field have been demonstrated in many studies (Guo and Zhang, 2004; Deng and Cai, 2009; Ren and Chen, 2010; Ren, Fang and Deng, 2010; Han and Luo, 2013). Therefore, this study has made good use of the RSM merit by applying the RSM method for vibration-based damage detection.

1.2 Problem statements

As mentioned previously, the common method used in model updating-based damage detection based on sensitivity matrices is prone to ill-conditioning and is time-consuming due to dependency on the computationally expensive FE model. An alternative has been initiated to replace the complex FE model with simple and inexpensive surrogate models to reduce the computational complexity via RSM. Many studies have proven the efficiency of RSM in model updating. However, the applications are limited to updating the baseline of the FE model only while studies pertaining to RSM in the application of vibration-based damage detection are somewhat scarce and limited to the employment of modal frequency as the sole response feature. As frequency is a global parameter that is insensitive to spatial information, the frequency-based RSM is less reliable in providing information about damage location. Due to the limitations above, this study proposed a new RSM method for damage detection by considering both frequency and mode shapes for better damage localisation.

1.3 Research objectives

With the aim of developing a new model updating-based method damage detection, this study is undertaken with the following objectives:

i. To investigate the applicability of RSM for damage detection based on modal data.
ii. To study the behaviour of RSM parameters in vibration-based damage detection.
iii. To validate the proposed RSM numerically and experimentally.

1.4 Significance of study

The motivation for this study is the drawbacks of the traditional FE model updating-based damage detection, which as mentioned earlier features convergence difficulty and long computation time, especially for complex structures. During iteration in the model updating process, the updated parameters will be sent to the FE software such as ANSYS to run the FE model with new updated parameters. This back and forth process limits the applications of the model updating-based approach in real practice of damage detection. By having a new and practical method using RSM, mathematical functions that explain the input-response relationship in structural systems can be expressed explicitly. These explicit functions, called the response surface (RS) model are beneficial as they can be employed to provide an efficient updating process to detect damage. Given that the application of model updating-based RSM in vibration-based damage detection particularly with the use of mode shapes is not yet discovered, the existing RSM-based damage detection is improved by considering combined frequencies and mode shapes as the response features. With this improvement, the accuracy of the output of damage detection can be increased.

1.5 Research scope and limitations

This study is focused on the use of RSM in the application of structural damage detection considering frequency and mode shapes data for better damage localisation. However, the scope of this study is limited as follows:

i. The comparison between RSM-based and traditional model updating methods is conducted through literature study only since this study focused primarily on the applicability of RSM in damage detection by considering both frequency and mode shapes data.
ii. The structural damage in this study is solely presented by the changes of stiffness and thus, no alteration is made to the mass property. Another assumption applied in this study is that the stiffness is reflected in the elastic modulus of the structure, hence selected as the RSM updating parameters.
iii. In the context of vibration data, the modal domain, especially the modal frequencies and mode shapes, are the focus of this study and are subsequently utilised in the RSM method for damage detection. To show the superiority of the proposed RSM method, the method is compared to the existing frequency-based RSM in terms of damage detectability.
iv. Since a proper sampling is crucial in achieving an adequate representation of the relationship between the selected input parameters and response features

to serve as a surrogate model, a series of sensitivity studies on two sampling parameters are conducted. The purpose of conducting sensitivity studies is to investigate the effect of DOE and design space parameters on the ability of RSM to detect structural damage. Since the quadratic response surface (RS) model is mainly used in this study, only three DOEs comprising CCD, Box–Behnken design (BBD) and D-optimal design are considered due to the their wide usage in deriving quadratic RS models.

v. The applicability of the proposed method is demonstrated through numerical models of a simply supported beam and a portal frame and further verified using a lab tested steel frame. The experiment is conducted within the control condition in a laboratory.

1.6 Outline of thesis

This thesis consists of six chapters and is organised as follows:

Chapter 1 presents the background, problem statements, research objectives, significance, scope of the study and outline of the thesis.

Chapter 2 reviews the studies related to SHM, basic theory of vibration-based damage detection as well as various damage detection methods. The advantages and disadvantages of each method are discussed and the applicability of RSM in model updating and damage detection is also reviewed in the chapter.

Chapter 3 outlines the proposed RSM method employing frequencies and mode shapes through a three-phase procedure: sampling, RS modelling and model updating. The description of numerical models, experimental models and sensitivity studies are also given in the chapter.

Chapter 4 demonstrates the applicability of the proposed method through numerical study using a simply supported beam and a steel frame. Sensitivity study on the DOEs, design bounds and type of response features to the damage detectability are conducted.

Chapter 5 provides the details of experimental model, modal testing procedures, damage scenarios and damage detection procedures that consist of a two-stage process comprising model updating of the reference state and damaged state.

Chapter 6 summarises the methodology and findings from numerical and experimental studies and finally proposes recommendations for future research related to the subject of the study.

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