EMPIRICAL MODEL OF NATURAL FREQUENCY FOR SINGLE SPAN INTEGRAL BRIDGE

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ABSTRACT

Natural frequency has been used as a reliable indicator for damage and condition assessment in civil engineering application, where the in situ natural frequency is compared to the theoretical natural frequency to determine the condition of a structure. However, the theoretical natural frequency for integral abutment bridge can be difficult to attain. It involves modelling for full bridge and required extended knowledge of bridge modelling. Furthermore, the integral abutment bridges in Malaysia are unique by themselves, due to the use of different standard T-Beam by JKR and bored piles as the supporting element which are different from other countries. Although there are several studies on the model equation on predicting the natural frequency of a bridge, the prediction model for integral type bridge is yet to be discovered. Therefore, this research is carried out to produce model equation to determine theoretical natural frequency for integral abutment bridge. This research consist of two major tasks. The first task is to produce the theoretical model. The total numbers of 168 finite element models of integral abutment bridge were modelled using ABAQUS software with considering a combination of various bridge configurations, including length, number of beam, modulus of elasticity and soil types. Each combination model of integral abutment bridge was analysed using Lanzcos Eigen Extraction to obtain the natural frequency. The natural frequency was then recorded for further analysis. A step-wise multiple linear regression approach was adopted to develop the prediction model describing natural frequency relationship for a various combination of bridge configuration. Then, the model equation was validated using empirical data from experimental modal analysis as the second task of the research. The data were collected on site from three different integral abutment bridges using impulse hammer as excitation method. Dewesoft signal processing software was used to acquire the raw data from the test. Then, the data was further analysed using ME scope software. The determination of the natural frequency from this software was based on the coherent, real part and modal indicator function. Subsequently, the theoretical and observed natural frequencies were compared statistically using T-test. The prediction model equation of natural frequency shows a good conformance with the experimental modal analysis obtained at site. The model equation describing the natural frequency for integral abutment bridge is found to be influenced by length, number of beam and modulus of elasticity significantly.

ABSTRAK

Frekuensi semulajadi telah digunakan sebagai penanda yang diterima pakai dalam proses mengenal pasti kerosakan dan pemeriksaan keadaan sesebuah struktur kejuruteraan awam. Kerosakan yang wujud dikenalpasti dengan cara membandingkan frekuensi yang dicerap dengan frekuensi semula jadi yang diperolehi secara teori. Walau bagaimanapun, frekuensi semula jadi teori jambatan agak sukar diperolehi memandangkan ianya memerlukan pemodelan keseluruhan struktur jambatan dan kepakaran dalam memodelkan struktur jambatan. Tambahan pula, jambatan jenis *integral* di Malaysia merupakan sebuah rekabentuk yang unik kerana menggunakan rasuk jenis standard oleh JKR dan juga menggunakan cerucuk jenis tergerek yang berbeza dengan struktur di negara lain. Walaupun terdapat banyak kajian berkaitan frekuensi semula jadi, kajian berkaitan frekuensi semula jadi bagi jambatan jenis *integral* masih kurang. Dalam kajian ini terdapat dua tugas utama. Tugasan pertama adalah bagi menghasilkan model matematik bagi mengenalpasti frekuensi semula jadi bagi jambatan jenis *integral.* Sebanyak 168 model unsur terhingga disediakan dengan merangkumi panjang jambatan, bilangan rasuk, modulus keanjalan dan jenis tanah. Setiap gabungan model dianalisa menggunakan kaedah *Lanzcos Eigen Extraction* bagi memperolehi frekuensi semulajadi. Frekuensi ini direkodkan dan digunakan untuk analisa regresi pelbagai menggunakan kaedah *step wise* bagi mendapatkan model matematik. Model matematik ini kemudiannya ditentusahkan menggunakan data empirik menggunakan pengujian di tapak. Data frekuensi daripada 3 buah jambatan jenis *integral* diperolehi menggunakan tukul *impulse* sebagai penguja. Perisian Dewesoft digunakan bagi mengumpulkan data frekuensi dan seterusnya dipindahkan kepada perisian lain iaitu ME Scope bagi membolehkan data frekeunsi semula jadi diperolehi berdasarkan kepada koheren, bahagian *real* dan *modal indicator function.* Kemudiannya data secara teori dan data yang diperolehi di tapak dibandingkan menggunakan kaedah statistik T iaitu ujian T. Ujian T telah mengesahkan bahawa model matematik untuk mendapatkan nilai frekuensi semula jadi boleh memberikan nilai yang agak tepat berbanding dengan data yang diperolehi di tapak. Hasil kajian ini mendapati model matematik bagi mendapatkan nilai frekuensi semula jadi untuk jambatan jenis *integral* bergantung kepada panjang jambatan, bilangan rasuk dan modulus keanjalan.

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LIST OF ABBREVIATIONS

JPJ	Jabatan Pengangkutan Jalan
PWD	Public Work Deparment
3D	Three Dimensional
ITD	Ibrahim Time Domain
Hz	Hertz
ODE	Ordinary Differential Equation
PDE	Partial Differential Equation
FRF	Frequency Response Function
FFT	Fast Fourier Transform
CD3R8	3-Dimensional Deformable Solid Body
PRT	Pre-tensioned
PTT	Post-tensioned
FE	Finite Element
UTM	Universiti Teknologi Malaysia
RF	Radio Frequency
USB	Universal Serial Bus
MISO	Multiple Input Single Output
NJB	New Jersey Barrier
BS	British Standard
BS EN	British Standard : Eurocode
Gpa	Giga Pascal
FREQ	Frequency
FT	Federal Trunk
MIF	Modal Indicator Function

LIST OF SYMBOLS

m	Mass
$\ddot{u}$	Acceleration
c	Damping coefficient
$\dot{u}$	Velocity
k	Stiffness
u	Displacement
t	Time
ω	Circular frequency
ξ	Damping factor
c_{cr}	Critical Damping
Φ	Eigenvector
E	Modulus Of Elasticity
I	Moment of Inertia
P	Density
A	Area
L	Length
f	Natural Frequency

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CHAPTER 1

INTRODUCTION

1.1 Background

Bridges form a critical infrastructural connection for the road network in Malaysia. Several cases of bridge collapse are due to unforeseen damage and poor bridge monitoring management. In the event of these occurrences, the continuity of daily traffic and business would be affected tremendously. Apart from serious disruption to the public, bridge collapse could also resulted in huge economic losses. For instance, in the case of the collapse of I35 bridge in Minneapolis, the economic losses were approximately USD 200 Million (Kim and Lynch, 2012).

Repair and maintenance of infrastructure facilities are rapidly becoming a major financial burden for authorities bringing forth many new challenges for civil engineers (Whelan et al, 2009). Key to the successful upgrading of such structures is timely detection and quantification of damage and deterioration, and in particular, those which build-up over time during the operational lifetime of the structure. Aging infrastructure facilities, especially those made of concrete, are currently deteriorating at a rapid pace, and this poses a big challenge to the authorities and owners who need to manage a large inventory of these structures.

In 2003, government of Malaysia has gazetted a new Weight Restriction Order 2003 (JPJ, 2003) which affected almost 9000 structures along the federal route (JKR, 2009). In conjunction with the order, the government of Malaysia through the Jabatan Kerja Raya has come up with the reviewed report on the existing structures along the federal route throughout Peninsular Malaysia.

From the report, almost 1200 structures are considered substandard, damaged and unsuited to service and recommended to be replaced (JKR, 2006). The report however, did not cover all the structures in State Roads, Municipal Roads and Rural Roads.

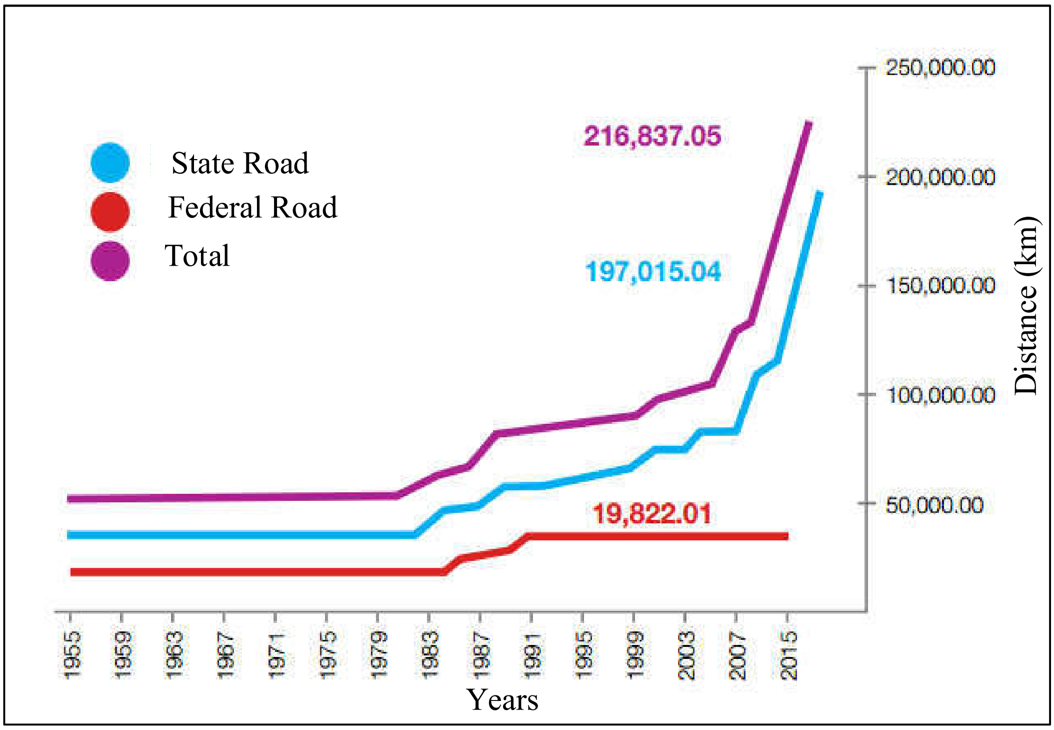

Figure 1.1 Length of Road in Malaysia (JKR, 2016)

Figure 1.1 shows the total length of roads in Malaysia (JKR, 2016). The increased trend on road link in Malaysia according to JKR (2016) also showed the possibility of increasing number of bridges all over Malaysia. The federal roads and the state roads is under provision and maintenance of Jabatan Kerja Raya Malaysia. This two types of road forming the basic networks inter-state and within a state. It serves intermediate trip lengths and medium travelling speed.

Jabatan Kerja Raya Malaysia is entrusted to execute the Bridge Replacement Program which was one of the biggest programmes in every consecutive Malaysia Plan. In 2011, the Deputy Minister of Works stated that, 94 bridges would be replaced with the total budget of RM 500 million in second term of 10th Malaysian Plan. (Utusan Online, 2011; Berita Harian Online, 2011).

With a huge allocation of for bridge replacement annually, the accuracy of condition assessment is vital to assure that the allocation of spending can be beneficial and objective. It is a necessity to find a suitable method to accurately accessing all the structures along the route. Given the cost of rebuilding is quite expensive, and allocation rather scarce, the method of detection of damage in the structure should be accurately assessed to prioritise the allocation of government spending.

In addition, the Jabatan Kerja Raya Malaysia carry out yearly bridge inspection to monitor the performance and damage in the bridges all over Malaysia under the supervision of Jabatan Kerja Raya Malaysia. This annual inspection also has some practical weightage to justify that the replacement is necessary.

The inspection would also include visual inspection to foresee any noticeable damage to the structures. Visual inspections are time-consuming and resource exhausted. The inspection also solely relies on the visual which may lead to the error in accepting the bridge condition assessment.

The condition rating as the outcome from the inspection reports is subjective and varies from person to person. The rating given for the assessment may result in significant differences between experienced personnel with new personnel. Any unforeseen damages on the structure may not be addressed and thus may jeopardize the road users and the public.

1.2 Problem Statement

Currently structural health monitoring is an emerging field in the structural engineering due to the rapid development of monitoring equipment such as wireless transducers, lightweight signal analysers, new operating systems. (Miao et al, 2013b; Shye et al, 1987; Ko and Ni, 2005).

One of the trending approaches in damage detection nowadays is using vibration characteristics (Kuras et al, 2011; Stubbs and Kim, 1996). There are numerous researches on the use of vibration characteristic as damage detection and health monitoring tools. Among the various parameters, the natural frequency is widely used as a reliable indicator of damage occurring in a structure since it can be readily identified from model tests (Kim et al, 2003).

The inference that being made is, if the damage occurs in a structure, stiffness degradation will take place, which accordingly causes the change of resonant frequencies for various modes (Flesch and Kernbichler, 1988; Sawalu, 1997; Kuras et al, 2011).

The significant reduction in stiffness can be inferred when the measured resonance frequencies are substantially lower than the baseline values (usually defined as frequencies in the undamaged state) (Atamturktur et al, 2013; Kim et al, 2003).

Baseline dynamic characteristics is now being captured right after the bridges completed before the bridges is opened to the public. The recorded data is then being kept by the relevant authorities and the monitoring of dynamic characteristic is done from time to time. If there is a change in the dynamic signatures of the bridge, the data is then being analysed to see the fitness of the bridge for the next action.

These initial vibration signatures are precious pieces of information that can be used for further damage identification and damage detection. This information also a vital information for the bridge monitoring purposes.

Currently in Malaysia, the vibration data of bridges are difficult to obtain, largely due to a lot of procedures to be met and lengthy processes required by the authorities before getting access to the bridge or bridge data. The initial natural frequencies of the newly built bridges also not being documented unless there is a provision under the construction or contract terms which specify that the data of natural frequency should be recorded before the bridge is opened to the public.

If there is a tool or prediction theory to predict the natural frequency of a bridge at service, it may favour the researcher and authority to further use the technique to investigate the bridge structural health. Therefore, this study is carried out to establish a reliable baseline to determine the natural frequency of an integral bridge which may come handy for the authorities and researchers, should further investigation need to be done.

1.3 The Research Motivation

Integral bridge is a bridge that being designed with the elimination of expansion joints and bearing so that the superstructures and substructures are cast together and worked integrally. This design is an innovation in bridge technology due to its ability to cater for movement and the rotation of the whole structure, compared to the conventional type of bridge where the movement and rotation are being addressed by expansion joints and bearings (Ahn et al, 2011).

Considering the beneficial contribution of integral bridges, most of the design for simple bridges in Malaysia started to embark on this type of construction since 2003. Integral bridge type has been proven to be cost effective in terms of construction as well as its overall lifespan (Dicleli, 2000).

Integral bridge construction method has become a matter emphasized in the Design Terms of Reference since 2008 by the Bridge Unit of the Jabatan Kerja Raya to be considered by bridge designers, whether in the private or government sector (JKR, 2008).

Integral Abutment Bridges are likely to be adopted as the concept of construction if the bridges are going to use the integral system for single span structures. In Malaysia, most of the integral bridges are from the integral abutment bridge type (JKR, 2014).

Considering the unavailability of the vibration data and the current procedure by the authority, this study will be focusing on the prediction model of an integral abutment bridge.

1.4 Research Objectives

i. To develop and validate the finite element model of an integral abutment bridge.
ii. To develop and validate the empirical prediction model of natural frequency of integral abutment bridge
iii. To establish the measurement procedures conducting experimental modal testing on integral abutment bridges.

1.5 Research Scopes and Limitations

i. The research will focus on the integral bridges made from JKR Standard Pre-Stressed T-Beam with lengths from 15m to 30m.
ii. The designed abutment bridge is kept at 1000mm width.

iii. The selected bridges are those constructed using 600 mm bored piles as the foundation.

1.6 Research Significance

Due to the relevancy using dynamic signature as a practical approach in bridge monitoring, the accurate empirical model determining the baseline natural frequency definitely assist the successive procedure to determine the damage level in bridge. Hence, this study contributes significantly towards modal experimental fields.

The contributions of the study are listed in the following:

i. Establish the alternative equation of predicting the natural frequency to other established equations.
ii. Establish the empirical model to determine natural frequency of single span integral bridge.
iii. The established model is capable to determine the natural frequency considering the factor of length, number of beams and modulus of elasticity.
iv. Simplification of present modelling procedure or method in determining the natural frequency of an integral bridge.
v. The direct and simple prediction model can be used by the practitioners and researchers to anticipate the natural frequency in the design process and optimizing the design.

1.7 Organisation of Thesis

The organisation of the thesis is as follows:

Chapter 1 presents the background of the research, the problem statements, the objectives of the research, the scopes and the limitations, significance of the research and the outlines of the thesis.

Chapter 2 discussed the previous literature on vibration characteristic, the modal analysis and experimental, the established models and the modal experimental test conducted on real bridges.

Chapter 3 discussed the details methodology on conducting this research, the sequence of research works and the details of each phase. In this chapter as well, the calibrations of each method and instrumentation are presented.

Chapter 4 presents the numerical model of Integral Abutment Bridge technique using ABAQUS as the modelling tools. In this chapter the steps of modelling the 3 D finite element model of the Integral Abutment bridges are listed down including all the types of elements, the selection boundary condition, the analysis and the element parameters.

Chapter 5 discussed on the development of the empirical prediction model of an integral bridge. Each factors or manipulations affecting the natural frequency will be discussed separately and the final prediction models used multiple regression to find the relationship of each factor to natural frequency of the integral bridge. The final empirical expression is presented to predict the first natural frequency of integral abutment bridge.

Chapter 6 presented and discussed the results of site validation for the prediction model of integral bridge. In this chapter, the location, the arrangement of beam, the soil profile as well as the configuration of the selected integral bridges are presented. The result of the experimental modal analysis of the bridges is tabulated and compared to the finite element model and the empirical model developed.

Chapter 7 provides the conclusion of this research and the contribution to the current field of health monitoring. The recommendations for future research are also presented.

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