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DEVELOPMENT OF OPERATIONAL MODAL ANALYSIS TECHNIQUES IN WIND TUNNEL ENVIRONMENT FOR A CANTILEVERED COMPOSITE WING MODEL

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By

ZETTY AZLEEN BINTI CHE SAFFRY

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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Chair: Dayang Laila Binti Abang Haji Abdul Majid, PhD
Faculty: Engineering

Identification of modal parameters is crucial especially in aerospace applications whereby the interactions of airflow with aircraft structures can result in undesirable structural deformations. This structural deformation can be predicted with knowledge of the modal parameters. This can be achieved through conventional modal testing that requires a known excitation force in order to extract these dynamic properties. One particular challenge using this technique is that it can be experimentally complex because of the need for artificial excitation and it also does not represent actual operational condition likewise external disturbance loads, e.g instruments and surrounding noise, aerodynamic loads and turbulence. Therefore, a good understanding of the dynamic properties and application of the technique to implement this experimental work needs to be generated.

Basic approach is to conduct Ground Vibration Testing (GVT) and use the modal data to determine the flutter onset. The unknown sources or dynamic excitation can be difficult to be applied using the conventional testing. As the industry has expanded with implementation of modal testing, there is a need to have different technique applied which convenient and easy to use. So this is where technique such as Operational Modal Analysis has its application in the field. Not just that, the opportunities of using hybrid composite material can be an attractive prospect for aerospace application.

This study utilize Operational Modal Analysis (OMA) on extracting the modal properties. Operational Modal Analysis acquires information about the dynamic characteristics of a structure in terms of natural frequencies, damping and mode shapes without the need for explicit measurement of input vibration inducing loads. This technique is yet to be applied on composite structures in the subsonic range within a wind tunnel environment. Therefore in the current work, it was implemented and demonstrated on a cantilevered hybrid composite plate and wing model exposed to low speed airflow in a wind tunnel. To do so, a single contactless sensing system via a laser vibrometer as well as an accelerometer as reference was employed to measure the vibration response in subsonic speed. Experimental Modal Analysis (EMA) and

computational analysis using Finite Element Analysis (FEA) were also conducted as baseline reference.

Results from the extensive experimental works had successfully shown that OMA can be implemented in subsonic range on both models and provide modal data with some level of accuracy. From the experiment testing, the testing technique and data handling as well as the aerodynamics effects from the airflow play a major role in affecting the modal parameters. For composite thin plate model, the structure is too light which may affects the modal data. As for wing model which has a stiffer structure, the mode shape for some modes were classified as unidentified as these modes displayed combination of bending and torsional modes, which may indicate coupling of these two modes due to aeroelastic effects. Due to the same reason, the frequencies of the modes extracted are found either decrease or increase with air speed especially on merging modes that will lead to flutter.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PELAKSANAAN TEKNIK OPERASI MODAL ANALISIS DALAM TEROWONG ANGIN TERHADAP HYBRID KOMPOSIT SAYAP MODEL

Oleh

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Mengenalpasti parameter modal adalah penting terutamanya dalam aplikasi aeroangkasa di mana interaksi aliran udara dengan struktur pesawat boleh menyebabkan ubah bentuk struktur yang tidak diingini. Perubahan bentuk struktur boleh diramal dengan pengetahuan parameter mod. Ini boleh dicapai melalui ujian mod konvensional yang memerlukan daya ujaan yang diketahui untuk mengeluarkan sifat-sifat dinamik. Antara cabaran menggunakan teknik ini ialah ia boleh menjadi uji kaji kompleks kerana keperluan untuk pengujaan luaran atau buatan dan ia juga tidak mewakili keadaan sebenar operasi juga beban gangguan luar, misalnya instrumen dan bunyi sekitar, beban aerodinamik dan pergolakan. Oleh itu, pemahaman yang baik tentang sifat-sifat dinamik dan aplikasi teknik untuk melaksanakan kerja eksperimen ini perlu dijana.

Pendekatan asas adalah untuk menjalankan Ground Vibration Testing (GVT) dan menggunakan data modal untuk menentukan permulaan keribas. Sumber-sumber yang tidak diketahui atau pengujaan dinamik boleh menjadi sukar untuk digunakan menggunakan ujian konvensional. Sebagai industri yang telah berkembang dengan pelaksanaan ujian mod, terdapat keperluan untuk mempunyai teknik yang berbeza gunaan yang mudah dan senang untuk digunakan. Jadi ini adalah di mana teknik seperti Analisis Modal Operasi mempunyai aplikasi di lapangan. Bukan itu sahaja , peluang menggunakan bahan komposit hibrid boleh menjadi prospek yang menarik bagi aplikasi aeroangkasa.

Tesis kajian ini membincangkan cara-cara menggunakan Analisis Modal Operasi (OMA) yang digunakan untuk plat dan sayap komposit hibrid model kantiliver terdedah kepada aliran udara kelajuan rendah di dalam terowong angin. Analisis Modal Operasi memperoleh maklumat mengenai ciri-ciri dinamik struktur dari segi frekuensi semulajadi, redaman dan bentuk mod tanpa memerlukan pengukuran yang jelas getaran input beban mendorong. Untuk berbuat demikian, sistem sentuh sensing tunggal melalui meter getar laser serta pecutan yang telah digunakan untuk mengukur maklum balas getaran dalam keadaan terowong angin yang beberapa ujaan teknik telah diperkenalkan menggunakan Pulse Modal Testing Consultant (MTC) untuk perisian

pengambilalihan data. Experimental Modal Testing (EMA) dan analisis pengiraan menggunakan Finite Element Analysis (FEA) juga telah diadakan untuk pengesahan sifat-sifat mekanik dan dinamik struktur.

Keputusan daripada eksperimen ini telah berjaya menunjukkan bahawa OMA dapat dilaksanakan dalam persekitaran terowong angin dengan bacaan mod data yang diterima telah diperolehi. Dari ujian percubaan, teknik pengujian dan pengendalian data serta aerodinamik kesan daripada aliran udara memainkan peranan utama dalam mempengaruhi parameter mod. Untuk model komposit plat nipis, struktur adalah terlalu ringan yang mempengaruhi data mod terutamanya dalam bentuk mod OMA ujian disebabkan keadaan aliran angin berbanding dengan pengujaan menoreh rawak. Bagi model sayap yang mempunyai struktur yang lebih keras, data mod diperolehi bersetuju dengan data mod eksperimen menyediakan cara yang sangat baik untuk mengenal pasti ciri-ciri dinamik yang ujian terowong angin semasa operasi. Di samping itu, didapati bahawa, kekerapan mod dipengaruhi oleh aliran udara. Ini menunjukkan bahawa ciri-ciri modal yang diperolehi melalui ujian EMA konvensional tidak mewakili tingkah laku sebenar apabila terdedah pada aliran udara. Bukan itu sahaja, frekuensi tabii dan bentuk mod struktur juga telah ditunjukkan untuk menjadi sangat bergantung kepada jisim dan kekukuhan struktur, keadaan sempadan dan juga teknik ujaan bagi apa-apa teknik ujian mod.

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I certify that a Thesis Examination Committee has met on 30 July 2015 to conduct the final examination of Zetty Azleen binti Che Saffry on her thesis entitled "Development of Operational Modal Analysis Techniques in Wind Tunnel Environment For A Cantilevered Composite Wing Model") in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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LIST OF ABBREVIATIONS

E_{11}	**Longitudinal elastic modulus**
E_{22}	**Transverse elastic modulus**
G_{12}	**Major shear modulus**
ν_{12}	**Poisson's ratio**
t	**Ply thickness**
ρ	**Density**
[M]	**Mass matrix**
[C]	**Damping matrix**
[K]	**Stiffness matrix**
ω	**Circular frequency**
ζ	**Damping ratio**
$f(t)$	**aerodynamic force**
σ	**standard deviation of a stochastic variable**
$X(\omega)$	**Fourier Transform of excitation input**
$Y(\omega)$	**Output**
$H(\omega)$	**Set of FRF in frequency domain**
m	**Number of measurement channels**
$\ddot{x}(t)$	**Acceleration vector**
$x\ (t)$	**Displacement vector**
n	**Number of modes**
r	**Number of excitation inputs**
t	**Time, continuous or discrete**
$\{\psi\}_r$	**Mode shaper vector**
ω_{dr}	**Modal frequencies**

A(ω)	**Imaginary number of frequencies**
R	**Real number of modes**
I	**Identity matrix**
j	**Imaginary unit**
ϕ	**Eigenvector or mode shape**
γ	**Kurtosis**
$\gamma_{\mathbf{k}}$	**Modal participation vector**
g(t)	**Impulse response function**
y(t)	**Output**
τ	**Time lag**
$\mathbf{G_{xx}}$	**PSD matrix of inputs**
$\mathbf{G_{yy}}$	**PSD matrix of measurements**
□	**Complex conjugate**
T	**Transpose**
λ	**Poles of FRF matrix**
ω_{dk}	**Damped natural frequency of the kth mode**
q(t)	**modal coordinates**
$[G_{qq}(\omega)]$	**The spectrum matrix of the modal**
[S]	**Singular value diagonal matrix**
[V]	**Singular vectors of orthogonal matrix**
[A]	**State matrix**
[C]	**Observation matrix**
w_t	**Process noise**
v_t	**Measurement noise**

CHAPTER 1

INTRODUCTION

1.1 Introduction

In aerospace applications, interactions of airflow with aircraft structures can result in undesirable deformations that can be destructive in nature and compromise its structural stability. Contemporary design of aeronautical structures requires it to become increasingly lighter, flexible and durable. Consequently, the strict demands on the design structures often made them more likely exposed to unwanted vibrations. The science that studies these interactions is known as aeroelasticity and aeroelastic instabilities can either be static or dynamic in nature (Raymond et al., 1955). For example, flutter is a dynamic aeroelastic predominant on aircraft's lifting surfaces. To predict flutter occurrence, knowledge of the natural modes of a structural system is necessary. In this work, the development of an experimental technique to determine these natural modes in a wind tunnel condition is carried out.

The technique used to determine the natural modes of a system is known as modal analysis. In the past two decades, modal analysis has been widely applied for determining, improving and optimizing dynamic characteristics of the structures (Jimin & Zhi Fang, 2001). Modal analysis is a process whereby a structure can be described in terms of its natural dynamic characteristics which are the natural frequency, modal damping and mode shapes. These characteristics are also inherent to a dynamic system and are determined completely by its physical properties which are mass, stiffness, damping and their spatial distributions. By artificially exciting the structure, measuring its operating deflections shapes (motion at two or more DOFs) and post-processing the vibration data, the modal properties can be obtained.

Modal analysis embraces both theoretical and experimental techniques (W. T. Thomson, 1981). The theoretical modal analysis consists of physical model of a dynamic system comprising its mass, stiffness and damping properties. As for experimental technique, modal testing is used to measure the vibration.

Experimental modal analysis involves three constituent phases which are test setup, frequency measurements and modal parameter identification. Test setup involves selection of a structure's support, type of excitation forces, location of excitation, hardware to measure forces and responses, determination of a structural geometry model which consists of points of response to be measured as well as identification of mechanisms which could lead to inaccurate measurement. During the test, a set of frequency response functions (FRFs) data is measured and stored which is then analysed to identify modal parameters of the tested structure.

Ground vibration testing (GVT) involves experimental modal testing which basically the technique to derive the model of a linear time-variant vibratory system. This traditional modal testing has few limitations which are cited in Zhang et al., 2009:

1. Artificial excitation is normally conducted in order to measure FRFs or Impulse Response Functions (IRFs). FRF or IRF would be very difficult or even impossible to be measured for very large structures, or in the field test.
2. Traditional EMA is normally conducted in the lab environment. However, in many industrial applications, the real operation condition may differ significantly from those applied in the lab testing.
3. Boundary condition is difficult to simulate reasonably and accurately.

These factors will contribute significantly to the accuracy of aeroelastic predictions. However, modal analysis will always be inherent part and more realistic approach in determining the modal properties. This is where operational modal analysis (OMA) can be utilized where only the output of response is measured and natural excitation is employed.

1.2 Operational modal analysis

Since early 1990's, OMA has drawn great attention in many engineering fields such as mechanical, civil and aerospace community itself. The objective of OMA is to identify the modal properties of a system which are the frequency resonances, damping and mode shapes by using only output measured responses and without knowledge of the inputs. The most fundamental assumption is that the excitation is both frequentially and spatially white, i.e. that the auto-spectrum of each input has a constant value across the frequency range of interest, and that the independent excitations are all of equal magnitude (Tcherniak et al.,2011). Thus, it explained that the output data will be robust due to non stationarity of the natural input excitation in in-situ condition.

There are few distinguished advantages of using OMA (Rainieri et al, 2011) which include :

1. Ease to use, no need to introduce the excitation equipment.
2. Fast and no boundary condition simulation is required as in the lab testing.
3. Simple, modal testing is simplified as response measurements.
4. Powerful since all or part of measurements can be adopted as references which closely spaced or repeated modes can be handled.

When exerting to excite large structures for the purposes of modal testing, a balance must be struck in the level of excitation employed. Clearly, a very high level of excitation is required to properly excite the entire structure. The level of excitation cannot be so large that it damages the structure or induces non-linearity as mentioned by Rainieri et al., (2011). Further, large structures obviously cannot be tested under ideal laboratory conditions. Rather, modal testing must be performed while operating with all the extraneous environmental noise and operational limitations likewise having airflow in the wind tunnel testing. While these may give significant challenges for EMA, while as for OMA, it seeks to take advantage of these environmental factors by using the additional noise as the excitation source, and estimating the modal properties of the system in its operational condition.

It is known that, large structures such as bridges and buildings are ably excited by wind loading, the passage of traffic and wave action. For mechanical systems such as vehicles are subjected to aerodynamic loading, excitation from on-board equipment, road or rail induced vibration (W. T. Thompson, 1981 □ Zhang et al., 2009). By introducing OMA, it seeks to use these natural exciters to excite the system, rather than having to overcome and subsequently remove, by averaging or filtering, these environmental noises.

Perhaps more importantly, OMA seeks to identify the modal properties of the system in-service although the system can be brought into the laboratory and an EMA performed, the artificial excitation almost certainly will not represent the distribution, level and type of excitation the system that experienced in operation condition. Most systems provides some degree of non-linearity which therefore means that the modal properties estimated in such an EMA will not be suitable for the system to be applied in operation.

1.3 Modal analysis of hybrid composite materials

Composite materials have long been used in the aerospace industry. In the early 1970s, composites found in many applications especially in the military field where composite mostly applied for commercial aircraft and rotorcraft industry due to its advantages of exhibits high strength-to-weight and stiffness-to-weight ratio. According to Quilter, A. (2001), Due to the opportunities of weight saving, composites have become the most important materials for aerospace application besides aluminium. The characteristic of the composite material advantageous over isotropic material such as Aluminium is their anisotropy which they possess different properties in different directions (Jones, R. M., 1998).

Complex modern aircraft design had shown the constant struggle the aerospace industry faced in coming up with lighter, more flexible and yet strong structures. On the other hand, complex composite structures, such as aircraft wing commonly created problems in terms of unwanted or excessive vibrations that may lead to flutter problems. Therefore, predictions of aeroelastic effect and modal properties are necessary for composite materials.

Numerous applications of composite materials have been done especially in determination of modal properties of the structures but the introduction of hybrid composite materials has been lacking in the literature. Hybrid composite material is the combination of two or more types of fibres, which possible to club advantages of materials while simultaneously mitigating their less desirable qualities (Jones, R. M., 1998). The advantage of hybrid composite material is that the superior properties of each fiber material can be utilized to optimize the composite product depending on the application requirements. The opportunities of using hybrid composite material in determining how it can be used for aerospace can be an attractive prospect for aerospace applications to have stronger and lighter structures.

1.4 Problem statement

Advancement in analytical and experimental technologies fostered to determine the modal parameters. Many new methods have been developed for data processing and modal parameter identification where most of those data processing techniques were adapted from theory of controls and digital signal processing into structural engineering. Even though those efforts resulted in successful application examples in various industries especially mechanical and civil engineering, possible benefits of aerospace application has not been enjoyed which involves aeroelastic condition.

Basic approach is to conduct ground vibration test (GVT) on the model and use the modal data for the numerical/theoretical determination of the flutter onset in order to measure input and output. However, aircraft structures are expose to dynamic excitation from various different sources all at the same time. This is where Operational Modal Analysis (OMA) has its application field of which difficult and almost impossible to measure during operation.

The objective of OMA, also known as Output-Only Modal Analysis, is to derive a modal model of the system by using only the measured response and without explicitly knowing the excitation input. As many applications have practiced contact transducers employed in their approach, current application of non contact system to be employed in wind tunnel testing can provide easier and convenient technique approach to be used. It is also a realistic estimation of the actual modes through OMA which will provide an immediate prediction of flutter onset.

Therefore, in this study, effectiveness of OMA is demonstrated on small hybrid composite wing model in low subsonic speed.

1.5 Objective of Research

The sole purpose of this work is to develop a technique that used operational modal analysis for subsonic wind tunnel application that characterize the dynamic behavior of hybrid kevlar/carbon composite thin plate and wing model that is subjected to low speed excitation. The objective can be divided into following sub-objectives which are:

a) To determine in-situ the modal parameters of small cantilevered composite wing models under low subsonic speed in the wind tunnel.
b) To evaluate the reliability of response data obtained from laser scanning device in wind tunnel testing condition.
c) To assess the effect of airflow intensity on the modal parameter extraction.

1.6 Scope of Research

The scope of work to complete objectives are summarized in the form of experimental work.

1. Development of thin plate and wing models using hybrid Kevlar/Carbon composite which involving fabrication and tensile testing to determine material properties.
2. Non-contact system development which involves laser fixture and attachment.
3. Demonstration of experimental modal analysis with deterministic and random inputs on two different models with different techniques of contact and non contact system.
4. Investigation of the impact of different excitation method on operational modal analysis which involves wind on/off excitations.
5. Investigation of the impact of modal parameters identification method under deterministic and different random inputs or excitations.

1.6 Thesis Outline

The whole thesis comprises of six chapters. Chapter 2 highlights the previous studies and background of modal analysis and operational modal analysis, followed by a discussion on the various theories involved. Chapter 3 is the methodology which will describe the experimental setup and the wind tunnel testing for the operational modal testing. Details on the analytical approach on procedures of developing system will also be covered in the same chapter. Chapter 4 will present the results and discussion for the identification of modal testing. Finally conclusions are drawn and possible future work is addressed in chapter 5.

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