UNIVERSITI PUTRA MALAYSIA

LOAD CASE SELECTION GUIDELINE FOR COMBINED MODAL FINITE ELEMENT APPROACH FOR STATIC AEROELASTIC DEFORMATIONS OF RECTANGULAR HAR WING MODELS

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By

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High aspect ratio (HAR) and flexible wing models have multiple benefits. However, due to the nonlinear properties of this type of structure, the linear solution of static aeroelastic response is not sufficient to analyse the wing characteristics. Thus, making the option become more and more undesirable due to the complexity of the conventional finite element (FE) nonlinear analysis. To improve the computational efficiency of the nonlinear analysis of the HAR and flexible wing models, the Combined Modal Finite Element approach is used to characterize the nonlinear properties of the HAR wing model by the development of nonlinear reduced order models (NROM). However, till time no set of clear guidelines on the production of load cases to develop the NROM using the CMFE approach. Therefore, the research proposes a load case selection technique to develop the NROMs and investigates the possibility of predicting the nonlinear static aeroelastic response by prescribing eigenmode based load cases. For the conduct of the study in a systematic manner, the programming routine was developed and coupled with the finite element solver. The selection guideline starts with the selection of the normal modes with the most significant contribution. With the modes selected, the loading profiles were prescribed and the load cases were developed with the maximum force range criteria set. The load cases are then with the use of CMFE approach are utilized to develop the NROM to predict the nonlinear static aeroelastic deformations. The predicted nonlinear static aeroelastic response are verified with the conventional nonlinear finite element analysis and compared in terms of mean error and standard deviation. The load cases developed based on the load case selection technique is able to produce highly accurate NROMs. The study also concludes the possibility of using eigenmode based load cases to predict the nonlinear static aeroelastic response is encouraging. The NROM developed based on the eigenvector load case is a viable option since the overall results show good agreement with the nonlinear deformations obtained from the FE analysis. It is also suggested that the NROM to be developed with individual based bending and torsional load cases since these show a more accurate result than the combined bending and

torsional load case. From the results, it is concluded the accuracy of the NROM is up to 97.5% of the maximum bending deflection of the wing model whereas for the twist deflection the accuracy is up to 99%. With the availability of a detailed guideline for the load case selection and the suggestion of using eigenmode based load cases, enables researchers to explore more into the option of development NROMs using the CMFE approach. Hence, this provides a more desirable alternative solution in comparison to the more complex and tedious approach of nonlinear FE analysis approach in a case of static aeroelastic deformation of high aspect ratio and highly flexible wing model.

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

PANDUAN PEMILIHAN KES BEBAN UNTUK KAEDAH GABUNGAN MODAL UNSUR TERHINGGA BAGI PERUBAHBENTUK AEROKEKENYALAN STATIK SAYAP BERSEGIEMPAT TEPAT NISBAH ASPEK TINGGI

Oleh

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Model sayap nisbah bidang tinggi (HAR) dan fleksibel mempunyai pelbagai kelebihan. Walau bagaimanapun, disebabkan sifat ketidakselarian jenis struktur ini, penyelesaian selari bagi tindak balas aerokekenyalan statik tidak mencukupi untuk menganalisis ciri sayap. Oleh itu, pilihan ini semakin tidak diingini kerana kerumitan analisis unsur terhingga (FE) tidak selari. Untuk meningkatkan kecekapan komputasi analisis unsur terhingga tidak selari bagi model sayap HAR dan fleksibel, pendekatan kaedah gabungan modal unsur terhingga (CMFE) digunakan untuk mencirikan sifat tidak selari model sayap HAR dengan pembinaan Model Ketidakselarian order terturun (NROM). Namun, sehingga kini masih tiada set garis panduan yang jelas terhadap terbitan kes beban untuk membangunankan NROM menerusi kaedah CMFE. Maka, kajian ini mencadangkan teknik pemilihan kes beban untuk membangunkan NROM dan menyiasat kemungkinan bagi meramal tindak balas aerokekenyalan statik dengan menentukan kes beban berasaskan mod eigen. Garis panduan pemilihan dimulakan dengan pemilihan mod normal dengan sumbangan paling ketara. Bagi menjalankan kajian secara sistematik, rutin pengaturcaraan dikembangkan dan digabungkan dengan pemecah elemen hingga. Garis panduan pemilihan dimulakan dengan pemilihan mod normal dengan sumbangan paling ketara. Dengan mod yang dipilih, profil pemuatan ditetapkan dan kes beban dikembangkan dengan kriteria julat daya maksimum yang ditetapkan. Kes beban kemudian dengan penggunaan pendekatan CMFE digunakan untuk mengembangkan NROM untuk meramalkan ubah bentuk aeroelastik statik nonlinier. Tindak balas aerokekenyalan statik tidakselari yang diramalkan disahkan dengan menggunakan kaedah lazim analisis unsur terhingga tidak selari dan dibandingkan dari segi purata perbezaan dan sisihan piawai. Kes-kes beban yang dibangunkan berdasarkan teknik pemilihan kes beban dapat menghasilkan NROM yang sangat tepat. Kajian ini juga menyimpulkan bahawa kemungkinan untuk menggunakan kes beban berasaskan mod eigen bagi meramalkan tindak balas aerokekenyalan statik tidak selari adalah memberangsangkan. NROM berdasarkan kes beban vector eigen merupakan pilihan yang dapat dilaksanakan kerana keputusan keseluruhan

menunjukkan persetujuan yang baik dengan perubahan bentuk tidak selari yang diperolehi daripada analisis unsur terhingga. Juga dicadangkan agar NROM dibangunkan dengan kes beban mod kilas dan lentur secara individu dimana keputusan yang lebih tepat diperolehi jika dibandingkan dengan kes beban gabungan dua mod ini. Dari hasilnya, dapat disimpulkan bahawa ketepatan NROM adalah hingga 97.5% dari pesongan lenturan maksimum model sayap sedangkan untuk pesongan lilitan ketepatan hingga 99%. Dengan ketersediaan garis panduan terperinci bagi pemilihan kes beban dan cadangan menggunakan kes beban berasaskan mod eigen, membolehkan para penyelidik untuk meneroka lebih banyak pilihan bagi pembangunan NROMs menggunakan kaedah CMFE. Maka, ini menyediakan penyelesaian alternatif yang lebih diinginkan berbanding dengan kaedah analisis unsur terhingga tidak selari yang lebih complex dan merumitkan bagi kes ubah bentuk aeroekekenyalan statik untuk model sayap nisbah bidang tinggi dan sangat fleksibel.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
ACARE	Advisory Council for Aeronautics Research in Europe
AR	Aspect Ratio
CMFE	Combined Modal Finite Element
D	Drag
DLM	Doublet Lattice Method
E	Efficiency Factor
F	Frequency
FEA	Finite Element Analysis
FEM	Finite Element Method
HALE	High Altitude Long Endurance
HAR	High Aspect Ratio
L	Lift
L_C	Plate chord length
L_S	Span length
L_R	Rib length
n	Number of Nodes along the Span
NACA	National Advisory Committee for Aeronautics
NROM	Nonlinear Reduced Order Model
R	Range
ROM	Reduced Order Model
TSFC	Thrust Specific Fuel Consumption
UAV	Unmanned Aerial Vehicles
V	Velocity
Wi	Initial Weight
Wf	Final Weight
Z	Damping ratio
C_{d_i}	Induced Drag Coefficient
C_l	Lift Coefficient
$\{F\}$	Global Load Vector on The Specimen or Model

$[K]$	Global Tangent Stiffness Matrix of The Specimen or Model
$\{U\}$	Global Displacement of the Specimen or Model
$\{\Delta F\}$	Global Incremental Load Vector
$[K(U)]$	Global Tangent Stiffness Matrix as a Function of the Global Displacement Vector
$\{\Delta U\}$	Global Incremental Displacement Vector
ρ_{ss}	Density of spring steel-plate
υ_{ss}	Poisson's ratio of spring steel-plate
$[\boldsymbol{E}_{\mathbf{L}}]$	Assembled Linear Stiffness Matrices of size NR × NR
$\{\boldsymbol{F}\}$	NR × 1 applied modal force
ψ	N × NR matrix of the linear mode shapes of the selected mode
μ_{err}	Mean Error of the Profile
x_{NROM}	Predicted Nonlinear Deflection
x_{NL}	Finite Element Nonlinear Static Deflection
σ_{err}	Standard Deviation of The Mean Error

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CHAPTER 1

INTRODUCTION

This chapter details the motivation behind the study and the study scope. The sections are detailed to as well as to enlighten the reader the reasoning, the importance of the study and the objectives to be achieved at the completion of the research.

1.1 Background and Motivation

The aviation industry is at a blooming stage and is commonly seen as a lucrative industry. However, the truth is the industry has a very low-profit margin and is susceptible to the slightest change in world economics (Rogeria.G.E, Michael.M, 2014). This can be clearly seen with the bankruptcy of Thomas Cook. Hence, with this in mind airlines try their very best to maximize their profit margin and it is claimed by the International Air Transport Association (IATA) that approximately 24% of the operating cost is constituted of fuel cost (IATA, 2019; IATA, 2019). Moreover, some countries prohibit non-native airlines to tanker fuel into the country hence leaving the airlines susceptible to the high Jet-A fuel in the country.

Furthermore, the fragility of the aviation industry can be seen during the Coronavirus pandemic where the whole world went into total lockdown. The aviation industry was hit hard by this pandemic, with some airlines being in serious financial circumstances and some opting to reduce their crew total to sustain the heavy lost endured. European constituencies such as ACARE has initiatives in place like the FlightPath 2050 which require the aircraft manufacturers to achieve a certain threshold in terms of aircraft competence and efficiency. These are the pitfalls dealt by operating airlines hence airliners look into more into the efficiency of the aircraft as way to cut down their operating costs hence maintaining a relatively higher profit margin.

Some of the possible alterations which can affect the range of the aircraft to maximize the profit margins are; by improving the (V/TSFC) term via engine improvement, reduce the structural weight which increases the (Wi/Wf) term and by increasing the lift to drag ratio by increasing the aspect ratio of the wing. In this study, the aspect ratio of the wing is given focus.

However, the problem with high aspect ratio wings are these wings are susceptible to geometric nonlinearity as these wings will have a larger wing deformation. Moreover, the wings are prone to higher deflections at same conditions compared to the aircraft having a lower aspect ratio. This leads on to the problem where the aeroelastic analysis of the wing based on linear theory fails. High aspect ratio wings and flexed wings are subjected to nonlinear behavior with similar loading conditions in comparison to relatively lower aspect ratio wings. The above statement is reinforced with the incident of the B787's wing flexed upwards by 25 ft which is approximately thrice more than the deformation due to most extreme condition that will be faced by aircraft during their life span (Nhan T. N, Eric.T, Daniel.C, 2017; Arezu.J, 2015).

Although HAR wings have very beneficial properties which can be exploited but these wing models are not preferred due to the complexity of the nonlinear analysis and high computing time. In general, the finite element software has the capability to analyze the nonlinear behavior of the model in static and dynamic systems however the time and effort to be invested in these analyses make it an unappealing option to have. Thus, a faster simulation is more desirable in order to characterize the nonlinearity of the model and predict the nonlinear behavior of the model without compromising on the accuracy of the analysis. Hence, to reduce computing time and modelling time, a reduced order model is utilized. With the assistance of curve-fitting techniques, the study is to investigate the accuracy of the reduced order model with the analysis of nonlinearity with MSC PATRAN and MSC NASTRAN. With regards to the development of the NROMs, a common method used by many is the NROM development based on the Combined Modal Finite Element (CMFE) technique. The accuracy of the NROMs using the CMFE technique is mainly dependent on the selection of the load cases to develop the NROMs as well as the normal mode selection.

However, the development of the NROMs based on the CMFE approach has set-back due to the vague description of the procedures involving the NROM development. This hinders many to the use of this approach to develop a more efficient NROM. Moreover, with the absence of guidelines to develop this mode of analysis, the efficiency of the analysis is compromised along with the increment of workload especially in the load selection and normal mode selection section. This will lead into the use trial and error method which severely hampers the efficiency of the CMFE based approach. Hence, this study is orientated into the development of a guideline for the development of the NROM equations based on the CMFE approach. Based on this development, the accuracy of the equations is verified amongst three varying wing aspect ratios which would ensure the flexibility of the guideline. The study also adventures into the suggestion of the type of loading profiles to be used during the load case definition stage to improve the accuracy of the NROMs.

1.2 Problem Statement

Since there are no clear procedures available for the development of NROMs using the CMFE approach, the study mainly centers on the proposal of an effective guideline on the load case selection and normal mode selection. The study further adventures into investigating the accuracy of the proposed guidelines.

1.3 Aim and Objectives

The aim of this study is to investigate the proposed guideline on the development of nonlinear reduced order model (NROM) for static aeroelastic conditions for HAR cantilevered wing models via the Combined Modal Finite Element (CMFE) approach. Three aspect ratio wing models were considered for the analysis to ensure confidence that the proposed guideline is versatile to be used in multiple HAR wing models.

The objectives of the study are as the following:

I. To model CMFE design environment of cantilevered HAR wing models.

II. To develop the load case selection guideline for the CMFE based NROM development.

III. To evaluate the effectiveness of NROM using the proposed load case selection guideline in the prediction of the static aeroelastic deformations in comparison to the FEA based deformation results for a predefined range airspeed and angle of attack.

1.4 Research Questions

The research questions of the study are as the following:

I. How is the CMFE design environment modeled to describe the nonlinear properties of the cantilevered HAR wing models?

II. How is the load case and normal mode selected for the development of the NROMs?

III. How accurate is the nonlinear static reduced order model when compared to conventional finite element nonlinear static solution?

1.5 Scope and Limitations

The study is conducted with several limitations and within a prescribed scope. First of all, the study is modeled based on rectangular HAR wing models of varying aspect ratios based on the wing model used by N.A.Rosly et al (Rosly, N. A., & Harmin, M. Y., 2017). The deformation due to the aerostatic loading are only considered in the z-axis where both bending deflection and twist deflection are accounted for. The aerostatic condition set are in the subsonic range. Furthermore, the initial position of the wing model is considered in the undeformed condition where the act of gravity acts through the span of the wing model.

1.6 Significance of the Study

With the help of the proposed guidelines on the development of the NROMs based on the CMFE approach, more interest on using the method would arise hence leading into more efficient analysis of the nonlinearity of the wing models. This encourages more aircraft manufacturers to instill the benefits of the HAR wings on their aircraft without the draw-back of the conventional nonlinear static analysis which not only increases their workload but also isn't computationally efficient.

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