# AEROELASTIC CHARACTERISTICS ON DEFORMED HIGH ASPECT RATIO WING WITH VARIOUS TIP DEFLECTIONS

By

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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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**October 2019**

**Chair: Mohammad Yazdi Harmin, PhD**
**Faculty: Engineering**

A high aspect ratio (HAR) wing model that exhibits geometric nonlinearities has been analysed to observe its impact in terms of static and dynamic characteristics. The research work was motivated by the lack of study from past researchers towards the modal properties of the HAR wing model using experimental modal analysis (EMA) in undeformed and deformed configurations. The undeformed configuration refers to exclusion of gravitational loading effect while deformed configuration considers the gravitational effect in bending direction. A number of tip store models was also considered in order to represent various degree of bending deformations, which is quantified in terms of tip deflection. To idealize an experimental model of HAR wing, the parametric sizing was conducted by considering the size of the wind tunnel test section, as well as its maximum speed with both undeformed and deformed configurations were taken into account. The final wing dimension was then chosen to be of 800mm×50mm×1.25mm along with three various tip store diameter of 10mm, 12mm, and 14mm. Following this, the wing model was fabricated to enable the EMA testing, ground static testing, and wind tunnel flutter testing to be conducted.

In terms of EMA testing, the findings confirmed that the chordwise-bending and torsion modes for the undeformed configuration changes to chordwise-torsion and torsion-chordwise modes respectively when the wing was in the deformed configuration. The natural frequency for both chordwise-torsion and torsion-chordwise modes decreases as the tip deflection increases, with the chordwise-torsion mode occurs at a much lower frequency than the torsion-chordwise mode. This clearly shows that wing in undeformed and deformed configuration have different modal characteristics and behave differently. Following this, the model updating was employed to bring the FE model closer to its experimental counterpart, where the discrepancies in terms of the first seven natural

frequencies were minimized from 44% to be about 10% with the magnitude of frequencies difference is lesser than 1.5Hz. In addition, good agreement in mode shapes were also acquired in terms of modal assurance criterion (MAC) with no occurrence in mode shape swap between the experimental and FE models.

The updated FE model was further validated against the ground static testing for an incremental tip force on the wing model and the result provides a good agreement between them in terms of tip deflection. Following this, the wind tunnel flutter testing envelope was idealised and the updated FE model has successfully predicted the flutter speed of undeformed wing configuration whereby the percentage of differences is not more than 10%. Since there is still no commercially available software for flutter prediction of deformed wing configuration; hence, the available validated numerical solution along with its corresponding experimental results may provide a certain degree of insight in understanding its flutter characteristics. Based on the finding, the flutter speed may unnecessarily decrease when the tip deflection increase although reduction in chordwise-torsional mode frequency led to a reduction in the frequency gap between the flutter modes. Hence, it is concluded that the flutter speed of the deformed HAR wing only reduces until a certain degree of tip deflection and beyond this point the flutter speed begins to increase.

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

**CIRI AEROELASTIK KE ATAS MODEL SAYAP BERNISBAH BIDANG TINGGI YANG BERUBAH BENTUK DENGAN PELBAGAI PEMESONGAN HUJUNG**

Oleh

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Model sayap bernisbah bidang tinggi yang menunjukkan ketidakselarian geometri telah dianalisis untuk melihat kesannya dari segi ciri statik dan dinamik. Kerja penyelidikan ini didorong oleh kekurangan kajian penyelidik terdahulu terhadap sifat modal bagi model sayap bernisbah bidang tinggi dengan menggunakan ujikaji analisis modal terhadap konfigurasi tidak berubah dan berubah bentuk. Konfigurasi tidak berubah bentuk merujuk kepada pengecualian kesan beban graviti, manakala konfigurasi berubah bentuk mengambil kira kesan graviti pada arah lenturan. Beberapa buah model stor hujung juga dipertimbangkan bagi mewakili pelbagai tahap lenturan berubah bentuk, yang diukur dari segi pemesongan hujung. Untuk mewujudkan model ujikaji bagi sayap bernisbah bidang tinggi, pensaizan parametrik telah dikendalikan dengan mempertimbangkan saiz pada bahagian ujian serta kelajuan maksimum terowong angin dengan mengambil kira kedua-dua konfigurasi tidak berubah dan berubah bentuk. Dimensi muktamad sayap kemudiannya dipilih sebagai 800mm×50mm×1.25mm bersama-sama dengan tiga stor hujung berdiameter 10mm, 12mm dan 14mm. Berikutan ini, model sayap difabrikasi bagi membolehkan ujian ujikaji analisis modal, ujian statik di bumi dan ujian kibaran terowong angin dapat dilaksanakan.

Dari segi ujian ujikaji analisis modal, hasil kajian mengesahkan bahawa mod arah rentas-lenturan dan mod kilasan pada konfigurasi tidak berubah bentuk telah bertukar masing-masing menjadi arah rentas-kilasan dan kilasan-arah rentas pada konfigurasi berubah bentuk. Frekuensi asli bagi kedua-dua mod arah rentas-kilasan dan kilasan-arah rentas berkurangan apabila pemesongan hujung dinaikkan, di mana mod arah rentas-kilasan berlaku pada frekuensi yang lebih endah berbanding mod kilasan-arah rentas. Ini jelas menunjukkan bahawa sayap pada konfigurasi tidak berubah dan berubah bentuk mempunyai perbezaan pada ciri modal dan kelakuannya. Berikutan itu, pengemaskinian

model telah dilakukan bagi merapatkan model unsur terhingga kepada model ujikajinya, dimana percanggahan dari segi tujuh frekuensi asli yang pertama telah diminimumkan daripada 44% kepada lebih kurang 10%, dengan magnitud perbezaan frekuensi adalah lebih rendah daripada 1.5Hz. Tambahan lagi, persetujuan yang baik telah diperolehi dari segi kriteria jaminan modal tanpa kejadian pertukaran bentuk mod di antara model ujikaji dengan model unsur terhingga.

Model unsur terhingga yang dikemaskini telah disahkan dengan lebih lanjut melalui ujian statik di bumi dengan meningkatkan daya hujung dan keputusan di antara mereka menunjukkan persetujuan yang baik dari segi pemesongan hujung. Berikutan itu, lingkungan ujian kibaran terowong angin telah diwujudkan dan model unsur terhingga yang dikemaskini telah berjaya meramal kelajuan kibaran bagi sayap berkonfigurasi tidak berubah bentuk yang mana perbezaan peratusannya adalah tidak melebihi 10%. Memandangkan masih tiada perisian yang tersedia secara komersial bagi ramalan kibaran sayap berkonfigurasi berubah bentuk, maka penyelesaian berangka yang telah disahkan berserta keputusan daripada ujikaji boleh memberi tahap pengetahuan tertentu terhadap pemahaman ciri kibarannya. Daripada penemuan, kelajuan kibaran adalah tidak semestinya berkurangan apabila pemesongan hujung ditingkatkan walaupun terdapat pengurangan frekuensi mod arah rentas-kilasan yang membawa kepada pengurangan jurang frekuensi di antara mod kibaran. Maka, kesimpulannya, kelajuan kibaran bagi sayap bernisbah bidang tinggi berubah bentuk hanya akan berkurangan sehingga pemesongan hujung mencapai tahap tertentu dan selepas itu kelajuan kibaran akan meningkat.

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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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| | |
|---|---|
| $AIC$ | Aerodynamic Influence Coefficient |
| $AIC_I$ | Imaginary part of AIC |
| $AIC_R$ | Real part of AIC |
| $AR$ | Aspect Ratio |
| $b$ | Half of Chord |
| $\boldsymbol{C}$ | Damping matrix |
| $C_{d_i}$ | Induced Drag |
| $C_l$ | Lift coefficient |
| $D$ | Drag |
| $e$ | Efficiency factor |
| $E$ | Convergence criteria |
| $f_n$ | Natural frequency |
| f | Frequency |
| $\boldsymbol{F}$ | Force Matrix |
| g | Gravity |
| **I** | Imaginary |
| $k$ | Reduced frequency |
| $\boldsymbol{K}$ | Stiffness Matrix |
| $L$ | Lift |
| $\boldsymbol{M}$ | Mass Matrix |
| $N_{max}$ | Maximum allowable iteration |
| $p$ | Applied Load Vector |
| $R$ | Range |
| $S_j$ | Sensitivity matrix |
| $TSFC$ | Thrust Specific Fuel Consumption |

| | |
|---|---|
| $\boldsymbol{u}$ | Displacement |
| $\boldsymbol{U}$ | Eigenvector of the system |
| $V$ | Velocity |
| $W_i$ | Initial Weight |
| $W_f$ | Final Weight |
| $z_m$ | Assembled measured eigenvalues |
| $z_j$ | Assembled numerical prediction eigenvalues |
| $\zeta$ | Damping ratio |
| $\rho$ | Density |
| $\phi$ | Eigenvector of mode shape |
| $\lambda$ | Eigenvalue of the system in the form Of $\omega(\gamma \pm \mathrm{i})$ |
| $\gamma$ | Transient decay rate coefficient |
| $\theta$ | Updating parameters |
| $\{\varphi_A\}_r$ | Reference modal vector, mode r |
| $\{\varphi_A\}_r^T$ | Transpose of $\{\varphi_A\}_r$ |
| $\{\varphi_x\}_q$ | Test modal vector, mode q |
| $\{\varphi_x\}_q^T$ | Transpose of $\{\varphi_x\}_q$ |
| ABS | Acrylonitrile Butadiene Styrene |
| AOA | Angle of Attack |
| CHEXA | Six-Sided solid element connection |
| CMFE | Combined Modal/Finite Element |
| CNC | Computer Numerical Control |
| CONM2 | Lumped mass |
| CPENTA | Five-Sided solid element connection |
| CQUAD4 | Quadrilateral plate element connection |
| CTRIA3 | Triangular plate element connection |
| DLM | Doublet Lattice Method |

| | |
|---|---|
| EI | Bending rigidity |
| EMA | Experimental Modal Analysis |
| FAA | Federal Aviation Administration |
| FE | Finite Element |
| FEA | Finite Element Analysis |
| FFT | Fast Fourier Transformation |
| FRF | Frequency Response Function |
| GJ | Torsional rigidity |
| HALE | High Altitude Long Endurance |
| HAR | High Aspect Ratio |
| IATA | International Air Transport Association |
| IRS | Intelligence, Surveillance And Reconnaissance |
| LCO | Limit Cycle Oscillation |
| LROM | Linear Reduced-Order Model |
| MAC | Model Assurance Criterion |
| MPC | Multi-point constraint |
| NI | National Instrument |
| NLROM | Nonlinear reduced-order Model |
| RBAR | Rigid bar connection |
| ROM | Reduced-Order Models |
| UAS | Unmanned Aircraft System |
| UAV | Unmanned Aerial Vehicle |

## LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Since the first successful flight by the Wright's brother back in 1903, the design of an airplane has undergone numerous technological advances in order to improve its overall efficiency while at the same time reducing its operational cost. One of the key parameters is to deal with an aerodynamic shape of an airplane, especially on the geometry of the wing. Figure 1.1 illustrates the market trend in terms of the wing aspect ratio parameter with respect to its first year of flight. It can be observed that over the years, the wing aspect ratio for mid to long haul aircraft has been gradually increased, with some cases it was up to 10% increases from its previous design [13]. By referring to equation (1-1) [51], it can be seen that the relationship between the induced drag and aspect ratio parameters are inversely proportional. Hence, increases in wing aspect ratio permits in reduction of induced drag, which in turn leads into a higher lift-to-drag ratio. In addition, this will also enable improvement in terms of the range and endurance of the aircraft.

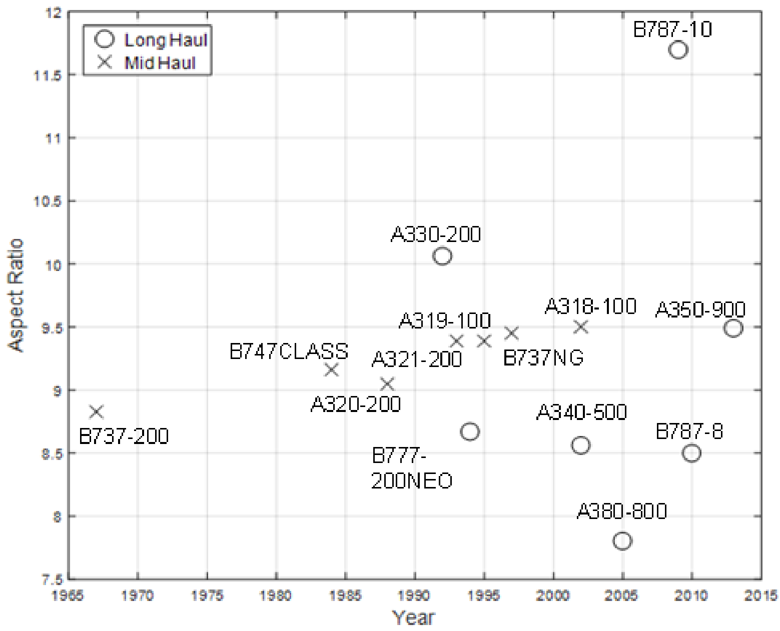


**Figure 1.1: Comparison of wing aspect ratio over the years**

$$C_{d_i} = \frac{C_l}{\pi ARe} \tag{1-1}$$

where;

| | | | | | |
|---|---|---|---|---|---|
| $C_{d_i}$ | = | Induced drag | $C_l$ | = | Lift coefficient |
| $AR$ | = | Aspect ratio | $e$ | = | Efficiency factor |

This trend, as described in the previous paragraph, was not only applicable for passenger aircraft but also for the unmanned aerial vehicles (UAVs), where having a long-range and endurance have become one of the primary criteria in designing the UAV. With the recent technology advancement for airborne sensors and communication packages, the UAV missions include airborne intelligence, surveillance, scientific research, and commercial use. It requires the UAV to operate and fly for a very long period at a very high altitude, which sometimes can be up to 25 days [53]**.** Due to this reason**,** this type of UAV is generally known as a High Altitude Long Endurance (HALE) UAV.

A number of HALE UAV have been developed over the past decades. For instance, Zephyr Stratospheric UAV by Airbus Defence and Space [5] has been produced to act as a surveillance platform similar to the satellite while offering the flexibility of a UAV and at a much lower cost. In 2010 Airbus launched its first high aspect ratio (HAR) model UAV with a wingspan of 25m and a weight of only 75kg. They also have plans on developing a UAV with a longer wingspan of 33m. In August 2010, Global Observer HALE UAV made its first flight [12]. It is built for US Defence to perform intelligence, surveillance, and reconnaissance (IRS) operations with real-time operation data, which is transmitted to the ground control station through a satellite communication data link. Global Observer is also equipped with a HAR wing with a wingspan of 48.7m and a weight of 159kg. On the other hand, in 2013, another IRS system is launched by the name of Orion Unmanned Aircraft System (UAS) [6]. This UAS, which has a wingspan of 40.2m, also acted as a situational awareness to provide direct support to troops.

From here, it can be seen that the HAR wing concept has been steadily gained much interest in aerospace fields due to its attractive solution in achieving a better lift to weight ratio. Nevertheless, its dynamic characteristics are still required to be further explored before a certain level of design maturity on the HAR wing concepts can be idealised.

## 1.2 Problem Statement

Even though increasing the wing aspect ratio enables more extended range and endurance of the aircraft as well as for the UAV, it will cause an issue due to its high structural flexibility. This will significantly change the overall dynamic behaviour of the wing, which in turn leading to a drastic change in aeroelastic characteristics. A notorious example was the catastrophic event of NASA Helios Prototype with a HAR wing of 31, which failed and crashed in the Pacific Ocean. Various investigations have been conducted, and NASA reported that the aircraft failed due to nonlinear instability due to the interaction between flexible structure, unsteady aerodynamics, flight control system, propulsion system, environmental conditions, and vehicle flight dynamic [55]. Quoted from the report, "Lack of adequate analysis methods led to an inaccurate risk assessment of the effects of configuration changes leading to an inappropriate decision to fly an aircraft configuration highly sensitive to disturbances." Hence, the most important outcome from this event is to develop more advance multidisciplinary method that is appropriate to predict a highly flexible wing behaviour.

A great deal of work has since been done to study the aeroelasticity of a HAR wing. HAR wing that consists of light, slender, and flexible structure has a prominent characteristic of geometric nonlinearity, which occurs as the wing is highly deflected. These circumstances defy the validity of the conventional linear approach; hence, consideration of the nonlinear effect is crucial in order to predict the static and dynamic behaviour of the wing system correctly. Relatively great studies have been conducted by other research through experimental testing to validate the simulation analysis to study the HAR static and dynamic behaviours (e.g. [18], [19], [25], [26], [27]). The effect of the slender body at the tip of the wing model has also been employed by a number of researchers (e.g. [25], [26], [27], [30]) in order to assess the dynamic behaviour of the wing at its deformed configuration, which subsequently have been assumed to reduce the flutter speed.

However, reviews of the literature fails to identify works that include the experimental testing of flutter characteristics of wing in the deformed configuration with various tip deflections (through the installation of tip slender body). There is also no specific work concentrating on the EMA testing that compares the modal properties with regards to the tip deflection. Hence, this research work focuses on this aspect, including the comparison with other researchers in terms of flutter characteristics.

## 1.3 Aim and Objectives

The primary aim of this research is to investigate the effect of geometric nonlinearities on the dynamic behaviour of the HAR wing for undeformed and deformed configurations. This is idealized through the following objectives:

1. To conduct a parametric design study of the HAR wing model for the wind tunnel flutter testing through numerical analysis.

2. To compare the modal properties of the HAR wing model between the undeformed and deformed configurations through an EMA for various tip stores with different tip deflection.

3. To investigate flutter instability for both deformed and undeformed configurations through the wind tunnel testing for various tip stores and deflections.

## 1.4 Research Questions

1. What is the design requirement and design variables for the HAR wing model?

2. How to fabricate the HAR wing model with a relatively simple process?

3. What are the differences between the undeformed and deformed configurations in terms of their modal properties?

4. What are the differences between the undeformed and deformed configurations in terms of flutter instability?

5. Does increasing the tip deflection always resulted in lowering the flutter speed?

## 1.5 Scope of Work & Limitation

In this work, a HAR wing model with various tip store diameter (that is added as to represent various tip deflection) is selected to investigate the aeroelastic characteristics due to different configurations, namely in undeformed and deformed states. The study only highlighted the investigation of the HAR wing, which exhibits a geometric nonlinearity without considering the effect of force follower.

The wing model is a rectangular shape with an aspect ratio of 16, which consists of spar, ribs, fairing, and tip store. It is designed based on the size of the wind tunnel test section and its maximum operational speed. The flutter speed of the wing is made sure to occur within the wind tunnel operational speed of 40 m/s in order to make a verification against the numerical value. Therefore, this work is limited to only a low subsonic region, whereby the nonlinearity of the flow is not accounted for.

As there is still no proprietary finite element analysis (FEA) tools that can solve for flutter analysis of deformed wing configuration, only flutter analysis for undeformed wing configuration could be employed. Hence, studying the modal characteristics of the wing model in both configurations through normal mode analysis and EMA testing is crucial as it can provide an assumption on the flutter modes of the system, which can provide a certain insight in understanding flutter characteristics of deformed wing configuration. Typically, flutter modes occur due to the coupling between bending and the first torsional modes, and increasing the tip deflection will reduce the frequency gap of the flutter modes. Hence, it is assumed that the flutter speed for deformed wing configuration to be lower than the undeformed wing configuration. During the EMA testing for deformed wing configuration, a tri-axial accelerometer is used instead, as the uni-axial accelerometer cannot capture the mode shape in the chordwise direction.

## 1.6 Arrangement of Thesis

The whole thesis includes five chapters and is organized as follows:

**Chapter 1** describe the trend of HAR wing over the years, the introduction of the HAR wing used in past researchers, the current work's problem statement, objectives, and scope and limitation.

**Chapter 2** covers the literature review from various journal studies and books that focuses on recent studies on research topics. It reviews the fundamental knowledge of aeroelastic behaviour for a HAR wing that exhibits geometrical nonlinearity.

**Chapter 3** generally describes the simulation and experimental approaches employed throughout the studies and discussing its impact in terms of dynamic characteristics and flutter instability.

**Chapter 4** describes the FEA conducted to optimize the sizing of the wing model, subsequently selecting the finalized wing model dimensions in detail. This chapter is followed by descriptions of the construction phase for the experimental model and focuses on the experimental work. The experimental work involves EMA and linear and nonlinear ground static testing. Correlation between the experimental work and analytical results are presented and discussed, and subsequently, the model updating process is also described in this chapter. Next, the wing model flight envelope is tested by performing a wind tunnel flutter testing.

**Chapter 5** summarize the research work and conclude the important findings based on the analyses and results that have been presented in the previous chapter. This chapter provided valuable insight on the achievement of the research objectives as well as giving suggestions for future research based on the current work.

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