Finite element analysis of high aspect ratio wind tunnel wing model: A parametric study

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Abstract. Procedure for designing the wind tunnel model of a high aspect ratio (HAR) wing containing geometric nonlinearities is described in this paper. The design process begins with identification of basic features of the HAR wing as well as its design constraints. This enables the design space to be narrowed down and consequently, brings ease of convergence towards the design solution. Parametric studies in terms of the spar thickness, the span length and the store diameter are performed using finite element analysis for both undeformed and deformed cases, which respectively demonstrate the linear and nonlinear conditions. Two main criteria are accounted for in the selection of the wing design: the static deflections due to gravitational loading should be within the allowable margin of the size of the wind tunnel test section and the flutter speed of the wing should be much below the maximum speed of the wind tunnel. The findings show that the wing experiences a stiffness hardening effect under the nonlinear static solution and the presence of the store enables significant reduction in linear flutter speed.

1. Introduction
Recent advancement of new aircraft designs leads to more flexible and lighter aircraft, thus improving its operational range and also operating cost per mile. Nonetheless, an unfortunate consequence of this development is the substantial increase in nonlinear effects, which gives rise to the dramatic changes in terms of the static and dynamic characteristics of the aircraft. One of the characteristics of a highly flexible aircraft is the nonlinear behaviour of their structural stiffness due to either geometric stiffening or softening. Another characteristic is the significant changes in air loads direction under a follower force, where the force direction is dependent on the wing surface deformation. These circumstances defy the validity of conventional linear approach, hence consideration of the above effects is crucial in order to correctly model the system.

A study has been conducted on nonlinear aeroelasticity and flight dynamics for High Altitude Long Endurance (HALE) aircraft, which discovered that the HALE wing does not necessarily have to be in extreme flight state to be highly curved and this condition might occur at relatively low aerodynamic loading too [1]. The study implies that the curved wing exhibits differences in modal characteristics as compared to the straight wing especially in terms of torsional and edgewise mode coupling, causing the aeroelastic behaviour to act differently. Hence, the inclusion of geometric nonlinearity is of great importance and cannot be neglected. A great deal of researches have been devoted to study the effect of nonlinearities on the aeroelastic behaviour. However, most of these studies are solely focussing on developing numerical formulation and there is a lack of research in validating the reliability of their
numerical model [2-10]. Tang and Dowell [11-14] are among the researchers that have made a great effort in performing experimental studies on the effects of the structural geometrical nonlinearity with respect to flutter boundary, limit cycle oscillation (LCO) and gust responses. In their studies, a wing store of slender body is introduced at the wing tip of a high aspect ratio (HAR) wing in order to reduce the frequency gap between flutter modes, resulting in the reduction of flutter speed within operational envelope of the wind tunnel. This is in line with the results of another study that show the influence of vibration and flutter properties is greater by varying the position of the store along the span instead of having the mass equally distributed along it [15]. This finding suggests the flutter frequency reduces as the store is moved towards the tip of the wing. This work has been validated through an experimental investigation [16].

In this study, procedure for designing a HAR wing for the wind tunnel is developed, taking into account the geometric nonlinearities and the tip store effects with respect to the static deflection and flutter characteristics. The solutions are selected such that all defined design limits and constraints are satisfied.

2. Methodology
In this study, the experimental model is divided into two main parts: HAR wing model with a tip store and a wing root mechanism. These components are designed such that the wing root mechanism could rigidly hold the root of the wing as well as able to rotate in order to control the root angle of attack of the wing system. On top of that, it is crucial to ensure the basic features of the experimental model to have a simple manufacturing and assembly process. This enables easy modification and repairs when required.

The wing model is designed with a reasonably simple layout and loosely based on the wing model by Tang and Dowel (2001) [11]. It consists of spar, ribs, fairings and tip store as illustrated in Figure 1 and Figure 2(a). The wing spar is made of spring steel, which is chosen due to its high yield strength and durability in spite of significant deformation. One end of the spar is held tightly by the wing root mechanism while the other end is used for store attachment. The wing ribs are made of Acrylonitrile Butadiene Styrene (ABS) with a cross-sectional of NACA0012 airfoil. Each rib has a slot with the size of the spar cross section. The spars are slid through the slots and they are distributed equally along the span with 50mm interval between them. The gap between each rib is covered by fairings that are made of Styrofoam, which completes the aerodynamic contour of the wing. In the mean time, the store is a symmetrical cylinder aluminium bar that is consisted of lower and upper parts in order to enable the clamping mechanism to the tip of wing spar. Figure 2(b) shows the wing root mechanism that consists of turning disc and clamp component, which are made out of model foam and block of aluminium, respectively. They are attached together via fasteners and are inserted to the slot that has been created at the middle of one of the sidewalls of the test section. Once the desired angle is set, the wing root mechanism is then locked to the test section.

![Figure 1: Exploded wing for experimental wing model](image)
The wind tunnel is of a closed loop type, with the test section having a cross sectional dimension of 1m×1m and maximum operating speed of 40m/s. Since the wing model is attached to the middle part of one side of the test section walls, this leaves a margin of ±0.5m between the upper and lower part of the test section. Therefore, the maximum allowable tip deflection is constrained to be within a range of ±0.3m in order to reduce the effects of the wall interference in the wind tunnel. On the other hand, the flutter speed has to be as low as possible to ensure the safety of the testing envelope. In this case, it is constrained to be lower than 40m/s. To assess the HAR wing type, the aspect ratio of the wing design has to be more than 10. The finite element representation of the studied wing consisting of spar, ribs, fairing and store is modelled with MSC NASTRAN shell elements of CQUAD4, CTRIA3, CHEXA and CPENTA as shown in Figure 3. Besides that, the lumped mass of CONM2 element is introduced to represent the weight of fasteners that attach the store to the spar. Fully clamped boundary condition is applied at the wing root to replicate a cantilever-like condition. The doublet lattice aerodynamic panel illustrated in Figure 4 is employed to represent the aerodynamic model and it is coupled with the structural model in order to establish a complete system of an aeroelastic system of the studied wing.

In this work, parametric study in terms of spar thickness, span length and store diameter is coded using MATLAB and the system is integrated with the finite element solver of MSC NASTRAN. The wing is examined under linear and nonlinear analyses to demonstrate undeformed and deformed wing cases.

3. Results and Discussions
The parametric study is performed by conducting linear and nonlinear analyses under the gravitational loading defined at the sea level in order to obtain the maximum tip deflection of the wing for the wind off condition. The nonlinear analysis is carried out due to the characteristic of the HAR wing that can undergo high deflection beyond the linear region even when it is under gravitational loading. The nonlinear solution is solved in iterative manner where the stiffness is updated upon convergence of the nonlinear problem for each of considered load steps. The design space is specified by the variables of spar thickness ranging from 1.0mm to 1.5mm and span length from 500mm to 800mm. The effect of
store is also studied by varying its diameter from 10mm to 14mm. It should be noted that the wing chord is kept constant at 50mm, which is twice the length of spar width, and the length of the store is fixed at 150mm. Since the system can be represented as a cantilever beam like model, the variation in the width parameter is insignificant for the bending calculation under uniform loading.

Figure 5 provides tip deflection results for both linear and nonlinear cases for all the considered design variables. It can be observed that the variation in spar thickness, span length and store diameter provide significant impact in terms of tip deflection. The tip deflection increases with increasing span length, decreasing spar thickness and increasing in store diameter. It is noted that the tip deflection for linear and nonlinear cases are significantly different as the deflection for nonlinear case is lower than the linear case. This demonstrates that the wing has experienced a stiffness hardening effect, where the effect is visible at higher magnitude of deflection. This finding suggests the importance of considering the geometrical nonlinearity in the analysis. Since the linear system is only valid for a small deflection, it may overestimate the actual bending deflection for highly deflected system. Overall, the nonlinear results show that all wing design options are acceptable as the wing tip deflection under gravitational loading is lesser than the allowable margin of ±0.3m.

Subsequently, with similar consideration of design variables and design space, the flutter analysis using p-k method is performed for a range of airspeeds at sea level condition. Figure 6 depicts the considered parametric study with respect to flutter speed and flutter frequency. From the plots, the shaded region provides an acceptable design options that is below than the flutter speed constraint of 40m/s. It can be seen clearly that, as the store diameter increases (which is reflected in increment of tip mass), the flutter speed reduces significantly as well as flutter frequency.

To understand more on this characteristic, the graphical representation of $V-f$ and $V-\zeta$ is plotted between the flutter modes of the clean wing and the wing with the biggest store diameter as illustrated in Figure 7. The flutter speed and frequency are identified when the damping ratio changes in sign, which indicates that the oscillation cannot be damped out at this particular condition. For both cases, flutter occurs due to coupling between second bending and first torsional modes, where the frequency gap between them decreases with increasing of airspeed. It should be noted that, with the presence of the store, the frequency gap between the flutter modes has reduced significantly compared to a clean
wing, which in turn brings down the flutter speed from 52m/s to 33m/s. Hence, this enables the flutter testing to be performed at a much lower speed and lowering the risk level at the same time.

Figure 6: Flutter analysis for (a) wing, (b) wing with store diameter 10mm, (c) wing with store diameter 12mm, (d) wing with store diameter 14mm

Table 1 provides the linear and pre-stressed normal mode analyses for the first seven modes of both clean wing and wing with the biggest store. The pre-stressed analysis is first carried out by performing nonlinear static analysis of the considered wing under gravitational loading and the solution is then restarted in the linear normal mode analysis upon the updated stiffness about its nonlinear statically deformed state. From the finding, the out-of-plane bending modes are not affected much as the wing is
deflected. Nonetheless, the chordwise bending and torsional modes of the undeformed condition have changed into ‘chordwise bending - torsion’ and ‘torsion - chordwise bending’ modes when the wing is in deformed state. The ‘chordwise bending - torsion’ implies that the mode is more prominent in the chordwise direction rather than torsional while the ‘torsion - chordwise bending’ mode indicates that the mode is more prominent in torsional direction than chordwise. From the results, it is clearly shown that the torsional-related mode of the deformed wing appears at a much lower frequency compared to the undeformed condition. Hypothetically, this finding suggests that the flutter speed can be reduced further as the torsional-related mode is getting closer to flutter mode of second bending in comparison to the fully linear system.

Table 1: Natural frequencies for linear and pre-stressed normal mode analysis

| Mode         | Freq | Mode         | Freq | Mode         | Freq |
|--------------|------|--------------|------|--------------|------|
| 1st Bending  | 1.53 | 1st Bending  | 1.59 | 1st Bending  | 1.09 |
| 2nd Bending  | 9.62 | 2nd Bending  | 9.61 | 2nd Bending  | 7.85 |
| 3rd Bending  | 26.95| Chordwise-Bending | 15.37| Torsion      | 21.18|
| Chordwise Bending | 30.17| 3rd Bending  | 26.72| Chordwise Bending | 21.48|
| 4th Bending  | 52.88| 4th Bending  | 52.58| 3rd Bending  | 23.31|
| Torsion      | 81.15| 5th Bending  | 87.19| 4th Bending  | 47.29|
| 5th Bending  | 87.55| Torsion-Chordwise | 98.02| 5th Bending  | 79.96|

4. Conclusion
The study is set out to determine the design options for the wind tunnel model of the HAR wing. One of the findings shows that the flutter speed can be reduced significantly with the presence of a store. In the mean time, another finding provides a possibility of the flutter speed to be further reduced when the wing is in the deformed state compared to the undeformed state. This highlights the importance of including geometric nonlinearity in the analysis to correctly model the system. Further research should be undertaken to validate the finite element HAR wing through experimental modal analysis and wind tunnel testing.

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