Aeroelastic effects of a simple rectangular wing-box model with varying rib orientations

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Abstract. A simple rectangular wing-box model with varying individual rib orientations has been analysed with the interest on studying their impact on flutter and divergence instabilities. The varying rib orientations offer an alteration in bending-torsional coupling characteristics, resulting in significant effect on aeroelastic behaviour of the wing. Substantial improvement is found in comparison with the baseline and parallel ribs orientation configurations, which leads to the possibility of significant weight reduction.

1. Introduction

Air transportation has emerged as a vital element in ensuring continuous growth of both economic and social benefits. However, due to rising jet fuel cost and increasing demand for air transportation, the cost efficiency has now become a major issue in the airline industry to sustain their quality standard of customer service and continue their market survival. Hence, there have been a great drive and demand in aerospace industry to produce more efficient and cost effective aircraft designs. The primary goal is to ensure that the improved aircraft will deliver a better efficiency in operating cost per miles without having to compromise its overall performance. In recent years, the approach of aeroelastic tailoring on the aircraft design has become an auspicious solution in improving its overall efficiency. This can be idealised through active or passive control of aeroelastic wing system, or both.

Significant research efforts have been expanded into active aeroelastic wing concepts with the main goal is to provide an optimal wing aerodynamic shape that can be adapted at any flight conditions [1, 2]. Even with the current advances in smart material and adaptive structure capabilities, the practical solution using this concept is still uncertain. This is mainly due to the conflicting structural condition where the aeroelastic wing has to be stiff but also flexible at the same time. On the other hand, current research and development in the use of aeroelastic tailoring in passive approach have been much more devoted in the use carbon-fibre composite structures.

Over the past decade, composite technology has progressively become an important area in the construction of aerospace structural components. Substantial advancements have already been made in improving their properties and also manufacturing processes. Following this trend, the commercial aerospace industry nowadays has utilised composite materials to greater extent in the new generation commercial aircraft designs like Boeing 787 and Airbus A350. The primary advantage from the use of the composite materials is their superior strength-to-weight ratio, which enables a significant weight
reduction without having to compromise strength and durability. In addition to this, their anisotropic characteristic also allows the exploitation of bending-torsional properties through altering the stacking sequence of the plies [3, 4, 5]. Nevertheless, aircraft configurations are still more or less the same such that conventional configuration of engines under-slung on pylons attached to swept back wings, spars in spanwise direction, ribs in perpendicular direction to spars and passengers carried in a cylindrical-like fuselage.

There have been several attempts on aeroelastic tailoring of interior wing configuration such that it behaves similar to anisotropic manner [6, 7, 8]. Most of these works are considering the ribs to vary at the same orientation, resulting in a parallel ribs arrangement at any desired orientation and leading to changes in the bending-torsion coupling behaviour. This notably improves the aeroelastic performance with no additional weight penalty. Inspired by their findings, further investigation is carried out in this study by assessing all possible orientations for each individual rib separately. The impact of variation in ribs orientation on the aeroelastic instabilities is the main focus in this work.

2. Methodology

A wing model loosely based upon a Goland rectangular wing-box [6, 9] is considered in this study and shown in Figure 1. The wing-box consists of front and rear spars, and six ribs. It is measured 1000mm in span, 200mm in width and 50mm in height with the spar's thickness of 10mm. The ribs are equally divided along the span with 200mm margin between each of them. By default, the ribs are of 10mm thick and they are positioned in perpendicular direction to the spar. Both spars and ribs are modelled as a simple flat plate using MSC NASTRAN's four-node quadrilateral shell elements (CQUAD4) with material properties entry of aluminium alloy 2024 [10] and a fully clamped boundary condition at the root of the wing. A mesh convergence study is performed in order to establish the finite element (FE) model with a mesh density that is sufficiently fine to permit a good approximation of the solution.

![Figure 1. Planform view of the wing with the baseline wing-box represented by the shaded area](image)

Figure 2 illustrates the FE representation of the studied aeroelastic wing model. It should be noted that the structural FE model only considers the wing-box section, with the total planform of the wing is completed by the doublet lattice aerodynamic panels. This allows the problem to be simplified while retaining its essential characteristics. The varying rib orientations only consider the ribs that are located between the tip and root of the wing, which are numbered in sequence from 1 to 4 in Figure 2. Figure 3 and also Table 1 describe a number of considered rib orientations with the centre of rotation is defined at the mid chord. Each of these ribs is allowed to vary with a constraint that they will not overlap each other. Clockwise rotation is considered as positive orientation whereas counter clockwise rotation is considered as negative orientation. In addition, thickness of the ribs is also varied as they are oriented in order to ensure that the total weight of the wing remains constant in all cases. All the procedures involved have been coded in MATLAB and the system has been fully integrated with the MSC NASTRAN solutions to simulate the parametric studies.
3. Results and discussion

Normal modes analysis are conducted for all possible single oriented rib configurations leading a total of 32 configurations. Since aeroelastic instabilities are mainly related to the bending-torsional mode coupling, only bending and torsional modes are taken into account and highlighted in this work. The bending and torsional frequencies variation for each of the considered rib orientations are shown in Figure 4. These are mainly due to the change in structural mass and stiffness distribution as well as the position of shear centre along the wing.
In terms of bending modes, the variation in natural frequencies is very small and can be assumed negligible. In case of oriented ribs positioned towards the root of the wing, both bending frequencies are increased slightly as the rib is oriented away from its baseline position. This is possibly due to the dominant influence in structural stiffness over the mass distribution that acting in the direction of the bending related axes. Meanwhile, in the case of oriented rib positioned towards the tip of the wing, the bending frequencies decrease slightly but with a much reduced magnitude and this imposed opposite characteristic than the previous condition. The resulting torsional modes are in greater scale than the bending modes. The results clearly shows that both torsional frequencies are increased with increasing orientation of the ribs, which shows significant influence in structural stiffness over mass distribution that acting in the direction of torsional related axes. Interestingly, the impact is greater in the case of rib that is oriented towards the middle of the wing. Furthermore, the symmetrical trend in natural frequencies are due to the symmetrical impact for a similar orientation magnitude of both positive and negative directions. These findings suggest possibilities to increase the frequency spacing between the coupled flutter modes, which may result in significant improvement of the aeroelastic performance. Hypothetically, the bigger the frequency gap of the coupled modes, the weaker the interaction among them, resulting in increase in instability speeds.

A series of aeroelastic analyses are performed using well-known p-k method [11] that is available in MSC NASTRAN to assess the impact of the variation in ribs orientation on flutter and divergence instabilities. Figure 5(a) shows $V\cdot \zeta$ and $V\cdot \omega$ plots for the first two modes of the baseline aeroelastic model, depicting both flutter and divergence instabilities. These instabilities can be identified at the point where the damping changes in sign as the air speed increases, with the flutter represent the oscillatory instability while the divergence represent the non-oscillatory instability. Note that the flutter is a coupled effect between the first bending and torsional modes, whereas the divergence is obtained from a non-oscillatory solution of the first bending mode. Figure 5(b) compares the baseline system with the oriented configuration system of second rib oriented at -45°. It can be clearly seen that there is an increase in frequency spacing, causing both flutter and divergence instabilities to be further delayed. Meanwhile, Figure 6 shows that almost all the considered oriented individual rib cases are able to improve the aeroelastic instabilities with both flutter and divergence speeds can be increased by nearly 11 percent compared to the baseline system. Another important outcome that emerges from the result is that the individual rib orientation shows approximately a two-fold increase in aeroelastic stabilities than the parallel ribs orientation.

Figure 5. $V\cdot \zeta$ and $V\cdot \omega$ plots of baseline and selected oriented rib configurations: (a) baseline system, (b) baseline and oriented rib systems
4. Conclusion
This study is set out to determine the potential of wing rib modification via aeroelastic tailoring. It is found that variation of single rib’s orientation resulted in an increase of frequency spacing between the bending-torsional modes, which led to a remarkable improvement in aeroelastic performance when compared to the baseline and parallel ribs orientation systems. This encouraging outcome provides a promising potential in reduction of the aircraft weight without having to compromise its aeroelastic performance. Further research should be undertaken to explore all possible combinations of the rib’s orientation that can be idealised through the use of optimisation techniques.

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