

Aeroelastic tailoring via ribs orientation of NASA Common Research Model

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Abstract. A baseline model in reference to the NASA Common Research Model is selected to illustrate the concept of aeroelastic tailoring of wing ribs structure by varying the orientation of the ribs. This enables the torsional-bending modes characteristic to be altered, which results in a possibility of improvement in the aeroelastic performance without having to compromise its overall weight. Two strategies are implanted in this work: the first strategy considers the whole ribs to be oriented in parallel while the second one is by dividing the wing into six parts where the ribs are allowed to be oriented in parallel within their part only. In many cases, there are a significant improvement with up to 5.5% of flutter increment via orientating the ribs section, hence leading to a possibility in significant structural weight reduction.

1. Introduction

A massive growth of air transportation is seen in the past decades since it is the only sensible way to travel across long distance. The demand for air transport has increased significantly and able to act as a catalyst in economic and social growth. However, this rapid growth also consequently increases the impact on the environment through the aircraft carbon emissions. Various emission reduction options have been proposed in which the key agenda is to improve the aircraft overall efficiency while at the same time maintaining its overall performance.

Aeroelastic instabilities, namely divergence and flutter, are two most common design parameters that dictate the flight envelope of the aircraft [1]. Numerous studies have been done in delaying these aeroelastic instabilities through advancement in aircraft materials, aerodynamics, structures and also control technologies. Over the past decades, the composite technology has increasingly been employed in aerospace industry due to its attractive property of higher strength-to-weight ratio in comparison to the conventional metal alloys. This solution has been widely used in the current design of aircraft. For instance, AIRBUS aircraft has employed about 25% and 50% of composite materials on its A380 and A350XWB variants, respectively [2,3]. On the other hand, the advancement in aerodynamics is mostly directed in reducing the total drag with relative improvement in lift-to-drag ratio. One way to idealize this is through the usage of boundary layer control to delay the flow separation. In addition, morphing wing technology has also gained much attention with a focus to investigate a shape-changing ability in acquiring the best possible aerodynamic shape given the flight condition [4,5]. Apart from these, the approach of aeroelastic tailoring on aircraft design has also become a possible solution in improving the aircraft overall efficiency. This can be realized through active and/or passive control of aeroelastic



wing system [6]. It is intended that the aeroelastic instabilities such as the flutter, divergence and gust loads response to be delayed and influenced in a beneficial way without any compromise in weight.

Several researches have been performed in finding the optimum fibre orientation for a composite wing box with aeroelastic instability parameters as a maximizing cost function. One of the researches studies the effect of laminate lay-up of composite wing box with respect to the flutter speed [7]. It is found that the torsional rigidity properties can be altered by varying the composite stacking sequence, which in turn changes the coupling behaviour of the flutter modes. This offers an improvement in the flutter instability without affecting the overall structural weight. Another study performed aeroelastic tailoring on a composite forward-swept wing with a parametric study involving composite thickness and orientation parameters [8]. It is found that the overall structure weight of initial wing design could be reduced and the wing aeroelastic performance in terms of flutter and divergence speeds could also be improved simultaneously. Recently, there has been an interest in understanding the effect of wing structure arrangement to its aeroelastic performance. The concept presented by Harmin et al. (2011) is based upon the modification of wing ribs arrangements of a metallic wing by rotating each rib in the same orientation [9]. Meanwhile, Othman et al. (2016) has also adopted a similar aeroelastic tailoring technique on a Goland rectangular wing box by varying each of the ribs individually [10]. Both of the studies have resulted in an increment of frequency gap between the bending-torsional modes, which led to encouraging improvement in aeroelastic performance without any weight penalty. In addition, a few aeroelastic tailoring methods including the use of curvilinear rib and spar with varying orientation, tow steering composite laminates and also material and thickness grading have been implemented on a Common Research Model wing box [11]. In this study, each method has shown significant outcomes with varying degrees of success in weight reduction and improvement of flutter performance. A recent research has included also the effect of varying wing sweep angle and ribs arrangement on an un-tapered wing in terms of its static and dynamic aeroelastic behaviour [12]. With this motivation, further investigation is carried out using a much realistic wing representation nowadays.

2. Methodology

The parameterized model of the NASA Common Research Model (CRM) wing box is considered in this study. This model describes a single-aisle subsonic transport aircraft configuration with full-scaled cantilever wing that is generated by NASA for the purpose of research work within the aerodynamic community [13]. The wing has a semi span of 26.18m, root chord of 7m, taper ratio of 0.229, sweep angle of 35° and an aspect ratio of 9. It consists of 51 ribs and 3 spars where each gap between them are covered by the skins. In the baseline setup, the ribs are aligned perpendicular to the leading edge and they are equally distributed along the span. It should be noted that the height and thickness of the spars and ribs gradually decrease from the root to the tip of the wing. The studied wing is modelled with MSC NASTRAN shell elements of CQUAD4 and CTRIA3, and its material properties have been defined as anisotropic aluminium based [14]. The baseline wing model is illustrated in Figure 1 and a fully constrained boundary conditions are defined at the root of the wing. On the other hand, Figure 2 shows the finite element (FE) representation of the wing box section that is coupled with the doublet lattice aerodynamic panel in order to establish a complete system of aeroelastic model.

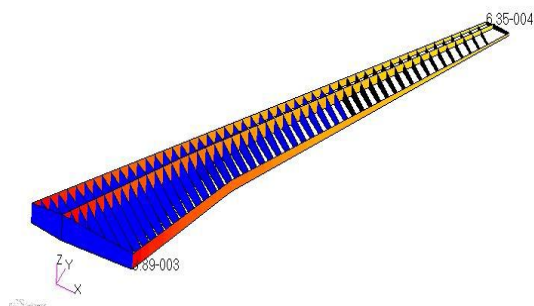


Figure 1: Baseline wing FE model

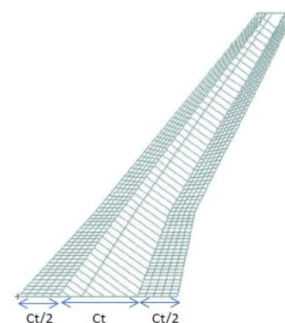


Figure 2: Aeroelastic wing model

The ribs have been numbered accordingly from root to tip in increasing order from 1 to 51. Only the ribs that are connected to all three spars are considered for varying orientations. In this case, they are the 8th rib and those onwards. The centre of rotation is set in the middle of each rib of the baseline configuration and nine different degrees of rotation are defined between -10° to $+10^\circ$. The negative angle of orientation represents clockwise rotation while the positive angle of orientation refers to anti-clockwise rotation about its baseline position. Each of these ribs is allowed to vary with the constraint that they do not overlap each other. In addition, as the rib is orientated, its thickness is accordingly adjusted due to the change in its length. This enables the total weight of the wing to remain the same in all cases. Figure 3 shows the schematic of possible rib's orientation as explained in this paragraph. If each of the ribs is allowed to be orientated via the defined setup, this leads to a total of 9^{44} possible orientations, which makes it extremely challenging to cover the whole design space. For ease of the computational effort and initial understanding, the wing is divided into six parts as shown in Figure 4. Table 1 provides the list of case settings that are considered in this study. All solutions involved in this work are coded in MATLAB and the system is integrated with MSC NASTRAN solver under solution 145 of the p-k method flutter analysis [15].

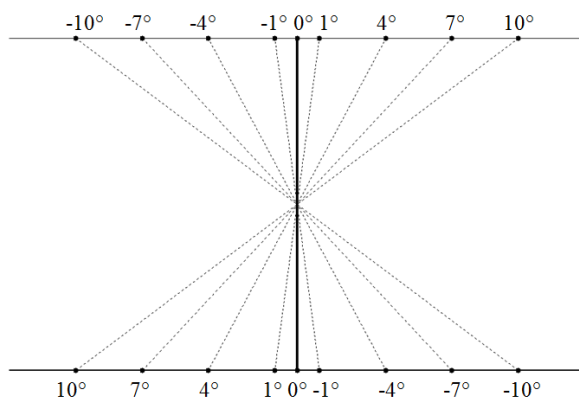
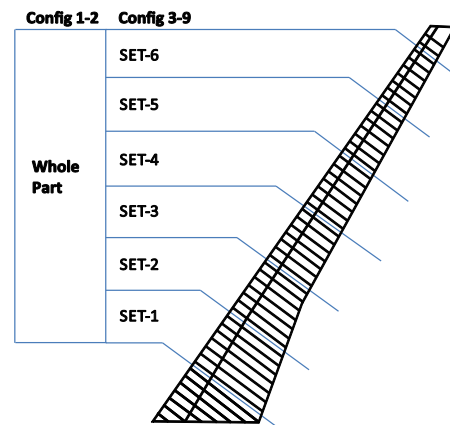
Figure 3: Possible rib's orientation, θ 

Figure 4: Division of the wing into 6 sets of ribs

Table 1: List of considered case studies

Case	Description
1	All ribs are rotated together in parallel with rotation angle θ
2	Odd numbered ribs are rotated in defined angle θ , while even numbered ribs rotated in opposite angle θ
3	Only ribs in Part 1 (8th to 14th rib) are rotated in parallel with angle θ
4	Only ribs in Part 2 (15th to 21st rib) are rotated in parallel with angle θ
5	Only ribs in Part 3 (22nd to 28th rib) are rotated in parallel with angle θ
6	Only ribs in Part 4 (29th to 35th rib) are rotated in parallel with angle θ
7	Only ribs in Part 5 (36th to 42nd rib) are rotated in parallel with angle θ
8	Only ribs in Part 6 (43rd to 49th rib) are rotated in parallel with angle θ
9	Ribs in odd numbered parts are rotated in defined angle θ , while ribs in even numbered parts are rotated in opposite angle θ

3. Results and Discussions

The combinations of ribs orientations that maximized the air speed at which the flutter occurred are of interest in this study. It should be noted that the divergence instability is not taken into account since it is found from the findings that divergence occurs later than flutter, thus making flutter instability as a maximum limit of the wing system. A series of flutter analysis using p-k method has been conducted for the nine considered cases to assess the bending-torsional characteristics with respect to aeroelastic

performance [15]. The flutter result is represented in terms of V - f and V - ζ plots, which describe the trends of frequency and damping ratio against the air speeds. Meanwhile, flutter speed and frequency parameters are identified at the condition where the damping ratio changes in sign, which implies that the oscillation cannot be damped out at the particular state.

Figure 5 shows graphical representation of V - f and V - ζ plots for the first five modes of the baseline system that consist of three bending and two torsional modes. It can be clearly observed that there is a strong coupling between second bending and first torsional modes as the airspeed increases. Note that the flutter occurs when the two modes are about to coalesce and move close enough for them to couple unfavourably. On the other hand, Figure 6 depicts the comparison between first torsional and second bending modes for both baseline configuration and Case-1 of positive 10° rib rotation cases. From the figure, an increment in the frequency gap is observed that results in the delay of flutter speed. For the considered oriented of Case-1, the flutter occurs right after the mode switch between the first torsion and second bending modes, which demonstrates that flutter is not merely due to the coupling between these two modes also the coupling effect from the third bending mode as well.

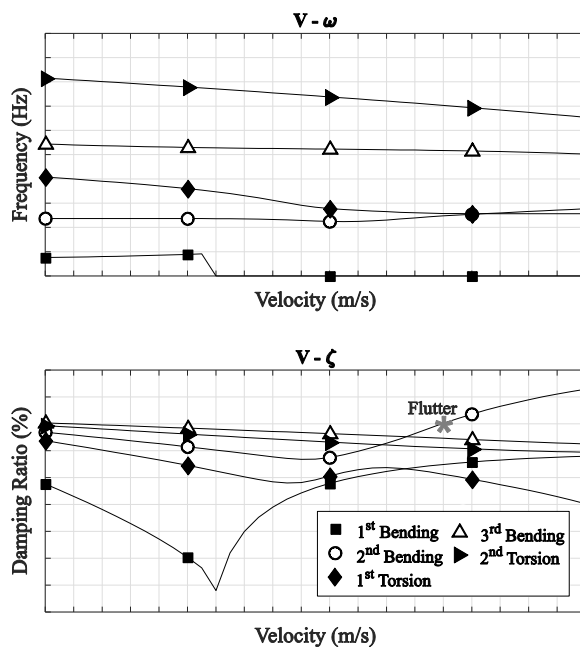


Figure 5: V - ζ and V - ω plots of baseline system

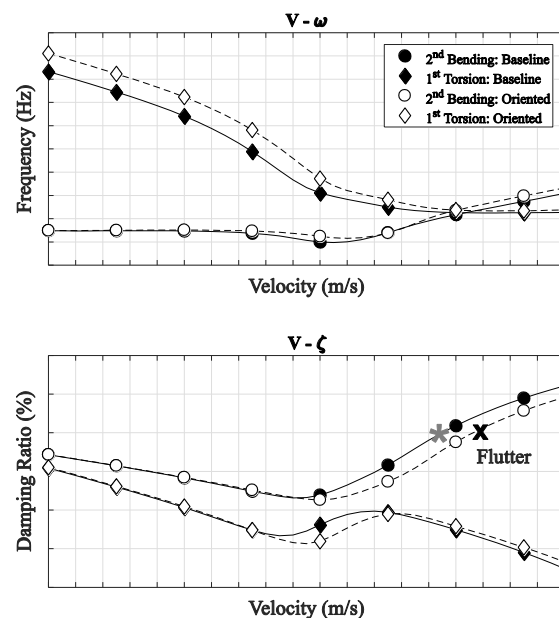


Figure 6: Comparison of V - ζ and V - ω plots between baseline system and Case-1

The influence upon bending-torsional characteristics is generally caused by changes in wing mass and stiffness distribution in both spanwise and chord wise directions, which result in different flexural axis. The torsional modes are observed to have greater impact compared to the bending modes, hence the frequency gap of flutter modes can only be increased with a possibility of an increment in torsional frequency. This finding is in agreement with the earlier study made by Othman et al. (2016) [10]. In addition, this also demonstrates that varying ribs orientation offers a greater torsional rigidity while the bending rigidity is not much affected.

To highlight the improvement and degradation of flutter performance, flutter results are normalized with respect to the flutter speed of the baseline system. Figure 7 shows the normalized flutter speed of Case-3 to Case-8, where only a set of ribs are oriented at a time. From the figure, it can be observed that the flutter results are improved as the ribs are oriented in positive angle and reached the maximum at the furthest possible orientation. Meanwhile, the opposite trend with degradation in flutter is seen as the ribs are oriented in the negative angle orientation. Design-1 of Case-5 provides the greatest flutter improvement, followed by Design-2 of Case-6 and Design-3 of Case-4. It should be noted that all the three designs are comprising a set of oriented ribs located in the middle of the wing, which indicate the

impact is greater at this location. Figure 8 shows the normalized flutter speed of Case-1, Case-2 and Case-9, where the ribs are varied in parallel and zig-zag arrangements. It is found that Design-4 of the parallel ribs orientation provides an overall best solution with the highest increment of flutter speed by 5.5% compared to the baseline system. On the other hand, the zigzag arrangements offer improvement in flutter speed for both positive and negative angles of orientation with Design-5 of set ribs zigzag arrangement outperformed the Design-6 of individual zigzag arrangement.

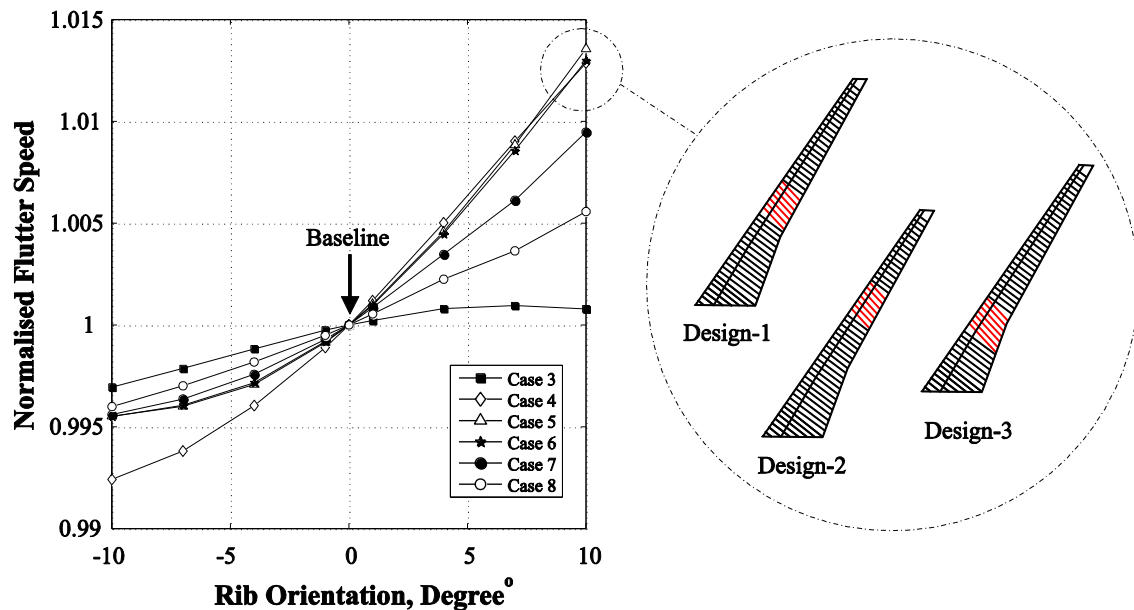


Figure 7: Normalized flutter speed for Case 3-8

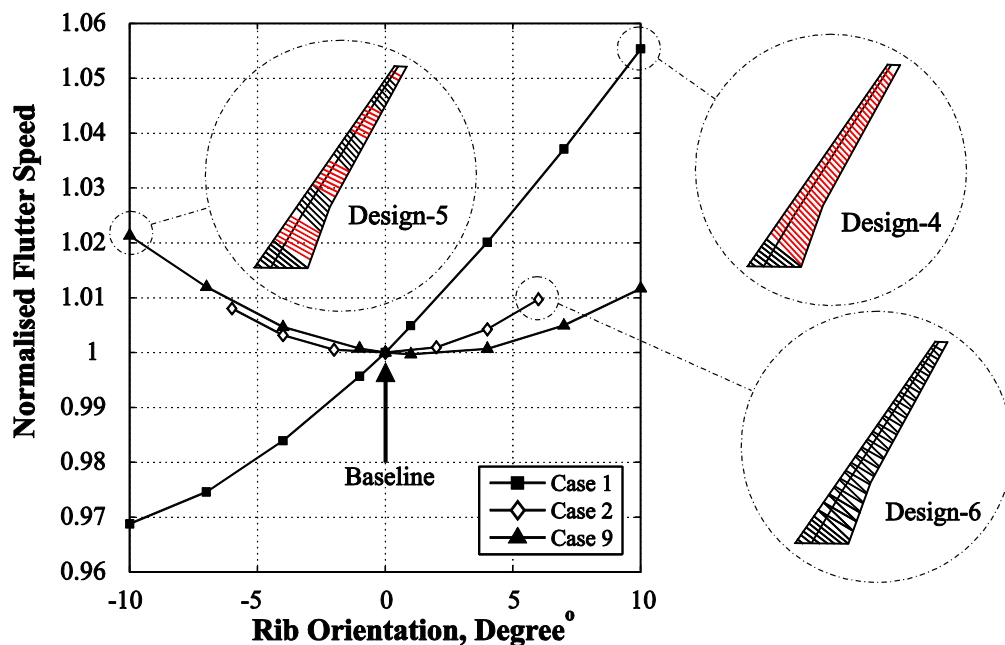


Figure 8: Normalized flutter speed for Case-1, Case-2 and Case-9

The optimum solutions for all the cases are still at their furthest possible angle of orientation, hence hypothetically the flutter speed may be further delayed if spacing between the ribs can be extended. One way to do this is by reducing the number of ribs and another way is by distributing the ribs with

increasing spacing along the spars. A major drawback that might arise from this is the proneness of the wing to skin wrinkling. Therefore, further investigation is required to assess the proposed wing design in further details. All in all, the findings from this study are encouraging and suggests that there is a possibility of weight reduction on the wing via the oriented rib concept without having to compromise its aeroelastic performance.

4. Conclusion

The findings from this study show that varying ribs orientation enables the exploitation of bending-torsional characteristics, which result in changes of aeroelastic performance. Besides that, the findings also highlight that the torsional modes are more sensitive to the modification of orientation made on the ribs located around the middle section of the wing. Overall, outcomes from this study can be taken to be encouraging since they indicate the possibility of wing's weight reduction by using the oriented rib concept without having to compromise its aeroelastic performance.

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