A study on the response of high aspect ratio composite wing structures due to gust load

Matza Gusto Andika*, Bambang Kismono Hadi, Rianto Adhy Sasongko

Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia

*matza.gusto@bppt.go.id

Abstract. The purpose of this study is to acquire the correlation between composite tailoring at symmetric balanced laminate and gust response on high aspect ratio wing. As a flexible structure, the high aspect ratio wing had a susceptibility from dynamic loading. Gust or turbulence load is one of dynamic loading which can have a bad impact on the wing structure. There are many incidents caused by turbulence load, hence to obtain structural response is important. Because gust load is a stiffness problem, one way to handle these effects is to make the airframe more rigid which is not favorable due to the weight penalty in the gross weight of the aircraft. Plies orientations can be an alternative to make structure stiffer without adding structural weight. From this study, plies-orientations at symmetrically laminated composite had been varied starting from 0 to 90 degrees with 5 degrees increment at the skin of the wing. Bending and torsional natural frequencies have changed where changed in play orientation as well as the vibration response from the gust load. The discrete gust cases defined in the EASA requirements are used in this study. The structural response from the gust problem had different characteristics between angle plies laminate, cross-plies laminate, and various plies orientation. As a result of this research that symmetrically balanced laminate composite with fiber direction ±15 or ±75 degrees had a good bending characteristic, nevertheless that direction have the lowest bending stiffness. Further research needs to optimize the plies orientation to design the high aspect ratio wing which has a good aeroelastic response and minimize weight.

1. Introduction

In recent years, the Unmanned Aerial Vehicle (UAV) industry is competing to increasing endurance, increasing payload, and reducing emissions. One potential solution for competing in that matter is to increase the wing aspect-ratio as it improves the lift and reducing drag. Nevertheless, higher aspect-ratio composite wings increase structural flexibility which in turn may lead to an aeroelastic problem. The aeroelastic phenomenon is the result of the interaction of elastic and aerodynamic forces, the event of which during the flight condition can be a destructive and catastrophic failure. That is the cause that structural designers notice that phenomenon as a design constraint related to aircraft flight envelope. Because of aeroelasticity is a stiffness problem, one way to handle these effects is to make the airframe more rigid which is not favorable due to the weight penalty in the gross weight of the aircraft [1].
Modification on the spar planform geometry done by Francois et al. to reduce the root bending moment during the worst-case scenario gust [2]. Changing the structural shape to increase stiffness can affect the weight penalty issued because it can reduce weight or increase the weight of the structure. That situation can be solved by using composite materials where the considerable stiffness-to-weight ratio and tailoring properties of the structural stiffness of that materials. Sanches et al. [3] propose an investigation on the aeroelastic tailoring of a typical section with hardening nonlinearity in pitching stiffness, seeking to expand the flutter onset boundary and minimum stable LCO amplitudes in post-flutter. Higher pitch natural frequency LCO amplitude is decreased and higher plunge frequency then pitch frequency LCO amplitude is also decreased. Therefore, ratio plunge and pitch frequency are important to explore to minimize LCO amplitude [3]. Research by Munk et al. proposes to avoid severe vibration by shifting the fundamental frequency of the structure away from the frequency range of dynamic loading. After 55 iterations, 15 percent of the material is removed and the gap between natural frequencies 2 and 3 has been increased by over 200 percent from 3.39 Hz to 8.23 Hz. This resulted in a 3 percent increase in wing flutter velocity [4]. From Swain et al [5] research, we know that angle-plies laminates (45,-45) had better flutter characteristics then cross-plies laminates, and the gap between first and second mode frequency increases lead to an increase in flutter characteristics. From Lancelot et al [6] the equivalent static load method applied to gust response optimization of an aircraft wing and most of the tailoring is done through the thickness distribution, rather than fibers orientations. This study aims to obtain the correlation between the bending and torsional natural frequencies of the skin-high aspect ratio wing and the structural response of the gust load. The discrete gust cases defined in the EASA requirements are used in this study. The finite element model used to analyze bending and torsional frequencies at high aspect ratio wing with carbon fiber composite at different plies angles.

2. Method and finite element modeling

2.1. Modeling high aspect ratio wing

Aircraft wing with aspect ratio equal to 20 with 8 meters half span had been modeled with finite element software. The structural wing consists of box spar, rib, and skin with composite material. The wing and the internal wing structure described in figure 1.a. Numerically obtained using the commercial finite element analysis software (Nastran). The laminates under study include 10 plies and 6 plies at wing skin, 8 plies at the box spar, 4 plies at the rib, and 66 plies at the joint between wing and fuselage by using carbon fiber composite. The mechanical properties of carbon fiber composite are, $E_1 = 77400$ MPa, $E_2 = 72900$ MPa, Poisson Ratio = 0.05, $G_{12} = 3150$ MPa, and density = 1.56 x 10^4 kg/mm^3. The finite element analysis procedure is described, the natural frequencies and mode shapes calculated using Nastran are first validated with the results obtained from demonstrating true mesh independence. Element refinement was accomplished via the convergence of the wing natural frequency and mode shape. Eight models with an increasing element from lowest to highest were used for convergence test, such us model with 9471, 9517, 9768, 12840, 20018, 44267, 77975, 143604 Elements. The validated and converged model will be used to acquire the correlation between composite tailoring and gust response on a high aspect ratio wing. Form the figure 1.b. We can see that after 40000 elements the convergence criteria have been reached, therefore for composite tailoring study we use 42846 elements.

![Figure 1. Wing structure layout (a), convergence study (b)](image)
2.2. Natural frequency and gust analysis

The wing aircraft generates aerodynamic forces in a way to relative velocity to the surrounding air. Then, a sudden change in the velocity of the surrounding air, caused for example by the presence of a wind gust, or in wind direction, introduces a change in these aerodynamic forces [7]. Because the gust response is related to structural dynamic characteristics, then we have to know the natural frequencies and mode shape as a part of structural dynamic characteristics from various tailoring model to acquire the correlation between composite tailoring and gust response at wing structure. The laminates under study include 8 plies and 4 plies at wing skin, 8 plies at the box spar, 4 plies at the rib, and 66 plies at the joint between wing and fuselage by using carbon fiber composite. In this study, as described in Table 1, 18 various models had been analyzed with different fiber directions at wing skin symmetric balance laminate at section 1 (from root to 4490 mm wingspan) and section 2 (from 4490 mm to wingtip) as described in figure 2a. Figure 2b shows the boundary conditions for the analysis where the location is at the joint between wing and fuselage.

| No | Section 1 | Section 2 | No | Section 1 | Section 2 |
|----|-----------|-----------|----|-----------|-----------|
| 1  | [0,90,0,90]s | [0,90]s | 10 | [45,-45,45,-45]s | [45,-45]s |
| 2  | [5,-5,5,-5]s | [5,-5]s | 11 | [50,50,50,50]s | [50,50]s |
| 3  | [10,-10,10,-10]s | [10,-10]s | 12 | [55,55,55,55]s | [55,55]s |
| 4  | [15,-15,15,-15]s | [15,-15]s | 13 | [60,60,60,60]s | [60,60]s |
| 5  | [20,20,20,20]s | [20,20]s | 14 | [65,65,65,65]s | [65,65]s |
| 6  | [25,25,25,25]s | [25,25]s | 15 | [70,70,70,70]s | [70,70]s |
| 7  | [30,30,30,30]s | [30,30]s | 16 | [75,75,75,75]s | [75,75]s |
| 8  | [35,35,35,35]s | [35,35]s | 17 | [80,80,80,80]s | [80,80]s |
| 9  | [40,40,40,40]s | [40,40]s | 18 | [85,85,85,85]s | [85,85]s |

Figure 2. Section at wing span (a) and boundary conditions at wing (b)

The most common model of a discrete deterministic gust, which has evolved over the years from the isolated sharp-edge gust function in the earliest airworthiness requirements [8], is the “one-minus-cosine” function with the formulation are:

\[ U = \frac{U_{ds}}{2} \left[ 1 - \cos \left( \frac{2\pi s}{L} \right) \right] \] \hspace{1cm} (1)

\[ U_{ds} = U_{ref} F_g \left( \frac{H}{350} \right)^{1/6} \] \hspace{1cm} (2)

\[ F_{(t)} = 0.5 \rho U(t)^2 S C_l \] \hspace{1cm} (3)
where $U_{ds}$ is the design gust velocity and $H$ is the gust gradient distance, that is, the distance over which the gust velocity increases to a maximum value. $U_{ref}$ is the reference gust velocity, $F_g$ is the flight profile alleviation factor, $F(t)$ is aerodynamic gust load in 3-second gust velocity ($C_l = 1.4$ and $S = 12.8m^2$). Airworthiness requirements prescribe a relationship between the design gust velocity and the gust gradient distance. From the screen distribution method, aerodynamic load divided into 5 parts, where $F_1 = 0.26\% F$, $F_2 = 0.24\% F$, $F_3 = 21\% F$, $F_4 = 18\% F$, and $F_5 = 11\% F$. Figure 3 describe the location of gust load in 3 second. Transient response analysis was made using MSC Patran /Nastran with the natural frequency analysis that had been performed previously to create the databased for the transient response analysis.

![Figure 3](image)

**Figure 3.** Location of gust load (a) “one-minus-cosine” gust load (b)

3. **Results and discussion**

3.1. **The result from natural frequency analysis**

The effects of different fibers-paths have also been studied and compared by Viglietti et al. The results confirm that an appropriate tow lay-up can be used to improve the performances of wing structures [9]. From Pingulkar et al research, we can know that as the orientation of the outermost layer was changed from $0^\circ$ to $+45^\circ$, the natural frequencies also changed. The first and third natural frequency decreased, whereas the second natural frequency increased [10]. Optimization of the fundamental frequencies has been presented by Munk et al. The maximization of the 1st natural frequency and increasing the gap between two coinciding frequencies for increasing dynamic stability [4]. From the previous research, the natural frequency has a significant effect on the aeroelastic stability and gust response, therefore this research starts from natural frequencies and mode shapes analysis. From the normal mode analysis with various composite tailoring number 1 - 18 that has been done.

![Figure 4](image)

**Figure 4.** First bending natural frequency (a), First torsion natural frequency (b), First bending / first torsion natural frequency (c)
Figure 4, shows that the tailoring numbers 4 and 16 had the highest first bending natural frequency, and tailoring no. 10 had the lowest first bending natural frequency. For the first torsion natural frequency, tailoring no. 7 and 13 had maximum value and tailoring no. 1 and 18 had minimum value. The maximum gap between the first bending and first torsion natural frequency is at tailoring no. 10. A symmetric balanced laminate composite with fiber direction 15 or 75 degrees has a good bending characteristic. Meanwhile, symmetric balanced laminate composite with fiber direction 30 or 60 degrees have a good torsion characteristic. Furthermore, 45-degree fiber direction from symmetric balanced laminate has the highest gap between torsion and bending frequency.

3.2. The result from gust load

The gust loads have to be defined with a half wave-length going from 9 to 110 m. The gust amplitude is a function of its wavelength and altitude at which the aircraft is flying. Gust load response analyzed with the transient response in MSC Patran/Nastran for various tailoring numbers of composites. By using a 3-second discrete gust method, we can know the structural response every second during the gust load and search for the maximum response. Figure 5 describes the gust response at 0.05 s, 0.08 s, 0.12 s, 1.41 s, and 3 s gust load.

![Figure 5. Gust response at 0.05 s (a), 1.41 s (b), and 3 s (c)](image)

To study the correlation between composite tailoring and gust response on high aspect ratio wing can be done with exploring the various symmetric balanced laminate composite fiber direction with gust load. Figure 6 describes the maximum displacement at various composite tailoring with the same gust load. From figure 6 can be seen that tailoring number 10 which consist of ±45 degrees fiber direction has maximum displacement amplitude compare to the other tailoring, and tailoring number 4 and 16 have minimum displacement. It means that tailoring which consists of 15 or 75 at symmetric balanced laminate have good gust response characteristics.

![Figure 6. Maximum displacement response for various tailoring composite](image)
4. Conclusion

A computationally finite element method approach has been presented for symmetric balanced laminate composite with different plies orientations at the skin high aspect ratio wing. Results show that composite tailoring at symmetrically balanced laminate has an impact on natural frequencies, mode shape, and gust response. Eighteen tailoring strategies were undertaken, which consists of $0^\circ$ to $90^\circ$ plies. The following observations have been made, that symmetrically balanced laminate composite with fiber direction $\pm 15$ or $\pm 75$ degrees had a good bending characteristic, nevertheless fiber direction $\pm 15$ degrees have the lowest bending stiffness. Symmetrically balanced laminate composite with fiber direction $\pm 30$ or $\pm 60$ degree has a good torsion characteristic, however, fiber direction $\pm 85$ and 0 degree have the lowest torsional stiffness. Symmetric balanced laminate with fiber direction $\pm 45$ has the highest gap between torsion and bending. The layup strategy with $\pm 15$ or $\pm 75$ degrees symmetric balanced laminate has good gust response characteristics, and the worst gust response occurs at a symmetrically balanced laminate with fiber direction $\pm 45$. Symmetrically balanced laminate with $\pm 15$ degrees fiber direction has a 45% better displacement amplitude then $\pm 45$ degrees fiber direction. From the previous research from Swain et al show that $\pm 45$ fiber direction had better flutter characteristic, but from this research, we know that $\pm 45$ fiber direction had worst gust response, therefore optimization is needed for further research to have a composite structure which has good gust response and flutter characteristics.

References

[1] A. Attaran, D. L. Majid, S. Basri, A. S. M. Rafie, and E. J. Abdullah, “Structural optimization of an aeroelastically tailored composite flat plate made of woven fiberglass / epoxy,” *Aerosp. Sci. Technol.*, vol. 15, no. 5, pp. 393–401, 2011.

[2] G. Francois, J. E. Cooper, and P. M. Weaver, “Aeroelastic tailoring using the spars and stringers planform geometry,” *58th AIAA/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf. 2017*, no. January, pp. 1–45, 2017.

[3] L. Sanches, T. A. M. Guimarães, and F. D. Marques, “Aeroelastic tailoring of nonlinear typical section using the method of multiple scales to predict post-flutter stable LCOs,” *Aerosp. Sci. Technol.*, vol. 90, pp. 157–168, 2019.

[4] D. J. Munk, G. A. Vio, and G. P. Steven, “A novel method for the vibration optimisation of structures subjected to dynamic loading,” *Adv. Aircr. Spacecr. Sci.*, vol. 4, no. 2, pp. 169–184, 2017.

[5] P. K. Swain, B. Adhikari, D. K. Maji, and B. N. Singh, “Aeroelastic analysis of CNT reinforced functionally graded laminated composite plates with damage under subsonic regime,” *Compos. Struct.*, vol. 222, no. February, p. 110916, 2019.

[6] P. Lancelot and R. De Breuker, “Aeroelastic tailoring for gust load alleviation,” no. February, 2017.

[7] A. Rigaldo, “Aerodynamics Gust Response Prediction,” no. July, pp. 1–20, 2011.

[8] Y. Wang, A. Da Ronch, and M. G. Tehrani, “Adaptive feedforward control for gust-induced aeroelastic vibrations,” *Aerospace*, vol. 5, no. 3, 2018.

[9] A. Viglietti, E. Zappino, and E. Carrera, “Free vibration analysis of variable angle-tow composite wing structures,” *Aerosp. Sci. Technol.*, vol. 92, pp. 114–125, 2019.

[10] P. Pingulkar and S. B., “Free Vibration of Laminated Composite Plates Using Finite Element Method.pdf,” vol. 24, no. 7, pp. 529–538, 2016.