The Effect of Laminated Layers on the Flutter Speed of Composite Wing

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Abstract

The paper presents an investigation to the flutter speed   of composite wing for different ply orientation .Structurally the composite wing was idealized as a composite beam load carrying structure. Theodorsen's expression was used to get the 2- dimension unsteady lifting force and pitching moment in the limit of incompressible flow and subsonic speed which were integrated over the wing span. A free vibration analysis was first carried out to get the natural frequencies and mode shapes .The velocity-damping (V-g) method was used to calculate the flutter speed and the flutter frequency. A wing of unmanned aerial vehicle was manufactured from woven glass and polyester resin where the flutter speed was calculated experimentally by the wind tunnel test .The flutter speed was calculated analytically for different ply orientation, it is found that the increasing in torsion rigidity leads to increase in the flutter speed, the fiber combination with high torsion rigidity and relatively low coupling rigidity give higher flutter speed.

Keywords: flutter, composite wing, aeroelastic tailoring.

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الخلاصة

من خلال هذا البحث تم معرفة تأثير إتجاه الألياف للمواد المركبة التي تستخدم في صناعة اجنحة الطائرات على سرعة الرفرفة للجناح. من حيث مقاومة الاحمال المسلطة ، تم التعامل مع الجناح على انه عتبة مركبة تقاوم الاحمال المسلطة على الجناح . قوة الرفع وعزم الالتواء حُسبت لمقطع جناح ثنائي الأبعاد باستخدام صيغة ثيوديرسون لحساب قوة الرفع وعزم الالتواء المتغير مع الزمن لجريان غير انضغاطي وسرعة اقل من سرعة الصوت ومن ثم حسبت على طول الجناح باستخدام التكامل العددي . تم دراسة وتحليل الاهتزاز الحر للجناح المركب لغرض حساب الترددات الطبيعية وأشكال التشوه . إسُتخدمَت طريقة (السرعة – عامل التضاؤل) لحساب سرعة وتردد الرفرفة للجناح .تم تصنيع جناح مركب لطائرة بدون طيار من مادة الياف الزجاج المنسوج مع مادة البولستر حيث إن سرعة الرفرفة حسبت عملياً باستخدام النفق الهوائي. سرعة الرفرفة حسبت نظريا لعدة اتجاهات للالياف ،من خلال نتائج البحث تبين بان زيادة صلادة الالتواء يؤدي الى زيادة سرعة الرفرفة, ان افضل اتجاه للالياف الذي من خلاله نحصل على سرع رفرفة عالية هو الاتجاه الذي ينتج عنه صلادة التواء عالية مع صلادة ازدواج الانحناء-الالتواء نوعا ما واطئة.

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1. Introduction

The aircraft industry utilized a great deal of composite materials due to the opportunities they present for weight saving. Their share in aircraft applications has reached more than 15%of the structural weight of aircraft, and more than50%of the structural weight of helicopters and fighter aircraft for the last 40 years. In structural applications such as wing configurations, composite materials are popular choices because of additional advantage of tailoring their stiffness's to the directions of loading. This is especially critical when the wing interacts with the surrounding airflow, resulting in structural deformations, known as aeroelastic effects, which can be detrimental to the performance and stability of an aircraft. At high speeds , these deformations can exceed structural stiffness of the material and result in structural failure.

(Banerjee2000) ,investigated the flutter behavior of uniform composite wings. The wing is idealized as a bending torsion (materially)coupled composite beam with cantilever end condition for which the frequency equation and mode shapes in free vibration are presented in closed analytical form. The flutter problem is formulated by summing algebraically the expressions for generalized mass, generalized stiffness and generalized aerodynamic force terms. From the final expression containing all the above terms the flutter speed and flutter frequency are determined by using a standard root finding procedure .(Guo et al.,2003), presented an analytical study on optimization of a laminated composite wing structure for achieving a maximum flutter speed and a minimum weight without strength penalty. The attention has been paid mainly to the effect on flutter speed of the bending, torsion and, more importantly , the bending-torsional coupling rigidity, which is usually associated with asymmetric laminate lay-up. (Attaran et al.,2006), studied the effects of aspect ratio, sweep angle, and stacking sequence of laminated composites to find the optimized configuration of an aeroelastically tailored composite wing idealized as a flat plate in terms of flutter speed. To study the effect of stacking sequence the classical lamination theory (CLT) has been chosen. (Masaki Kameyama et al.,2007): treated the flutter and divergence characteristics of composite plate wings with various sweep angles. The effect of laminate configuration on the flutter and

divergence characteristics is investigated for composite plate wings. To examine the effect of laminate configuration , the flutter and divergence characteristics are represented on the lamination parameter plane. (Guo,2007), presented an investigation into a minimum weight optimal design and aeroelastic tailoring of an aerobatic aircraft wing structure . Based on a minimum weight composite wing box model of adequate strength the investigation was focused on the aeroelastic tailoring of the wing box by employing the gradient-based deterministic optimization method . (Dayang Laila et al.,2008): studied aeroelastic tailoring characteristics of a cantilevered composite wing ,idealized as a composite flat plate laminate .The composite laminate was made from woven glass fibers with epoxy matrix .Aeroelastic wind tunnel testing of the laminate was performed and the flutter speed and the flutter frequency were calculated experimentally. (Daniel et al.2010): introduced an aeroelastic tailoring approach using lamination parameters optimization. The main goal of this research is to analyze a composite plate wing subject to aeroelastic effects and the improvement in flutter speed by means of eigen frequency maximization. (Majid et al., 2011) : investigated the aeroelastic flutter of laminated hybrid composite wing .The composite wing was modeled as composite plates and aeroelastic analysis has been carried out in the frequency domine . Pre-determined fiber orientation of 3-layer carbon/epoxy and glass/epoxy laminated plate has been employed with various aspect ratios.

2. Free Vibration Analysis

A composite wing that exhibits both geometric and material coupling is shown in **Fig. 1**. The elastic axis, which coincides with the Y-axis is chosen to be the locus of the geometric shear centers of the wing cross-section. It is allowed to deflect out of the plane by h(y,t) whilst the cross-section is allowed to rotate about OY by $\psi(y,t)$ where y and t denote distance from the origin and time, respectively. The wing has a length of L , bending rigidity EI, torsional rigidity GJ, bending–torsion coupling rigidity K , mass per unit length m , and mass moment of inertia per unit length I_α about the Y-axis($I_\alpha=I_{c.g}+mx_\alpha^2$)., respectively . In the figure, x_α is the distance

between the mass and elastic axes, which are, respectively, the loci of the mass centre

(centroid) and the shear centre of the wing cross-sections, and is positive when the mass axis is after the elastic axis as shown. The two principal parameters that are responsible for the geometric and material coupling are x_α and K, respectively. The governing differential equations of the free vibration motion of composite wing shown in **Fig.1** ,are given by (Banerjee2007);

$$EI\frac{\partial^4 h}{\partial y^4} + K\frac{\partial^3 \psi}{\partial y^3} + m\frac{\partial^2 h}{\partial t^2} - m x_\alpha \frac{\partial^2 \psi}{\partial t^2} = 0$$

(1)

$$GJ\frac{\partial^2 \psi}{\partial y^2} + K\frac{\partial^3 h}{\partial y^3} - I_\alpha \frac{\partial^2 \psi}{\partial t^2} + m x_\alpha \frac{\partial^2 h}{\partial t^2} = 0$$

(2)

Assuming harmonic osillation so that ;

$$h(y,t) = H(y)e^{i\omega t}$$

(3)

$$\psi(y,t) = \Psi(y)e^{i\omega t}$$

(4)

Where(ω) is the frequency of oscillation ,H and Ψ are the amplitudes of (h) and (ψ) respectively .the solution of eqs. (1) and (2) gives;

$$H(\zeta) = A_1 \cosh\alpha\zeta + A_2 \sinh\alpha\zeta + A_3 \cos\beta\zeta + A_4 \sin\beta\zeta + A_5 \cos\gamma\zeta + A_6 \sin\gamma\zeta$$

(5)

$$\Psi(\zeta) = B_1 \cosh\alpha\zeta + B_2 \sinh\alpha\zeta + B_3 \cos\beta\zeta + B_4 \sin\beta\zeta + B_5 \cos\gamma + B_6 \sin\gamma\zeta$$

(6)

Where (ζ) is the normalized length $\zeta = \dfrac{Y}{L}$.

A_1-A_6 and B_1-B_6 are constants, which are determined by applying the boundary conditions .The expressions for the bending rotation

$\Theta(\zeta)$,shear force $S(\zeta)$, bending moment $M(\zeta)$and torque $T(\zeta)$ are respectively as follows;

$$\Theta(\zeta) = \frac{dH}{dy} = \frac{1}{L}\frac{dH}{d\zeta}$$

(7)

$$S(\zeta) = \frac{EI}{L^3}\frac{d^3 H}{d\zeta^3} + \frac{K}{L^2}\frac{d^2 \Psi}{d\zeta^2}$$

(8)

$$M(\zeta) = -\frac{EI}{L^2}\frac{d^2 H}{d\zeta^2} - \frac{K}{L}\frac{d\Psi}{d\zeta}$$

(9)

$$T(\zeta) = -\frac{K}{L^2}\frac{d^2 H}{d\zeta^2} - \frac{GJ}{L}\frac{d\Psi}{d\zeta}$$

(10)

For a cantilever wing , the fixed –free boundary conditions require that (Wang 2004):

At the fixed end, $y=0 \rightarrow \zeta =0$;

$$H(0) = \Theta(0) = \Psi(0) = 0$$

(11)

At the free end ,$y=L \rightarrow \zeta=1$;

$$M(1) = S(1) = T(1) = 0$$

(12)

Substitute eq.(11) into eqs.(5,6 and 7) and eq.(12) into eqs.(8,9 and 10), we can get the characteristic equation;

$$[\Lambda]A = 0$$

(13)

Where $A=[A_1\ \ A_2\ \ A_3\ A_4\ \ A_5\ \ A_6\ ]^T$,$[\Lambda]$ is a 6×6 characteristic matrix being function of the natural frequency .The natural frequencies can be obtained by solving;

$$[\Lambda]=0$$

(14)

In the present work eq.(14) was solved numerically by the secant method with (MATLAB 6.5) program .Substituting the natural frequency back into eq.(13) to compute the mode shape.

3. Structural Model of the Composite Wings

In the present work, the structural model of the composite wing ,is a laminated beam load carrying structure. The leading and trailing edges were only counted in calculating the mass ,inertia

and aerodynamic loads .The effective rigidities for a laminated beam shown in **Fig.2** are as follows(Stephan 2010);

$$EI = d\left(D_{22} - \frac{D_{12}^2}{D_{11}}\right)$$

$$GJ = 4d\left(D_{66} - \frac{D_{16}^2}{D_{11}}\right) \quad (15)$$

$$K = 2d\left(D_{26} - \frac{D_{12}D_{16}}{D_{11}}\right)$$

Where(d) is the chord of the laminate in (m) .

D_{ij} can be expressed as (NASA 1994);

$$D_{ij} = \sum_{k=1}^{N}\left[\overline{Q}_{ij}\right]_k \left(\frac{t_k^3}{12} + t_k z_k^2\right) \quad (16)$$

$$z_k = \frac{h_k + h_{k+1}}{2} \quad (17)$$

Where

z_k is the distance from the geometric midplane to the center of the kth ply in (m) .
N :number of layers.
t_k : the thickness of the kth ply in (m) .
$\overline{Q}_{ij}$:lamina stiffness in (N/m²).

4. Generalized Mass and Generalized Stiffness

The generalized mass and generalized stiffness are derived from the theory of the normal mode and orthogonality relation by following the procedure of [Thomson 1997],the expression for the generalized mass (M_i) and generalized stiffness (k_i) in the i-th mode of the cantilever wing ,respectively are as follows;

$$M_i = \int_0^1 (m H_i^2 - 2m x_\alpha H_i \Psi_i + I_\alpha \Psi_i^2)d\zeta \quad (18)$$

$$k_i = \omega_i^2 M_i \quad (19)$$

Where H_i , Ψ_i and ω_i are natural bending mode,torsion mode and the natural frequency respectively.

5. Unsteady Aerodynamic Load on Two Dimensional Airfoil

Fig.3 shows a strip of unit span in incompressible flow, the airfoil has two degree of freedom a vertical translation (*h*) called bending positive upward ,and a rotation (*ψ*),called pitching ,positive if leading edge nose up about the elastic axis which is located at distance (ab) from the mid chord, where (b) is the semi chord , (a) being positive toward the trailing edge . The Theodersen's expression for the unsteady lifting force and pitching moment about the elastic axis can be expressed as follows(Hodges and pierce 2009);

$$\overline{L} = 2\pi V b C(k)[V\psi - \dot{h} + b(\frac{1}{2} - a)\dot{\psi}]$$
$$+ \pi\rho b^2(V\dot{\psi} - \ddot{h} - ba\ddot{\psi})$$

$$\overline{M} = 2\pi\rho V b^2(a + \frac{1}{2})C(k)[V\psi - \dot{h} + b(\frac{1}{2} - a)\dot{\psi}]$$
$$- \pi\rho b^2[Vb(\frac{1}{2} - a)\dot{\psi} + ba\ddot{h} + b^2(\frac{1}{8} + a^2)\ddot{\psi}]$$

$$(21)$$

k: reduced frequency parameter, $k = \dfrac{\omega b}{V}$ $\quad (22)$

V: air speed (m/s).
ω : frequency of oscillation (rad/s).
b: semi chord (m).
a: elastic axis location from the mid chord(m/m).
ρ: air density (kg/m³).

C(k): Theodersen Function can be expressed as (Zhanming 2001);

$$C(k) = \frac{(0.021573 + 0.210400k + 0.512607k^2 + 0.500502k^3)}{(0.021508 + 0.251239k + 1.035378k^2 + k^3)}$$
$$- i\frac{(0.001995 + 0.327214k + 0.122397k^2 + 0.000146k^3)}{(0.089318 + 0.934530k + 2.481481k^2 + k)^3}$$

927

(23)

6. Generalized Aerodynamic Coefficients

The generalized aerodynamic force and moment of the cantilever wing had been formulated by the principle of the virtual work .The generalized aerodynamic forces can be expressed as follows (Mayuresh J.Patil 1997);

$$\{Q\} = \omega^2 \int_0^1 [\Phi]^T [A][\Phi] d\zeta \{q\} = \omega^2 [QA]\{q\}$$

(23)

Or eq.(23) can be expressed as (Banerjee 2000);

$$Q_{ij} = \int_0^1 (A_{11} H_i H_j + A_{12} H_j \Psi_i$$

(24)

$$+ A_{21} H_i \Psi_j + A_{22} \Psi_i \Psi_j) d\zeta$$

Where

$$A_{11} = -\pi\rho\,\omega^2 \frac{b^2}{k^2}(-k^2 + 2C(k)ik)$$

$$A_{12} = \pi\rho\,\omega^2 \frac{b^3}{k^2}[(a\,k^2 + ik) + 2C(k)(1 + ik(0.5 - a))]$$

$$A_{21} = -\pi\rho\,\omega^2 \frac{b^3}{k^2}[2C(k)ik(0.5 + a) - a\,k^2]$$

$$A_{22} = \pi\rho\,\omega^2 \frac{b^4}{k^2}[2(0.5 + a)C(k)(1 + ik(0.5 + a))$$

$$+ \frac{k^2}{8} + k^2 a^2 + (a - 0.5)ik]$$

(25)

7. Formlation of The Flutter Problem

Lagrange equation of motion can be written in the form(Mayuresh J.Patil 1997);

$$[M]\{\ddot{q}\} + [K]\{q\} = \omega^2 [QA]\{q\}$$

(26)

Where

[M] and [K] are n×n diagonal matrices of generalized mass and generalized stiffness (with i-th diagonal representing M_i and k_i) ,[QA] is the complex n×n generalized aerodynamic matrix.

8. Structural Damping

 The eq. (26) gives the equation of motion of a wing in an airstream. But, the aerodynamic model chosen, is valid only for simple harmonic motion. So to   force the system   to   undergo Harmonic oscillations, an artificial structural damping term is added. The structural damping is known as to be a force proportional to the displacement but in-phase with velocity. For a system undergoing simple harmonic motion ,the structural damping force (FD=i×constant =igK) ,where (K) is stiffness and (g) is an artificial structural damping .Adding artificial structural damping to our system ,eq.(26) becomes (Mayuresh J.Patil 1997);

$$[K]^{-1}([M] + [QA])\{\bar{q}\} = \lambda\{\bar{q}\}$$

(27)

Where

$$\lambda = \frac{(1 + ig)}{\omega^2}$$

(28)

9. Solution Of The Flutter Equation

Eq.(27) is an eigenvalue problem which represent the flutter equation to be solved ,in the present work ,the velocity-damping (V-g) method had been used to compute the flutter speed and the flutter frequency with (MATLAB 6.5) program.

10. Experimental Work

First , a tensile specimens was manufactured according   to   ASTM   D3039   standard dimensions(ASTM International 2011) to calculate the mechanical properties of the laminate .**Fig .4** shows the dimensions of the specimens.   The   composite   wing   was manufactured from woven glass fiber and polyester resin within a dimensions   that are suitable to the wind tunnel test section of the mechanical engineering department of Baghdad University.**Fig.5** shows the wing mounted in the test section.

928

Two strain gauges aligned in spanwise and $45°$ direction had been used to obtain bending and torsional strains, respectively which were attached at the root of the wing and connected to interfacing system work with visual basic program to display the bending and torsion response of the wing on the monitor of the computer .The air speed in the wind tunnel was calculated by using Manometer and Pitot static tube .Bernoulli equation is applied between two point in the test section ,thus the air speed can be calculated from the following relation;

$$V = \sqrt{2\,g_1\,h\frac{\rho_w}{\rho_a}} \qquad (29)$$

Where the subscript w,a represent water and air respectively.
ρ : density (kg/m^3).
g_1 : gravity acceleration (m/s^2).
h : water head (m) of the Manometer.

10.Results

The wing of (Suleman 2007) was scaled by(1/2.2),**Table 1** show the characteristics of the wing of the present work.

10.1 Material Properties of the Wing

The mechanical properties of the composite were calculated by the tensile test and stated in **Table 2**.

10.2 Validity of the Test Procedure

Table 3 shows the comparison of the flutter speed and the flutter frequency for the Goland wing.

10.3 The Effect of Ply Orientation on the Flutter Speed

The structural model is a composite beam load carrying structure . This composite beam was stacked for different ply orientation and the flutter speed was computed for each ply . The properties of the manufactured composite wing are;

Width of the beam d = 60.5 mm.
Thickness of the beam t = 4.24 mm.
Number of layers N = 8 .
Ply thickness t_k = 0.53 mm.
Mass of the wing m = 0.68 kg/m .
Polar moment of inertia about the elastic axis I_α =

2.75×10^{-4} kg.m .
Elastic axis location from the mid chord a =-0.39.
Distance between elastic and mass axis x_α = 9.5mm.

In the first ply ,all layers (8 layers) ,were orientated along common direction(θ=-20$°$),thus the first ply was [-20]$_8$, the natural frequencies at this ply and the corresponding normal mode shapes are shown in **Fig. 6**.

Substitute those three natural frequencies and mode shapes in the (V-g) method ,from **Fig. 7** the flutter speed is (V_F=67.85m/s) , and from **Fig. 8** the flutter frequency is (ω_F=134 rad/s).

The results of the flutter speed and the flutter frequency for different ply orientation are summarized in **Table 4.**

11. Experimental Flutter Results

Fig. 9 shows the response of the   composite wing at air speed (V=55.15 m/s) , it is obvious that   the amplitude is with increasing with time history , this motion indicate the unstable case , so that this speed may be represent as a flutter speed .**Table 5** states the comparison between the theoretical and experimental flutter speed and the relative error**.**

12. Discussion

From the free vibration results it is clear that the use of fibrous materials in the design of composite wing produce the bending- torsion coupling. In this analysis both the material and geometric coupling were taking into account . The results in **Table 4** state that the stiffness of composite wing depend on the fiber direction with respect to reference line ,therefore may be obtain different values of bending rigidity ,torsion rigidity and coupling rigidity for different fiber orientation , also the location of the specific layer from the geometric mid plane is of major effect on the stiffness of the composite wing .

it is clear that the selection of fiber directions that increase in bending rigidity (which has maximum value when the fiber orientation(0^0 or 90^0)), attending it decreasing in torsional rigidity which leads to decreasing in the flutter speed. Also it is

to be evident that the torsional rigidity is of the greater effect on the flutter speed of the aircraft wing , thus the flutter speed may be increased by increasing the torsion rigidity which is reached it's maximum value when the fiber orientation (45^0 or $-45^{0)}$, while the fiber orientation (0^0 or 90^0) produce minimum torsional rigidity . It is may be conclude that the fiber direction (45^0 or -45^0) is preferable in the aeroelastic tailoring of composite wing because it is produce high torsional rigidity , as a results the flutter speed is increase. From the calculated results it is shown that the coupling rigidity reached its maximum value when the fiber orientation (25^0 or -25^0), while the bending and torsion are materially decoupled when the fiber orientation(45^0 or 0^0 or 90^0 or -45^0).The selection of fiber orientation that produce high coupling rigidity don't attend it increase in the flutter speed . The ply $[-25]_8$ has a maximum coupling rigidity , but at this ply the flutter speed is low in comparison with the flutter speed at another plies as shown in **Table 4**,   despite that , the coupling rigidity has clear effect on the increasing in the flutter speed ,this effect may be shown in the two plies , the first $[45/-45/45/-45]_S$ has a flutter speed (V_F=99m/s) and K=0 with higher torsional rigidity, the second $[45/-45/45/30]_S$ which has a flutter speed (V_F=101.88m/s) and K=-0.022 Nm$^{2.}$ In this analysis the calculated results states that the best combination   of ply orientations to increase the flutter speed, is the ply of high torsional rigidity with low minus coupling rigidity.

13. Conclusion

The main conclusions may be obtained from this study are;

1-The stiffness of composite wing depends on the fiber orientation , also the location of the individual layer from the geometric mid plane has the significant effect on the stiffness of composite wings.

2-For the woven E-glass in the case $(E_1 = E_2)$, the bending and torsion are decoupled $i.e (K = 0)$ when the ply angle is one of the four orientations ($0^\circ or - 45^\circ or \, 45^\circ or \, 90^\circ$) .while   for   the unidirectional fiber , the bending and torsion are decoupled when the fiber orientation ($0^\circ \text{ or } 90^\circ$).

3-The   fiber   orientation $(\theta = 0^\circ \text{or } 90^\circ)$ gives maximum bending rigidity, the fiber orientation

$(\theta = 45^\circ \text{ or} - 45^\circ)$ gives maximum torsion rigidity while the fiber orientation $(\theta = 25^\circ \text{ or} -25^\circ)$ gives maximum coupling rigidity.

4-In comparison with the bending rigidity , both the torsional and the coupling rigidities have much more significant effect on the flutter speed of a composite wing .The torsional rigidity plays a relatively more dominant role in aeroelastic tailoring. Increasing in torsional rigidity (GJ) leads to increase in the flutter speed.

5-The desirable combination of fiber orientations, relatively large torsional rigidities with a relatively small coupling rigidity, this combination will increase the flutter speed.

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10

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Symbols

a :elastic axis location(-).
d:chord of the laminate(m).
EI:bending rigidity(Nm^2).
GJ:torsion rigidity(Nm^2).
K:coupling rigidity(Nm^2).
h:bending displacement(m).
H: normalized bending mode(-).
Ψ : normalized torsion mode (-).
k:reduced frequency parameter(-).
m:mass(kg).
x_α:mass axis location(m).
I_α:polar moment of inertia(kg.m).
h_k:location of the layer from the geometric mid plain(m).
V:air speed(m/s).
L: wing length (semi span)(m).
b:semi chord of the wing(m).
g:artificial structural damping(-).
g_1:gravity acceleration(m/s^2).
ζ:normalized length(-).
ω:frequency(rad/s).
ψ:torsion rotation(rad).
ρ:density(kg/m^3).
$\Theta(\zeta)$:bending rotation(rad).
$S(\zeta)$:shear force(N).
$M(\zeta)$:bending moment(N.m).
$T(\zeta)$: torque(N.m).
H :amplitude(m)
Ψ:amplitude(rad)
$A_1 \ldots A_6$:constants
$\overline{Q}_{ij}$:lamina stiffness (N/m^2).

z_k is the distance from the geometric mid plane to the center of the kth ply in (m) .
N :number of layers.
t_k : the thickness of the kth ply in (m) .
A.C: aerodynamic center.
E.A: elastic axis
c.g.: center of gravity.
ρ_w: water density(kg/m^3).
ρ_a: air density(kg/m^3).
g_1: gravitational acceleration (m/s^2).
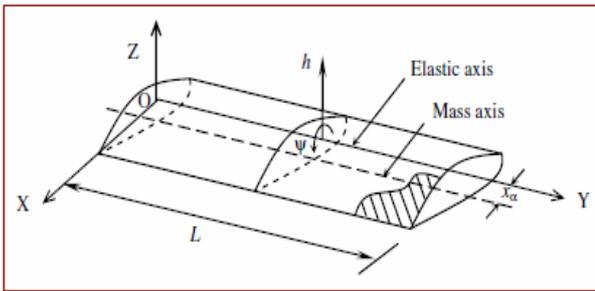C(k): Theodersen function.
q: generalized coordinates

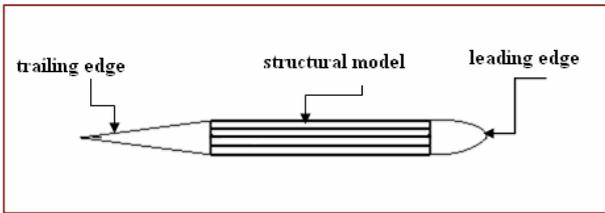Fig. 1 Coordinate of the composite wing.

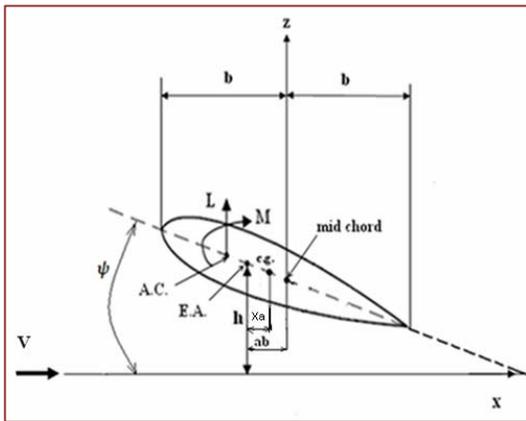Fig.2 Composite wing structural model (laminated beam) .

Fig.3 Two-dimensional typical section in
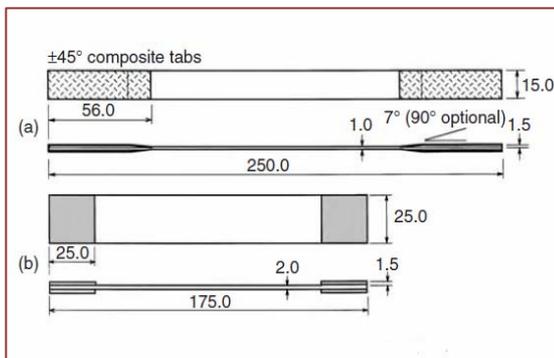
incompressible flow.

Fig.4 The standard dimensions of the specimens(mm). (a) Fiber Direction 0^0 .(b)Fiber Direction 90^0 or 45^0

Fig.5 The composite wing mounted in the test section

Table1 characteristic of the wing model.

| Semi span (m)	0.55
Chord(m)	0.1
Section profile	NACA 0006
shape	rectangular

Table 2 mechanical properties of the composite.

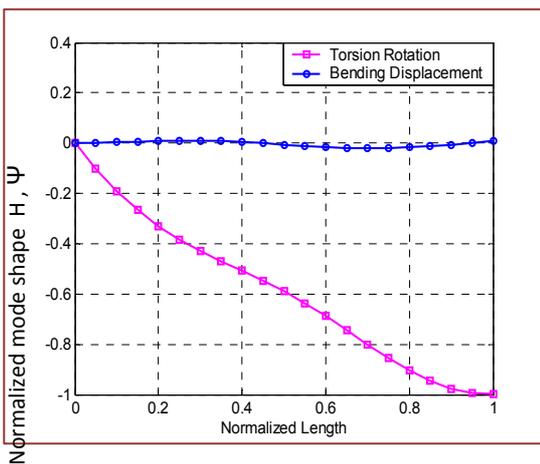| E_1(Gpa)	10.2
E_2 (Gpa)	10.2
G_{12} (Gpa)	1.767
ν_{12}	0.1
Density ρ_m (kg/m^3)	1800
Fiber volme fraction vf	0.5

Table 3 comparison the results for the Goland wing

Reference	flutter speed (m/s)	flutter frequency (rad/s)
(Mayuresh J.Patil 1999)	135.63	70.2
(Eric L.Brown 2003)	136.24	69.7
present	135.71	70.21
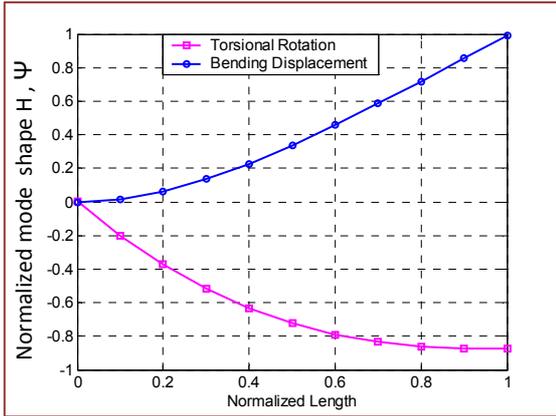
a first mode (ω_1=23.5711 rad/s).
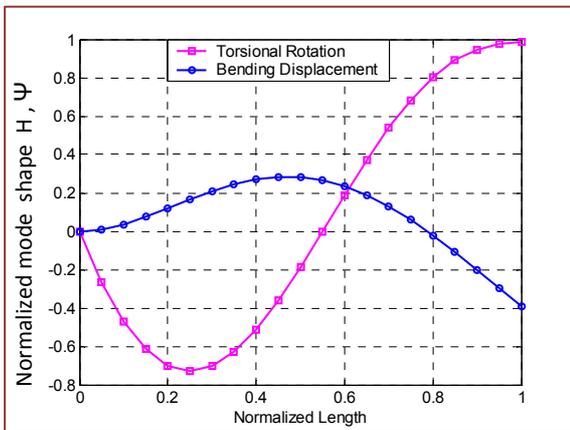
b second mode (ω_2 =147.1107 rad/s) .

c third mode (ω_3 =395.74673 rad/s).

Fig. 6 The three fundamental normal modes with
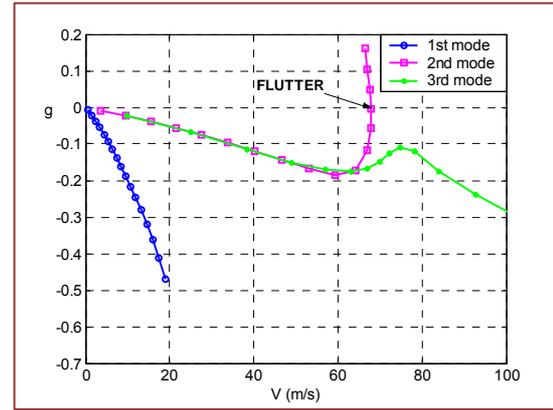
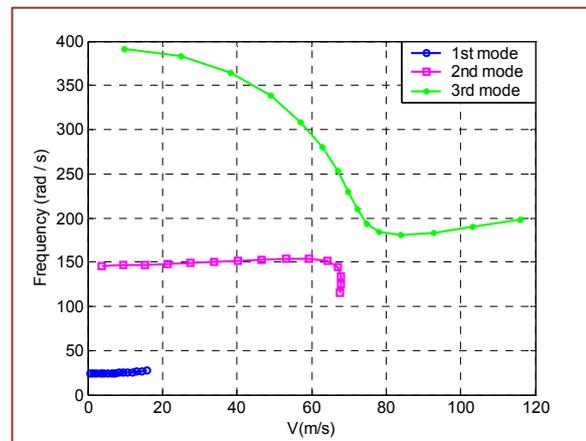[-20]$_8$ lay up

Fig. 7 (V-g) graph with [-20]$_8$ lay up.

Fig. 8 (V-F) graph with [-20]$_8$ lay up.

Table 4 flutter speed and flutter frequency for
different ply orientation.

Ply angle θ (degree)	Effective rigidities (Nm^2)	Natural frequency (rad/s)	Flutter speed (m/s) Flutter frequency (rad/s)
[-20]$_8$	EI=3.296 GJ=4.202 K=1.349	ω_1=23.571 ω_2=147.110 ω_3=395.747	V_F=67.85 ω_F=134
[0/30/30/0]$_S$	EI=3.475 GJ=4.018 K=-0.466	ω_1=26.161 ω_2=163.202 ω_3=391.573	V_F=70 ω_F=182.5

Table 4 flutter speed and flutter frequency for different ply orientation.

$[45/0/45/0]_S$	EI=2.785 GJ=5.748 K=0	ω_1=23.516 ω_2=147.059 ω_3=409.903	V_F=87 ω_F=186.65
$[0/45/0/45]_S$	EI=3.463 GJ=4.094 K=0	ω_1=26.215 ω_2=163.646 ω_3=395.571	V_F=71 ω_F=183.57
$[-25]_8$	EI=2.983 GJ=4.948 K=1.427	ω_1=22.368 ω_2=139.729 ω_3=387.316	V_F=72.742 ω_F=125.07
$[45/-45/45/-45]_S$	EI=2.070 GJ=7.127 K=0	ω_1=20.278 ω_2=126.923 ω_3=354.617	V_F=99 ω_F=197
$[45/30/45/-45]_S$	EI=2.255 GJ=6.772 K=-0.420	ω_1=21.086 ω_2=131.941 ω_3=368.516	V_F=99.286 ω_F=192.55
$[45/-45/45/-30]_S$	EI=2.080 GJ=7.109 K=0.022	ω_1=20.324 ω_2=127.212 ω_3=355.416	V_F=98.88 ω_F=195.83
$[45/-45/45/30]_S$	EI=2.080 GJ=7.109 K=-0.022	ω_1=20.329 ω_2=127.240 ω_3=355.496	V_F=101.88 ω_F=195.13

Table 5 the comparison between the theoretical and experimental flutter speed and the relative error.

Ply orientation	V_F(m/s) theoretical	V_F(m/s) experimental	Error
$[-20]_8$	67.85	55.15	18.7%

Volt(v)

Time(sec)
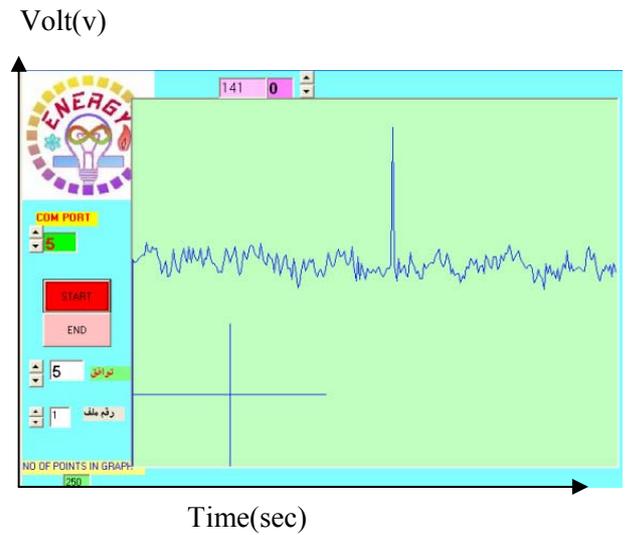
9a Bending response

Volt(v)

Time(sec)
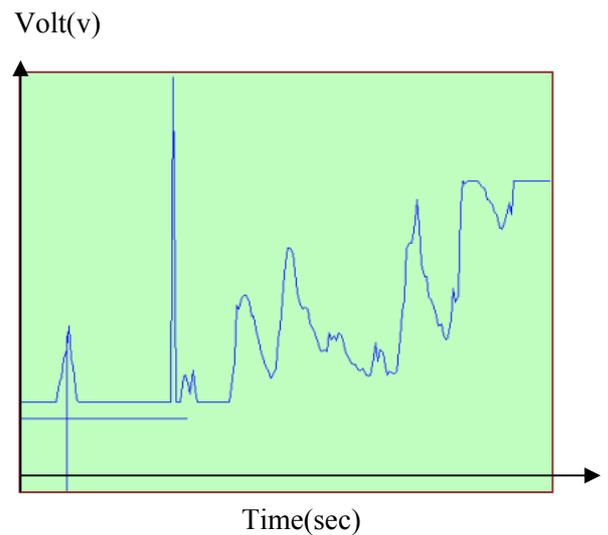
9b Torsion response

Fig. 9 Bending and torsion response when (V=55.15m/s).