International Journal of Mechanical Engineering and Applications
2015; 3(1-3): 35-40
Published online January 19, 2015 (http://www.sciencepublishinggroup.com/j/ijmea)
doi: 10.11648/j.ijmea.s.2015030103.16
ISSN: 2330-023X (Print); ISSN: 2330-0248 (Online)

Design of aeroelasticity bench test for NACA0012 wing model in the low speed wind tunnel: Influence of wing's parameters on flutter speed

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To cite this article:
Thi Tuyet Nhung Le, Chi-Cong Nguyen, Hoang Nam Vang. Design of Aeroelasticity Bench test for NACA0012 Wing Model in the Low Speed Wind Tunnel: Influence of Wing's Parameters on Flutter Speed. *International Journal of Mechanical Engineering and Applications.* Special Issue: Transportation Engineering Technology. Vol. 3, No. 1-3, 2015, pp. 35-40. doi: 10.11648/j.ijmea.s.2015030103.16

Abstract: The purpose of this study is to calculate the geometries parameters for a wing NACA0012 as well as its materials in order to observe the instability of aeroelasticity such as divergence and flutter phenomenon in the low speed wind tunnel (38 m/s). Approaches used are the theories of aeroelasticity for the static and dynamic instability problem of the wing. The 3D divergence problem is solved first by strip theory to preliminary design the non-tapper wing and the suitable material for static instability at low speed. The V – g method for flutter analysis is carried out to verify the dynamic instability speed designed. A wing with wing chord, wing length is obtained in accordance with the testing section of the considered wind tunnel, and the suitable material is PU. The preliminary design were carried out for the the divergence phenomenon and divergence speeds can be observed at 30.34 m/s [10]. This study continues with the results based on dimensionless analysis of wing's parameters on flutter speed.

Keywords: Aeroelasticity, Bench Test for NACA0012, Flutter velocity, V – G Method

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1. Introduction

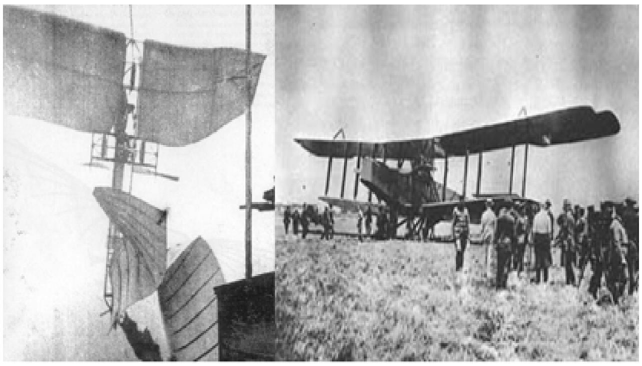

Figure 1. Langley Flyer and Hanley-Page O/400 bomber [1].

The study of flutter and aeroelasticity in general is of utmost importance to the aerospace industry in the early days of flight. Two historical failure cases are indicative of the two major aeroelastic failure modes: static instability and dynamic instability [1]. The first recorded and documented occurrence of aircraft flutter was the Handley Page O/400 bomber in 1916 by F. W. Lanchester as shown in Fig. 1.

This is an example of a combination of two or more modes of vibration coalescing to extract energy from the airstream to create flutter. The case of the Langley flyer failure points to a case of static aeroelastic of the wing structure once the aerodynamic forces caused the wing to twist beyond the structural restoring moment capacity [1]. Therefore, research about aeroelasticity phenomenon in aircraft design is very important. So the purpose of this study is design of aeroelasticity bench test for NACA0012 wing model to observe and study about static aeroelasticity (divergence) and dynamic aeroelasticity (flutter) phenomenon in the low speed Ho Chi Minh City University of Technology wind tunnel facility with the cross sectional area of 400 x 500 mm, the length of 1000 mm and the maximum velocity of 38 m/s.

Theodorsen has investigated the mechanism of flutter by formulating it through pitching and plunging motion of airfoils in two dimensional flows in 1934 [2]. In which, Theodorsen used linear unsteady aerodynamic model for aerodynamic forces. The result of this theoretical method was compared with the experimental data given in [3,11] by Theodorsen and Garrick. At early times the aerodynamic forces were formulated by one dimensional piston theory or strip theory [4] which was first formulated by Ashley and Zartarian. The most common application of the strip theory was formulated as modified for predicting wing flutter at subsonic to hypersonic speeds by Yates [5]. The aerodynamic models used in this study for aeroelastic prediction are linear unsteady aerodynamic model. It's is an unsteady extension of the quasi-steady thin airfoil theory to include added-mass forces and the effect of wake vorticity [6]. The aerodynamic forces are represented as functions of non-dimensional coefficients with small variation in angle of attack and attached flow. Linearized aerodynamic theories were pioneered by Theodorsen [2] and Collar [7], and serve as a foundation of aeroelastic analysis.

In our study, the geometries parameters of a wing NACA0012 is calculated as well as its materials in order to observe the divergence and flutter phenomenon in the low speed wind tunnel (38 m/s). Strip theory is used to solving the divergence problem for rectangular wing ignore the mass. Based on the geometry have found in the static aeroelastic, the velocity flutter is calculated by V – g method with the theoretical aerodynamic model of Theodorsen. We construct V – g – ω plots and flutter speed V_F is the lowest velocity at which a structure damping "g" branch becomes positives.

The preliminary design were carried out for the divergence phenomenon and divergence speeds can be observed at 37.98 m/s for material Polyurethane elastomer Soybean [10]. In this paper, the material Polyurethane elastomer was chosen for the reason of fabrication. The study continues with the results based on dimensionless analysis of wing's parameters on flutter speed.

2. Theoretical analysis

2.1. Applications of Strip Theory to Calculate the Static Aeroelasticity

Based on the theoretical of cross-sectional area in two dimensional, the theoretical of three dimensional wing was built [8]. Since, we apply to a wing which has span, b/2; chord, c; torsional stiffness, GJ (see Fig. 2) to calculate divergence speed, V_D. Normally we use two methods which are strip theory and panel method.

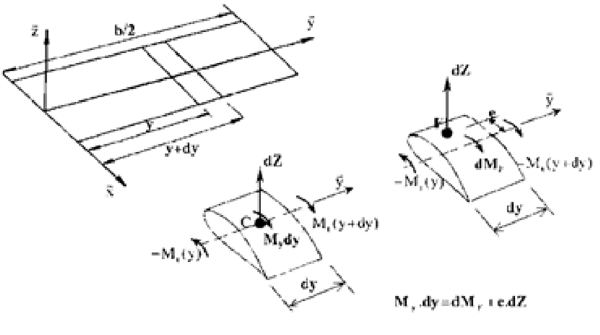

Figure 2. Strip theory.

Strip theory break the wing into spanwise small strips [5]. The lift and pitching moment acting on each strip are given by the 2D sectional lift and moment theories. Panel theory replaced the wing by its camber surface [1]. The surface itself was replaced by panels of mathematical singularities, solutions of Laplace's equation.

Strip theory is choosen to solve static aeroelastic problem. We assumed that the aerodynamic lift and moment depended only on the angle of attack.

Where,

- α (y) Nose up twist about the elastic axis at station y
- GJ(y) Torsional stiffness
- $M_t(y)$ Twist moment is created by behaviours of meterial and

$$M_t = GJ\frac{d\alpha}{dy}$$

- $M_y(y)$ Aerodynamic moment about elastic axis

The equation of static moment equilibrium is

$$-M_t(y) + M_t(y+dy) + M_y dy = 0$$

$$\text{or } \frac{dM_t}{dy} + M_y = 0$$

Thus,

$$\frac{d}{dy}\left(GJ\frac{d\alpha}{dy}\right) + M_y = 0 \qquad (1)$$

Associated with it are two boundary conditions. The boundary conditions are

$$\alpha = 0 \ at \ y = 0 \ and \ M_t = 0 \ at \ y = b/2 \qquad (2)$$

Applying boundary conditions, the divergence occurs when α → ∞ and we have

$$q_D = \frac{\left(\frac{\pi}{2}\right)^2 .GJ}{\left(\frac{b}{2}\right).S.e.\frac{\partial C_z}{\partial \alpha}} \qquad (3)$$

And then, the divergence airspeed is

$$V_D = \sqrt{\frac{2q_D}{\rho}} \qquad (4)$$

With a rectangular wing, if we have the necessary parameters which are length, L; chord, c; torsional stiffness, GJ we can calculate the divergence speed, V_D by the formula (4). Hence, we can design an aircraft's wing according to the parameters which are found and they are suitable to the speed of the wind tunnel which has known.

2.2. Solving Flutter Problem by V-G Method

In this section, we focus on solving the problem of dynamic instability that particular flutter phenomenon. Flutter is a phenomenon mechanical vibrations dynamic instability; the wing structure will be destroyed when aircraft move over critical velocity. Flutter phenomenon occurs under influence of the three forces: inertia forces, elastic forces and aerodynamic forces. In this article, V – g methods is used to calculating the necessarily velocity at which occur flutter phenomenon through eigenvalues problem [9].

2.2.1. Structural Model

The structural model used in this paper is the solid wing show in Fig. 3.

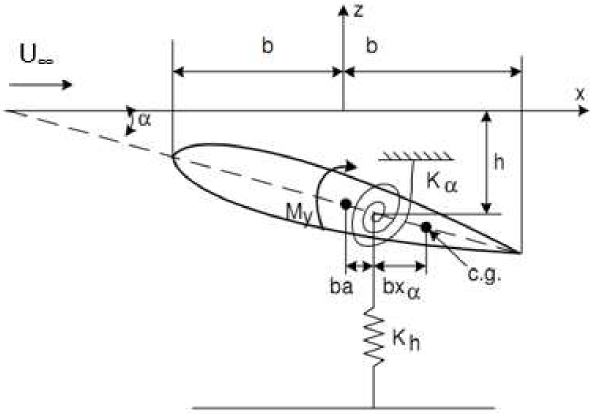

Figure 3. *Geometry of the wing cross-section.*

Building the Lagrange equations with 2 modes is the vertical displacement h and the twisting displacement α. Lagrange equations is expressed by generalized coordinates and linear independence.

$$\sum_i\left[-\frac{d}{dt}\frac{\partial(T-U)}{\partial \dot{q}_i}+\frac{\partial(T-U)}{\partial \dot{q}_i}+Q_i\right]\times\partial \dot{q}_i\,dt=0$$

Where T is the kinetic energy of the system, U is the potential energy of the system, q_i are generalized coordinates.

Through Lagrange equations we determine the equations of motion:

$$\begin{cases} m\ddot{h}+K_h h+S_\alpha\ddot{\alpha}=-L \\ S_\alpha\ddot{h}+I_\alpha\ddot{\alpha}+K_\alpha\alpha=M_{ac}+L\left(\frac{b}{2}+ba\right)=M_y \end{cases} \tag{5}$$

Where L and M_y respectively lift and aerodynamic moment at aerodynamic center, "m" is the mass per unit wing span, I_α is the mass moment of inertia, S_α is static mass moment per unit span.

And uncoupled natural bending frequency, uncoupled natural torsional frequency is:

$$\omega_h^2=\frac{K_h}{m};\quad \omega_\alpha^2=\frac{K_\alpha}{I_\alpha}$$

2.2.2. Aerodynamic Model

In order to replace L and M_y into (5), Theodorsen's model is used. Theodorsen's model includes these added-mass forces and multiplies the quasi-steady lift from thin airfoil theory by a transfer function C(K) to account for lift attenuation by the wake vorticity [6]. Based on the model of Theodorsen aerodynamics, aerodynamic lift and moment are written by Theodorsen's and moment are written by Theodorsen's function C (K)

Where reduced frequency.

$$K=\frac{\omega b}{U_\infty}$$

$$\begin{cases} L=\pi\rho b^2\left[\ddot{h}+U_\infty\dot{\alpha}-ba\ddot{\alpha}\right] \\ \quad +2\pi\rho U_\infty bC(k)\left[\dot{h}+U_\infty\alpha+b\left(\frac{1}{2}-a\right)\dot{\alpha}\right] \\ M_y=\pi\rho b^2\left[ba\ddot{h}-U_\infty b\left(\frac{1}{2}-a\right)\dot{\alpha}-b^2\left(\frac{1}{8}+a^2\right)\ddot{\alpha}\right] \\ \quad +2\pi\rho U_\infty b^2C(k)\left(\frac{1}{2}+a\right)\left[\dot{h}+U_\infty\alpha+b\left(\frac{1}{2}-a\right)\dot{\alpha}\right] \end{cases} \tag{6}$$

Where *"a"* is the pitch axis location measured in semi-chord with respect to the mid-chord, b is a half-chord length and U_∞ is the free-stream velocity.

In case of oscillations system consider damping and variables change over time, we put

$$\begin{cases} h=\bar{h}e^{i\omega t} \\ \alpha=\bar{\alpha}e^{i\omega t} \end{cases} \tag{7}$$

With

$$g_h=\frac{\omega C_h}{K_h};\quad g_\alpha=\frac{\omega C_\alpha}{K_\alpha}$$

are damping coefficients in the bending and twisting.

Replace (6) and (7) into equation (5) we obtain

$$\underbrace{\begin{pmatrix} A & B \\ D & E \end{pmatrix}}_{Qmatrix}\begin{bmatrix} \bar{h}/b \\ \alpha \end{bmatrix}=0 \tag{8}$$

in that,

$$A=\mu\left[1-\left(\frac{\omega_h}{\omega}\right)^2\left(1+ig_h\right)\right]+L_h$$

$$B=\mu X_\alpha+L_\alpha-L_h\left(\frac{1}{2}+a\right)$$

$$D=\mu X_\alpha+M_h-L_h\left(\frac{1}{2}+a\right)$$

$$E=\mu r_\alpha^2\left[1-\left(\frac{\omega_\alpha}{\omega}\right)^2\right]+M_\alpha-\left(L_\alpha+M_h\right)\left(\frac{1}{2}+a\right)+L_h\left(\frac{1}{2}+a\right)^2$$

The coefficient as a function of C(k)

$$L_h=1-\frac{2i}{k}C(k)$$

$$L_\alpha=\frac{1}{2}-\frac{i}{k}\left(1+2C(k)\right)-\frac{2C(k)}{k^2}$$

$$M_\alpha=\frac{3}{8}-\frac{i}{k} \qquad M_h=\frac{1}{2}$$

C(k) is the transfer function of Theodorsen theory, we compute eigenvalues λ of the system of equations (9).

Flutter occurs when g start positive, with λ the solution of the equation $\det\left(Q(k)\right)=0$. So Flutter velocity is calculated:

$$V_F=\frac{b\omega_\alpha}{k\sqrt{\lambda}} \tag{9}$$

3. Modeling and Results

From the theoretical of static aeroelasticity and dynamic aeroelasticity, the geometric dimensions of model are built to fit with the size of wind tunnel. The velocity divergence and velocity flutter must be less than the maximum speed of the wind tunnel 38 m/s.

3.1. Calculate the Geometric Parameters of the Wing

In the velocity divergence equation, we see that V_D depends on the material, typical section and length of wing span (L).

$$V_D=\sqrt{\frac{2\left(\frac{\pi}{2}\right)^2 GJ}{\rho.L.S.e.\frac{\partial C_L}{\partial\alpha}}} \tag{10}$$

The parameters need to be changed to achieve divergence velocity less than 38 m/s

Reduce polar moment of inertial J, shear module G

Increased length of wing span L, distance between the aerodynamic center and elastic center "*e*"

The steel bar $\phi 4$ (r = 2 mm) penetrate along the length of wing at 0.35c from leading edge. This elastic axis is put in the position shown Fig. 4 because the flutter phenomenon can occurs when elastic center is in front of gravity center of airfoil according to Pines rules [8]. Use the loop to find the geometric parameter follow 2 steps below:

Step1: Fixed material, changing the geometry c, L, J, e to find the velocity divergence

Step 2: Change the material, change size and geometry similar step 1.

Three different materials are used: Epoxy and PU plastic. We find the profile of wing with chord length c = 100 mm as shown in Fig. 4 and type of material in table 1 with elastic center between aerodynamic center and center of gravity, e=0.1c.

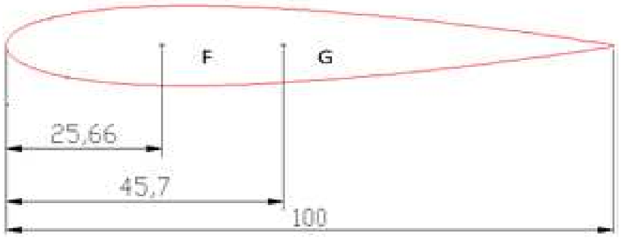

Figure 4. *Airfoil c = 100 mm.*

Table 1. *Table of materials results*

No.	c = 100mm		
	Material	**L (m)**	**V_D (m/s)**
1	Epoxy	0.4	550
2	Polyurethane elastomer	0.4	30.34
3	Polyurethane elastomer Soybean	0.4	14.55

From table 1, the material $N^0 2$ and $N^0 3$ are corresponded with test section of wind tunnel. We choose the material $N^0 2$ Polyurethane elastomer because of two main reasons. Firstly, Polyurethane elastomer is popular in the market, so it is easier for fabrication. Secondly, divergence speed of $N^0 3$ is too small; it may have the difficulty in observation of flutter phenomenon. The divergence velocity of material $N^0 2$ is 30.34 m/s at length of wing span L = 0.4m.

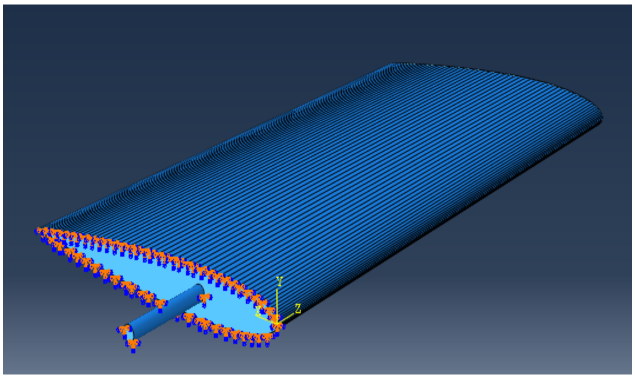

Figure 5. *3D model in ABAQUS.*

3.2. Calculate flutter velocity

From the parameters and material of the wing calculated in the static aeroelasticity, we apply Theodorsen's model with structural damping "*g*" to find out the velocity of flutter.

Table 2. *Table of parameters*

Parameters	Values
Chord length “c”	0.1 m
Wing span “L”	0.4 m
Young’s Module “E”	25.10^6 Pa
Wing mass “m”	0.35 Kg

Put

$$\lambda = \left(\frac{\omega_\alpha}{\omega}\right)^2 (1+ig) = \lambda_R + \lambda_I$$

We find the eigenvalues of the Q(k) matrix.

$$\det Q(K) = \left|\begin{pmatrix} A & B \\ D & E \end{pmatrix}\right| = 0$$

For each value of K we find the eigenvalues of the Q(K) matrix follow the diagram in Fig. 6.

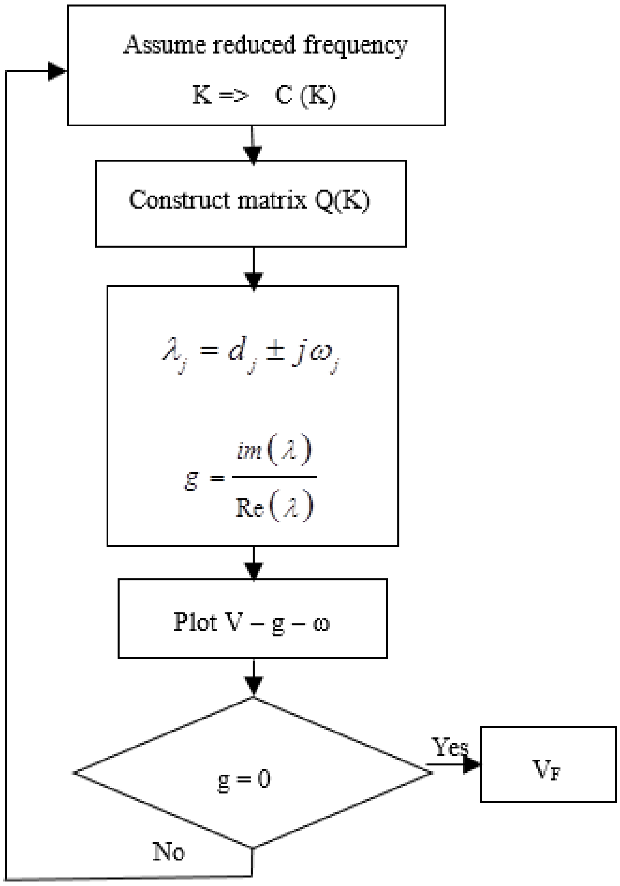

Figure 6. *Calculate flutter velocity diagram.*

Analysis dimensionless of wing’s parameters were carried out, thus the ratio of Flutter velocity dimensionless $V_F/b\omega_\alpha$ versus damping “g” was presented in Fig. 7.

At those precise values:

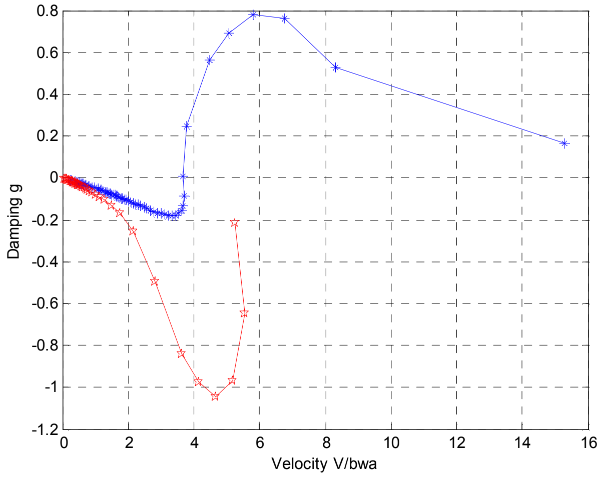

Figure 7. *The graph of velocity.*

The flutter speed is obtained at the point where value of “g” for the structure is zero

$$\frac{V_F}{b\omega_\alpha} = 3.68$$

Flutter velocity dimensionless can be plotted against frequency-dimensionless of the system, location

$$\frac{V_F}{b\omega_\alpha} = 3.68$$

as Fig. 8.

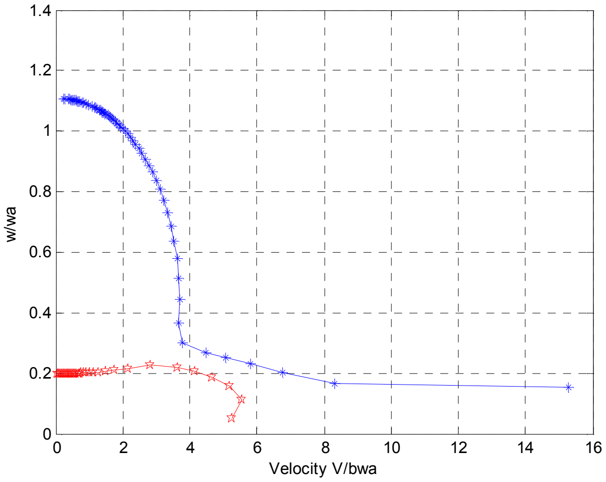

Figure 8. *The graph of velocity versus ratio frequency.*

Based on the graph we can identify the Flutter velocity for different oscillation frequency of systems by simulating them on the finite element software.

4. Conclusion

A two-degree of freedom aeroelastic test bench has been designed .The study presented the aeroelasticity bench test design process and optimize this design. Based on strip theory and V – g method, we design the geometric parameters of the wing fit with the wind tunnel in Ho Chi Minh City University of Technology. This model will be manufactured to research about aero elasticity phenomenon. Thus, If the PU plastic wings have wing chord length c = 0.1 m and length of wing span L = 0.4 m, the divergence could be observed at 30.34 m/s. Dimensionless parameter of wing were analyzed to design the wings parameters for flutter phenomenon.

The development of the project: Manufactured experimental models.

Acknowledgements

The authors would like thank to the Research Fund of Ho Chi Minh City University of Technology for its financial support to the research project T-KTGT-2014-76

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