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SIMULATED FLUTTER TEST OF WINGS

T.Birtan Balevi[1]
1st ASCM
Eskişehir, Türkiye

Altan Kayran [2]
Middle East Technical University
Ankara, Türkiye

ABSTRACT

Flutter is a dynamic instability which can result in catastrophic failures of an air vehicle. Flutter prediction analysis, ground vibration tests and flight flutter tests, are the most important certification processes in modern aviation. Flight flutter testing is a very expensive process. In flight flutter tests, the air vehicle is instrumented with exciters, accelerometers and transmitters to send the test data simultaneously to the ground station to be analyzed. Since flutter is a very severe instability, which develops suddenly, the data should be followed carefully by the engineers at the ground station and feedback should be provided to the pilot urgently when needed. Low test step numbers per flight, increases the cost of flutter testing. Increasing efforts in pre-flight test processes in flutter prediction may narrow the flight flutter test steps and decrease the costs. In this study, flutter prediction methods are investigated to aid the flutter test process for incompressible flight conditions. A simulated flutter test method is introduced utilizing the two dimensional typical section method. It is shown that with a simple two dimensional typical section method, flutter test simulation can be performed successfully as long as the typical section model approximates the dynamic properties of the wing closely.

INTRODUCTION

Flutter is a dynamic instability problem which occurs by the interaction of the elastic, inertia and aerodynamic forces. It can result in catastrophic failure of the wing, winglet, fin, vertical and horizontal stabilizer or any aerodynamic surface that is subjected to it.

The structure's response to the unsteady aerodynamic forces occurs with a damping effect at low speeds. This response increases with speed up to a critical speed level. At this critical speed level some of the structure's elastic modes are coupled by aerodynamic forces. This causes energy transfer from the airflow to the structure which results in increasing oscillations. The amplitude of these oscillations increases violently with a little speed increment so that the person who controls the aircraft may not response before catastrophic failure occurs.

In theoretical background, Theodore Theodorsen introduced the Theodorsen Function C(k), for the steady motion and sinusoidal motion in his report [2]. In this report the wing section is modeled as a flat plate assuming that it oscillates about elastic axis. Theodorsen investigated the effects of the parameters such as mass ratio, bending torsion frequency ratio, dimensionless static unbalance, dimensionless radius of gyration to critical flutter speed and frequency. Theodorsen and Garrick suggested a numerical approach to solve flutter problem and compare their solution with wind tunnel test results in their report [2].

After the work done by Theodorsen and Garrick, various flutter prediction methods are developed by researchers. k-method which is also known as American method or Air Material Command Method in the literature is used by Smilg and Wessermann [3]. In the k-method, an eigenvalue problem is built and solved by the addition of an artificial damping term. In the first half of 1950's Irwin and Guyett presented p-k method which is also known as the British method in literature [4]. P-k method is an approximate method constructed to find out the decay rate. In both methods for solution damping vs. speed curves are plotted, although damping values determined are physically meaningless except around the flutter boundary at which the damping value is equal to zero [5].

[1] Flight Test Engineer, Email: bbalevi@hvkk.tsk.tr
[2] Prof. in the Department of Aerospace Engineering, Email: akayran@metu.edu.tr

Dimitriadis and Cooper investigated the damping variation with airspeed, flutter margin, envelope function and Autoregressive Moving Average-Based (ARMA) methods to predict flutter from flight flutter test data [6]. They introduced simulated flutter test and outlined the steps to perform it.

The main aim of this study is to get the sub-critical damping trend from a simple analysis to aid the actual flutter test planning. In the actual flutter test of aircraft, critical structures such as wing, tail plane are excited by external exciters and damping is estimated either online or off-line for each test speed until the dive speed. The damping trend obtained until the dive speed is then extrapolated to zero damping to predict the flutter speed. Obviously, in simulated flutter test damping estimates can be made until flutter speed. The critical issue in the damping trend is to decide whether the flutter is mild flutter with gradually decreasing damping or explosive flutter with sharp decrease of damping once the flutter speed is approached. Deciding on the flutter type, mild or explosive, is very important to make appropriate plans for the flutter test. Explosive flutter is very dangerous since damping decreases suddenly with slight increases in airspeed. Therefore, in this study with simple 2D typical section models, sub-critical damping trend is studied and demonstration of the simulated flutter test is made via time domain solution of the governing equations of motion to decide on the flutter type, and also on the flutter speed. Flutter speed obtained through simulated flutter test is compared with the results obtained by the k and p-k methods. For this purpose, 2 degree of freedom typical section model is introduced and equations of motions are derived for incompressible flow. A code is generated for flutter solutions using k-method and p-k method. Comparisons of the flutter speed obtained by the frequency domain solution methods k and p-k are made with the simulated flutter test solution to see how closely the simulated flutter solution predicts the flutter speed.

METHOD

Mathematical Modeling of 2 DoF Typical Section Model and Equations of Motion

Figure 1 shows the location and description of the coordinate system used and some dimensional quantities of primary interest in modeling the typical section aeroelastic system. This airfoil is a representative “2 DoF typical section” used by Theodorsen and Garrick in their famous reports [1],[2]. They suggest that for the purposes of theoretical flutter prediction, inertial and geometric properties of a large span and straight wing can be represented by a typical section with inertial and geometric properties of the wing at ¾ of the distance from root of the wing. This suggestion holds where the aspect ratio is large, the sweep is small, and the sectional characteristics vary smoothly across span.

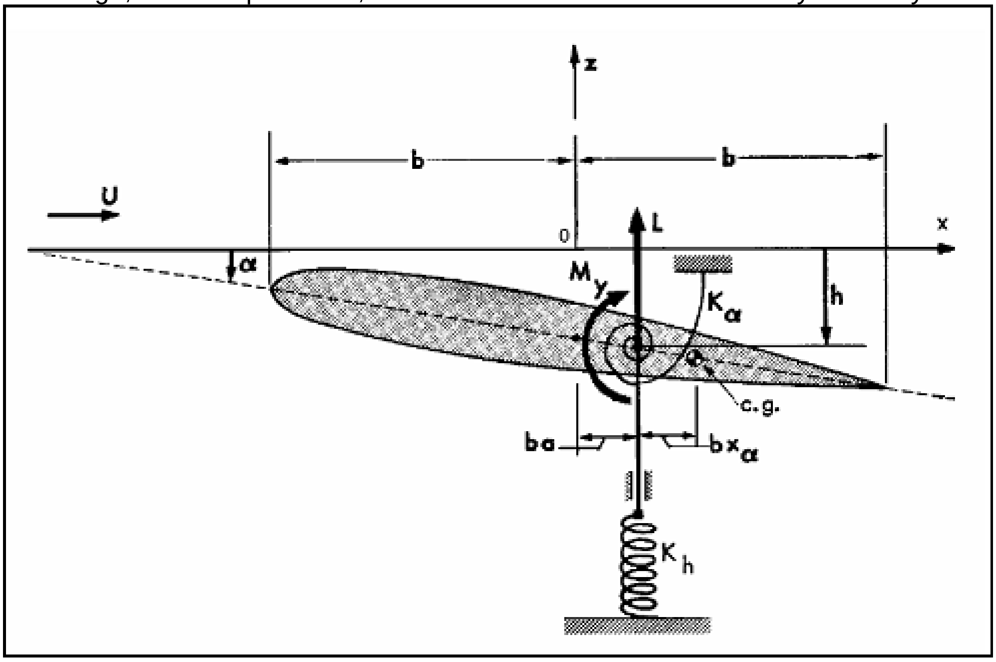

Figure 1. The 2 DoF Typical Section [7]

In Figure 1, z=0 line represents the undeflected airfoil centerline, “b” is the half-chord length, “a” is the ratio of the distance between the centerline and the elastic axis to the half-chord length “b” x_α is the ratio of distance between the elastic axis and the center of gravity of the airfoil to the half-chord length b, h is the deflection of the airfoil in plunge direction and α is the deflection angle in pitch direction. K_h

and K_α are the restraining spring stiffness values in plunge and pitch degree of freedoms, respectively. L is the aerodynamic lift force and M_y is the aerodynamic moment.

The general equation of motion for the typical section model can be expressed in matrix form.

$$[M]\{\ddot{q}\}+[K]\{q\}-\pi\rho_\infty b^3\omega^2[A(k)]\{\bar{q}\}=0 \qquad (1)$$

where [*M*], [*K*], [*A*], {*q*}, ρ_∞, ω are the mass, stiffness and aerodynamic coefficient matrix, generalized coordinates vector, density of air and frequency respectively. In Eq.(1), aerodynamic coefficient matrix is obtained for the simple harmonic motion of the typical section model.

k Method

In this method an artificial damping term is introduced to the aeroelastic system equation. The terms in the equation are simplified by nondimensionalizing and then the simplified equation is solved and the eigenvalues for aeroelastic modes, which is defined as a function of artificial damping, are obtained. The values of damping are obtained for a range of reduced frequencies. The point where the value of this damping goes to positive from negative is the point of flutter. Flutter speed and flutter frequency are obtained after determining this point [8].

p-k Method

In comparison to k-method p-k method is more sophisticated, because in p-k method frequency matching process is performed. It is an iterative process which includes the calculation of the eigenvalue p for a pre-assumed reduced frequency k, and computation of k from the calculated p value until the k values converges. This process is performed for the whole speed range of interest. Then, similar to k-method the graphs, U vs. ω (airspeed versus frequency) and U vs. g (airspeed versus damping) are plotted to find out the flutter speed and the frequency.

Simulated Flutter Test of Wing Based on a Typical Section Model

The main aim of this study is to get the sub-critical damping trend from a simple analysis to aid the actual flutter test planning. In the actual flutter test of aircraft, critical structures such as wing, tail plane are excited by external exciters and damping is estimated either online or off-line for each test speed until the dive speed. The damping trend obtained until the dive speed is then extrapolated to zero damping to predict the flutter speed. Obviously, in simulated flutter test damping estimates can be made until the flutter speed. The critical issue in the damping trend is to decide whether the flutter is mild flutter with gradually decreasing damping trend or explosive flutter with sharp decrease of damping once the flutter speed is approached. Deciding on the flutter type, mild or explosive, is very important to make appropriate plans for the flutter test. Explosive flutter is very dangerous since damping decreases suddenly with slight increases in airspeed. Therefore, with simple 2D typical section models one can study the sub-critical damping trend and decide on the flutter type via simulated flutter test as long as typical section model represents the key parameters of the actual wing closely. However, in any case simulated flutter test approach gives an opportunity to train the flutter test engineer with regard to what actually could happen in an actual flutter test by studying the damping trend.

For simulated flutter test, first lift and moment equations are derived in time domain for a typical wing section model which is used in the simulated flutter test. Non-dimensional time parameter is introduced and the equations of motion for a 2 DoF typical section model given above, are defined in the non-dimensional time domain. A time dependent external excitation is introduced and the aeroelastic response equations of a two dimensional lifting surface subjected to this external excitation is derived in time domain. To have the response in time domain first Laplace transform of the equations of motions including the aerodynamic terms and, excitation terms are taken. Finally, by taking the inverse Laplace transform of the pitch and plunge responses, time domain solutions are obtained. A case study is introduced and the flutter speed parameter is also calculated for the case study using k method and p-k method to compare the flutter speed obtained by the simulated flutter test with the k and p-k method of solutions. A code is generated to calculate the responses in time domain for the case study by performing the inverse Laplace transforms for a range of velocities starting from a sub-critical speed getting closer to the flutter speed. For each velocity case, amplitude vs. time plots are determined. Damping for each velocity case is calculated using logarithmic decrement method, using the amplitude vs. time plots of the pitch and plunge responses. After performing this process for all velocities, damping vs. velocity plots are established. Extrapolating the plots, the velocity value corresponding to zero damping is found out and the results are compared to those determined using the p-k method.

The equation of motion for the typical section model in non dimensional time domain can be written as [9]

$$m\omega_\alpha^2 bV^2 \frac{h''(\tau)}{b} + mX_\alpha \omega_\alpha^2 bV^2 \alpha''(\tau) + m\omega_h^2 h(\tau) = -L(\tau) + F(\tau) \qquad (2)$$

$$mX_\alpha \omega_\alpha^2 b^2 V^2 \frac{h''(\tau)}{b} + mr_\alpha^2 \omega_\alpha^2 b^2 V^2 \alpha''(\tau) + mr_\alpha^2 b^2 \omega_\alpha^2 \alpha(\tau) = M(\tau) \qquad (3)$$

where

α : Pitch motion of airfoil.
F : External excitation force.
h : Plunge motion of airfoil.
L : Aerodynamic lift force acting at the elastic axis.
m : Mass of the typical section.
M : Aerodynamic moment about the elastic axis.
r_α : Nondimensional radius of gyration about the elastic axis.
V : Reduced velocity ($V = \frac{U}{b\omega_\alpha}$)
X_α : Nondimensional distance between the elastic axis and the center of mass.
τ : Nondimensional time ($\tau = \frac{tU_\infty}{b}$)
ω_α, ω_h: Natural pitching and plunging frequency.

The equations of pitch and plunge responses in Laplace domain can be determined as [9]:

$$s^2 \frac{\hat{h}}{b} + X_\alpha s^2 \hat{\alpha} + \left(\frac{\sigma}{V}\right)^2 \frac{\hat{h}}{b} + \frac{2}{\mu}\left(s\hat{\alpha} + s^2\frac{\hat{h}}{b} + s^2\left(\frac{1}{2} - a\right)\hat{\alpha}\right)\hat{\phi}(s) + \frac{1}{\mu}s^2\left(\frac{\hat{h}}{b} - a\hat{\alpha}\right) + \frac{1}{\mu}s\hat{\alpha} = \frac{\hat{F}(s)}{m\omega_\alpha^2 bV^2} \qquad (4)$$

$$\frac{X_\alpha}{r_\alpha^2} s^2 \frac{\hat{h}}{b} + s^2\hat{\alpha} + \frac{1}{V^2}\hat{\alpha} - \frac{1}{\mu r_\alpha^2}(1+2a)\left(s\hat{\alpha} + s^2\frac{\hat{h}}{b} + s^2\left(\frac{1}{2} - a\right)\hat{\alpha}\right)\hat{\phi}(s) - \frac{1}{\mu r_\alpha^2} as^2\left(\frac{\hat{h}}{b} - a\hat{\alpha}\right) + \frac{1}{\mu r_\alpha^2}\left(\frac{1}{2} - a\right)s\hat{\alpha} + \frac{1}{8}\frac{1}{\mu r_\alpha^2}s^2\hat{\alpha} = 0 \qquad (5)$$

where, σ ($\sigma = \frac{\omega_h}{\omega_\alpha}$), μ ($\mu = \frac{m}{\rho_\infty \pi b^2}$) and φ are the ratio of natural frequencies, mass ratio and Wagner's function respectively, and "^" represents parameters whose Laplace transforms are taken. Wagner's function describes the growth of circulation and its approximate expression is given by [9]:

$$\phi(\tau) = 1 - 0.165e^{-0.0455\tau} - 0.335e^{-0.300\tau} \qquad (6)$$

Grouping the same terms together Equations (4) and (5) above can be written as:

$$A(s)\frac{\hat{h}}{b} + B(s)\hat{\alpha} = \frac{\hat{F}(s)}{m\omega_\alpha^2 bV^2} \qquad (7)$$

$$C(s)\frac{\hat{h}}{b} + D(s)\hat{\alpha} = 0 \qquad (8)$$

where

$$A(s) = s^2 + \left(\frac{\sigma}{V}\right)^2 + \frac{2}{\mu}s^2\hat{\phi}(s) + \frac{1}{\mu}s^2 \qquad (9)$$

$$B(s) = X_\alpha s^2 + \frac{2}{\mu}\left(s + s^2\left(\frac{1}{2} - a\right)\right)\hat{\phi}(s) - \frac{1}{\mu} a s^2 \hat{\alpha} + \frac{1}{\mu} s \tag{10}$$

$$C(s) = \frac{X_\alpha}{r_\alpha^2} s^2 - \frac{1}{\mu r_\alpha^2}(1+2a)s^2 \hat{\phi}(s) - \frac{1}{\mu r_\alpha^2} a s^2 \tag{11}$$

$$D(s) = s^2 + \frac{1}{V^2} - \frac{1}{\mu r_\alpha^2}(1+2a)\left(s + s^2\left(\frac{1}{2} - a\right)\right)\hat{\phi}(s) + \frac{1}{\mu r_\alpha^2} a^2 s^2 + \frac{1}{\mu r_\alpha^2}\left(\frac{1}{2} - a\right)s + \frac{1}{8}\frac{1}{\mu r_\alpha^2} s^2 \tag{12}$$

Solving the equations for pitch and plunge, one gets the responses in Laplace domain as [10]

$$\frac{\hat{h}(s)}{b} = \frac{\hat{F}(s)}{m\omega_\alpha^2 b V^2} \frac{D(s)}{A(s)D(s) - B(s)C(s)} \tag{13}$$

$$\hat{\alpha}(s) = \frac{\hat{F}(s)}{m\omega_\alpha^2 b V^2} \frac{C(s)}{B(s)C(s) - A(s)D(s)} \tag{14}$$

Taking the inverse Laplace transforms of the Equations (13) and (14), one gets the responses in non-dimensional time domain.

Simulated Flutter Test Method

The main aim of this study is to get the sub-critical damping trend from a simple analysis to aid the actual flutter test planning. Simulated flutter tests are performed for a case study using a similar method introduced in Reference [6]. The simulated flutter test method is performed by following the steps listed below.

1. First, p-k method is applied to a typical section model of the wing and a flutter speed is predicted.
2. Excitation with respect to reduced time is introduced.
3. Using Equations (13) and (14) response of each mode is obtained at a speed equal to the 22.7% of the flutter speed parameter calculated in the first step [6]. The responses are analyzed to provide estimates for the damping ratios. Logarithmic decrement method is used to determine the damping ratios.
4. The flight speed is increased by an increment equal to the 7% of the predicted flutter speed parameter and estimates for the damping ratio are obtained [6].
5. The flight speed is increased again by the same increment of the predicted flutter speed parameter and estimates for the damping ratio are obtained. The curve of estimated damping ratios vs. flight speed is plotted. The next flight speed would be an extra addition of 7% of the predicted flutter speed parameter predicted in the first step to the latest flight speed.
6. The plot is extrapolated using cubic piecewise polynomial method to cover the next flight speed. In cubic piecewise polynomial method, a third degree polynomial is assigned for each interval. At the knot points, the first and the second derivative values of the neighboring polynomials are equal to each other.
    a. If the extrapolated curve does not intersect the zero damping line step 5 is repeated for the next flight speed and a new extrapolated curve is obtained.
    b. If the curve intersects the zero damping line at a speed, and 80% of this speed is higher than the next test speed step 5 is repeated [6].
    c. If the curve intersects the zero damping line at a speed, and 80% of this speed is lower than the next test speed, test is stopped and the speed where the curve intersects zero damping line is accepted as estimated flutter speed.

Simulated flutter tests are performed for a 2DoF typical section model. Tests are performed at the sea level. The properties of the typical section model are given below.

$$
\begin{aligned}
&a=-0.2, \\
&x_{\alpha}=0.1, \\
&m=45\ \text{kg/m}, \\
&r_{\alpha}^{2}=0.24, \\
&\omega_{\alpha}=7.958\ \text{hz}, \\
&\omega_{h}=3.183\ \text{hz}.
\end{aligned} \tag{15}
$$

Using the p-k method, the plots given in Figure 2 are obtained. Predicted flutter speed parameter is 83 m/s as seen from Figure 2. This value is used in simulated flutter test to determine the test speeds.

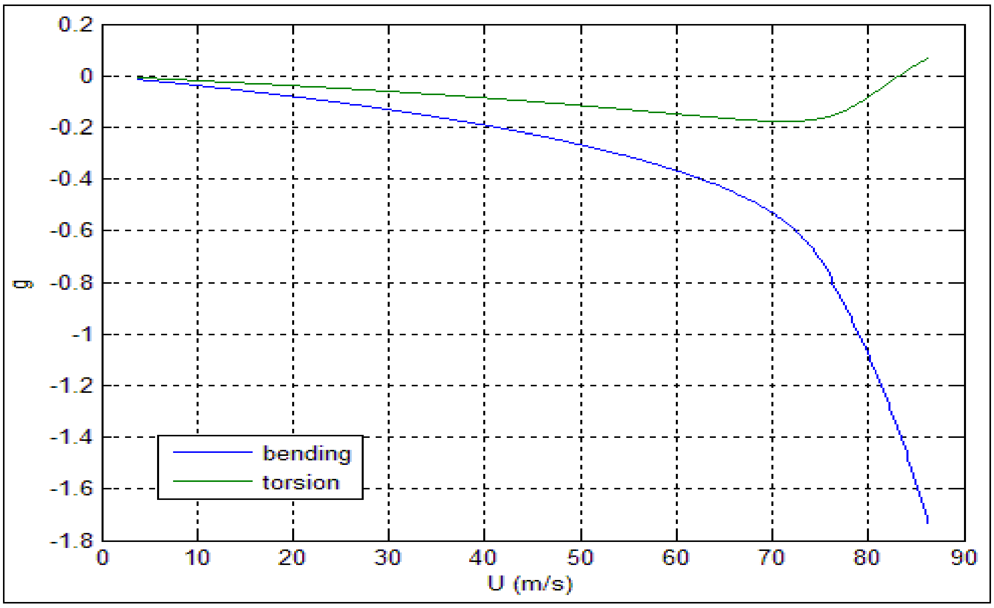

Figure 2. Damping vs. speed curve of p-k method solution

For the external excitation to be used in the time domain analysis, a blast load is modeled. Blast loading which changes with respect to reduced time is given by Equation (16).

$$
F(\tau)=20\left[H(\tau)\left(1-\frac{\tau}{15}\right)-H(\tau-30)\left(1-\frac{\tau}{15}\right)\right] \tag{16}
$$

where, H is the unit step function.

The first test speed is taken as 18.841 m/s which is the 22.7% of the predicted flutter speed parameter 83 m/s. For the test speed of 18.841 m/s, the excitation is applied at the elastic axis and the Laplace domain responses given in Equations (13) and (14) are obtained for the excitation. The equations are first converted from Laplace transformed domain to dimensionless time domain, and then to the time domain. It should be noted that taking the inverse Laplace transforms of Equations (13) and (14) by hand is almost impossible. A proper mathematical tool which has an efficient symbolic toolbox should be chosen to solve these equations since equations are very complicated and the time domain solution is performed parametrically. When the expressions for the responses are obtained in time domain, the time interval of interest is substituted into these expressions and response vs. time plots are determined. The peak points of these plots are used to estimate the damping ratios using the logarithmic decrement method. It should be noted that to examine how the excitation induced vibration dies out the time interval chosen should not interfere with the time region when the excitation is being applied. Logarithmic decrement is the logarithm of the ratio of two successful cycles's amplitudes of a dying out free vibration [11]. Damping ratio is expressed as a function of logarithmic decrement in the logarithmic decrement method. It is one of the most popular experimental damping estimation techniques. Logarithmic decrement is expressed as [11]

$$\delta = \frac{1}{n}\ln\left(\frac{x_1}{x_n}\right) \tag{17}$$

where n denotes the number of cycles and x denotes to the amplitudes of the peaks. The relation between logarithmic increment and the damping ratio is given as [11]

$$g = \frac{\delta}{\sqrt{4\pi^2+\delta^2}} \cong \frac{\delta}{2\pi} \tag{18}$$

One should note that δ^2 in the denominator can be neglected since it is very small compared to $4\pi^2$.

First, bending mode responses are analyzed. Using the generated MATLAB code, the response vs. time curve in the interval of 2-4 seconds is plotted in Figure 3 for the first test point speed 18.841 m/s. Figure 3 shows that bending response is a damped oscillation which indicates that the wing is free of flutter at the test speed of 18.841 m/s.

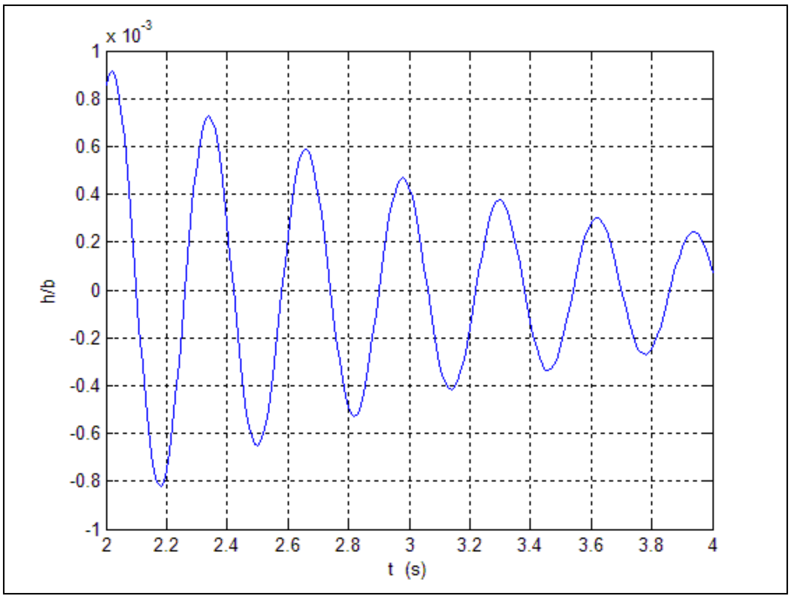

Figure 3. Bending response at 18.841 m/s, 22.7% of the predicted flutter speed

Applying the logarithmic decrement method to the response vs. time plot given in Figure 3, the damping ratio for the test speed of 18.841 m/s (22.7% of the predicted flutter speed) is calculated as:

$$g_{22.7} = 0.0281 \tag{19}$$

The second test speed is 24.651 m/s which is the 29.7% of the predicted flutter speed parameter 83 m/s. Having the response vs. time plot using the MATLAB code and applying the logarithmic decrement method, the damping ratio for speed 24.651 m/s which is the 29.7% of the predicted flutter speed is calculated as:

$$g_{29.7} = 0.0387 \tag{20}$$

Following the same steps, the damping ratio for the next test speed 30.461 m/s which is the 36.7% of the predicted flutter speed is obtained as:

$$g_{36.7} = 0.0503, \tag{21}$$

The curve of estimated damping ratio vs. flight speed is plotted and extrapolated using cubic piecewise polynomial method to cover the next test point which is at 36.271 m/s to check the stability of that point. This curve is given in Figure 4. The red vertical line indicates the next test point. It can be seen that the next test speed is safe from flutter since the extrapolated damping vs. airspeed curve does not intersect zero damping line. Therefore, one can proceed with the next test point.

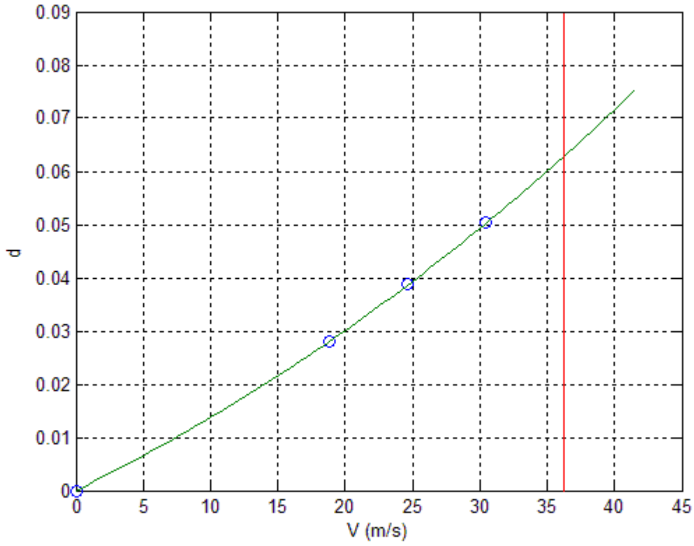

Figure 4. Extrapolated damping vs. speed curve for the first three test points

The same procedure is followed checking the stability of the next test point before going for the next point. For 4th and 5th test points the following damping ratios are obtained using logarithmic decrement method and response vs. time plots.

$$g_{43.7} = 0.0634$$
$$g_{50.7} = 0.0793 \qquad (22)$$

Extrapolated damping vs. speed curves are plotted in Figure 5, and the stability of the next test point is checked for each one.

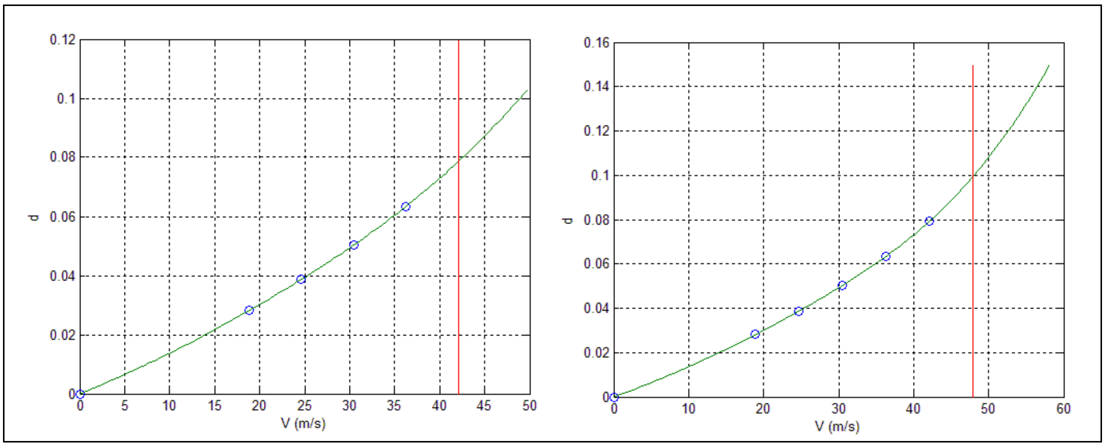

Figure 5. Extrapolated damping vs. speed curve for the first four and five test points respectively.

Damping ratio for the 6th test point is calculated as 0.0957 and the extrapolated damping vs. speed curve is plotted for the first six test points. The plot is given in Figure 6.

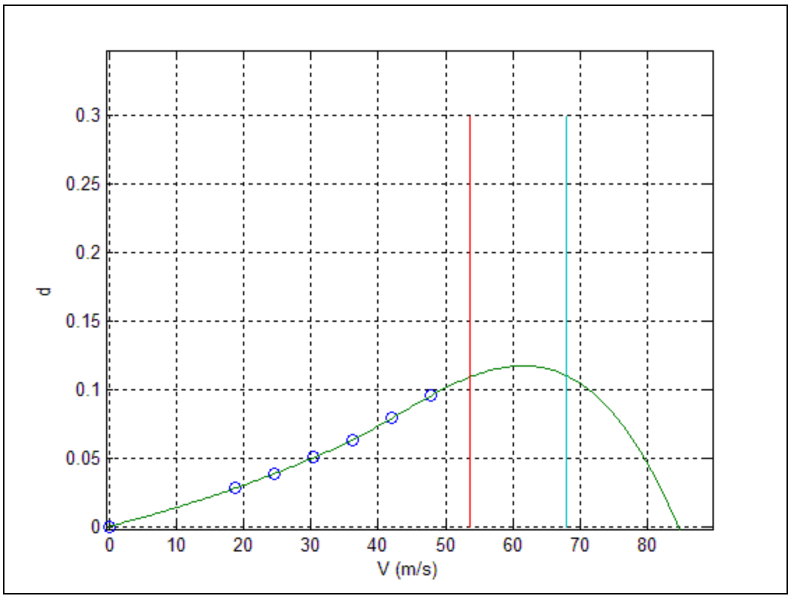

Figure 6. Extrapolated damping vs. speed curve for the first six test points.

As can be seen from Figure 6, flutter speed is estimated as 85 m/s. The vertical red line indicates the 7th test point. One should remember the stability criteria, which is stated previously, for the next test point. If the damping vs. airspeed curve intersects the zero damping line at a speed and 80% of this speed is lower than the next test speed, test is ended. The vertical blue line shows the 80% of the estimated flutter speed. Since 80% of the estimated flutter speed is higher than the next test point speed one can continue to the next test point which is 53.701 m/s.

The damping ratio is calculated as 0.1176 for the 7th test point, and the extrapolated damping vs. speed curve is plotted for the first seven test points. The plot is given in Figure 7.

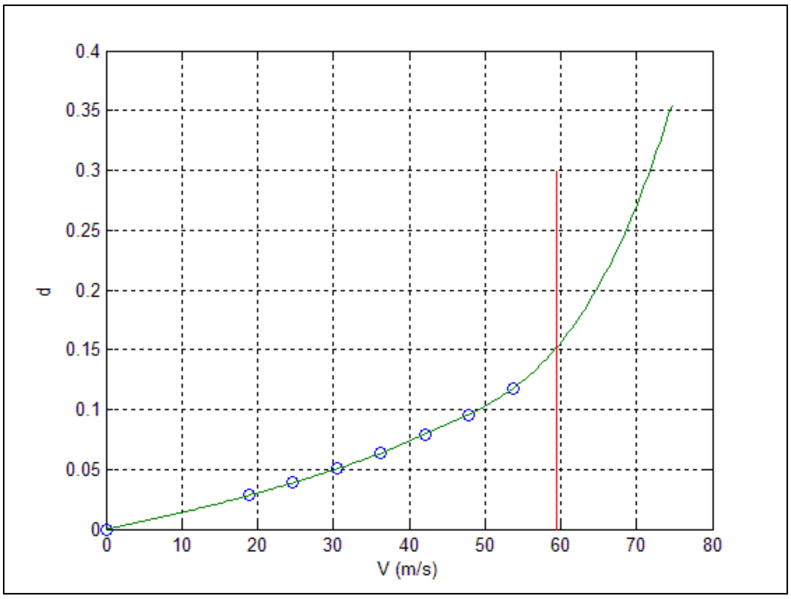

Figure 7. Extrapolated damping vs. speed curve for the first seven test points.

As can be seen from Figure 7, 59.511 m/s test speed, which is test point 8, is clear from flutter. So test is continued for the 8th test point. The damping ratio is calculated as 0.1387 for the 8th test point. Extrapolated damping vs. speed curve for the first eight test points is given in Figure 8.

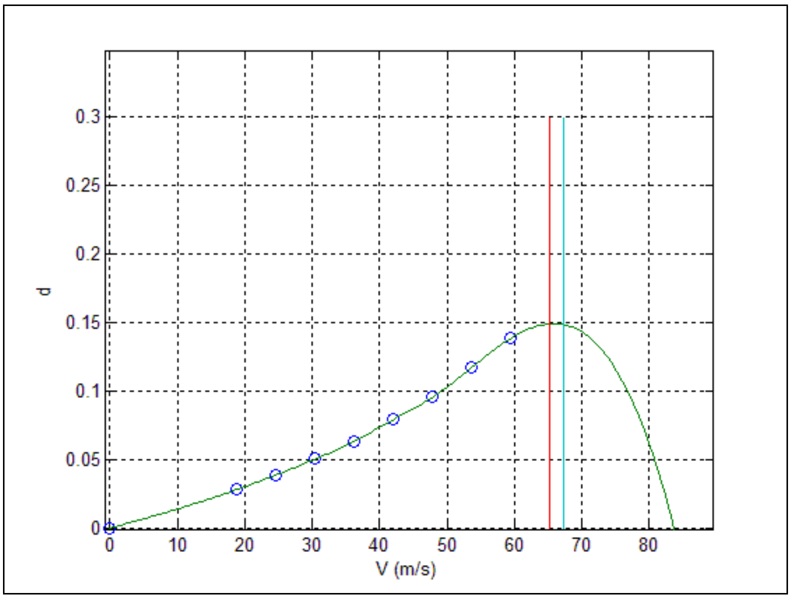

Figure 8. Extrapolated damping vs. speed curve for the first eight test points.

As can be seen from Figure 8, flutter speed is estimated as 83 m/s. The vertical red line indicates the next test point. The vertical blue line shows the 80% of the estimated flutter speed. Since 80% of the estimated flutter speed is higher than the next test point speed, one can again continue to the next test point which is 65.321 m/s.

The damping ratio is calculated as 0.1570 for the 9th test point and the extrapolated damping vs. speed curve is plotted for the first nine test points. The plot is given in Figure 9.

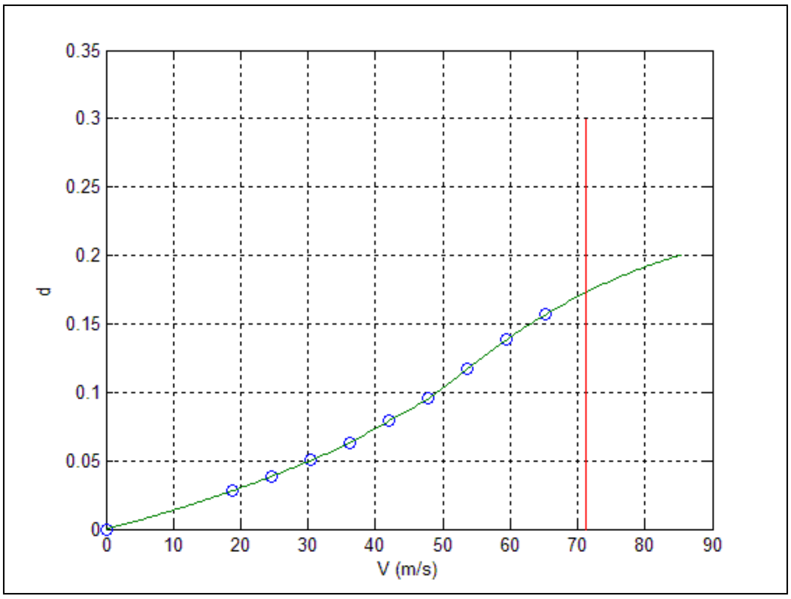

Figure 9. Extrapolated damping vs. speed curve for the first nine test points.

From Figure 9 for test point 10, for the 71.131 m/s speed the flutter clearance is ensured. So, test is continued. For test point 10 damping ratio is calculated as 0.0855, and the extrapolated damping vs. speed curve is plotted for the first ten test points. The plot is given in Figure 10.

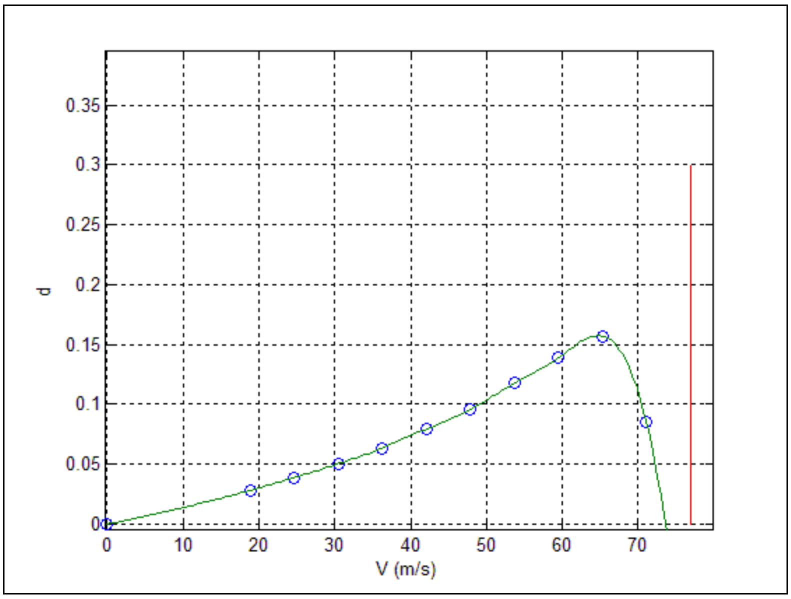

Figure 10. Extrapolated damping vs. speed curve for the first ten test points.

From Figure 10, flutter speed is estimated as 74 m/s. The vertical red line indicates the next test point. Since the next test point 76.941 m/s is greater than the estimated flutter speed test is ended. The final estimation for flutter speed for bending mode by simulated flutter test for the case study is determined as

$$U_f = 74\,\mathrm{m/s} \tag{23}$$

One should notice that in the earlier test steps, higher flutter speed estimations were made. Relying on those estimations and skipping the presteps may cause dangerous situations in real flight flutter testing. This case study shows how crucial incremental approach is in flight flutter testing.

Torsion mode simulated flutter test results are also analyzed following the same test steps. The simulated flutter test results for the first eight test points are given in Figure 11. At the test point eight, stability check for the next test point fails and therefore test is ended. Test results for the test point nine is given in Figure 12. The final estimation for the flutter speed for torsion mode by simulated flutter test for the case study is determined as

$$U_f = 80\,\mathrm{m/s} \tag{24}$$

It should be noted that using the p-k method, the flutter occurence is expected in torsional mode at a speed of 83 m/s. Analyzing the damping trends of the time responses both in bending and torsional modes, one can see flutter is induced in both modes at close speeds.

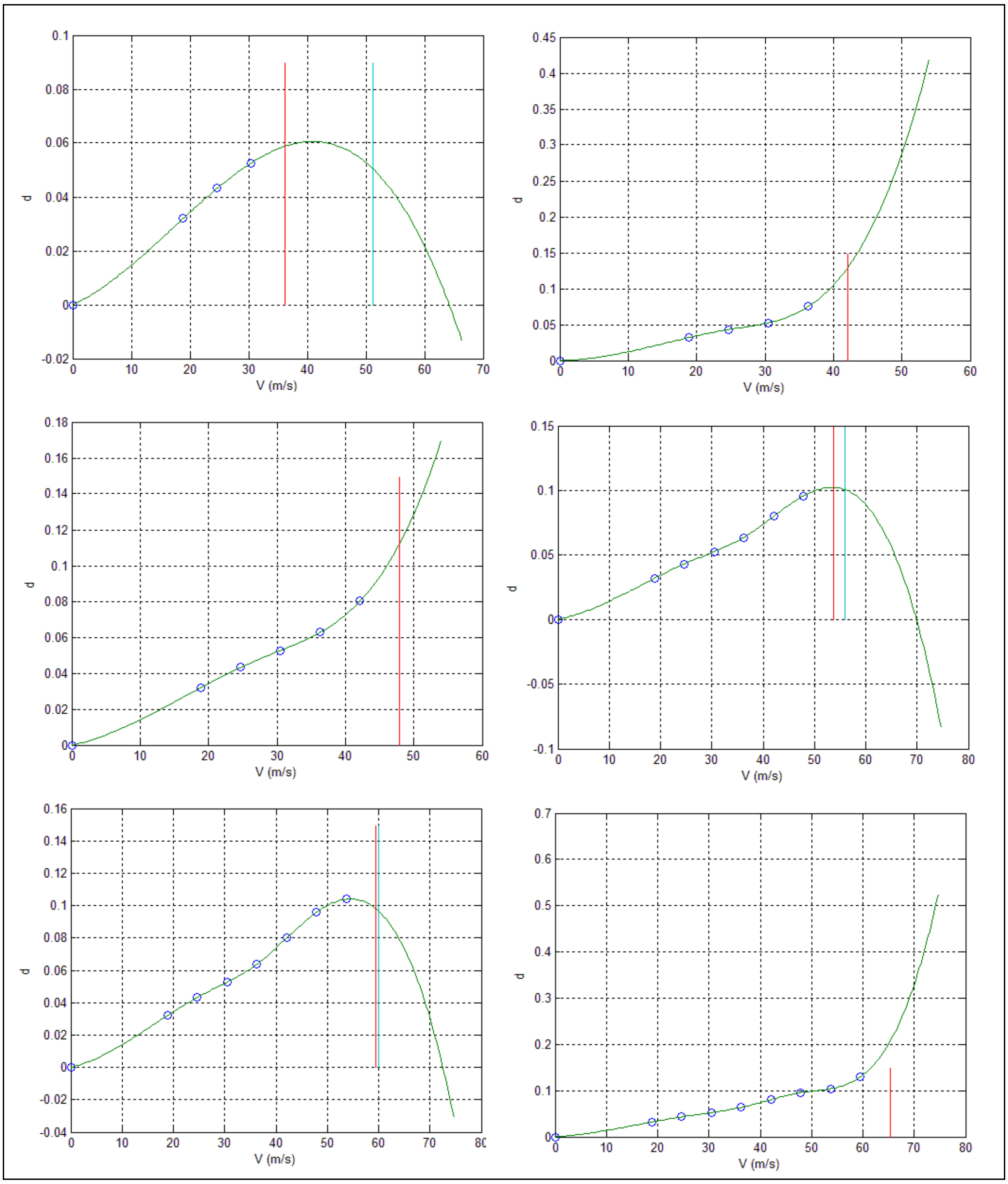

Figure 11. Extrapolated damping vs. speed curve for the first eight test points for the torsion mode

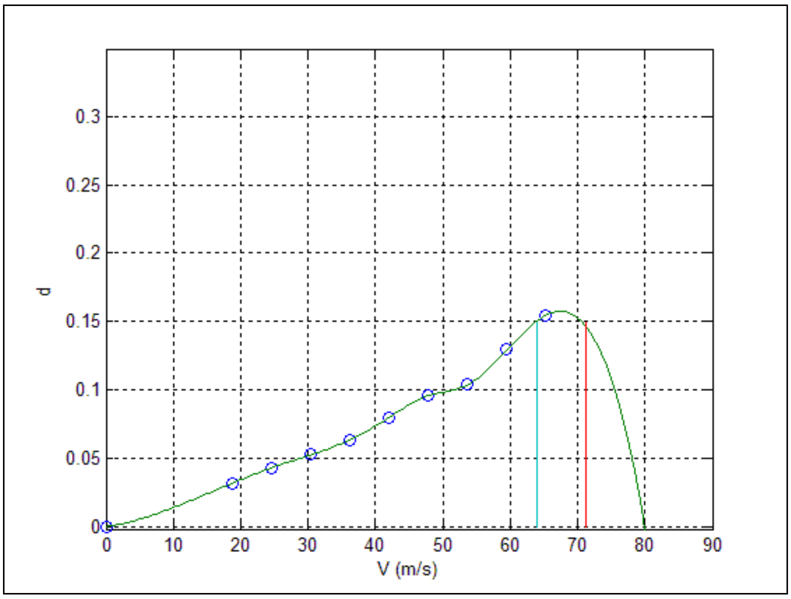

Figure 12. Extrapolated damping vs. speed curve for the first nine test points for the torsion mode

A further study is also conducted in which the 2D typical section on which the simulated flutter test is performed is subjected to a sinusoidal excitation and the results are obtained following the same procedure that has been used in performing simulated flutter tests using the blast loading as the external excitation.. However, in this case, the stability check for the next test point is excluded to see how the damping changes while getting close to the flutter speed. Figure 13 shows the sinusoidal excitation which is given as force vs. dimensionless time plot.

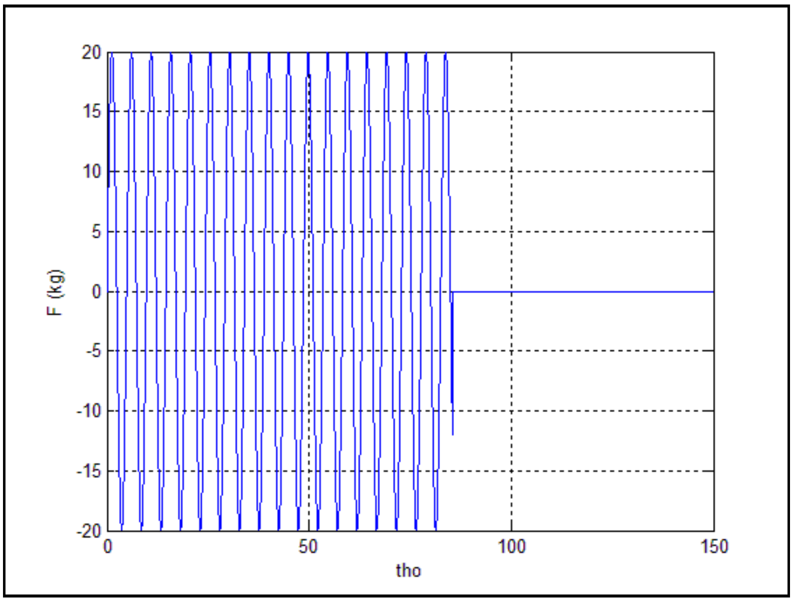

Figure 13. Sinusoidal excitation used in simulated flutter test

Response plots for pitch and plunge motions are plotted for 22.7%, 29.7%, 36.9%, 43.7%, 71.7% and from 90% to 100% by 1% increments of the predicted flutter speed by the p-k method. Damping estimations are obtained using the logarithmic decrement method at each speed. Cubic piecewise polynomial interpolation is used to generate curve fit through the discrete data points. Figures 14 and 15 give the damping versus airspeed plots for the plunging (bending) and pitching (torsion) modes, respectively. From Figures 14 and 15 one can notice that the estimated flutter speeds for both modes using time domain solution are between 99% and 100% of the predicted flutter speed by the p-k method. Namely, for bending mode estimated flutter speed is 82.805 m/s, and for the torsion mode estimated flutter speed is 82.718 m/s.

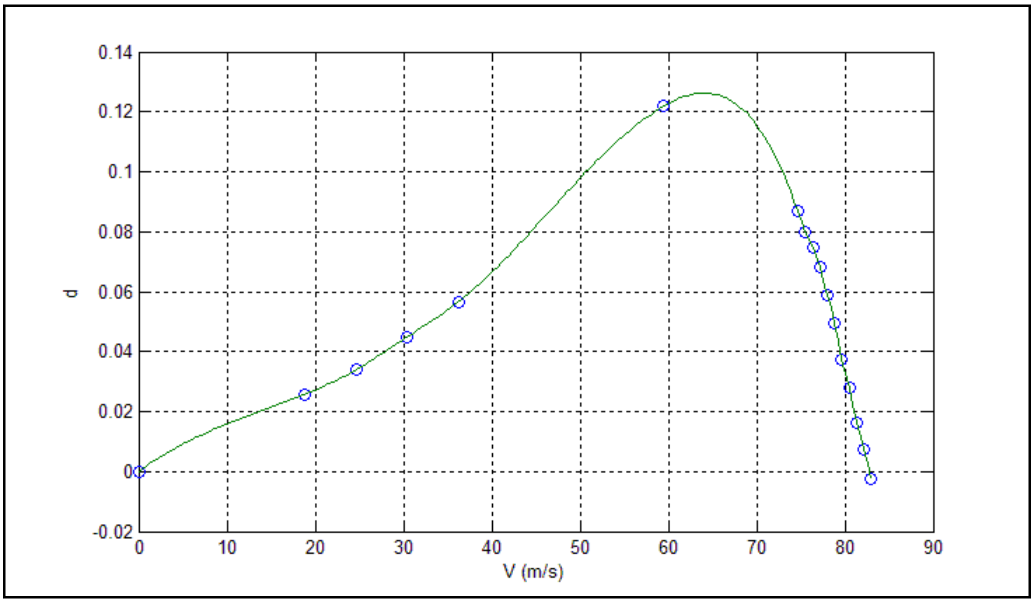

Figure14. Damping vs. speed curve for the bending mode for the sinusoidal excitation

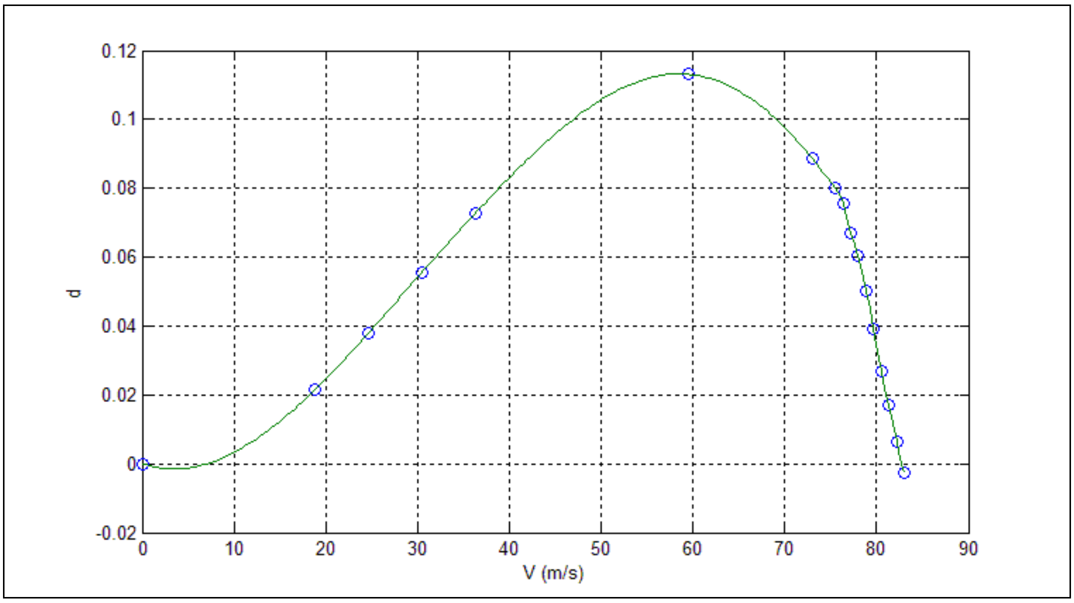

Figure15. Damping vs. speed curve for the torsion mode for the sinusoidal excitation

Response vs. time plots for the bending and the torsional modes are given in Figure 16 for the 99% of the predicted flutter speed by the p-k method, and the response vs. time plots for the bending and the torsional modes are given in Figure 17 for the 100% of the predicted flutter speed the by p-k method.

One can notice that the plunge and pitch responses shown in Figure 16 are lightly damped, while the responses given in Figure 17clearly show diverging behaviour. As seen from the results obtained using the time domain solution and the p-k method solution, very close results are obtained for flutter speed. However in time domain solution, flutter occurrence is predicted in both modes.

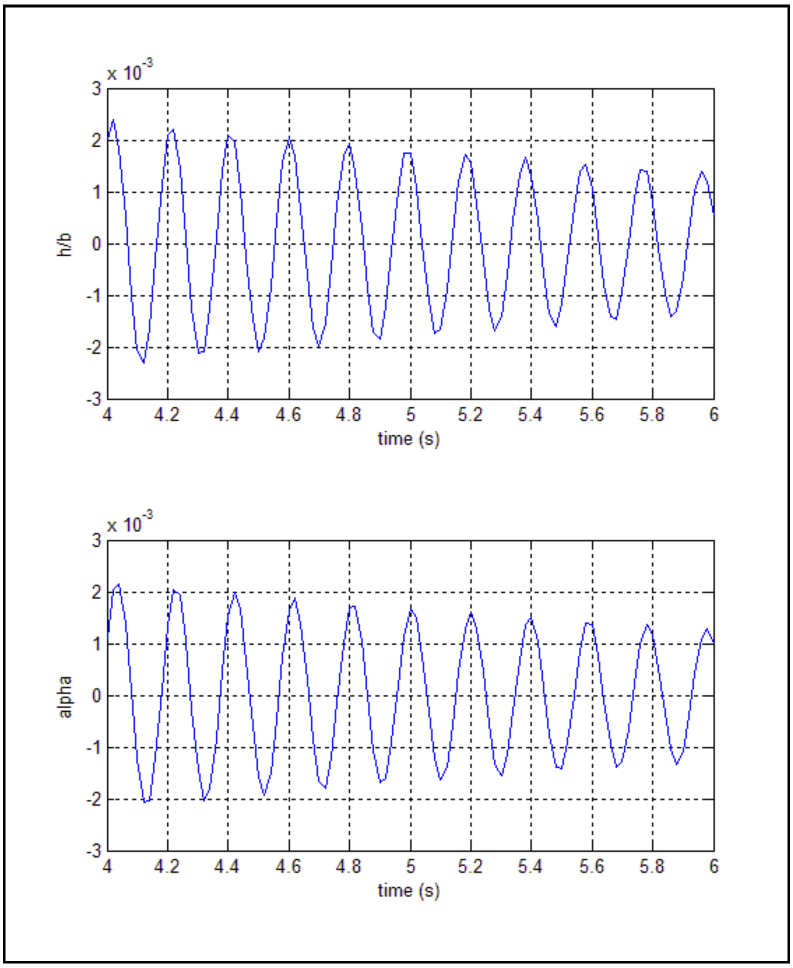

Figure16. Response vs. time plots for bending and torsional mode for 99% of the predicted flutter speed by p-k method

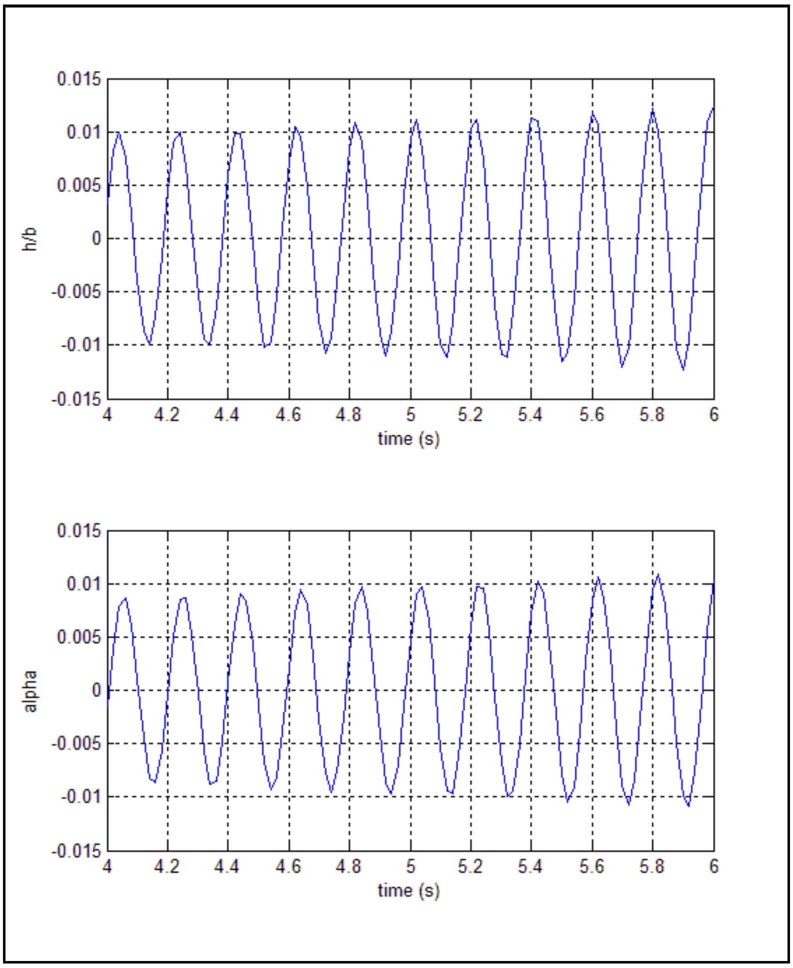

Figure17. Response vs. time plots for bending and torsional mode for 100% of the predicted flutter speed by p-k method

CONCLUSION

Simulated flutter test method is an appropriate method to gain insight about the real flight flutter testing. One can get the simulated test data after complex time domain analysis which is similar to the test data of a real flight flutter test. The major difference of the simulated test data, from the real flight flutter test data collected by accelerometers is that it does not contain noise due to experimental deficiencies. Simulated flutter test may be very helpful to determine the test points which will be used in the flight flutter tests since the damping trend is traced every time a new test point is added to the damping versus airspeed curve. Simulated flutter test approach gives an opportunity to train the flutter test engineer with regard to what actually could happen in an actual flutter test by studying the damping trends. In a real flutter test, decision to continue with the next test point is based on the value of the flutter speed predicted by the extrapolation of the damping vs. airspeed curve. Extrapolation of the damping vs. airspeed curve is performed every time a new test point is added. In this respect, simulated flutter test provides the flutter test engineer with the necessary background on what to expect in an actual flight flutter test.

In the present study, damping vs. speed curves are obtained using time domain solutions. Blast and sinusoidal type external excitations are used to obtain time responses for the bending and torsion modes. It is shown that if the damping estimates are obtained up to speeds close to the flutter speed determined by the p-k method, flutter speed obtained by the time domain solutions is in excellent agreement with the flutter speed predicted by the p-k method. However, in time domain solutions flutter is predicted in both modes whereas p-k method predicts flutter only in one mode.

It should be noted that in this study only incompressible flow is investigated. In further studies compressible flow and supersonic flow may be covered. In the simulated flutter test section only damping extrapolation method is used to estimate flutter speed. In the future, other methods such as flutter margin, envelope function and Autoregressive Moving Average-Based (ARMA) methods may be used to analyze the simulated flutter test data.

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