A PRELIMINARY STUDY ON BUFFETING PROBLEM UTILIZING DYNAMICS RESPONSE APPROACH

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Abstract

Buffeting problems have important consequences in aircraft design because they limit cruise velocity and aircraft performance. For this purpose, a preliminary analytical study of dynamic response caused buffeting is neccesary.

In present paper, an analytical approach of buffeting is performed utilizing dynamic response technique based on assumption that there are no coupling between motion-induced unsteady aerodynamic force and independent-motion unsteady airload. The motion-induced unsteady airload is calculated based on a method developed by Djojodihardjo et. al. and the buffeting exitation load is based on Powell and Bull's experiment. The dynamic response of the structure is determined according to methods developed by Forching and Zingel.

Introduction

The problem of dynamic response of an aircraft structure due to flow separation, known as buffeting, is an important problem in aeroelasticity when the aircraft is operated at high speed or high angel of attack. For ciivil transport aircrafts, buffeting phenomenon will limit their cruise speed and comfort. Whereas, for fighter aircrafts, this will limit their manuvering performance. In aircraft design, the problem is related with fatigue and fracture of aircraft structure [1]

The analytical approach to buffeting problem associated with subsonic flow was developed by many reasearchers, such as Forching [1], Mabey[2], Zingel [3], Becker [4] and others. Because of the complexity of the phenomenon, no purely analytical approach were used in their approach. All their predictions were based on semi empirical method, where the quantity of unsteady aerodynamic forces associated with separation and attached flow are measured by wind tunnel experiment and then the dynamic response of the structure are calculated by using several methods such as the power spectrum method. A purely analytical approach to predict the quantity of unsteady airloads on buffeting problem was developed by Djojodihardjo et. al., using Kernel function technique [5][6][7][8][9]. This technique are used in the present paper to predict the buffeting behaviour.

Problem Formulation

Figure 1 illustrate a typical cross secti-onal of wing or horisontal tail on uniform flow with the separation region on the upper surface [8]. By asssuming that there are no coupling between motion-induced unsteady airloads and independent-motion unsteady airloads, the problem of anaytical buffeting prediction can be modelled as forced vibration system as illustrated in Figure 2 [1]. In this model the independent-motion unsteady airloads is associated with the driving exitation forces or buffeting forces, and the motion induced unsteady airloads produce aerodynamics damping that together with structural damping will limit the dynamics aeroeslastic response of the structure.

The motion induced-unsteady airloads can be determined by using lifting surface theory and the buffeting forces are approximated base on Powell and Bull's experiment result [10]

Mathematical Formulation

From flexure beam theory, if the wing are treated as a slender beam in which the cross-sectional dimensions are small in comparison with the length, the equation of equilibrum can be written as [11]

$$\frac{\partial^2}{\partial y^2}\left[EI\frac{\partial^2 u(y,t)}{\partial y^2}\right] = -m\ddot{u}(y,t) \quad (1)$$

where EI and m are bending stiffness and mass distribution per unit span respectively. Mean while $u(y,t)$ and $\ddot{u}(y,t)$ are deflection and acceleration of structure element. Hence, the equation of motion of wing is:

$$\frac{\partial^2}{\partial y^2}\left[EI\frac{\partial^2 u(y,t)}{\partial y^2}\right] = -m\ddot{u}(y,t) + F^A(t) + F^F(t) \quad (2)$$

Where $F^A(t)$ is motion-induced force and $F^F(t)$ indicate independent-motion forces.

In the application of oscillation model approach to predict the structural buffeting response aircraft, the principle of superpotition may be applied. Hence, the deflection of the aircraft structure at any point P and any time t can be expressed in the form :

$$u(P,t) = \sum_{r=1}^{n} u_r(P)q_r(t) \quad (3)$$

such that the equation of motion can be written as :

$$M_r\ddot{q}_r(t) + K_r q_r(t) - \sum_{r=1}^{n} A_{rs}q_s(t) = Q_r^F(t) \quad (4)$$

where K_r and M_r are generalized stiffness and generalized mass of the strucrure, and can be determined by following equation:

$$K_r = \int_0^l \frac{\partial^2}{\partial y^2}\left[EI\frac{\partial^2 u_r(y)}{\partial y^2}\right]u_r(y)dy$$

$$= \omega_r \int_0^l u_r(y)m(y)u_r^T(y)dy = M_r\omega_r \quad (5)$$

In equation (4) the generalized unsteady aedynamic forces of the motion-induced unsteady pressure, $p_s^A(P,t)$, when the structure vibrates in the s-th mode terms, is given by:

$$A_{rs}(t) = \iint_{(S)} u_r(P)p_s^A(P,t)dS \quad (6)$$

The term on the right hand side of equation (4) expresses the generalized aerodynamics forcing term associated with pressure fluctuation $p^F(P,t)$ due to flow separation, which can be writen as

$$Q_r^F(t) = \iint_{(S)} p^F(P,t) u_r(P) dS \qquad (7)$$

or in term of cross spectral densities of the generalized unsteady airloads:

$$S_{Q_{rs}}(\omega) = \iint_{(S)(S)}\iint u_r^T(P) S_P(P,P',\omega) u_s(P') dS dS' \qquad (8)$$

where $S_p(P,P',\omega)$ is the diagonal matrix of cross-spectral density of the fluctuating pressure at two different point *(P,P')*

Hence, the power spectrum of deflection of aircraft structure at point *P* can be determined by the following input-output relation [12]

$$S_u(P,\omega) = \sum_{r=1}^{n}\sum_{s=1}^{n} H_r^*(P,\omega) H_s^T(P,\omega) S_{Q_{rs}}(\omega) \qquad (9)$$

where $H_r(P,\omega)$ is the transfer function of dynamic system mode-r, and $H_r^*(P,\omega)$ is conjugate form.

By assuming that both input and output are harmonic, $q_r(\omega) = \bar{q}_r(\omega) e^{i\omega t}$; $Q_r(\omega) = \bar{Q}_r(\omega) e^{i\omega t}$, equation (4) can be transformed into

$$M_r(\omega_r^2 - \omega^2)\bar{q}_r(\omega) - \sum_{s=1}^{n} A_{rs}\bar{q}_s(\omega) = \bar{Q}_r^F(\omega) \qquad (10)$$

Solving the linear simultan equation of equation (10), the transfer function can be determined as follow :

$$H_{u,r}(P,\omega) = \frac{u_r(P)\bar{q}_r(\omega)}{\bar{Q}_r^F(\omega)} \qquad (11)$$

The bending moment at point *P* of wing can be derived from the simple beam theory will give :

$$M(P,t) = EI\frac{\partial^2}{\partial y^2} u(P,t) \qquad (12)$$

Combining equation (12) and (11) yields transfer function for the bending moment of the structure and is given by

$$H_{M,r}(P,\omega) = \frac{[EIu_r''(P)]^2 \bar{q}_r(\omega)}{\bar{Q}_r^F(\omega)} \qquad (13)$$

where $u_r''(P)$ indicates second derivative form of $u_r(P)$. By neglecting the structure damping the mean-square values of bending moment can be formulated as [3][13]

$$\overline{M_{P,r}^2} = \frac{[EIu_r''(P)]^2}{8\pi M_r^2 \omega_r^3 \gamma_{aero}} S_{Q,r}(\omega_r) \qquad (14)$$

Where γ_{aero} is aerodynamic damping factor. If it is assumed that mean value of both displacement and bending moment are zero then the values of their deviation standard are equal to the root-mean-square value, $\overline{M}_{rms}$.

Unsteady Airloads

Motion Induced Unsteady Airloads

Because of the motion-induced unsteady airloads on the buffeting problem are assumed to have a linear relationship with respect to the system displacements, then their quantities can be obtained by using lifting surface theory.

By assuming small disturbance with respect to the free stream condition, the equation of unsteady linearized compressible potential flow in pertubation velocity potential is given by[14]:

$$(1-Ma^2)\varphi_{xx}+\varphi_{zz}-\frac{i2kMa}{a_\infty}\varphi_x+\frac{k^2}{a_\infty^2}\varphi=0 \qquad (15)$$

where φ are complex quantities representing the amplitude of pertubation potential and Ma is Mach number.

For inviscid flow case, the boundary condition on the attached flow region read as

$$w(x,\tau)=(\frac{\partial}{\partial x}+\frac{\partial}{\partial \tau})z(x,\tau) \qquad (16)$$

with

$$w(x,\tau)=\overline{w}(x)e^{ik\tau} \qquad (17)$$

$$z(x,\tau)=\overline{z}(x)e^{ik\tau} \qquad (18)$$

and for pure heaving motion

$$\overline{w}(x)=-ik \qquad (19)$$

where k is the reduced frequency and τ is nondimensional time.

Presssure distribution on the airfoil surface can be determined by solving equation :

$$\overline{w}(x)=\oint_{chord}\Delta C_p(x)K(kx_o,Ma)dx \qquad (20)$$

where $K(kx_o,Ma)$ is Kernel function defined at [14]

The separation in considered to take place only on the upper side of the wing. On this region some assumption have to be made regarding the velocity and the pressure of the fluid, based on the experimental evidence. The true situation may be obtained using viscous flow approach, which is beyond the scope of this work.

It may be assumed that the velocity on the separated region is the same as that of undistributed flow. Alternatively, it may be assumed a priori that the pressure difference in separation region is equal to some value

$$\overline{C}_{P_u}(x)=\overline{\gamma} \qquad (21)$$

More detile procedures to determine pressure distribution on the separation flow region are on Djojodihardjo and Kresna Sekar [5][7][8]. The pressure distribution on wing surface then calculated by stryp theory method.

Motion Independent Unsteady Airloads

By assuming that the pressure fluctuatuions have a stastitical regurality, then the magtitude of the motion independent unsteady airloads can be written in by means of stastitical form. If the structure can be approximated to have a plate shape and the flow separations are turbulent, the pressure fluctuation can be modelled based on Bull and Powell's experiment.

Based on Bull and Powell's experiment acceptantion function read as follow [10][15]

$$J_{rs}(\omega)=\frac{1}{S^2S_p(\omega)}\iint_{(S)}\iint_{(S)}u_r(P)S_p(P,P',\omega)u_s(P')dSdS' \qquad (22)$$

where S and $S_p(\omega)$ are wing surface area and auto-correlation power spectrum density of pressure fluctuation respectively.

According Crocos's experiment [15], the cross-correlation power spectral density of fluctuation pressure is

$$S_p(P,P',\omega) = S_p(\omega)\exp\left[-\frac{\omega}{U_c}(0.1|\xi_1| + 0.55|\xi_2|)\right]\cos\left(\frac{\omega}{U_c}|\xi_1|\right) \quad (23)$$

ξ_1 and ξ_2 are distance between two point in the logitudinal and transversal direction to flow, and U_c is convection velocity which often assumed equal to about 70% of free stream velocity. For two dimensional case equation (23) can be reduced to the form

$$S_p(P,P',\omega) = S_p(\omega)\exp\left[-\frac{\omega}{U_c}(0.1|\xi_1|)\right]\cos\left(\frac{\omega}{U_c}|\xi_1|\right) \quad (24)$$

The auto-correlation power spectral density at $\omega = \omega_1$ can be approximated by [15] :

$$S_p(\omega) = 4K^2q^2c^3 \quad (25)$$

q and c are dynamic pressure and chord. K is constant which determined base on experiment (will be disscused later).

Computational Results And Discussion

The wing structure which is used in this study is approximated by a rectangular semispan-wing which was used in Boyden and Johnson's experiment [17]. The computational result of the first natural bending mode of this model is about 270 Hz. This value is the same as Boyden and Johnson's experiment result.

Separation points are not determined by computational method. Approximation as a first estimate to the locations has been attemped by estabilishing a model by capitalizing on the available experimental result of Boyden and Johnson. Following this approach, approximation function of the locations of separation points has been constructed as a function of angle of attack which are modelled to be as follow :

$$\frac{x_s}{b} = \begin{cases} 1.0 & \text{if } \alpha_s < \alpha \\ 2\dfrac{(\alpha-\alpha_s)}{(\alpha_f-\alpha_s)} - 1.0 & \text{if } \alpha_s \le \alpha \le \alpha_f \\ -1.0 & \text{if } \alpha < \alpha_f \end{cases} \quad (26)$$

where α_s and α_f are the angle of attack associated with the onset of separation, and a fully separated situation, respectively, expressed in degree which are modelled to be as follows :

$$\alpha_s = (2.357)10^{-6}\,\mathrm{Re} + 5.162 \quad (27a)$$

$$\alpha_f = (1.010)10^{-6}\,\mathrm{Re} + 12.212 \quad (27b)$$

where Re is Reynold's number. Figure 3 illustrates non dimensional form of the chordwise coordinate of the separation points which are assumed to be located in a straight line along the span as illustrated by Figure 1b.

Figure 4 to Figure 7 illustrate the real and the imaginary parts of the motion-induced unsteady aerodynamic load for various location of separation points, the pressure distribution on the separated region of the upper surface is assumed to be equal to zero. The independet-motion unsteady airload quantities in term of the acceptance function quatities for third first free mode are illustrated by Figure 7.

Based on experimental result of Boyden and Johnson [17], the K value of equation (25) is found to be :

$$K = \frac{\rho_\infty U_\infty}{\mu} \quad (28)$$

where ρ_∞, U_∞ and μ are air density, velocity and viscosity of the undistrubed flow, respectively. Utilizing this approach, the root-mean-square bending moment coefficients, M_{rms}/qcS, for various Reynold's number and angle of attack can be found, as illustated in Figure 8 to Figure 12.

Compared to experimental results, the computational results give lower values of standar deviation of the bending moment. These results may be attributed to the following :

a. Before the onset of buffeting, the flow is asummed to be fully attached in the computation. Therefore no unsteady load results.
b. At the onset of buffeting, the pressure in the separation bubble is assumed to be zero.

The results also showed that this method is capable of the mechanism for buffeting.

Conclusion And Further Work

A method for the dynamic response calculation wing with separated flow has been developed. The procedure is based on forced vibration model approach suggested by Forsching and Zingel utilizes power spectrum method. In addition, the motion-dependent unsteady aerodynamic forces have been calculated following the method of Djojodihardjo et. al. and the motion-independent unsteady aerodynamic forces have been estimated utilizing experimental result of Bull and Powell, that has been adapted. Results have shown the following :

a. For simplified case, dynamic response behaviour that qualitatively agree with experimental data have been indicated.
b. the method has indicated the validity and plausibility of a systematic approach for buffeting prediction, with utilizes theoritical approach for the motion-dependent aerodynamic forces and empirical approach for motion independent aerodynamic forces.

However, further work is required to estabilish the method for more general case.

Acknowledgments

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Reference

1. Forsching,H, *Aeroelastic Buffeting Prediction Techniques- A General Review,* DFVLR, Gottingen, April 1981.
2. Mabey; D.G., *Wing and Tail Buffeting on The Effects of Buffeting and Other Transonic Phenomena on Manuvering Combat Aircraft;* AGARD-AR-82, July;1975
3. Zingel, H., *Zur Bestimmung des aeroelastischen Verhaltens von Auftriebssystemen infolge von Stromungsablosung,* DFVLR, Gottingen, August, 1986.
4. Becker, J., and Gravelle, A., *Some Results of Experimental and Analytical Buffeting Investigations On A Delta Wing, International* Symposium on Aeroelasticity , Aachen, April 1-3, 1985.
5. Djojodihardjo, H., Sekar W.K., Laschka,B., *Calculation of Pressure Distribution on Two Dimensional Wing in Unsteady Subsonic Flow with Separation Bubble using Kernel Function Method,* International Forum on Aeroelasticity and Structural Dynamics, Aachen, FR

Germany, 1991.
6. Dojodihardjo, H., *Some Solotion Method Of Wave Equations Appearing In unsteady Aerody-namics and Aeroacoustics,* Proceedings, Institut Teknologi Bandung, Vol. 24, No. 1, 1991.
7. Djojodihardjo, H., Sekar, W.K., Prananta, B.B., *Calculation of 3D Unsteady Subsonic Flow with Separation Bubble using Singularity Method, 18th,* ICAS Congress, Beijing, 1992.
8. Djojodihardjo,H., Sekar,W.K., *Flutter Calculation of Two and Three Dimen-sional Subsonic Wing With Separation Bubble as Peliminary Estimation of Buffeting Problem,* The International Forum on Aeroelasticity and Structural Dynamics, Strasbourg, France, May 24-26, 1993
9. Djojodihardjo, H., Sekar, W.K., Suleman, E., *Flutter And Dynamic Response Calculation Of Unsteady Separated Flow Using Singularity Method For Preliminary Estimation Of Buffeting Problem,* Symposium of The Advances in Aerospace Sciences, Stanford, Califomia, USA, September 23-24, 1993.
10. Chyu,W.J., Au-Yang, M.K., *Random Response of Rectanguler Panels To The Pressure Field Beneath A Turbulent Boundary Layor In Subsonic Flows,* NASA TN D-6970, Oktober, 1972.
11. Timoshenko,S., D.H. Young, and. Weaver, W., *Vibration Problems in Engineering*, John Wiley & Sons, Inc., New York, 1974.
12. Bendat, J.S., Piersol, A.G., *Random Data : Analysis and Measrument Procedure*, John Wiley and Sons Inc.,Canada, 1971.
13. Newland, D.E., *An Intoduction to Random Vibration and Spectral Analysis,* 2th edition, Longman Group Ltd., Hong Kong, 1984.
14. Biisplinghoff, R.L., Ashley, Halfman, R.L., *Aeroelasticity,* Addison-Wesley Publising Company, Reading, Massachusetts, 1955.
15. Blevins, R.D., *Flow-Induced Vibration,* van Nostrand Reihold Co., New York, 1977.
16. Bolotin, V.V., *Random Vibrations of Elastic Systems*, Martinus Nijhoff Publishers, The Hague, 1984.
17. Boyden, R.P., Johson, Jr., W.G., *Result of Buffet Tests in a Cryogenic Wind Tunnel,* NASA-TM 84520, September, 1982.

(a)

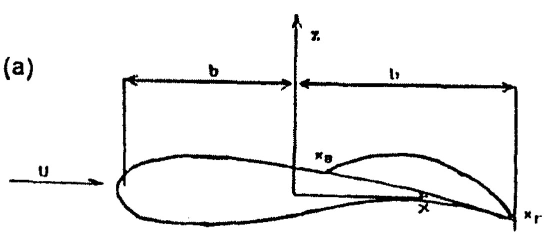

Fig 1a. Airfoil with separation bubble

(b)

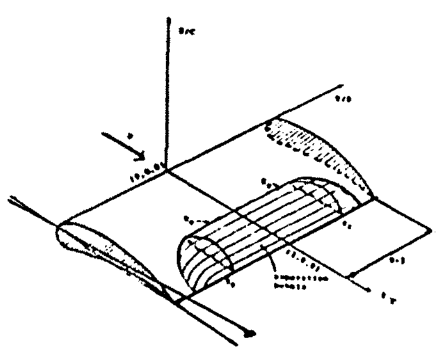

Fig. 1 Airfoil (a) and wing (b) with separation bubble (Ref. 8)

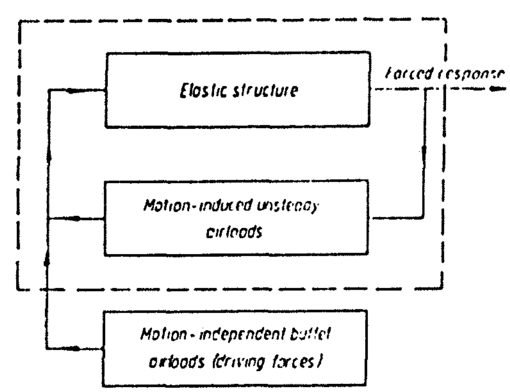

Fig. 2 Forced oscillation model of buffeting (Ref. 1)

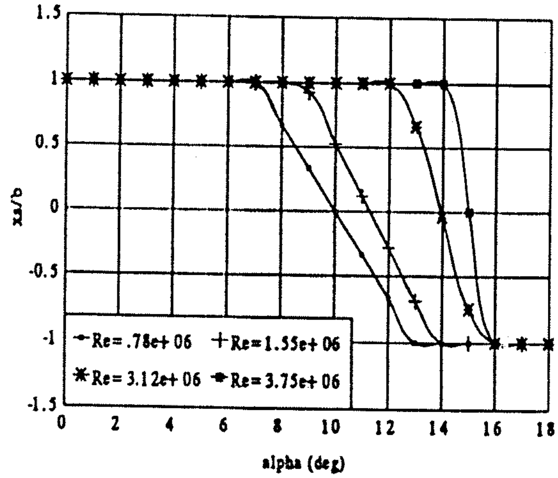

Fig.3 Separation point model as a function of Reynold's number and angle of attack

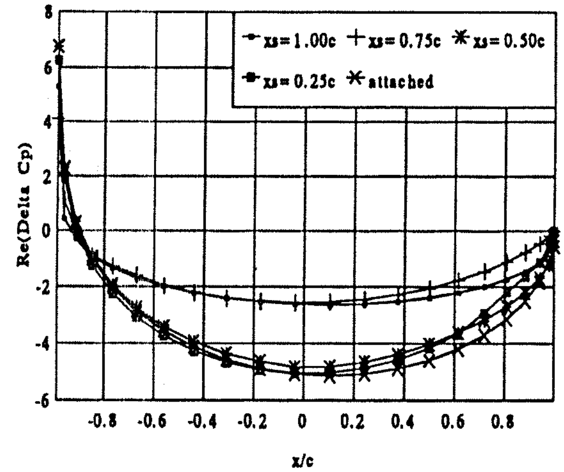

Fig.4 Real part pressure distribution of bending mode y/l= 0.5, k= 1.67 and M= 0.3

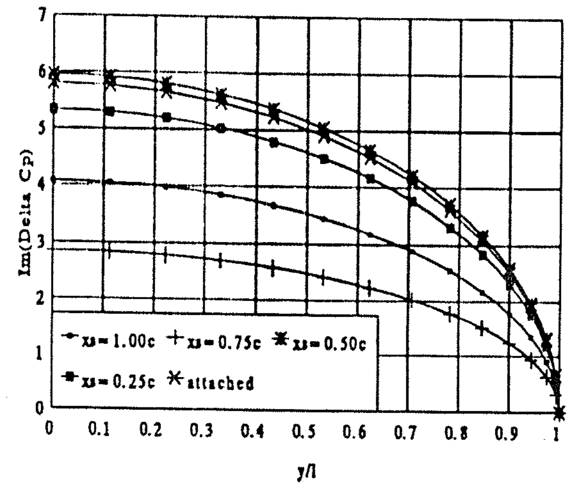

Fig.7 Imaginary part pressure distribution of bending mode x/c= 0.55, k= 1.67 and M= 0.3

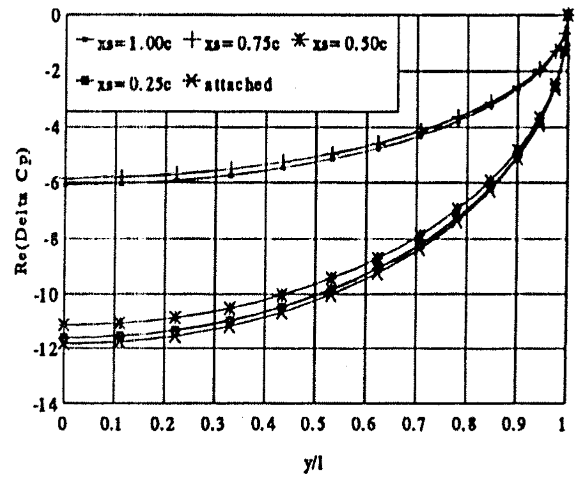

Fig. 6 Real part pressure distribution of bending mode x/c= 0.55, k= 1.67 and M= 0.3

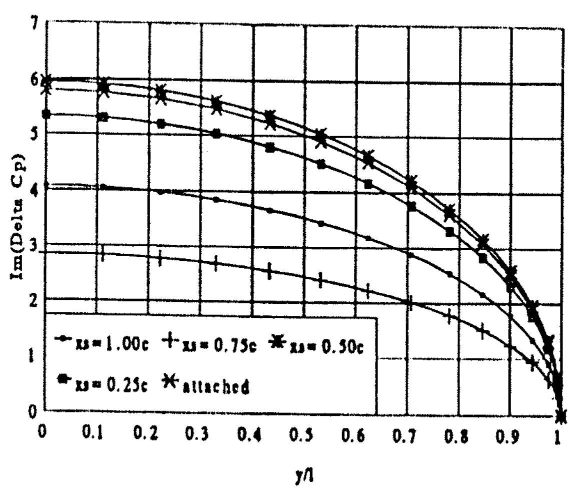

Fig.7 Imaginary part pressure distribution of bending mode x/c= 0.55, k= 1.67 and M= 0.3

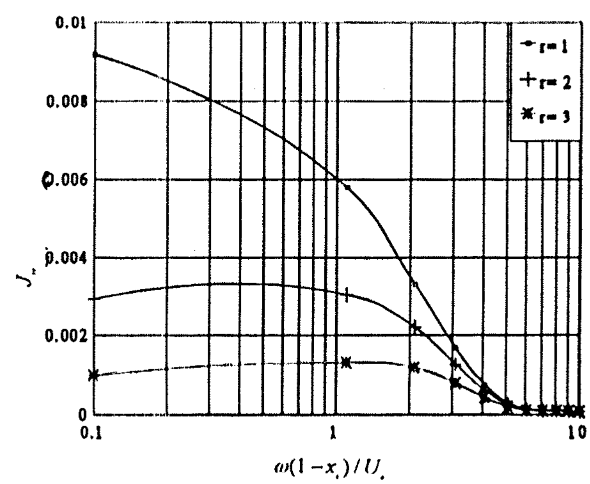

Fig. 8 Acceptance function for independent-motion airloads

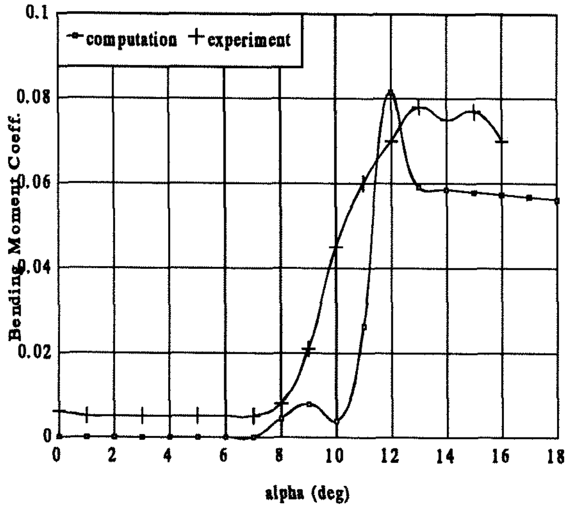

Fig. 9 Bending moment coeficcient for Re=.78e+06

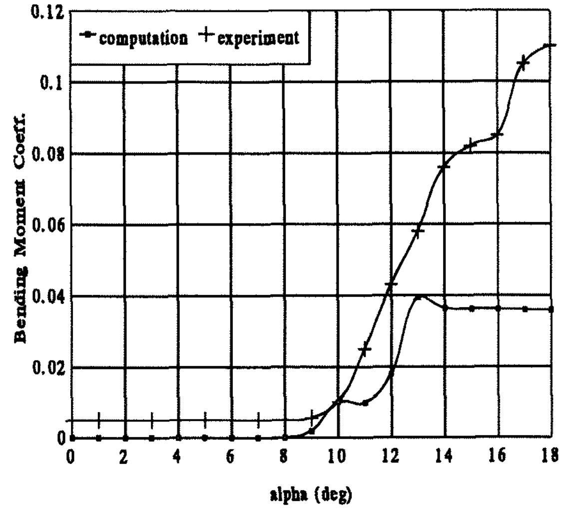

Fig. 10 Bending moment coefficient for Re=1.55e+06

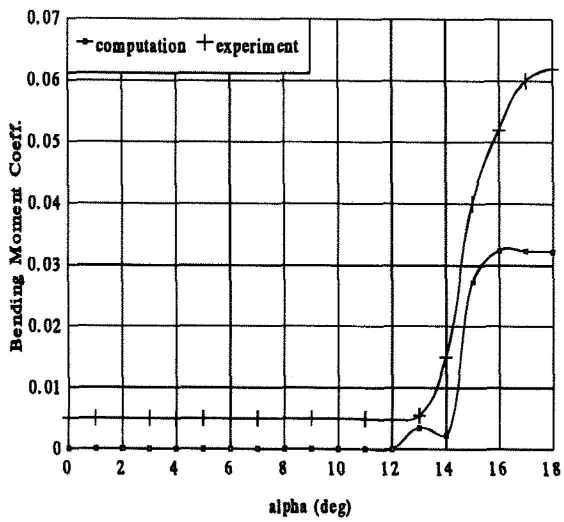

Fig. 11 Bending moment coefficient for Re=3.12e+06

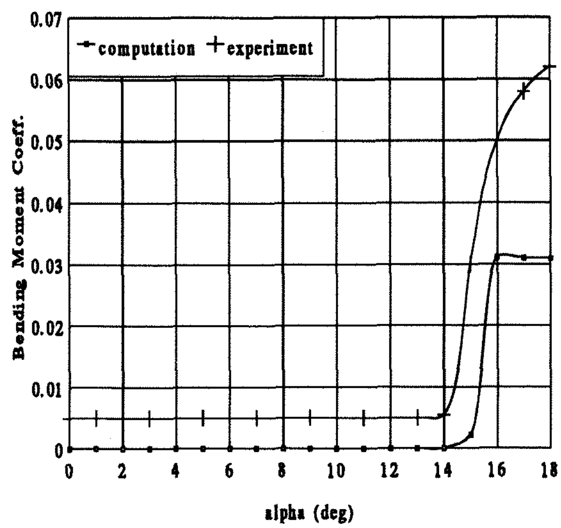

Fig. 12 Bending moment coefficient for Re=3.75e+06