ACOUSTIC EFFECTS ON BINARY AEROELASTICITY MODEL

KOK HWA YU[1]*, HARIJONO DJOJODIHARDJO[2] AND A HALIM KADARMAN[1]

[1]School of Aerospace Engineering, Engineering Campus,
Universiti Sains Malaysia, 14300 Penang, Malaysia.

[2]Aerospace Engineering, Faculty of Engineering,
Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

**Email: yukokhwa@yahoo.com*

ABSTRACT : Acoustics is the science concerning the study of sound. The effects of sound on structures attract overwhelm interests and numerous studies were carried out in this particular area. Many of the preliminary investigations show that acoustic pressure produces significant influences on structures such as thin plate, membrane and also high-impedance medium like water (and other similar fluids). Thus, it is useful to investigate structural response to acoustics on aircraft, especially on aircraft wings, tails and control surfaces which are vulnerable to flutter phenomena. The present paper describes the modelling of structure-acoustic interaction to simulate the external acoustic effect on binary flutter model. Here, the model is illustrated as a rectangular wing where the aerodynamic wing model is constructed using strip theory with simplified unsteady aerodynamics involving the terms for flap and pitch degree of freedom. The external acoustic excitation, on the other hand, is modelled using a four-node quadrilateral isoparametric element via finite element approach. Both equations are then carefully coupled and solved using eigenvalue solution. Next the mentioned approach is implemented in MATLAB and the outcome of the simulated results are later described, analyzed and illustrated.

ABSTRAK: Akustik adalah ilmu yang berkaitan dengan kajian bunyi. Pengaruh bunyi pada struktur menarik perhatian dan banyak kajian telah dilakukan dalam bidang tersebut. Banyak penyelidikan awal menunjukkan bahawa tekanan akustik menghasilkan pengaruh yang signifikan terhadap struktur seperti plat tipis, membran dan juga medium yang mempunyai impedansi yang tinggi seperti air (serta cecair lain yang serupa). Dengan demikian, hal ini berguna untuk mengetahui respon struktur terhadap akustik pada pesawat, terutama pada sayap pesawat terbang, ekor dan kawalan permukaan yang terdedah kepada fenomena flutter. Artikel ini memaparkan pemodelan interaksi struktur-akustik untuk mensimulasi kesan akustik luaran pada model flutter binari. Di sini, model tersebut digambarkan sebagai sayap persegi panjang di mana model sayap aerodinamik dibina menggunakan teori jalur dengan aerodinamis tidak tetap yang dimudahkan melibatkan istilah untuk darjah kebebasan bagi flap dan pitch. Manakala, eksitasi akustik luaran dimodelkan dengan elemen empat-node isoparametrik segiempat melalui pendekatan elemen terbatas. Kedua-dua persamaan kemudian digabungkan dan diselesaikan dengan menggunakan penyelesaian eigenvalue. Pendekatan tersebut kemudian dilaksanakan melalui MATLAB dan hasil dari simulasi kemudian dijelaskan, dianalisis dan digambarkan.

KEYWORDS : *Aeroelasticity, binary model, flutter, structural-acoustic coupling.*

1. INTRODUCTION

Aeroelasticity, a study on structure stability in response to aerodynamic loads, is regarded as a major aspect in designing an aircraft. In aeroelastic phenomena, the interaction of aerodynamic, elastic, and inertia forces on elastic structures cause undesired distortions in deformed mode shape and could even lead to a destructive vibration known as aeroelastic flutter. This type of instability produces unstable oscillation which may trigger catastrophic damages to the whole structure. For an aircraft, slender bodies such as aircraft wings, tails, and control surfaces are typically vulnerable to this unexpected threat and each aeroelastic factor need to be taken into consideration upon the design and flight performance of the aircraft. Due to their significant influences, these aeroelastic problems have been widely addressed in classical and standard text books [1,2] which also discuss the theory and basic principles toward the understanding of aeroelasticity. In taking steps to reduce this catastrophic risk, heavier structures were purposely designed for flutter prevention. However, this approach creates a major drawback in reducing the aircraft efficiency in term of mission performance and operation cost. An improved approach was later proposed by employing an active control system on a lifting surface called active flutter suppression [3] to stabilize the vibration of airframe structures and also overcome the weight penalty caused by the former approach. However, cheaper alternatives are being considered to replace the current flutter control system.

One of the alternative solutions which is presently being investigated, comprises the use of external acoustic excitation. To our best knowledge, the initial studies on structural analysis with the presence of acoustic excitation can be found in the work of Fahy and Wee [4] and also Rama Bhat *et al.* [5]. Both studies were carried out due to the concern of aircraft structural integrity when dealing with intense acoustic environments. For an aircraft, the sound, or frequently referred to as noise is generated from the propeller, exhaust, engine vibration and airflow around aircraft structure. For example, the sound pressure level produced by multiengine of a typical aircraft is approximately 130dB and can reach 150dB under supersonic condition. For the past few decades, many of the preliminary investigations show that acoustic pressure produces significant influences on structures such as thin plate, membrane and also high-impedance medium like water (and other similar fluids). The aeroelastic flutter analysis on rotating disk in an unbounded acoustic medium [6] for instance, is one of the latest studies conducted in this specific research area. On the other hand, the previous works of Djojodihardjo [7-9] demonstrate that the acousto-aeroelastic problem using BE-FE approach leads to significant influence on the performance of aeroelastic structure. It is thus useful to investigate the acoustic effect on aircraft wing structure using a different method in which the acoustic is formulated using FEM approach [10].

2. COMPUTATIONAL METHOD

2.1 Binary Aeroelastic Model

Due to the complexity of aircraft structures, it is often crucial to take account of simplifying assumptions in this methodology to allow computational of the elastic properties. Here, a simple model– a two-degree-of-freedom system (bending and torsion) consisting of a rigid wing with constant chord is adopted. Considering the two-dimensional airfoil, the airfoil with the chord length c is visualized in the flight condition with a uniform free stream of velocity, V , shown in Fig. 1.

Using the notation given in Fig. 1, the binary model is constructed based on the binary concept used in reference [11]. Illustrated in Fig. 2, the rectangular wing of span s and chord c is assumed to be rigid with two rotational springs at the root to provide flap (κ) and pitch (θ) degrees of freedom. In addition, the aerodynamics is modelled using a modified strip theory which allows calculations for unsteady effects.

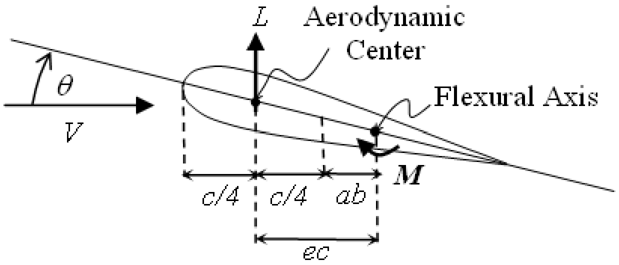


Fig. 1: A two-dimensional airfoil with notations.

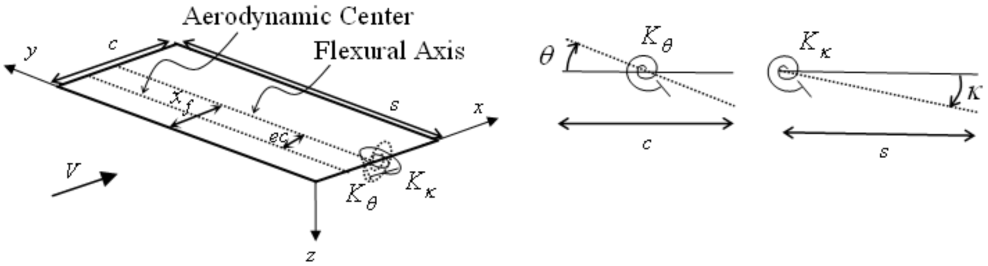


Fig. 2: Schematic layout of binary aeroelastic model (Hancock wing model)

According to [12], the full equations of motion can be written in the form of

$$[M_s]\{\ddot{q}_s\}+[C_s]\{\dot{q}_s\}+[K_s]\{q_s\}=0 \tag{1}$$

where mass matrix $[M_s]$, damping matrix $[C_s]$ and stiffness matrix $[K_s]$ for wing structure can be expressed as

$$[M_s]=\begin{bmatrix} \frac{1}{3}ms^3c & \frac{1}{2}ms^2\left(\frac{1}{2}c^2-cx_f\right) \\ \frac{1}{2}ms^2\left(\frac{1}{2}c^2-cx_f\right) & ms\left(\frac{1}{3}c^3-c^2x_f+cx_f^2\right) \end{bmatrix},$$

$$[C_s]=\rho V\begin{bmatrix} \frac{1}{6}cs^3a_W & 0 \\ -\frac{1}{4}ec^2s^2a_W & -\frac{1}{8}c^3sM_{\dot{\theta}} \end{bmatrix}+[D_s],\quad [K_s]=pV^2\begin{bmatrix} 0 & \frac{1}{4}cs^2a_W \\ 0 & -\frac{1}{2}ec^2sa_W \end{bmatrix}+\begin{bmatrix} K_k & 0 \\ 0 & K_\theta \end{bmatrix}.$$

2.2 Structural-Acoustic Coupling

To predict the acoustic effect on binary aeroelastic model, a proper coupling mechanism involving acoustic and structural interaction is included [13]. Taking this into consideration and by referring to Eq. (1), the equations for a flexible structure with an acoustic enclosure can now be written as:

$$[M_s]\{\ddot{q}_s\}+[C_s]\{\dot{q}_s\}+[K_s]\{q_s\}-[R_{as}]^T\{p\}=0 \tag{2}$$

While the equation of motion for an acoustic enclosure coupled to a flexible structure is given by

$$[M_a]\{\ddot{p}\}+[K_a]\{p\}-\rho[R_{as}]\{\ddot{q}_s\}=0 \tag{3}$$

where $[M_a]$ and $[K_a]$ are the acoustic mass and stiffness matrices and $[R_{as}]$ is the structural-acoustic coupling matrix. They can be expressed as

$$M_a = t\int_A N_f^T N_f \, dA \tag{4}$$

$$K_a = a^t t\int_A D^T D \, dA \tag{5}$$

$$R_{as} = tG^T \int_0^L N_S^T N_f \, d\bar{x} \tag{6}$$

where a is the speed of sound and t is the thickness of the fluid medium, whilst, N_f and N_S is the shape function for acoustic fluid and wing structure. The matrices G and D are the transformation matrix and strain displacement matrix.

Combining both Equations (2) and (3), the coupled system can be written as

$$\begin{bmatrix} M_s & 0 \\ -\rho_0 R_{as} & M_a \end{bmatrix}\begin{Bmatrix} \ddot{q}_s \\ \ddot{p} \end{Bmatrix}+\begin{bmatrix} C_s & 0 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} \dot{q}_s \\ \dot{p} \end{Bmatrix}+\begin{bmatrix} K_s & -R_{as}^T \\ 0 & K_a \end{bmatrix}\begin{Bmatrix} q_s \\ p \end{Bmatrix}=\begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{7}$$

This can be expressed in simpler form as

$$[A]\{\ddot{u}\}+[B]\{\dot{u}\}+[C]\{u\}=0 \tag{8}$$

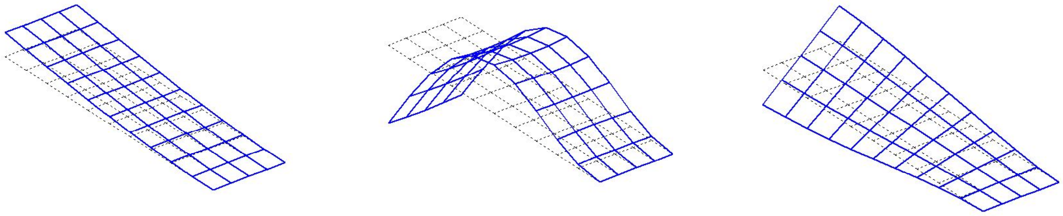
2.3 Flutter Solution

The acoustic-aeroelastic system in frequency domain is then solved by the use of solutions of eigenvalues and eigenvectors in a state-space form. Thus, the corresponding equation can be written as

$$\begin{bmatrix} I & 0 \\ 0 & A \end{bmatrix}\begin{Bmatrix} \dot{u} \\ \ddot{u} \end{Bmatrix}-\begin{bmatrix} 0 & I \\ -C & -B \end{bmatrix}\begin{Bmatrix} u \\ \dot{u} \end{Bmatrix}=\begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{9}$$

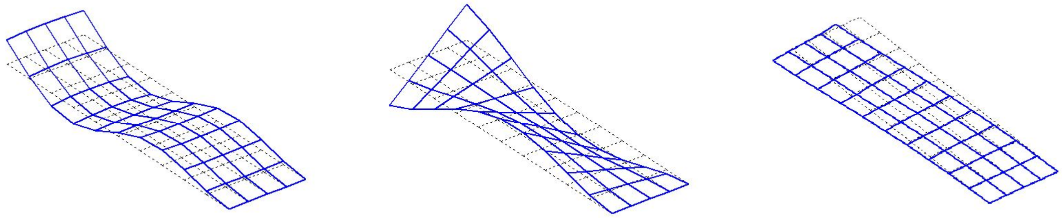
RESULTS AND DISCUSSION

Before analyzing the acoustic influence on wing structure, the rectangular wing model with semi-span $s = 7.5m$ and chord $c = 2m$ was first modelled using Finite Element Method (FEM) in order to determine more precise estimation on flutter occurrence condition in term of the natural frequencies involved. Using the in-house FEM code written in MATLAB, the mode shapes of the flexible wing made of Aluminum 6061 (with Young's modulus, $E = 69GPa$ and Poisson's ratio, $\nu = 0.33$ are illustrated in Fig. 3 for low frequency modes and Fig. 4 for high frequency modes.



5.78Hz 30.21Hz 38.13Hz

Fig. 3: Mode shapes of binary aeroleastic model at low frequency modes.



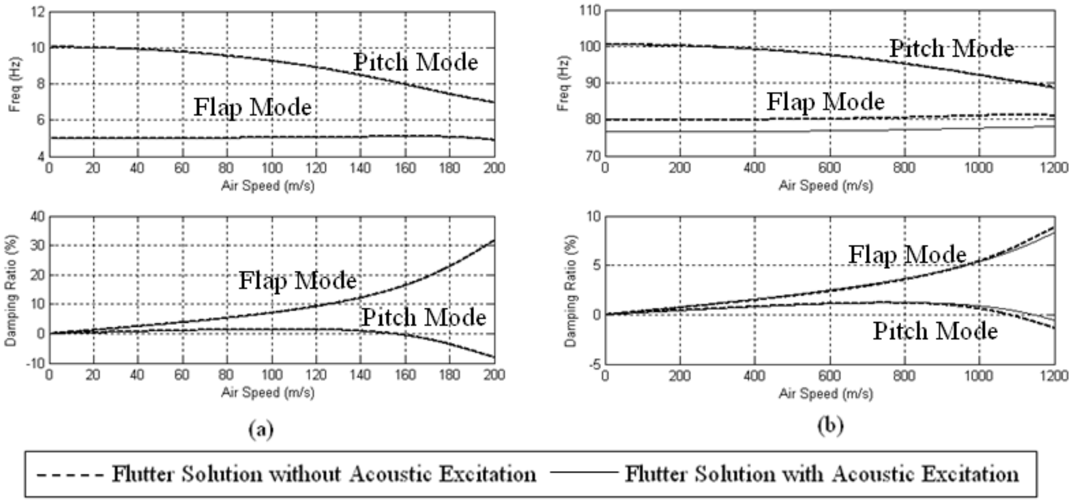
83.568Hz 102.06Hz 167Hz

Fig. 4: Mode shapes of binary aeroleastic model at high frequency modes.

Adopting from [12], the wing structure is assumed to have a uniform mass distribution of $100kg/m^2$. The mass axis is placed at the semi chord $x_m = 0.5c$ and the flexural axis is at $x_f = 0.48c$. In addition, other specified parameters like the lift curve slope $a_w = 2\pi$, air density $\rho = 1.225kg/m^3$ and non dimensional pitch damping derivative which is assumed to be -1.2 were included. Based on the information obtained from FEM simulation, the flutter analysis for two cases (low frequency vibration and high frequency vibration) was carried out. The detailed specifications for both cases are listed as below:

a) Low frequency vibration $(K_\kappa = I_K(5\times 2\pi)^2\, Nm/rad \quad \& \quad K_\theta = I_\theta(10\times 2\pi)^2\, Nm/rad)$
b) High frequency vibration $(K_\kappa = I_K(80\times 2\pi)^2\, Nm/rad \quad \& \quad K_\theta = I_\theta(100\times 2\pi)^2\, Nm/rad)$

Using the parameters mentioned, the acoustic-aeroelastic problem was solved via MATLAB and the outcomes of the analysis are shown in Fig. 5.



(a) (b)

Fig. 5: Frequency and damping plots for binary aeroelastic model with:
(a) low frequency vibration (b) high frequency vibration

As shown in the Fig. 5(a), the acoustic excitation has no significant influence on flutter performance at low frequency mode as both flutter solution results (with and without acoustic source) are the same. Meanwhile, for the case of high frequency mode in Fig. 5(b), the result obtained presents small changes for flutter solution with the inclusion of acoustic excitation compared with pure flutter solution. By observing the pitch mode in Fig. 5(b), the flutter speed (damping ratio equal to zero) for acoustic-aeroelastic problem has increased. From the result, the flutter speed for binary wing model under acoustic influence has increased to 1145m/s from 1080m/s. This indicates that the flutter suppression involving external acoustics source has the potential which can be implemented in order to delay flutter condition from occurring.

3. CONCLUSION

In this paper, simulations of a two-degree-of-freedom flutter system have been performed with and without the presence of external acoustics excitation. Two different cases were conducted and the results provide information which are helpful to better understand the acoustic effect on aircraft wing performance and support the possibility to delay the occurrence of flutter using acoustic for high frequency vibration modes. However, the implementation of acoustic needs special attention and random acoustic excitation might potentially reverses the flutter performance of airplane wing.

ACKNOWLEDGEMENT

The first author was supported by USM Fellowship and the third author would like to acknowledge Universiti Sains Malaysia – Research University Grant no. RU814042 and USM Incentive Grant for sponsoring this project.

REFERENCES

[1] R.L. Bisplinghoff, H. Ashley, R.L. Halfman, "Aeroelasticity". Addison-Wesley Publishing Company, Inc, US, 1955.

[2] Y.C. Fung, "An introduction to the theory of aeroelasticity". Dover Publications, 1968.

[3] E. Nissim, "Flutter suppression using active controls based on the concept of aerodynamic energy". NASA TN D-6199, 1971.

[4] F.J. Fahy, R.B.S. Wee, "Some experiments with stiffened plates under acoustic excitation". *J. Sound Vib.* Vol. 7, Issue 3, 1968, pp. 431-436.

[5] B. Rama Bhat, B.V.A. Rao, H. Wagner, "Structural response to random acoustic excitation". *Earthquake Engineering and Structural Dynamics*, Vol. 2, 1973, pp. 117-132.

[6] A. Jana, A. Raman, "Aeroelastic flutter of a disk rotating in an unbounded acoustic medium". *J. Sound Vib.* Vol. 289, 2006, pp. 612-631.

[7] H. Djojodihardjo, "BEM-FEM fluid-structure coupling due to acoustic or structural loading disturbance". Proceedings of Aerotech-II 2007 Conference on Aerospace Technology of XXI Century, 20-21 June 2007, Kuala Lumpur, 2007.

[8] H. Djojodihardjo, "BE-FE coupling computational scheme for acoustic effects on aeroelastic structures". paper IF-086, Proceedings of The International Forum on Aeroelasticity and Structural Dynamics, held at the Royal Institute of Technology (KTH), Stockholm, Sweden, June 2007, pp. 18-20.

[9] H. Djojodihardjo, "Unified BE-FE aerodynamic-acoustic-structure coupling scheme for acoustic effects on aeroelastic structures". paper ICAS 2008 7.7.7.5, 26th International Congress of the Aeronautical Sciences, Anchorage, Alaska, June 200714-19 September 2008.

[10] G. Sandberg, P.-A. Wernberg, P. Davidsson, "Fundamentals of fluids-structure interaction". In G. Sandberg, R. Ohayon, Eds. Computational aspects of structural acoustics and vibration. Springer, New York, 2008.

[11] G.J. Hancock, A. Simpson, J.R. Wright, "On the teaching of the principles of wing flexure/torsion flutter". *Aeronaut. J.*, Vol. 89, 1985, pp. 285-305.

[12] J.R. Wright, J.E. Cooper, "Introduction to aircraft aeroelasticity and loads". John Wiley & Sons Ltd, 2007.

[13] L. Coskuner, "Combined direct-adjoint approximations for large-scale design-oriented structural-acoustics finite-element analysis". Master Thesis, University of Washington, 2004.

NOMENCLATURE

$[C_s]$	Structural damping matrix	-
$[D_s]$	Proportional structural damping matrix	-
$[K_a]$	Acoustic stiffness matrix	-
$[K_s]$	Structural stiffness matrix	-
$[M_a]$	Acoustic mass matrix	-
$[M_s]$	Structural mass matrix	-
$[R_{as}]$	Structural-acoustic coupling matrix	-
$\{p\}$	Vector of generalized pressures	-
$\{q_s\}$	Vector of generalized structural displacements	-

$\{u\}$	Vector of generalized displacements-pressures	-
A	Combined structural-acoustic mass matrix	-
B	Combined structural-acoustic damping matrix	-
C	Combined structural-acoustic stiffness matrix	-
D	Strain displacement matrix	-
G	Transformation matrix	-
I	Identity matrix	-
I_k	Moment inertia for flap	kgm^2
I_θ	Moment inertia for pitch	kgm^2
K_κ	Flap stiffness	Nm/rad
K_θ	Pitch stiffness	Nm/rad
L	Lift	N
M	Pitching moment	Nm
$M_{\dot{\theta}}$	Nondimensional pitch damping derivative	-
N_f	Shape function of acoustic fluid	
N_s	Shape function of wing structure	
V	Freestream velocity	m/s
a	Speed of sound	m/s
a_w	Two-dimensional lift curve slope	-
c	Wing chord	m
m	Mass per unit area	kg/m^2
ec	Distance between aerodynamic centre with flexural axis	m
s	Wing span	m
t	Thickness of acoustic medium	m
x_m	Mass axis	m
x_f	Flexural axis	m

Greek letters

ρ	Air density	kg/m^3
κ	Flap degree of freedom	-
θ	Pitch degree of freedom	-