

# UNIFIED AERODYNAMIC-ACOUSTIC FORMULATION FOR AERO-ACOUSTIC STRUCTURE COUPLING

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## Abstract

As a follow-up on the author’s work on coupled BE/FE Method and modeling of structural-acoustic interaction, the present work utilizes BE formulation for both the acoustic and aerodynamic problem. For this purpose the unsteady aerodynamic problem which was earlier utilizes well-established lifting surface method is reformulated using BE approach. This scheme is presently outlined and worked out in the general framework of acousto-aeroelastic stability problem developed previously.

## 1. Introduction

Earlier work by the author and colleagues [1]-[6] addressed progressive stages of the development of coupled BE/FE Method and Modeling of structural-acoustic interaction. The computational approach based on the formulation of the boundary element computation of the acoustic load following the governing Helmholtz equation for acoustic disturbance propagation on the structure allows the incorporation of the direct or hydrodynamic part of the acoustic influence on the aeroelastic stability as a specific problem investigated. Various components of the method has been validated and the method produced results in qualitative agreement with well established analytical and experimental results of Holström, [7], Marquez, Meddahi. and Selgas [8], and Huang [9].

To address the problem associated with fluid structure interaction, in particular the vibration of structures due to sound waves, aerodynamics and their combined effects, a generic approach to the solution of the acousto-aeroelasto-

dynamic interaction has been followed. The development of the foundation for the computational scheme for the calculation of the influence of the acoustic disturbance to the aeroelastic stability of the structure [2-6], starts from a rather simple and instructive model to a more elaborate FE-BE fluid-structure one. The formulation of the problem is summarized in Fig. 1.

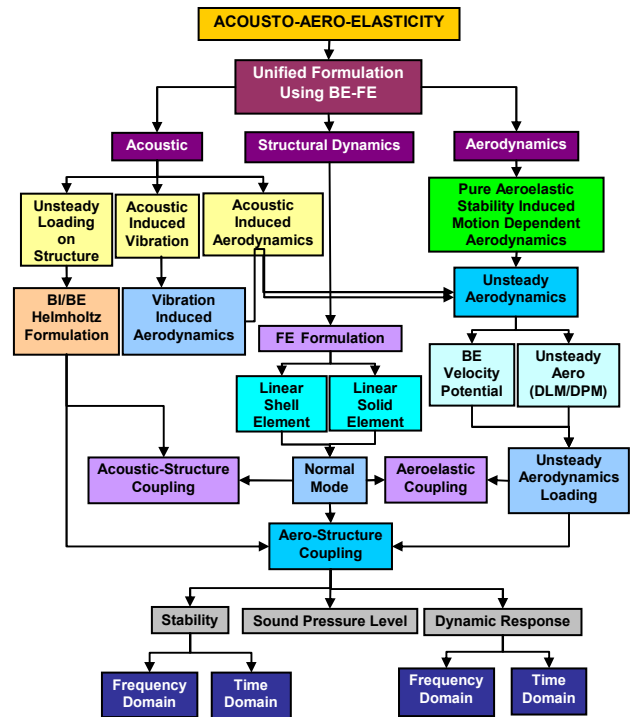


Fig. 1 Logical approach to treat the aeroacoustic effects on aeroelastic structure.

It is of interest at this point to recall the concluding remarks made by Farassat [10] that linear unsteady aerodynamics should be viewed as part of the problem of aeroacoustics. There are still many problems in aeroacoustics as well as in unsteady aerodynamics to be solved by combined analytic and numerical methods. The

efforts devoted here is only a small attempt in that direction.

## 2 Governing Equation for Acousto-Aeroelastic Problem

Referring to the development already carried out in earlier work [2-6], the governing equations for the acousto-aeroelasticity problem for an elastic wing submerged in a fluid and subject to acoustic pressure disturbance can be represented by the structural dynamic equation of motion with a general form of

$$[[\mathbf{K}] - \omega^2 ([\mathbf{M}] + [\mathbf{A}_{Aero}] + [\mathbf{P}_{Acou}])] \{x\} = \{F_{Ext}\} \quad (1)$$

where, with appropriate considerations on their actual form

$\mathbf{K}$  - stiffness related terms

$\mathbf{M}$  - inertial mass related term

$F_{Aero}$ ,  $\mathbf{A}_{Aero}$  - aerodynamic related term

$F_{Acou}$ ,  $\mathbf{P}_{Acou}$  - acoustic related term

$F$  - external forces other than those generated aerodynamically or acoustically.

The acoustic pressure is governed by Helmholtz equation, in discretized form can be written as

$$[\mathbf{H}] \{p_{Acou}\} = i\rho_0\omega[\mathbf{G}] \{v\} + \{p_{inc}\} \quad (2)$$

where, with appropriate considerations on their actual form

$\mathbf{H}$  - acoustic pressure influence coefficient

$\mathbf{G}$  - acoustic velocity influence coefficient

$v$  - acoustic velocity

$p_{Acou}$  - acoustic pressure

The unified treatment which was the focus of the earlier work capitalizes on the following:

a. The set of Eqs. (1) and (2) represent the unified state of affairs of acousto-aeroelastic problem being considered, which in principle can be solved simultaneously. However, prevailing situations may allow the solution of the two equations independently.

b. The acoustic term incorporated in Eq. (1), as can be seen in subsequent development, is considered to consist of three components to be elaborated below, and are also treated in unified fashion.

c. Analogous to the aerodynamic terms, the total acoustic pressure in the acoustic term incorporated in Eq. (1), will be separated into elastic structural motion dependent and

independent parts, which is referred to here as acoustic-aerodynamic analogy. Such approach allows the incorporation of the structural motion dependent part to the aerodynamic term in Eq. (1).

In the work of Huang [9], by introducing acoustic pressure field using vibrating membrane of loud-speaker, his theoretical prediction of the direct influence of the acoustic pressure field to the aerodynamically induced structural vibration has been demonstrated to agree with his experiments. On the other hand, Lu & Huang [11] and Nagai et al [12] have introduced the influence of the acoustic pressure field to the aerodynamic flowfield, recognizing the influence of trailing edge receptivity not accounted for in the earlier work.

With such perspective in mind, the unsteady aerodynamic loading can be considered to consist of three components, i.e.:

1. The unsteady aerodynamic load component induced by the elastic structural motion in the absence of acoustic excitation;
2. The unsteady aerodynamic load due to structural vibration which is induced by the ensuing acoustic pressure loading ( $P_{inc}$ );
3. The unsteady aerodynamic flow-field induced by acoustic pressure disturbance.

The combined acoustic and aerodynamic loading on the structure is then synthesized by linear superposition principle of small oscillation for the acoustic pressure disturbance to the aeroelastic problem, the latter due to aerodynamic-structure interaction. To facilitate the solution of the acousto-aeroelastic stability equation solved by V-g method, a novel approach is undertaken. Analogous to the treatment of dynamic aeroelastic stability problem of structure, in which the aerodynamic effects can be distinguished into motion independent and motion induced aerodynamic forces, the effect of acoustic pressure disturbance to the aeroelastic structure (acousto-aero-elastic problem) is considered to consist of structural motion independent incident acoustic pressure and structural motion dependent acoustic pressure, which is the scattering pressure. This is referred to in this work as the acoustic aerodynamic analogy. The governing equation for the acousto-aeroelastic problem is

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then formulated incorporating the total acoustic pressure (incident plus scattering pressure), and the acoustic aerodynamic analogy. A generic approach to solve the governing equation as a stability or dynamic response equation is formulated allowing a unified treatment of the problem.

### 3 Review of Linearized Unsteady Aerodynamics and Acoustics Differential Equations

The present work dwells further into the unified formulation of the unsteady aerodynamics and the acoustic terms.

The unsteady velocity potential  $\Phi$  satisfies the gas-dynamic equation [6]:

$$\nabla^2 \Phi - \frac{1}{a^2} \left[ \frac{\partial^2 \Phi}{\partial t^2} + \frac{\partial}{\partial t} (\nabla \Phi)^2 + (\nabla \Phi) \cdot \nabla \left( \frac{(\nabla \Phi \cdot \nabla \Phi)}{2} \right) \right] = 0 \quad (3)$$

For flows having free-stream velocity  $U_\infty$  in the direction of the positive x-axis, and assuming  $\phi$  to be the perturbation velocity potential which satisfies:

$$\Phi = \phi + U_\infty x \quad (4)$$

$$u = \frac{\partial \phi}{\partial x} \quad u \ll U_\infty \quad (5)$$

Then one obtains (Ashley & Landahl, [13], Morino & Kuo [14])

$$\nabla^2 \phi - \left( \frac{1}{a_\infty} \right)^2 \left[ \frac{\partial}{\partial t} + U_\infty \frac{\partial}{\partial x} \right]^2 \phi = F \cong 0 \quad (6)$$

where F is the contribution of non-linear terms, which for practical purposes consistent with perturbation linearization assumption, can be neglected. Furthermore, it will be convenient to consider harmonic motion as an element of any unsteady motion which can be built up using the principle of superposition Then one may assume:

$$\phi(\mathbf{x}, t) \equiv \bar{\phi}(\mathbf{x}, t) e^{i\omega t} \quad (7)$$

Substitution into Eq. (6) gives

$$\frac{\partial^2 \bar{\phi}}{\partial x^2} - \frac{1}{a^2} \left[ i\omega + U_\infty \frac{\partial}{\partial x} \right]^2 \bar{\phi} = 0 \quad (8)$$

Defining  $M \equiv \frac{U_\infty}{a}$ , Eq. (8) can be recast into:

$$(1-M^2) \frac{\partial^2 \bar{\phi}}{\partial x^2} + \frac{\partial^2 \bar{\phi}}{\partial z^2} - 2 \frac{i\omega M}{a} \frac{\partial \bar{\phi}}{\partial x} - \frac{\omega^2 \bar{\phi}}{a^2} = 0 \quad (9)$$

Define a new variable  $\Phi^*$  following Prandtl-Glauert Transformation as:

$$\bar{\phi} \equiv \Phi^* \exp \left[ i \frac{M^2}{(1-M^2)} \frac{\omega}{U_\infty} x \right] \quad (10)$$

and substitute into Eq. (9), then one obtains

$$\left\{ (1-M^2) \left[ \frac{\partial^2 \Phi^*}{\partial x^{*2}} + \frac{\partial^2 \Phi^*}{\partial z^{*2}} \right] + \Phi^* \left[ \frac{M^2}{(1-M^2)} \frac{\omega^2}{U_\infty^2} \right] \right\} \exp \left[ i \frac{M^2}{(1-M^2)} \frac{\omega}{U_\infty} x \right] = 0 \quad (11)$$

If one defines :

$$K \equiv \frac{M^2}{(1-M^2)} \frac{\omega^2}{U_\infty^2} \quad (12)$$

then the linearized unsteady aerodynamic equation (11) can be recast as

$$\nabla^2 \Phi^* + K^2 \Phi^* = 0 \quad \text{or} \quad \{ \nabla^2 + K^2 \} \Phi^* = 0 \quad (13)$$

which has the wave-equation form similar to the Helmholtz equation for the acoustic pressure disturbance[1]-[6],[7][8]:

$$\{ \nabla^2 + k^2 \} p = 0 \quad (14)$$

### 4 Boundary Element Formulation of the Solution of the Linearized Unsteady Aerodynamics Equations

To solve for the differential equation (13), Boundary Integral formulation can be obtained by the application of the Green's theorem, similar to the approach taken for the solution of the acoustic pressure equation (14).

Applying the Green's Theorem to equation (13)[4][15][16], then one obtains

$$\begin{aligned} \iiint_D \nabla \Phi^*_1 \cdot \nabla \Phi^*_2 \, dV &= \iint_S \Phi^*_1 (\nabla \Phi^*_2 \cdot \mathbf{n}) \, dS \\ &= \iint_S \Phi^*_1 \frac{\partial \Phi^*_2}{\partial n} \, dS \end{aligned} \quad (15)$$

in which  $\Phi^*_1$  is the transformed potential of interest and  $\Phi^*_2$  the corresponding free-space Green's function, i.e.

$$\{ \nabla^2 + K^2 \} \Phi^*_1 = 0 \quad \text{and} \quad (16)$$

$$\{ \nabla^2 + K^2 \} \Phi^*_2 = \delta(\mathbf{R} - \mathbf{R}_1) \quad (17)$$

Then it follows that [6][15][16]

$$\Phi^*_1 = \frac{1}{4\pi} \iint \Phi^*_1 \left( \frac{\partial}{\partial \nu} \right) \left( \frac{e^{-iK|\mathbf{R}-\mathbf{R}_1|}}{|\mathbf{R}-\mathbf{R}_1|} \right) dS \quad (18)$$

Here the free-space Green's function with the general form

$$G(|R-R_1|) = \frac{e^{-iK|R-R_0|}}{4\pi|R-R_1|} \quad (19)$$

is used, where refers to the  $\mathbf{R}$  coordinate of the field point of interest and  $\mathbf{R}_1$  the coordinate of the source element [4]-[6],[16], and  $\nu$  (or  $n$ , as appropriate) is the unit outward normal vector of a surface element on  $S$ .

In the development that follows, attention is focused on lifting surfaces, for which the wing (or airfoil) thickness is assumed to be reasonably small so that many nonlinear terms can be neglected[14].<sup>1</sup> Then equation (18) reduces to

$$\Phi^*_1(x, y, z, \omega) = \frac{1}{4\pi} \iint_{S(B+W)} \Delta\Phi^*_1 \left( \frac{\partial}{\partial z_1} \right) \left( \frac{e^{-iK|x-x_1|}}{x-x_1} \right) dS \quad (20)$$

where now  $\Delta\Phi^*_1$  refers to the difference between the values of  $\Phi^*_1$  at the upper and lower surface at the same coordinate location.

Inverse transformation of (19) gives:

$$\bar{\phi} = \left[ \frac{1}{4\pi} \iint_{S(B+W)} \Delta\bar{\phi}_1 \exp \left[ -\frac{M^2}{(1-M^2)} \frac{i\omega}{U_\infty} x_1 \right] \frac{\partial}{\partial z_1} \left( \frac{e^{iKr}}{r} \right) dS \right] \exp \left[ \frac{M^2}{(1-M^2)} \frac{i\omega}{U_\infty} x \right] \quad (21)$$

where  $\bar{\phi}$  stands for the stationary part of the perturbation velocity potential of the flow field.

### Integral equation for Pressure-Downwash relationship.

The velocity potential  $\phi$  is related to the harmonically varying pressure difference  $\Delta P$  by the Bernoulli equation:

$$\Delta\bar{P} = -\rho \left[ i\omega\bar{\phi} + U_\infty \frac{\partial\bar{\phi}}{\partial x} \right] \quad (22)$$

where

<sup>1</sup> Such assumptions can be relieved, and similar expression can be obtained by superposing equation (17) with the internal problem inside the body and wing surface, as carried out in reference [17].

$$\Delta P = \Delta\bar{P} e^{i\omega t} \quad (23)$$

Using the method of variation of parameter [18], the solution of the Bernoulli equation (22) can be obtained as

$$\bar{\phi} = \int_{-\infty}^x \frac{-\Delta\bar{P}}{\rho U_\infty} \left( e^{\frac{i\omega}{U_\infty}(\lambda-x)} \right) d\lambda \quad (24)$$

The boundary condition of no-flow through the surface of the body (and wing) defines the normal velocity or downwash  $w$  at the surface, and is given by

$$\frac{\partial\bar{\phi}}{\partial n} \equiv \frac{\partial\bar{\phi}}{\partial z} = w \quad (25)$$

### Exterior Problem

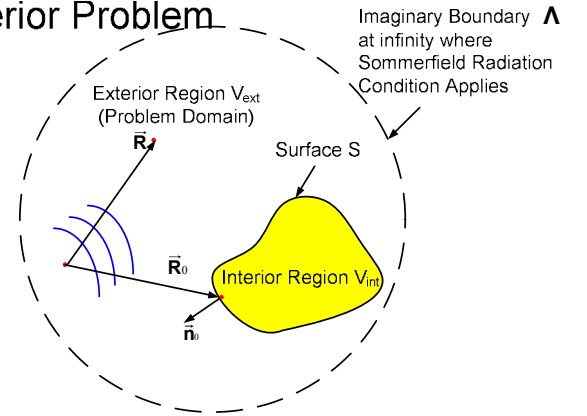


Fig. 3 Schematic of Acoustic Domain

Substituting Eqs. (24) and (25) into Eq. (21) (with appropriate algebraic manipulation) gives:

$$\frac{w}{U_\infty} = -\frac{1}{8\pi} \iint \frac{\Delta\bar{P}_1(x_1, y_1)}{\frac{1}{2}\rho U_\infty^2} K(x-x_1, y-y_1) dS \quad (27)$$

where

$$K(x, y) = \lim_{z \rightarrow 0} \exp \left[ -\frac{i\omega}{U_\infty} x \right]$$

$$\left[ \int_{-\infty}^{x-x_1} \exp \left[ \frac{1}{(1-M^2)} \frac{i\omega}{U_\infty} \xi \right] \frac{\partial^2}{\partial z^2} \left( \frac{e^{-iKr}}{r} \right) d\xi \right] \quad (28)$$

which is the well known standard Kernel function representation in lifting surface or panel method [19], and leads to further utilization of DPM or DLM in the unsteady aerodynamic problem as solution of (13) with appropriate boundary conditions. The detail of

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the formulation is elaborated elaborated in [20]-[21].

## 5 Unified Treatment of Aerodynamic-Acoustic Forcing in the Acousto-Aeroelastic Boundary Element Formulation

The revisit to the treatment of the aerodynamic problem elaborated above motivates further elaboration of the unified approach of the aerodynamic and acoustic part of the forcing function on the elastic structure, which leads to the governing equation (1) to be rewritten as:

$$\left[ [\mathbf{K}^*] - \omega^2 \left( [\mathbf{M}^*] + \rho_0 [\mathbf{F}_{ac}(ik_w)] + \frac{\rho}{2} \left( \frac{b_R}{k} \right)^2 [\mathbf{A}(ik)^*] \right) \right] \{q\} = \{P_{inc}^*\} \quad (29)$$

and

$$\rho_0 \omega^2 [\mathbf{G}_{11}] [T] [\Xi] \{q\} + [\mathbf{H}_{11}] \{p_a\} + [\mathbf{H}_{12}] \{p_b\} = i \rho_0 \omega [\mathbf{G}_{12}] \{v_b\} + \{p_{inc_a}\} \quad (30)$$

$$\rho_0 \omega^2 [\mathbf{G}_{21}] [T] [\Xi] \{q\} + [\mathbf{H}_{21}] \{p_a\} + [\mathbf{H}_{22}] \{p_b\} = + i \rho_0 \omega [\mathbf{G}_{22}] \{v_b\} + \{p_{inc_b}\} \quad (31)$$

where

$$[\mathbf{K}^*] = \Xi^T [\mathbf{K}] \Xi \quad (32a)$$

$$[\mathbf{M}^*] = \Xi^T [\mathbf{M}] \Xi \quad (32b)$$

$$[\mathbf{F}_{ac}(ik_w)] = \Xi^T [\mathbf{L}] [\mathbf{P}_{ac}(ik_w)] \Xi \quad (32c)$$

$$[\mathbf{A}(ik)^*] = \Xi^T \mathbf{G}_{ips}^T [\mathbf{A}(ik)] \mathbf{G}_{ips} \Xi \quad (32d)$$

where  $\Xi$  is the eigen-modes obtained from modal analysis of the purely elastic structure governed by

$$[\mathbf{K} - \omega^2 \mathbf{M}] \{x\} = \{0\} \quad (33)$$

and where  $\mathbf{L}$  is a coupling matrix of size  $\mathbf{M} \times \mathbf{N}$ , where  $\mathbf{M}$  is the number of FE degrees of freedom and  $\mathbf{N}$  is the number of BE nodes on the coupled boundary  $a$ , depicted in Fig.4. For each coinciding Boundary and Finite Elements, the acoustic pressure elemental coupling term is given by Djodjodhardjo et al [6], Holström [7] and Marquez et al [8].

$$\mathbf{L}_e = \iint_{S_e} N_F^T n N_B dS \quad (34)$$

where  $N_F$  and  $N_B$  are the shape function of the coinciding Finite Element and Boundary Element, respectively, and  $n$  is the normal vector to the corresponding coinciding surface. Here  $\{x\}$  is the structural deformation and transformed to the generalized coordinates  $\{q\}$  using the following relationship:

$$x = \Xi q \quad (35)$$

where  $\Xi$  is the modal matrix as solution to the eigen-value problem corresponding to the free vibration of the structure.

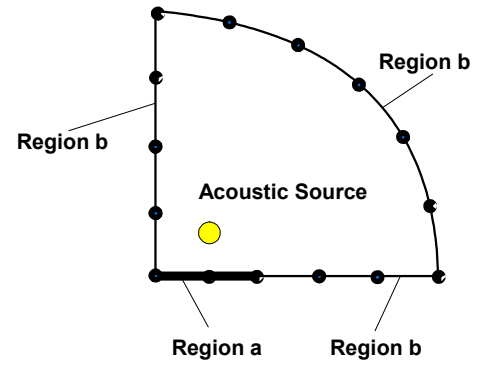


Fig.4 Schematic of BE-FE fluid-structure interaction domain represented as a quarter space with defined boundary conditions on the boundaries

By appropriate mathematical derivation, it was readily shown by Djodjodhardjo [4][6] that

$$\{p_a\} \equiv -\rho_0 \omega^2 [\mathbf{P}_{ac}(ik_w)] \{x\} \quad (36)$$

With such formulation, similar procedure as elaborated in [4]-[6] is then followed.

## 6 Acoustic-Aerodynamic Analogy

Analogous to the treatment of dynamic aeroelastic stability problem of structure, in which the aerodynamic effects can be distinguished into motion independent (self-excited) and motion induced aerodynamic forces, the effect of acoustic pressure disturbance to the aeroelastic structure (acousto-aero-elastic problem) can be viewed to consist of structural motion independent incident acoustic pressure (excitation acoustic pressure) and structural motion dependent acoustic pressure, which is known as the scattering pressure. However the scattering acoustic pressure is also dependent on the incident acoustic pressure.

Solution of Eq. (29) will be facilitated by the use of modal approach, i.e. transforming  $\{x\}$  into the generalized coordinate  $\{q\}$  following the relationship  $x = \Phi q$ , where  $\Phi$  is the modal matrix. In the examples worked out, a selected lower order natural modes will be employed in  $\Phi$ . Pre-multiplying Eq. (29) by  $\Phi^T$  and converting dynamic pressure  $q_\infty$  into reduced frequency ( $k$ ) as elaborated in [2]-[6], Eq. (29) can then be written as:

$$\Phi^T \left[ \mathbf{K} - \omega^2 \left( \mathbf{M} + \frac{\rho}{2} \left( \frac{L}{K} \right)^2 \left[ \mathbf{A}(ik) \right] + \rho_0 \left[ \mathbf{F}_{acsc}(k_w) \right] \right) \right] \Phi \{q\} = \Phi^T \{ \mathbf{F}_{acsc}(k_w) \} + \Phi^T \{ \mathbf{F} \} \quad (37)$$

Since all of the acoustic terms are functions of wave number ( $k_w$ ), Eq. (37) will be solved by utilizing iterative procedure. Incorporation of the scattering acoustic component along with the aerodynamic component in the second term of Eq.(37) can be regarded as one manifestation of what is referred to here as the acoustic-aerodynamic analogy followed in this approach.

### 7 Case Study and Numerical Results

Generic case of a fixed flat plate with a pulsating monopole acoustic source located at certain point on its upper surface has been considered for benchmarking in earlier work [4]-[6]. The present work will elaborate the application of the in-house Doublet Point Method code written in MATLAB©, which has been rederived using boundary integral formulation in sections 3 and 4. Further formulation of the acoustic-aerodynamic analogy as implied by Eq. (37) will account for the change in the flow boundary conditions due to the presence of the acoustic pulsating monopole source as was carried out in preceding work [6]. The use of modified BAH wing [2]-[4] as carried out previously will be utilized for benchmarking for the three dimensional case. Results from this approach, along with the previous results for the direct acoustic effect on the acoustic influence on aeroelastic stability [4]-[6], will be discussed. For this purpose, the in-house MATLAB program was developed following the Doublet Point (DPM) Scheme of Ueda & Dowell[22] for

incorporation into the combined acousto-aeroelastic solution of flutter stability problem of concern. The validation of the in-house DPM program by the benchmarking application of the in-house DPM code the equivalent BAH wing considered in ref. [2]-[6] is elaborated in ref.[20][21], and presented here.

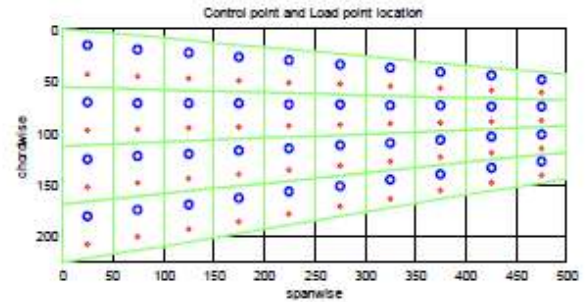


Fig. 5. Equivalent BAH wing discretization for unsteady aerodynamic load calculation

For the purpose of this study, the equivalent BAH wing planform was discretized for 40 aerodynamic boxes with 10 elements span-wise and 4 elements chord-wise as depicted in Fig.5. To validate the method, calculations were carried out for several values of  $k$  ( $k = 0, 0.3, 0.6, 0.8$ ). Figure 6a shows  $C_p$  distribution at station 1 for those  $k$  values. These results were then compared to typical  $C_p$  distribution from Zwaan [23] which is shown in Fig.6b

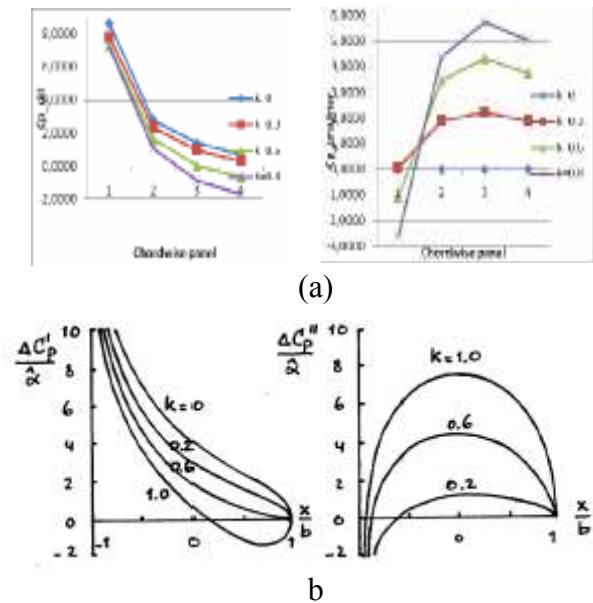


Fig. 6. (a) Present work,  $C_p$  distribution with  $k$  variation (real part-left, imaginary part-right); (b)  $C_p$  distribution with  $k$  variation (real part-left, imaginary part-right) of Zwaan [23] (validation based on  $k$ )

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The calculation of unsteady aerodynamics on equivalent BAH wing was carried out for reduced frequency of  $k = 0.01$ , by taking heaving motion amplitude  $h=1$  and pitching motion amplitude  $\alpha = 1.7$  rad. The results are presented in Fig.7 as the distribution of pressure coefficient ( $C_p$ ) over the wing surface and Fig.8 as the chordwise distribution of  $C_p$  at station 1, 5 and 10.

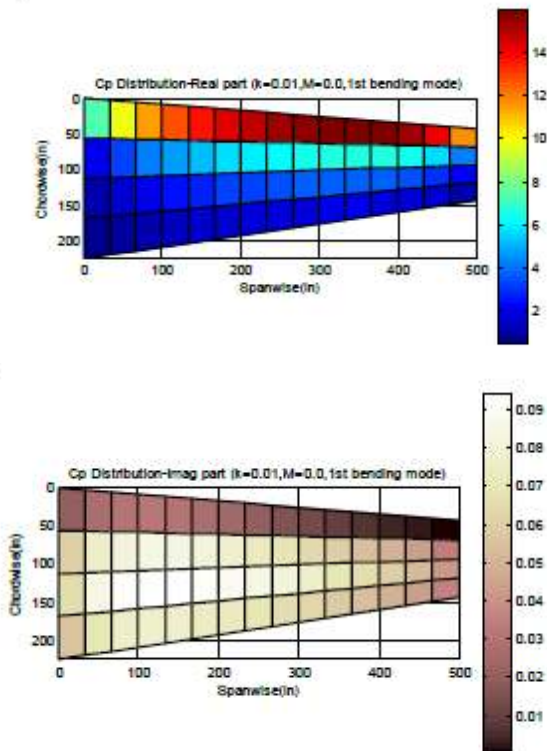
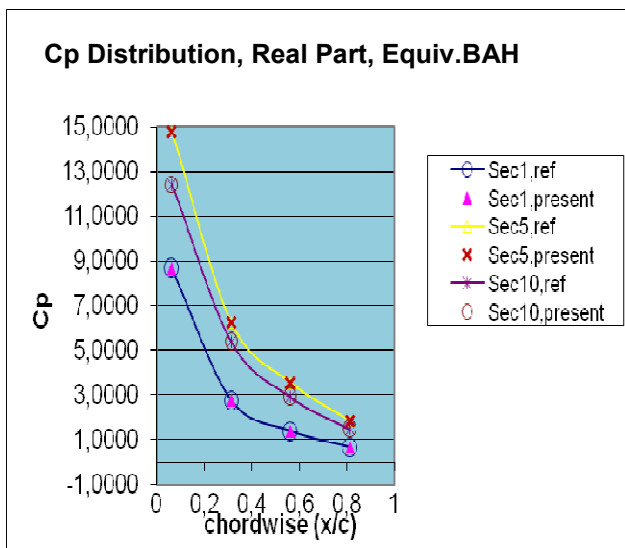
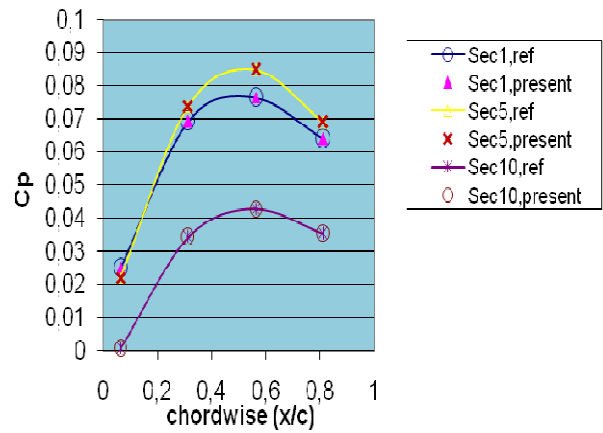


Fig. 8 (a) Real part of  $C_p$  distribution b. Imaginary part of  $C_p$  distribution



(a)

## Cp Distribution, Imaginary Part, Equiv.BAH Wing



(b)

Fig. 9 : Real (a) and Imaginary (b) parts of Pressure Distribution on modified BAH wing ( $k=0.01$ ,  $M=0.0$ , 1<sup>st</sup> bending); ref is associated with earlier work [3]

The computational result using the new in-house DPM program was also compared to earlier results (Djojodihardjo & Safari,[3]), which are shown in Fig. 9.

The in house DPM program was also applied to typical CN-235 wing, and the results are shown in Figs. 10 with planform exhibited in Fig.11.

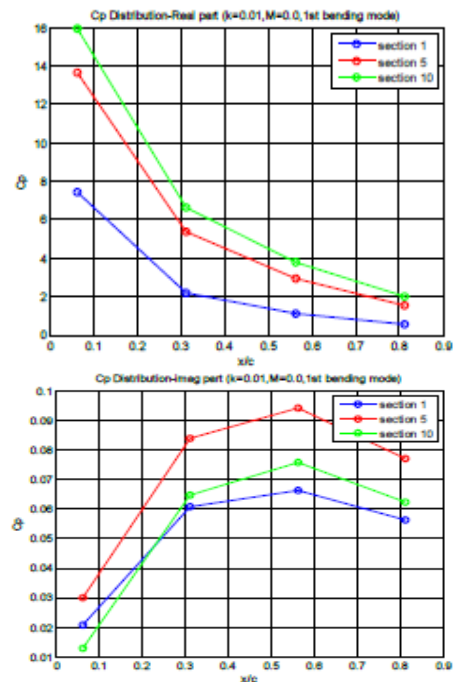


Fig. 10.  $C_p$  distribution on section 1, 5 & 10; (a) Real part, (b). Imaginary part

Fig. 11 exhibits the typical representation of CN-235 Wing being studied.



Fig. 11 Wing planform typically representing CN-235 Wing utilized for benchmarking, indicating sections 1, 5 and 10 of interest.

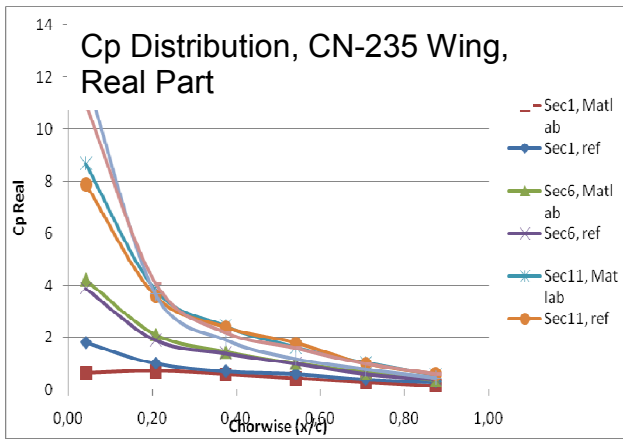
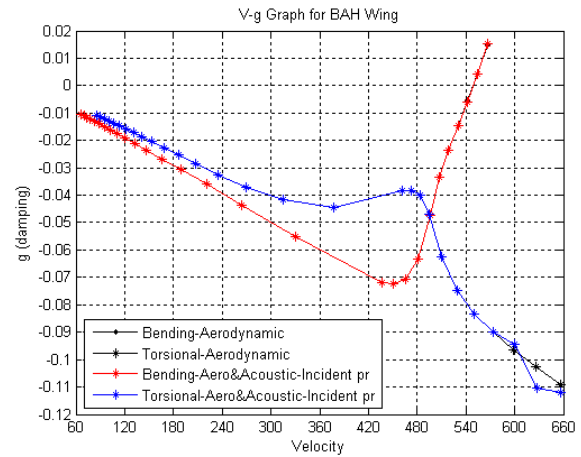


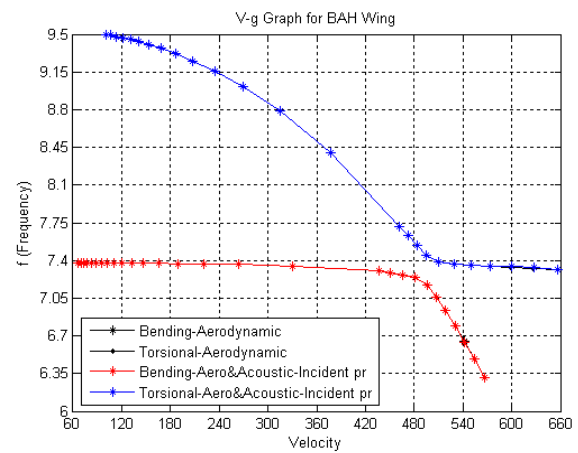
Fig. 12 :Real parts of Pressure Distribution on modified CN-235 wing (( $k=0.01$ ,  $M=0.0$ , 1<sup>st</sup> bending); ref is associated with earlier work in [24])

Fig. 12 compares the Cp distribution results of the in-house DPM code applied to typical representation of CN-235 wing with that previously obtained by Soeherman[14], indicating only the real part. The results shows good agreement. The results as exhibited by Figs. 6, 9 and 12 show that the in-house code, developed through the reformulation of DPM method through rigorous boundary integral formulation to allow unified approach with the treatment of acoustic problem, has produced plausible results.

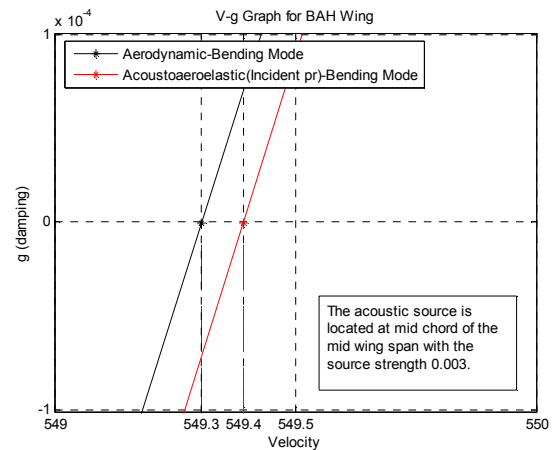
The present elaboration on the unsteady aerodynamics gives further rigorous foundation to the unified approach attempted in the present series of efforts. The computation and integration scheme for solving the acousto-aeroelastic problem follows the procedure depicted in Figure 1. The solution of Eq. (37) as a stability equation in a "unified treatment" already incorporates the total acoustic pressure, which has been "tuned" to behave like the aerodynamic terms in the modal approach .



(a)



(b)



(c)

Fig 13. (a) Damping and (b) frequency diagram for BAH wing calculated using V-g method written in MATLAB® for the acousto-aeroelastic problem (the total acoustic pressure already incorporates the scattering pressure). (c) enhanced V-g curve at flutter.

Figure 13 exhibits the application of the method using the reformulation of the aerodynamic problem for the flutter stability problem of modified BAH Wing; (a) Damping



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and (b) frequency diagram for BAH wing calculated using V-g method written in MATLAB® for the acousto-aeroelastic problem. The V-g diagrams are drawn for pure aeroelastic as well as for acousto-aeroelastic cases. The figure illustrates the influence of the acoustic disturbance on the aeroelastic behavior of the structure considered.

### 8 Conclusions

The objective of the present work to establish a unified approach for the acoustic and aerodynamic component of the acousto-aeroelastic problem using Boundary Integral Approach, which will facilitate the unified treatment of the acousto-aeroelastic governing equation (33) has been carried out by reformulating the unsteady aerodynamic load calculation. To this end the governing unsteady gas dynamics equation for the perturbation velocity potential recast into a form similar to the Helmholtz wave equation for the acoustic pressure disturbance and the assumption of harmonic motion as an element of the unsteady motion allows the mean disturbance velocity potential be written in a Boundary Integral Equation (21). Such formulation allows unified and combined treatment of the unsteady aerodynamic and acoustic terms in the combined Finite Element-Boundary Element expression of the acousto-aeroelastic governing equation (33) as well as facilitating the aerodynamic terms to be further transformed into the well established lifting surface type (kernel-function) expression relating the downwash on the surface of the structure to the pressure distribution there, as given by equation (27).

An in-house Doublet Point Method following the classical one has been developed and has been validated.

Accordingly, the computational scheme for the calculation of the influence of the acoustic disturbance to the aeroelastic stability of a structure follows the scheme that has been developed using a unified treatment and acoustic-aerodynamic analogy. By considering the effect of acoustic pressure disturbance to the aeroelastic structure (acousto-aero-elasto-

dynamic problem) to consist of structural motion independent incident acoustic pressure and structural motion dependent acoustic pressure, the scattering acoustic pressure can be grouped together in the aerodynamic term of the aeroelastic equation. By tuning the incident acoustic pressure, it can also be incorporated along with the scattering acoustic term, forming the acousto-aeroelastic stability equation. For this purpose the problem domain has been defined to consist of those subjected to acoustic pressure only and that subject to acoustic structural coupling, which is treated as acousto-aeroelastic equation. Using BE and FE as appropriate, an integrated formulation is then obtained as given by the governing Eq. (37), which relates all the combined forces acting on the structure to the displacement vector of the structure. The solution of Eq. (33) – and after using modal approach in structural dynamics, Eq.(37) - can be obtained by solving it as a stability equation in a "unified treatment". The disturbance acoustic pressure already incorporates the total pressure (incident plus scattering pressure), which has been "tuned" to behave like the aerodynamic terms in the modal Eq.(37). Such approach allows the application of the solution of the acousto-aeroelastic stability equation in the frequency domain using V-g method

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# UNIFIED AERODYNAMIC-ACOUSTIC FORMULATION FOR AERO-ACOUSTIC STRUCTURE COUPLING

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