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Numerical Aeroelasticity Testing and Assessment System Developed at NAL of JAPAN
NALで開発された数値空力弾性試験・評価プログラム

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Numerical Aeroelasticity Testing and Assessment System Developed at NAL of Japan*

Jiro NAKAMICHI*1

Abstract

Transonic flows are characterized by the presence of adjacent regions of subsonic and supersonic flows accompanied by shock waves. In the past, there have been many activities in the development of computational methods for the analysis of steady and unsteady transonic flow in the time-linearized frequency- and time-domain. These activities were motivated by the need to supplement expensive and time consuming wind tunnel tests subject to unsteady aerodynamics and aeroelasticity, especially, flutter, with an affordable and reliable alternative. In the present paper, the outline of the aeroelasticity analytical tool named as Numerical Aeroelasticity Testing and Assessment System (NATAS) developed at NAL is prescribed. This system consists of four modules; the Doublet Point Method module (The Linear Lifting Surface Theory), The TSD module (The Transonic Small Disturbance Theory), the FP module (The Full Potential Theory) and the EL/NS module (The Euler and Navier-Stokes's Theory). The prototypes of these codes were developed by the researchers at NAL of Japan. The NATAS uses GUI (Graphical User Interface) to interactively manage input, output and interlink among the modules, error processing and graphical results. The input data for the higher model can be automatically converted for the lower one. The user can choose the module depending upon the trade-off among the purpose of the calculation, the accuracy, the efficiency and the cost. There are still restrictions on the function of the NATAS at present stage. However, it continues to be evolving.

Key words: Aeroelasticity, Flutter, Unsteady Aerodynamics, Computational Fluid Dynamics

概　　要

航空機の空力弾性問題は、航空機の構造設計のみならず飛行力学の観点、さらには、高度な設計精度を要求される今日にいたっては、空気力学的な面からも重要視される、いわゆる多分野統合問題である。低速域、あるいは超音速域での空力弾性問題は、非定常空気力として古典的な揚力面理論を適用することで問題が解決する場合が多い。遷音速域においては周知のとおり翼面上の衝撃波、あるいはそれと境界層との干渉による剥離等に起因するいわゆるフラッタ境界の遷音速ディップが起こる。その結果、一般的には、超音速航空機においてもフラッタは遷音速域がクリティカルになることが知られている。

航空宇宙技術研究所では、これらの観点から従来、空力弾性の研究、特に遷音速域における非定常空気力の計算法の研究、あるいはそれを用いたフラッタ計算プログラムの開発に努力を傾注してきた。これらの知的財産を統合化して、汎用かつ種々の航空機の空力弾性解析のためのコンピュータソフトの開発を計画した。これらのソフトは、航空機メーカに対して有料ではあるが設計ツールとして提供される。本、ソフトの特徴は

1）揚力面理論、遷音速微少擾乱理論、フルポテンシャル理論、オイラー理論およびナビエ・ストークス理論による非定常空気力の適用が可能であること

2）したがって、ユーザーが、解析対象、目的、要求精度、計算時間（計算費用）の観点から、適切なモデルを選択しえること

3）基本的には、高度なモデルに対するデータおよび計算パラメターは、低次のモデルに対するそれらに自動的に変換可能であること

4）GUI(Graphical User Interface)で動作し、ユーザーと親密な関係で操作が可能なこと

5）UnixおよびWindowsの双方のOS上で動作が可能であること

である。

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1 INTRODUCTION

The NAL of Japan was formerly one of the national research institutes of Japan. However, it was privatized as a new organization in April 2001. After the privatization, the NAL has been promoting the technology transfer not only to Japanese aircraft industries but also to other field industries which need the advanced technology developed at the NAL.

The aeroelasticity Group, Structures and Materials Research Center, NAL of Japan, has been concentrating on developing the aeroelasticity analysis tools for more than the last two decades not only for safety design but also for weight reduction of aircraft wing structures. In the present work, the computational methods for the flutter analysis which were developed at NAL of Japan were integrated into a software package. The outline of the Numerical Aeroelasticity Testing and Assessment System (NATAS) developed at NAL is described, which is a computer software for the analysis and the numerical simulation of the aeroelastic phenomena mainly for lifting surfaces of aircraft.

Predictions of detailed unsteady flow field around aircraft and the associated aerodynamic forces are always challenging to aeroelastician.

Through the rapid progress of computational fluid dynamics (CFD) and computer hardware technology, comprehensive flow simulation around complicated configurations have just now been considered feasible. Moreover, the accuracy and efficiency of computation have been significantly improved through the rapid development of effective geometry modeling/grid generation and advanced numerical algorithms of the CFD technology.

There are several kinds of aeroelasticity phenomena; 1)classical flutter (like a bending- torsion coupled flutter) 2)transonic flutter (transonic-dip) 3)aileron buzz 4)Shock-stall flutter 5)low-speed stall flutter 6)buffeting 7)galloping and 8)other abnormal structural vibration due to complex flow patterns. Among these phenomena, the classical bending-torsion flutter can be estimated by the linear lifting surface theory based upon non-viscous flow model. 2) and 3) can partly be analyzed by non-viscous flow model, too, but shock-wave motions have a greatly important role on those phenomena. Therefore the viscous flow model is inevitable in order to calculate instability/stability boundary due to the shock wave motion. 4)-8) are caused by flow separations, or sometimes the separations due to the shock-boundary layer interaction. So the viscous flow models must be used for understanding the mechanism of those aeroelasticity phenomena.

The NAL has developed the analytical tools for the aeroelasticity based upon the viscous flow as well as the inviscid flow. The flow models available in the NATAS are (Fig.1) ;

1) lifting surface theory, Doublet Point Method (DPM) [1-4)]
2) Transonic Small Disturbance theory(TSD)
3) Full Potential model(USTF3D) [6-8)]
4) Euler/Navier-Stokes model [9-12)]

In the present paper, the outline of the NATAS is described from the view points of 1) the outline of the scheme 2) the capability 3) the performance and 4) several examples focusing the recent flutter simulations by the Euler/Navier- Stokes code.

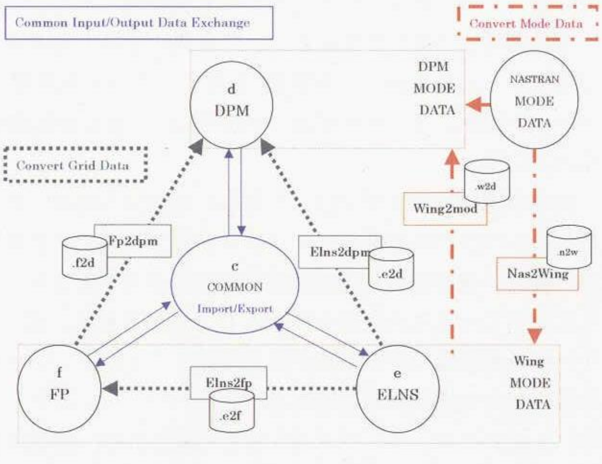


Fig.1 Concept of the NATAS

2 SYSTEM COMPOSITION

The NATAS (at present) consists of a work station (HP Kayak XU800 Intel Pentium III 733MHz, memory 512MB, Red Hat Linux Release 6.2) and the Numerical Wind Tunnel (NWT) at NAL. The all modules can run on the work-station. Jobs for the FP and the EL/NS modules can also submitted to the NWT through the work-station. The system has a function to produce the charts and the graphics clients need to show the computed results.

The NATAS uses GUI (Graphical User Interface) to interactively manage input, output, interlink between modules, error processing and graphical results. The GUI was developed so that the clients' efforts should be as little as possible by highlighting the processes path, saving the previous efforts on work directory and maximizing the use of mouse. The GUI uses javaVM, which enable the system to run on both Windows and Linux/Unix Systems. The graphical part of the system uses VTK (Visual Tool Kit) to produce charts or graphics. Some examples of the graphical outputs are illustrated in the last part of this paper.

3 FLUTTER ANALYSIS

The flutter equations are expressed in a general form as;

$$m_i\ddot{q}_i + k_i^2 m_i q_i = \overline{Q}\iint_S(-C_p n_z + C_f t_z)\Phi_i dS$$

Where, m_i :generalized mass, k_i :non-dimensional fundamental frequency, q_i:generalized coordinate, Φ_i:fundamental vibration mode, C_p:aerodynamic pressure coefficient, C_f:aerodynamic friction coefficient, dS :area vector, $\overline{Q}$:non-dimensional dynamic pressure. Incidentally, the NASTRAN Aeroelasticity Version employs linear theories; the Doublet Lattice Method(DLM) and the lifting body theory in the subsonic regime, and the ZONA51, the mach box method and the piston theory in the supersonic regime, respectively. On the contrary, the NATAS provides the linear theory, DPM in both subsonic and supersonic regions, and the nonlinear theories; the Full Potential model, the Euler and the Nvier-Stokes models.

4 OUTLINE OF THE DPM MODULE [3-5]

The DPM solves the linear small perturbation potential equation as,

$$(1-M_\infty^2)\phi_{xx} + \phi_{yy} + \phi_{zz} = \frac{2M_\infty}{a_\infty}\phi_{xt} + \frac{1}{a_\infty^{\ 2}}\phi_{tt}$$

Introducing the acceleration potential, the above equation will be reduced to the following integral equation by applying instantaneous flow tangency boundary conditions on the lifting surface.

$$w(x,y) = \frac{1}{8\pi}\iint_{Ra}\Delta p(\xi,\eta)K(x_0,y_0)d\xi d\eta$$

where, $w(x,y)$: up wash on the lifting surface, $\Delta p(\xi,\eta)$: load difference between upper and lower surfaces, $K(x_0,y_0)$: kernel function, which is switched from the subsonic kernel function to supersonic one depending on the free stream Mach number. The integral equation is discretized by dividing the lifting surface into small panels. A pressure doublet is arranged at the center of the quarter-chord line of each panel. The magnitudes of the pressure doublets are determined so as to satisfy the tangency flow conditions at the control point located at the center of 3-quarter-chord line of the panel. The surface integral of the kernel function is implemented analytically.

The DPM can be applied to a non-planer lifting surface like tip-fin and wing-let configurations.

The generalized aerodynamic forces are calculated in a linear form with respect to the generalized coordinates. The flutter calculations can be done systematically in both subsonic and supersonic regimes by either U-g or p-k method.

The aeroelastic phenomena such as transonic-dip and stall flutter are not simulated by the DPM module because the linear theory capture neither the shock waves in the transonic region nor the flow separations.

For the flutler computations, the fundamental vibration mode shapes, planform of the lifting surface and the aerodynamic parameters must be provided by the clients. The fundamental mode shapes can be obtained from either analysis by the NASTRAN or

GVT (Ground Vibration Test). At the present stage, the function to convert the mode displacements from the NASTRAN data to DPM data is not prepared. the clients have to provide the mode shape data in a form requested by the DPM module. The mode data must be given for the mass matrix so as to be unit one by the appropriate normalization. The data of aerodynamic panels are generated block by block. In a block, the panels are evenly divided. The fuselage also can be treated in this model. For the flutter calculations in this linear analysis, the classical U-g and the p-k method are available. The generalized aerodynamic forces are computed in a specified region of the reduced frequency. As for the graphic output, structural damping ratio vs. U and frequencies vs. U can be drown. The procedure of the DPM flutter analysis is as follows;

1. define the aerodynamic panels
   specify the 4 points coordinates of each block and the number of division in a block
2. convert the mode
   specify the in/output files for the NASTRAN and the aerodynamic panel data files to generate the mode data for the DPM
3. aerodynamic analysis
   specify the aerodynamic panel data and vibration mode data to generate the generalized aerodynamic forces
4. specify the spline parameters to interpolate the generalized aerodynamic forces with respect to the reduced frequency
5. flutter analysis
   choose p-k method or U-g method
6. postscript
   choose the graphic output of the unsteady aerodynamics and flutter analyses
   The above stream can be proceeded through the Graphic Unit Interface (GUI) between the machine. and the clients. Some examples of the postscript are given in Fig.2.

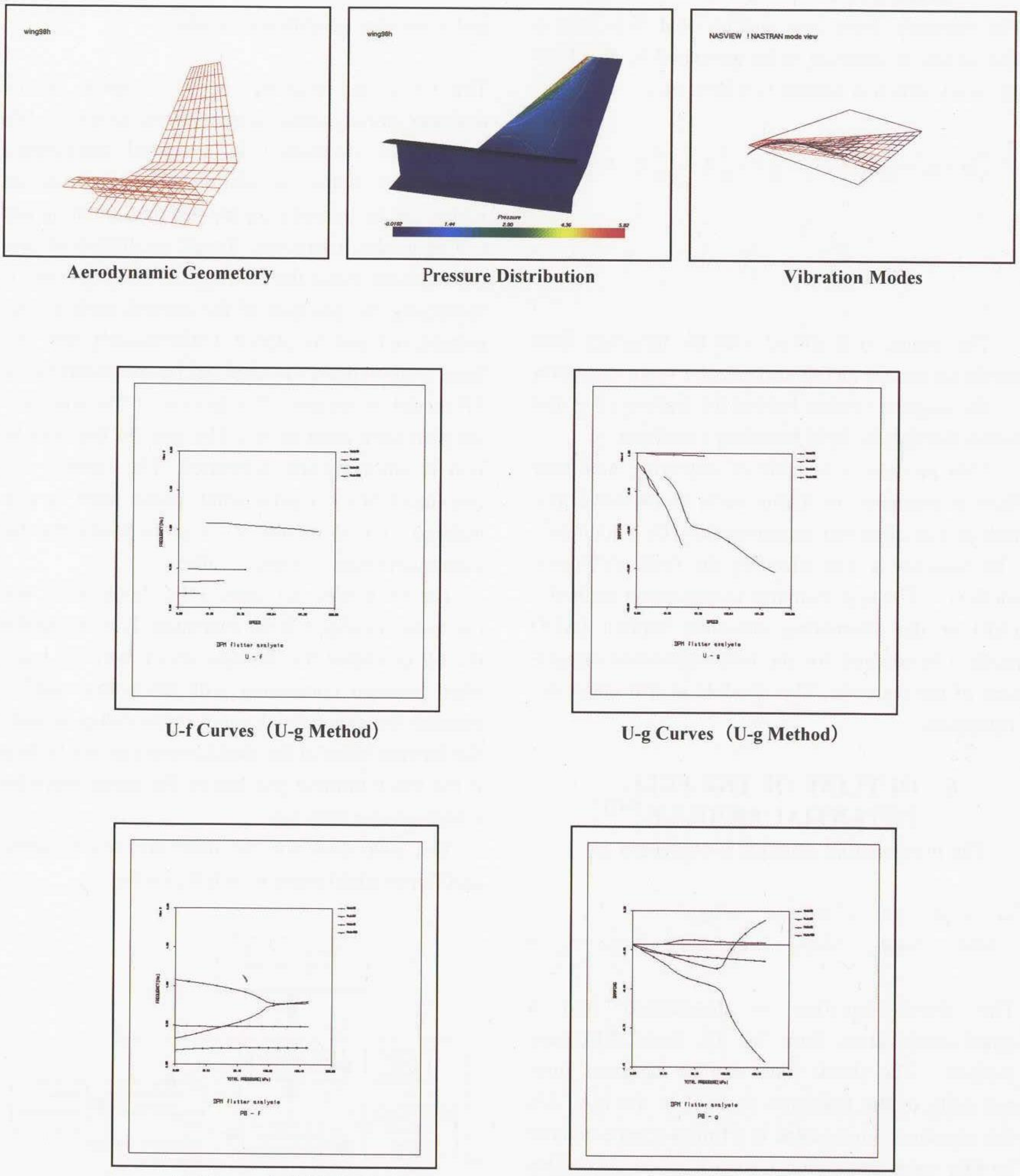


Fig.2 Examples of the Graphical Outputs From the DPM Module

5 OUTLINE OF THE TRANSONIC SMALL DISTURBANCE MODULE[6,7)]

The unsteady ,isentropic and inviscid flow over a thin airfoil is assumed to be governed by the TSD equation, which is written in a form as

$$M^2\frac{\partial}{\partial t}(\phi_t+2\phi_x)+\frac{\beta^2}{2\bar{u}}\frac{\partial}{\partial x}(\phi_x-\bar{u})^2-\frac{\partial}{\partial y}\phi_y-\frac{\partial}{\partial z}\phi_z=G\frac{\partial}{\partial x}\phi_y^2+H\frac{\partial}{\partial y}(\phi_x\phi_y)$$

$$\beta^2=1-M^2,\bar{u}=\frac{\beta^2}{(1+\gamma)M^2},G=\frac{1}{2}(\gamma-3)M^2,H=(1-\gamma)M^2$$

This equation is solved with the tangency flow condition on the airfoil surface, the wake condition on the singular surface behind the trailing edge and non-reflecting far field boundary condition.

This module is capable of capturing nonlinear flow phenomena, including such shock wave motion as was observed experimentally by Tijdeman[8)]. The equation is discretized by the finite difference method. The approximated factorization method (AF) or the alternating direction implicit (ADI) method is adopted for the time-dependent integration of the equation. This module is still under development.

6 OUTLINE OF THE FULL POTENTIAL MODULE [9-11)]

The full potential equation is expressed as

$$(a^2-u^2)\phi_{xx}+(a^2-v^2)\phi_{yy}+(a^2-w^2)\phi_{zz}$$
$$-2uv\phi_{xy}-2vw\phi_{yz}-2wu\phi_{zx}-2u\phi_{xt}-2v\phi_{yt}-2w\phi_{zz}-\phi_{tt}=0$$

The above equation is descretized into a quasi-conservation form by the finite difference method. The shock wave can be captured automatically in the transonic regime. In the NATAS, this equation is integrated in a time accurate manner by two steps employing a semi-implicit successive line over relaxation (SLOR) and a point implicit inversion with the subsidiary state relationship and the boundary conditions as;

$$a^2=\frac{1}{M_\infty{}^2}-\frac{\gamma-1}{2}[2\phi_t+q^2-1]$$

tangency flow condition on the airfoil : $v=f_t+uf_x+wf_z$

wake condition : $\Delta\phi_t+\Delta\phi_x=0$

and symmetry condition(if needed).

The FP model enables one to compute steady/unsteady aerodynamic computations around a lifting surface oscillating in a forced rigid/elastic modes and flutter simulation. The rigid modes which can be treated here are heaving, pitching and rolling modes, moreover, forced oscillation of control surfaces along the leading and trailing edge by specifying the position of the control surface, amplitude, reduced frequency. Unfortunately,only isolated wing without fuselage can be computed by the FP model at present. The section of the wing and the plan form must be fed. The grid for the calculation is automatically generated. The vertical displacement of the fundamental modes must be normalized so as to be unit at the point where the displacement takes maximum value.

The FP model can capture the shock wave, and the transonic-dip will be estimated. It is noted that the FP estimates the stronger shock wave at backward position comparing with the actual one[10,11)] because the exact shock-jump relationship between the for/rear sides of the shock wave can not be kept if the Mach number just before the shock wave becomes greater than 1.3.

The procedure for the unsteady aerodynamics and flutter simulations is as follows(Fig.3);

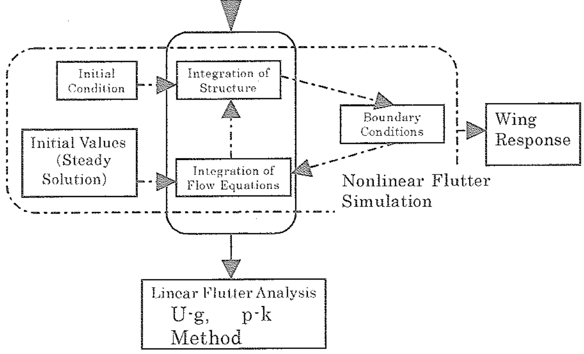


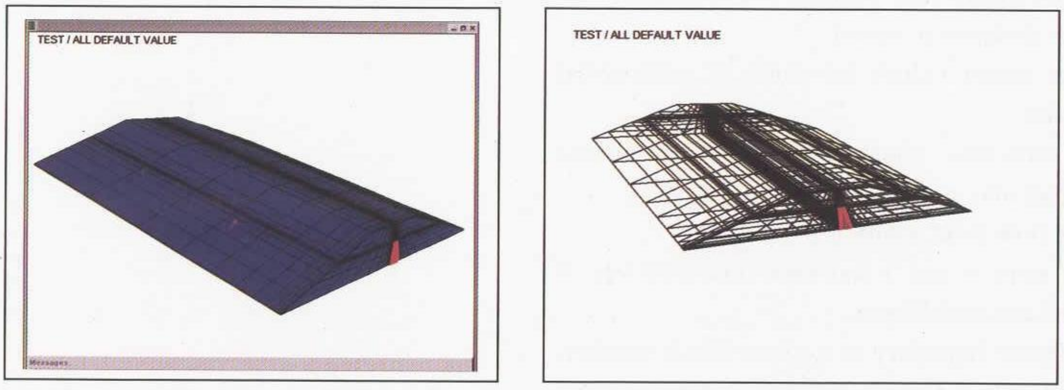
Fig.3 Flow of Works in the NATAS

1. compute steady state solution at a Mach number
2. assume dynamic pressure
3. assume initial values for some of generalized velocities
4. solve structural equations and update surface geometry and grids
5. update flow field solution
6. repeat steps 4 and 5 and save time histories of generalized coordinates.

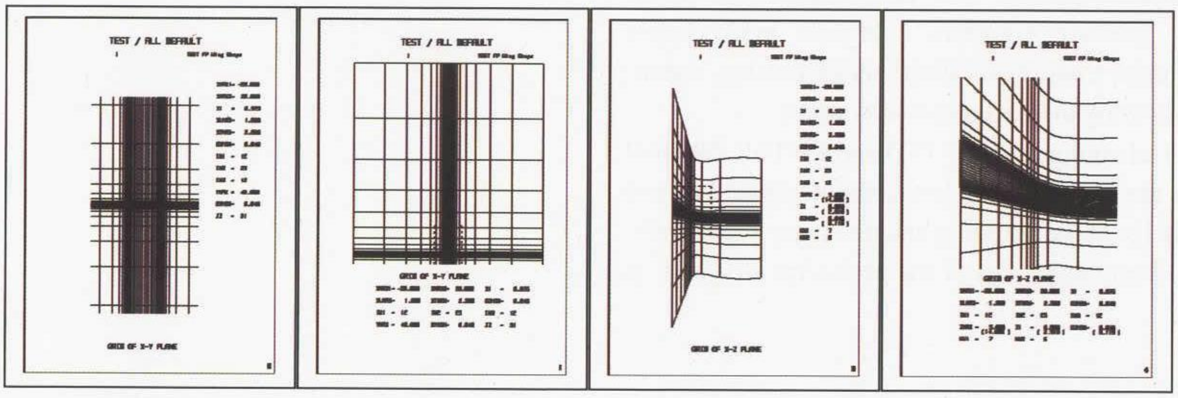
To find flutter boundary at a given Mach number, repeat steps 3 to 6 a range of dynamic pressures and find stable and unstable regions by anlyzing wing responses.

The charts to see C_p and ΔC_p distributions on the wing, pressure contours, vibration mode-shapes with nodal lines, generalized aerodynamics, instantaneous wing displacements are output.

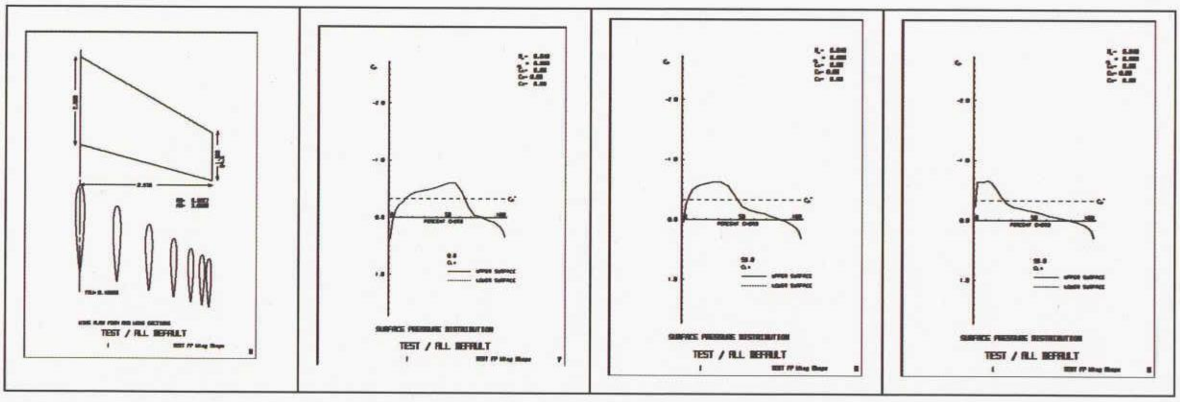
The advantages of the TSD and the Full Potential codes are the relatively low computational cost and simplicity of the gridding and geometry preprocessing. Some examples of the postscript are given in Fig.4.



Surface Grids

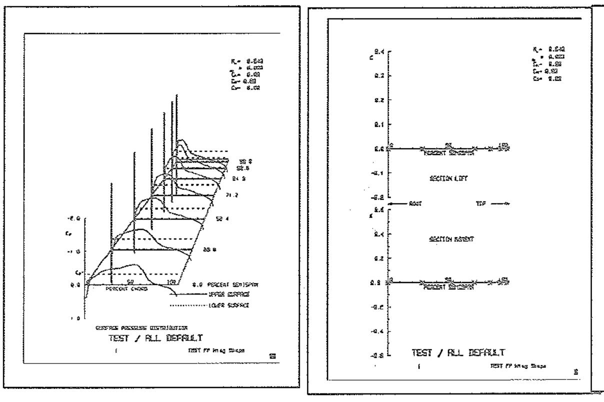


Grid(x-z) Grid (x-z) Grid (x-y) Grid(x-y)

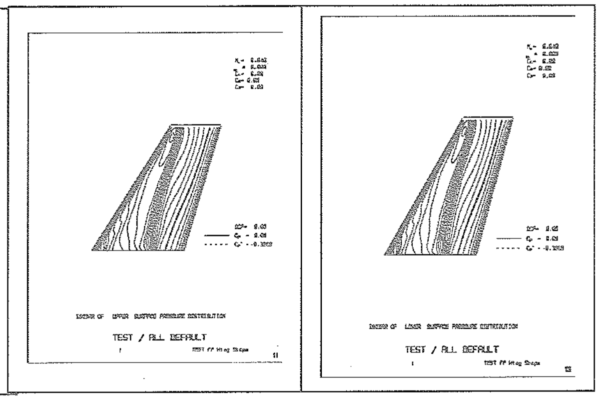


Wing Geometry Pressure Distribution Pressure Distribution Pressure Distribution

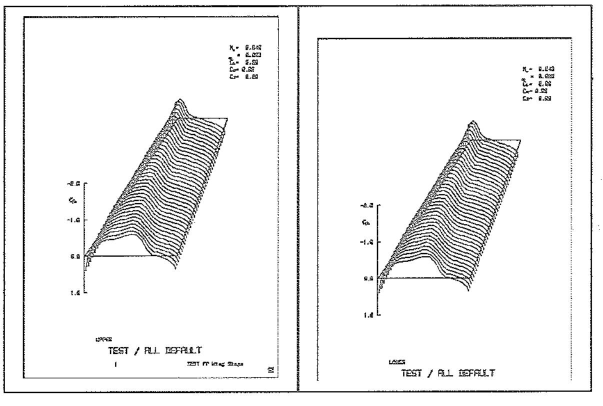
Fig.4 Examples of the Graphical Outputs From the FP Module -continued-



Animation of Pressure Distributions in Spanwise



Pressure Contours on Upper and Lower Surfaces



Pressure Distributions in Spanwise sections

Fig.4 Examples of the Graphical Outputs From the FP Module -closed-

7 OUTLINE OF THE EL/NS MODULE [14,15]

This section is concerning the CFD code for the unsteady simulation based on the 3D thin-layer approximated Navier-Stokes equations with the Baldwin-Lomax turbulence model. The governing equations for the fluid are written in a curve linear coordinate system as;

$$\frac{\partial \hat{Q}}{\partial \tau} + \frac{\partial \hat{F}}{\partial \xi} + \frac{\partial \hat{G}}{\partial \eta} + \frac{\partial \hat{E}}{\partial \zeta} = R_e^{-1} \frac{\partial \hat{S}}{\partial \zeta}$$

where

$$\hat{Q} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ e \end{bmatrix} \quad \hat{F} = \begin{bmatrix} \rho U \\ \rho u U + \xi_x p \\ \rho v U + \xi_y p \\ \rho w U + \xi_z p \\ U(e+p) - \xi_t p \end{bmatrix} \quad \hat{G} = \begin{bmatrix} \rho V \\ \rho u V + \eta_x p \\ \rho v V + \eta_y p \\ \rho w V + \eta_z p \\ V(e+p) - \eta_t p \end{bmatrix}$$

$$\hat{E} = \begin{bmatrix} \rho W \\ \rho u W + \zeta_x p \\ \rho v W + \zeta_y p \\ \rho w W + \zeta_z p \\ W(e+p) - \zeta_t p \end{bmatrix} \quad \hat{S} = \begin{bmatrix} 0 \\ \zeta_x \tau'_{xx} + \zeta_y \tau'_{xy} + \zeta_z \tau'_{xz} \\ \zeta_x \tau'_{xy} + \zeta_y \tau'_{yy} + \zeta_z \tau'_{yz} \\ \zeta_x \tau'_{xz} + \zeta_y \tau'_{yz} + \zeta_z \tau'_{zz} \\ \zeta_x (m_1 + m_4) + \zeta_y (m_2 + m_5) + \zeta_z (m_3 + m_5) \end{bmatrix}$$

and where

$$U = \xi_t + \xi_x u + \xi_y v + \xi_z w \qquad m_1 = u\tau_{xx}' + v\tau_{xy}' + w\tau_{xz}'$$
$$V = \eta_t + \eta_x u + \eta_y v + \eta_z w \qquad m_2 = u\tau_{xy}' + v\tau_{yy}' + w\tau_{yz}'$$
$$W = \zeta_t + \zeta_x u + \zeta_y v + \zeta_z w \qquad m_3 = u\tau_{xz}' + v\tau_{yz}' + w\tau_{zz}'$$

$$m_4 = \mu \Pr^{-1}(\gamma - 1)^{-1}\zeta_x \frac{\partial a^2}{\partial \zeta}$$
$$m_5 = \mu \Pr^{-1}(\gamma - 1)^{-1}\zeta_y \frac{\partial a^2}{\partial \zeta}$$
$$m_6 = \mu \Pr^{-1}(\gamma - 1)^{-1}\zeta_z \frac{\partial a^2}{\partial \zeta}$$

The structural equations of motion are derived by the assumption that the deformation of the wing and fuselage under consideration can be described by superposing the fundamental vibration modes weighted by generalized coordinates. The Wilson's θ implicit method is employed to integrate the structural equations of motion. The flow governing equations are descretized using a second order up-wind TVD finite difference method and the integration is implemented by the ADI scheme.

The equations are integrated on a dynamic grid that is adapted to the instantaneous wing deformations and the attitude. The initial grid must be provided by the clients. After the computation, the charts of pressure distributions, pressure contours, Mach number contours, iso-density contours can be delivered. The time histories of generalized coordinates, C_l, C_m and C_d are also output. Some examples of the postscript are given in Fig.5.

It is possible to simulate the unsteady aerodynamics and flutter phenomenon most realistically if the EL/Navier-Stokes model are used. However it is time-consuming task. Then it is important for the clients to choose the most appropriate model for their purposes. It depends upon what kind of aeroelastic phenomenon they want to analyze using the NATAS.

8 REMARKS

The computer softwares developed at NAL for the studies of aeroelastic phenomena have been packaged in the NATAS. The linear theory, the Doublet Point Method, the Full Potential Model and the Euler/Navier Stokes Model are involved. The graphic output will be collectively formatted in a common manner among the models provided in the NATAS. The small disturbance model is under development at present. That model will be installed into the NATAS in near future. Fully GUI environment is being developed. Utilization of the NATAS will be highly improved and offered to the aircraft engineers as well as the researchers in the field of aeronautics and aeronautical sciences.

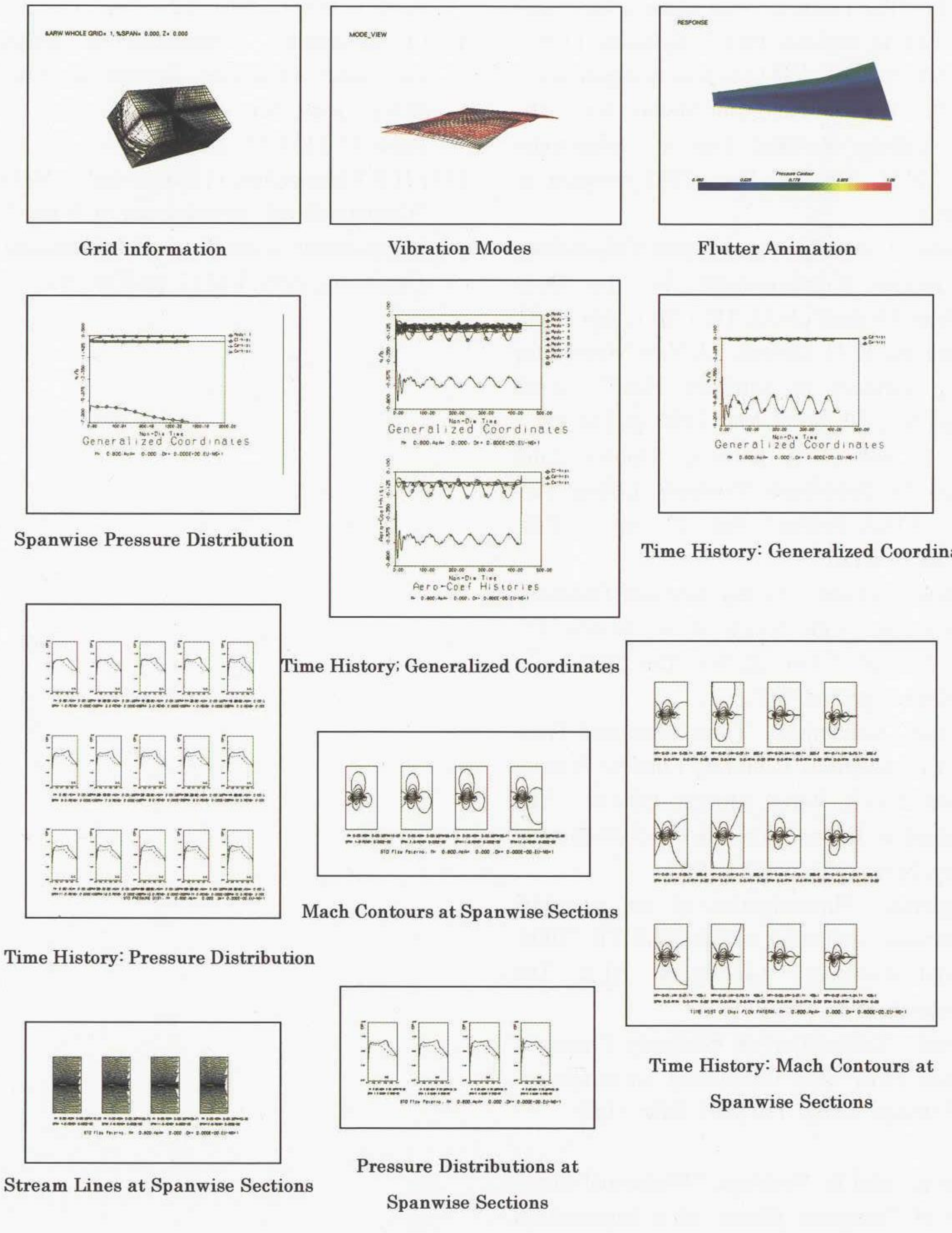


Fig.5 Examples of the Graphical Outputs From the EL/NS Module

9 REFERENCES

[1] T. Ueda, "The Doublet-Point Method for Oscillating Lifting Surface, Part 1, Subsonic Flow", NAL TR-781, Oct. 1983 (written in Japanese)

[2] T. Ueda, "The Doublet-Point Method for Oscillating Lifting Surface, Part 2, Supersonic Flow ",NAL TR-785, Nov. 1983 (written in Japanese)

[3] T. Ueda, "Unsteady Aerodynamic Calculations for General Configurations by the Doublet-Point Method", NAL TR-1101T, Apr. 1991

[4] T. Ueda and E. H. Dowell, "A New Method for Lifting Surfaces in Subsonic Flow", AIAA Journal, Vol. 20, No. 3, Mar. 1982, pp348-355

[5] T. Ueda and E. H. Dowell, "Doublet-Point Method for Supersonic Unsteady Lifting Surfaces", AIAA Journal, Vol. 22, No. 2, Feb. 1984, pp.179-186

[6] E.Ly and J.A.Gear, "Time-Linearised Transonic Computations with Shock Wave Motion Effects", Journal of Aircraft, Nov./Dec.2002, Vol.39,No.6, pp.964-972

[7] E.Ly and J.Nakamichi, "Time-Linearised Transonic Computations Including Entropy, Vorticity and Shock Wave Motion Effects", The Aeronautical Journal of the Royal Aeronautical Society, Nov. 2003, pp.687-695

[8] H.Tijdeman, "Investigation of the transonic flow around oscillating airfoils,NLR TR 77090, National Aerospace Laboratory, NLR, The Netherlands, Oct. 1997

[9] K.Isogai, "Calculation of Unsteady Transonic Potential Flow Over Oscillating Three-Dimensional Wings", NAL TR-706T, Mar. 1982

[10] K. Isogai and K. Suetsugu, "Numerical Simulation of Transonic Flutter of a Supercritical Wing", NAL TR-726T, Aug. 1982

[11] K. Isogai and K. Suetsugu, "Calculation of Unsteady Transonic Potential Flow over Three-Dimensional Wings with Oscillating Control Surfaces", NAL TR-746T, Jul. 1983

[12] J. Nakamichi, "A Verification of Unsteady Navier-Stokes Solutions Around Oscillating Airfoils", NASA TM-88341, Sep.1986

[13] J. Nakamichi, "Some Computations of Unsteady Navier-Stokes Flow Around Oscillating Airfoil / Wing", NAL TR-1004T, Oct. 1988

[14] J. Nakamichi, "Calculation of Unsteady Navier-Stoke Equations Around an Oscillating Wing Using Moving Grid System", AIAA, Paper 87-1158-CP, July.1987

[15] H.R.Kheirandish, G.Beppu and J. Nakamichi, "Computational Investigation of Wing Flutter", International Journal of Computational Fluid Dynamics, 1999, Vol.12, pp.279-290

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