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# Aeroelastic Modelling of the Active Flexible Wing Wind-Tunnel Model

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## INTRODUCTION

The Active Flexible Wing (AFW) is a full-span, sting-mounted wind-tunnel model that is currently being used by the NASA-Langley Research Center (NASA-LaRC) and the Rockwell International Corporation for evaluation of multifunction, digital control laws[1]. An understanding of the model's open-loop aeroelastic behavior is, therefore, essential for closed-loop analysis and safety during wind-tunnel testing.

Aeroelastic modelling of the AFW includes the structural and aerodynamic definition of the model via the ISAC (Interaction of Structures, Aerodynamics, and Controls) codes[2]. A state-space aeroelastic model that is appropriate for subsequent closed-loop analysis is generated. One of the ISAC codes is the linear doublet lattice unsteady aerodynamic theory for computing linear aeroelastic forces[3]. Aeroelastic analyses of the AFW in the transonic aerodynamic regime, where nonlinear aerodynamic effects are significant, were performed using the CAP-TSD (Computational Aeroelasticity Program-Transonic Small Disturbance) code[4].

This presentation will address the overall modelling process, including assumptions, approximations, modifications, and corrections (using experimental data) that went into obtaining the best "pre-test" aeroelastic model of the AFW. Details of the modelling assumptions required for the CAP-TSD code are also presented. Results for both the linear and nonlinear aerodynamic analyses are presented in the form of flutter boundaries. These predicted results are compared with results from the most recent tunnel entry in the fall of 1989.

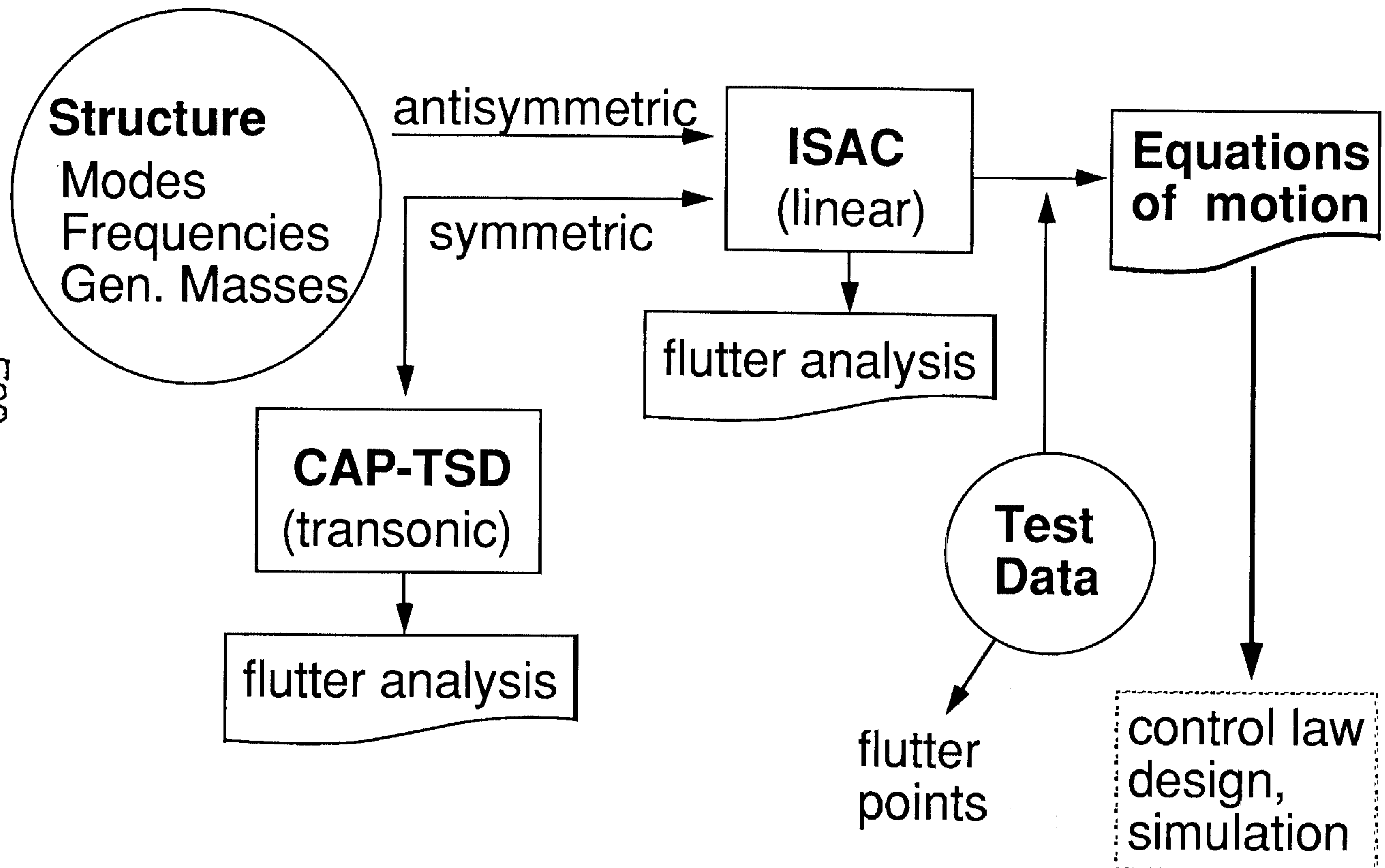
## LINEAR MATH MODEL DEVELOPMENT
### Flowchart and Outline

The first step in developing aeroelastic equations of motion for a flexible vehicle is to define the structural dynamic behavior of the vehicle, that is, the modes of vibration of the vehicle and their associated frequencies and generalized masses. For this purpose, a NASTRAN finite element model (FEM) of the AFW was developed by Rockwell International from which symmetric and antisymmetric sets of modal data were obtained.

Both the symmetric and antisymmetric structural models were used in the ISAC system of codes. The ISAC codes were used to generate state-space equations of motion to predict open- and closed-loop aeroelastic responses (with controller). Details of the ISAC codes and procedures for using test data to improve the accuracy of the equations of motion will be presented. The resultant equations of motion are then passed on to control law designers and simulation engineers.

Due to the large computational requirements of the CAP-TSD code, only symmetric analyses were performed. Details of the CAP-TSD code and its application to the AFW are described following the discussion concerning the linear modelling procedures.

# AEROELASTIC MODELLING AND ANALYSIS
## *Flowchart & Outline*



## LINEAR MATH MODEL DEVELOPMENT
### Configurations Analyzed

Six structural models of the AFW were developed: symmetric and antisymmetric with tip-ballast store coupled and decoupled. In addition, antisymmetric models were also developed with the roll-brake on and the roll-brake off. This presentation, however, will address only the roll-brake-on (no rolling) configurations. The resultant matrix of structural models is shown in the figure.

In the coupled configuration, the wing tip-ballast store is rigidly attached to the wing so that the motion of the ballast is felt by the wing. In the decoupled configuration, the ballast store is decoupled from the wing dynamics by means of a very flexible spring attachment between the store and the wing. The difference between these two configurations can be seen in the figure, which shows the first wing bending mode for both the coupled and decoupled cases. The coupled configuration is the more flutter critical of the two conditions. Experimentally, when flutter is encountered in the coupled configuration, the ballast is mechanically decoupled from the wing so that the vibration characteristics are altered to those of the decoupled configuration, thereby eliminating the flutter condition. Equations of motion (system quadruples) were generated for all of these models for subsequent use in control law design and analysis.

Vibration frequencies were measured during a ground vibration test (GVT) but only those measured for the coupled configuration were considered to be accurate. These GVT measured frequencies, and a subset of the original analytical modeshapes, were then used in the analysis of the coupled configurations.

# LINEAR MATH MODEL DEVELOPMENT
## *Configurations Analyzed*

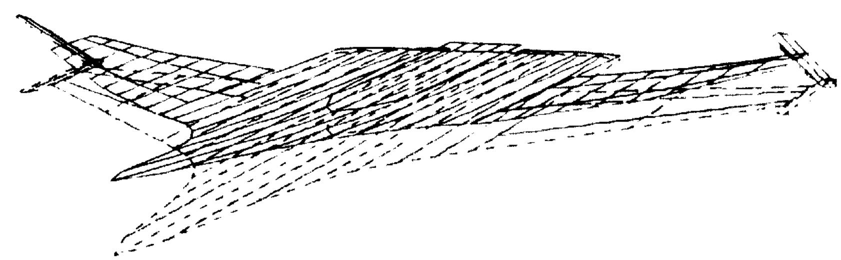
tip ballast store

| | coupled | decoupled |
|---|---|---|
| sym | x o | x |
| a/s | x | x |

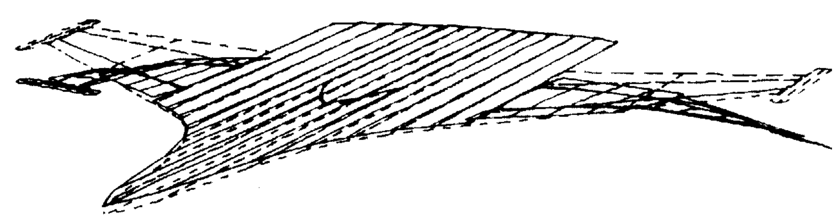
x - linear aerodynamic analysis (doublet lattice)

o - nonlinear aerodynamic analysis (CAP-TSD)

First Wing Bending



*Decoupled*

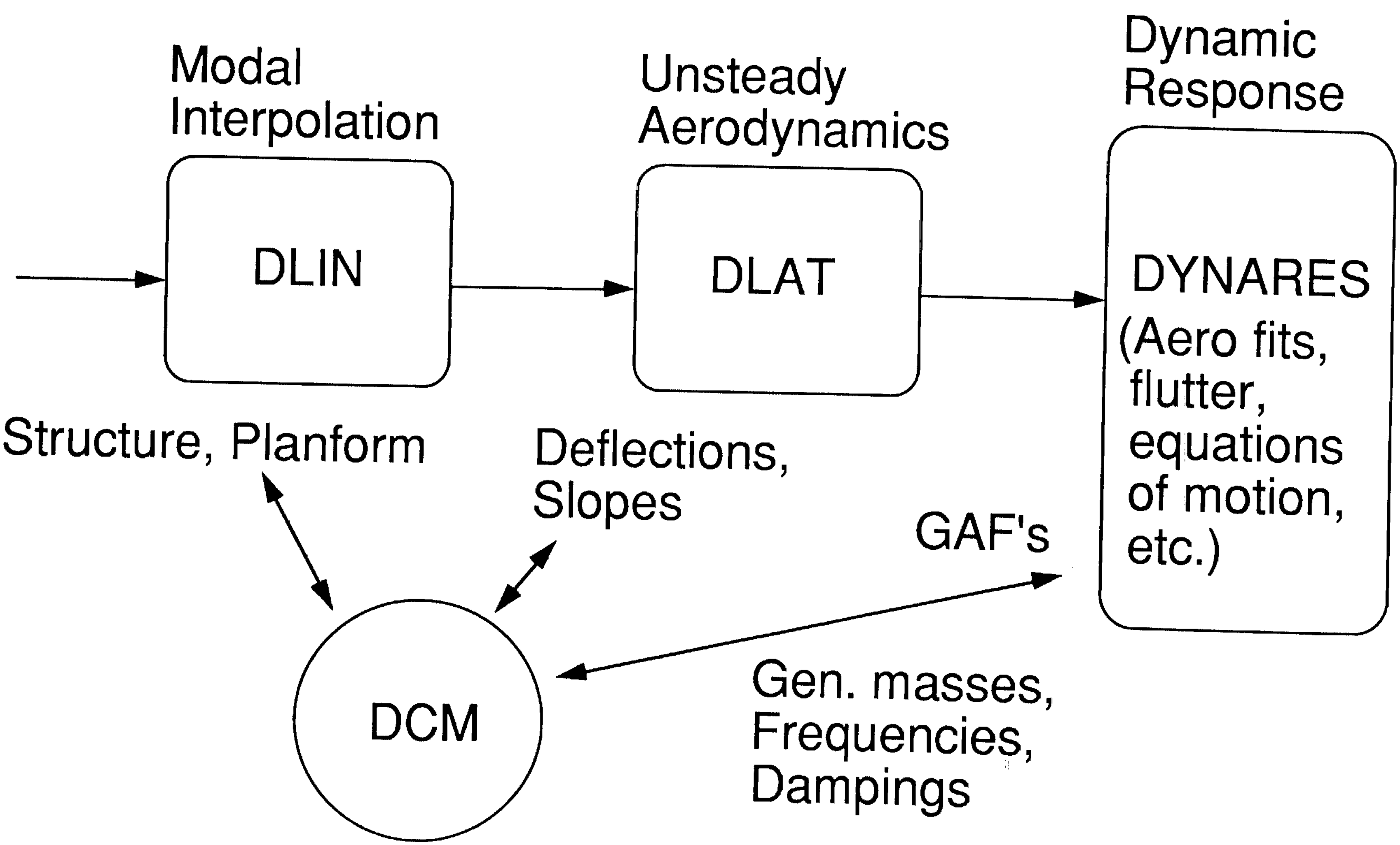


*Coupled*

## LINEAR MATH MODEL DEVELOPMENT
## The ISAC Modules

The ISAC compendium of codes consists of four primary modules. DLIN (Doublet Lattice INput) is a preprocessor to the doublet lattice unsteady aerodynamic code. DLIN takes modeshape and planform input and computes deflections and slopes of each modeshape at the quarter- and three-quarter-chord locations of the aerodynamic boxes (shown in a later figure). This information is then used by DLAT (Doublet LATtice), which uses the doublet lattice unsteady aerodynamic theory, to compute generalized aerodynamic forces (GAF's). The GAF's, along with generalized masses, frequencies, and dampings, are input to DYNARES (DYNamic RESponse) where several different analyses can be performed. These include the aerodynamic approximation to be addressed later, flutter analysis, frequency responses, time-history responses, and generation of the state-space system matrices. The fourth module, DCM (Data Complex Manager), handles the processing of data arrays from one module to the other.

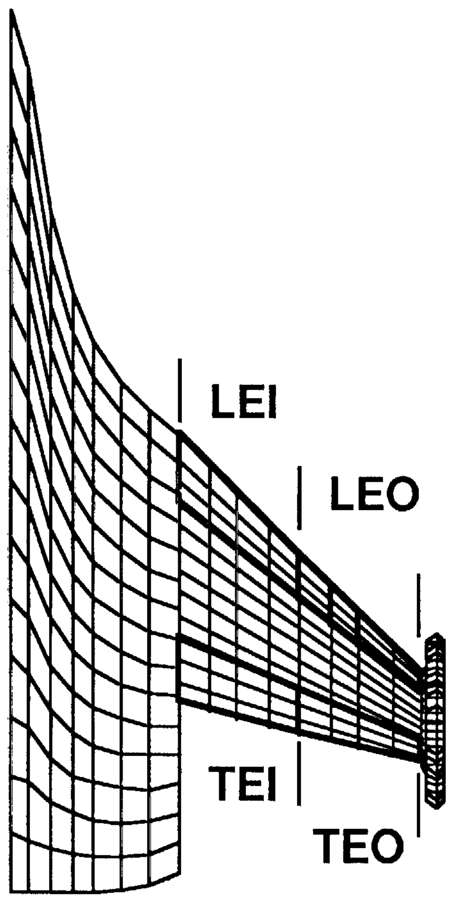
## LINEAR MATH MODEL DEVELOPMENT
### *The ISAC Modules*



## LINEAR MATH MODEL DEVELOPMENT
### Linear Aerodynamics

The unsteady aerodynamics induced by the flexible motion of the AFW were computed using the doublet lattice unsteady aerodynamic theory. Doublet lattice theory is a linear, frequency-domain theory limited to subsonic flows. The AFW was modelled aerodynamically as a half model with a plane of symmetry (or antisymmetry) at the fuselage centerline. In doublet lattice theory, lifting surfaces are modelled as flat plates with aerodynamic boxes as shown on the figure. Aircraft components such as fuselage or stores can be modelled as slender bodies. For this analysis, however, the fuselage and tip-ballast store were modelled as flat plates. Modelling of the tip-ballast store as a flat plate was done by varying the width of the paneling arrangement until the flutter dynamic pressure matched the flutter dynamic pressure of an analysis in which a slender body representation of the tip-ballast store was used. The reason for modelling with flat plates instead of slender bodies was to minimize the number of aerodynamic boxes, thereby increasing the efficiency of the code for generating equations of motion.

# LINEAR MATH MODEL DEVELOPMENT
## *Linear Aerodynamics*




- Applied doublet lattice code (ISAC)
  - linear
  - subsonic
  - frequency domain
  - flat plate lifting surfaces
- Used half model with symmetry
- Fuselage and tip ballast store modelled as flat plates

## LINEAR MATH MODEL DEVELOPMENT
### Linear Aerodynamics (cont'd)

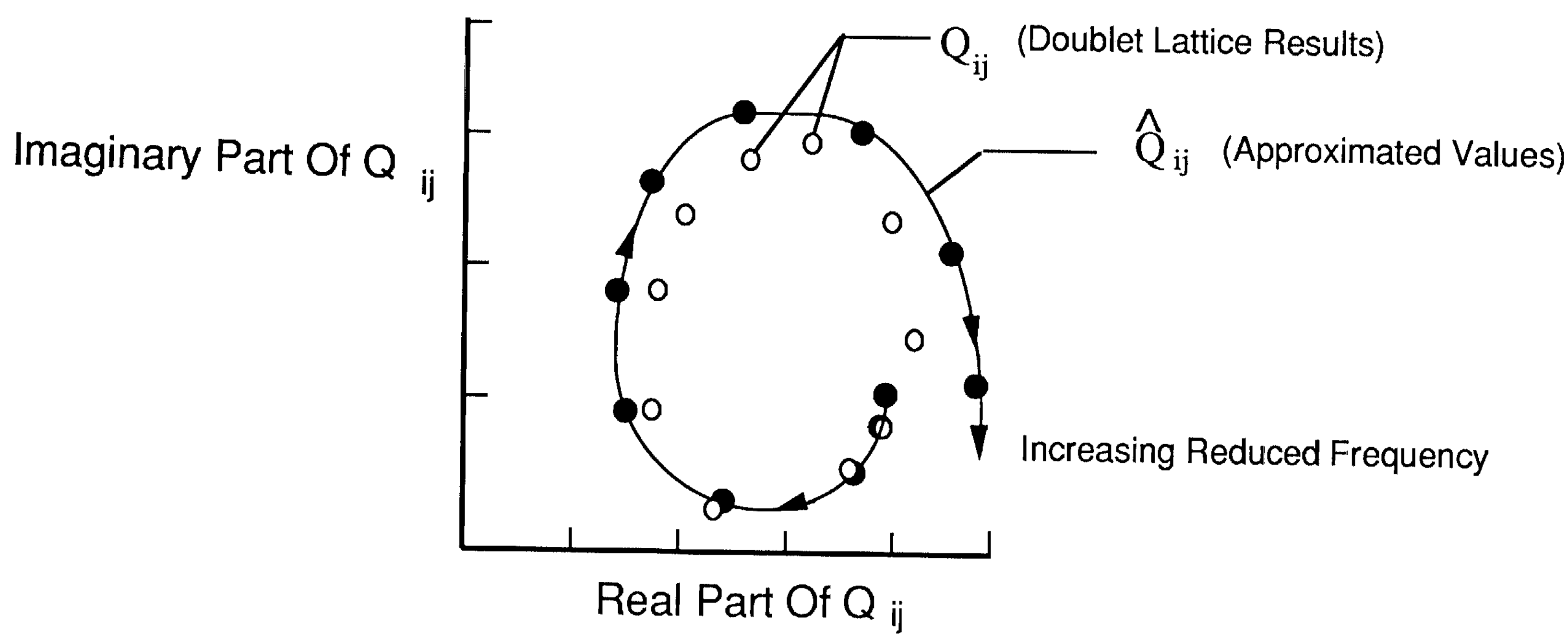
The output from the doublet lattice code consists of generalized aerodynamic forces (GAF's) which are tabular functions of Mach number and reduced frequency ($\omega b/V$, where $\omega$ is the frequency of oscillation, b is the root semi-chord, and V is the freestream velocity). In order to generate time-domain (state-space) equations of motion, however, these aerodynamic forces need to be in the time domain and not the frequency domain. The typical approach to this problem is to approximate the GAF's using rational functions[5] of the nondimensional Laplace variable p. The A coefficients are computed and the $b_l$ terms are the lags arbitrarily specified by the user or obtained using optimization. This then casts the frequency-domain GAF's into the time-domain. This process, however, can significantly increase the size of the state equations of motion. The number of states that the plant structural equations are augmented by due to the inclusion of rational function approximations, developed using a least squares approach, is equal to the number of modes times the number of lags. Ten modes and two lags result in twenty additional aerodynamic states. The larger the number of lags, however, the more accurate the approximation to the aerodynamics. Thus, a tradeoff between accuracy and computational size needs to be defined.

# LINEAR MATH MODEL DEVELOPMENT
## *Linear Aerodynamics (cont'd)*

$$Q_{ij} \cong \hat{Q}_{ij}$$

$$\hat{Q}_{ij}(p) = (A_0)_{ij} + (A_1)_{ij}\, p + (A_2)_{ij}\, p^2 + \sum_{\ell=1}^{n} (A_{(\ell+2)})_{ij} \frac{p}{p + b_\ell}$$

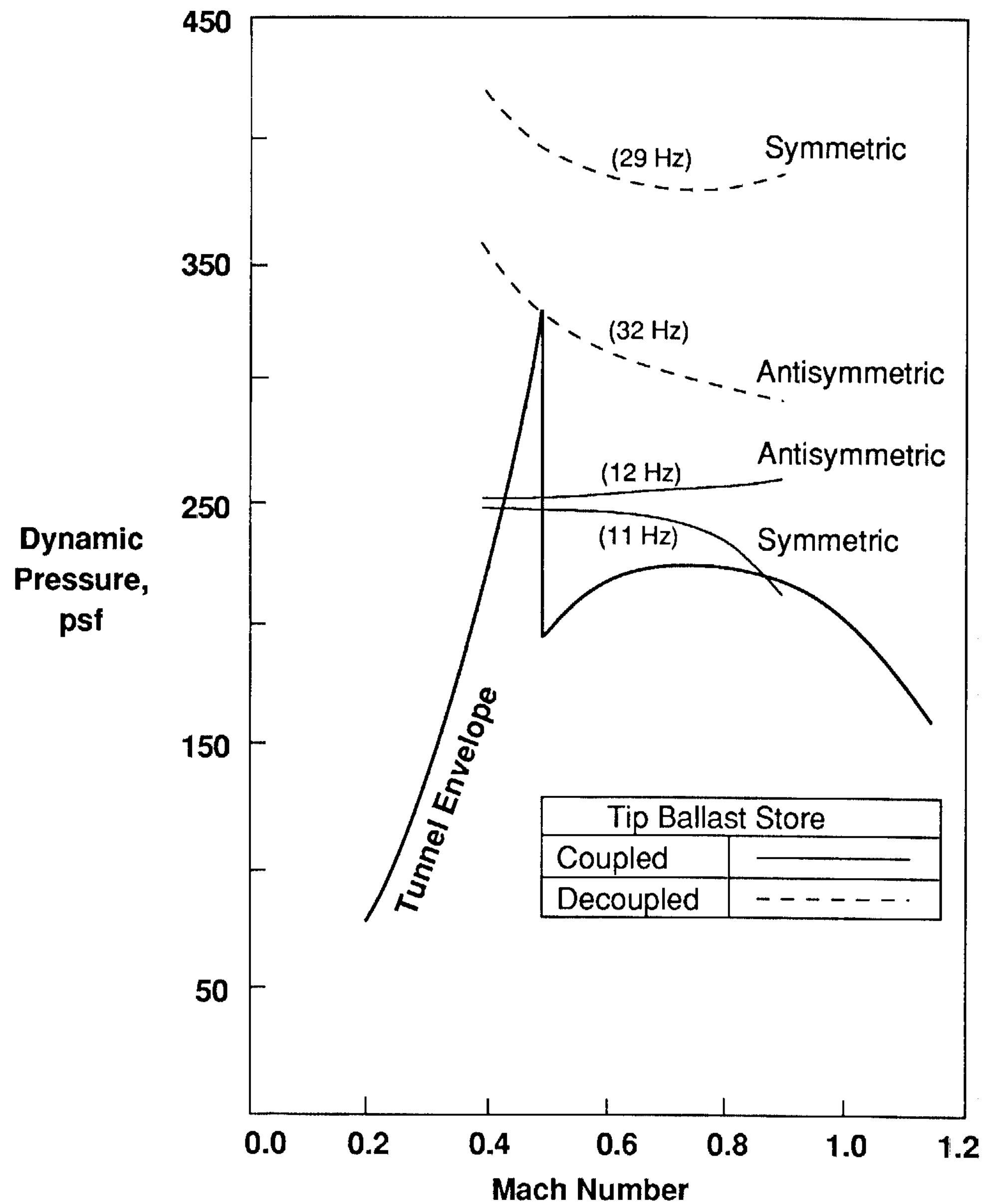
$$p = \frac{b\,s}{V}$$



## LINEAR FLUTTER PREDICTIONS

Flutter boundaries, computed using the linear doublet lattice unsteady aerodynamic theory, are shown on the figure for the tip-ballast store coupled and decoupled, symmetric and antisymmetric cases along with the Transonic Dynamics Tunnel (TDT) operating envelope. The effect of decoupling the tip-ballast store is evident: flutter boundaries are raised above the tip-ballast-store-coupled boundaries. For a given configuration, the region below the boundary is stable while the region above the boundary is unstable. These flutter boundaries are for a previous set of mode shapes and as such do not represent the latest results. They are being presented only to illustrate the decoupling effect on the flutter boundary. Results using an updated set of modeshapes and frequencies for the coupled tip-ballast store configuration are presented later in this paper; the decoupled flutter boundaries were not recalculated because test results indicated that the boundaries fall outside the tunnel's operating envelope.

# LINEAR FLUTTER PREDICTIONS



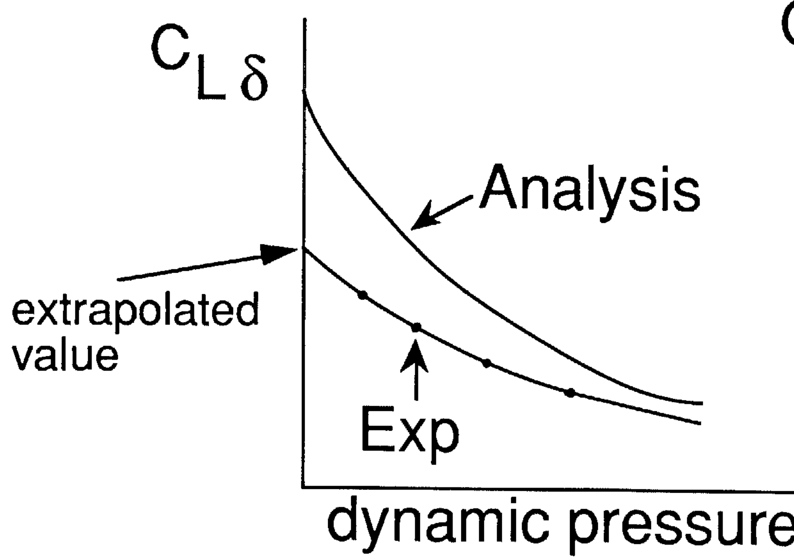
## LINEAR MATH MODEL DEVELOPMENT
### Control Surface Effectiveness

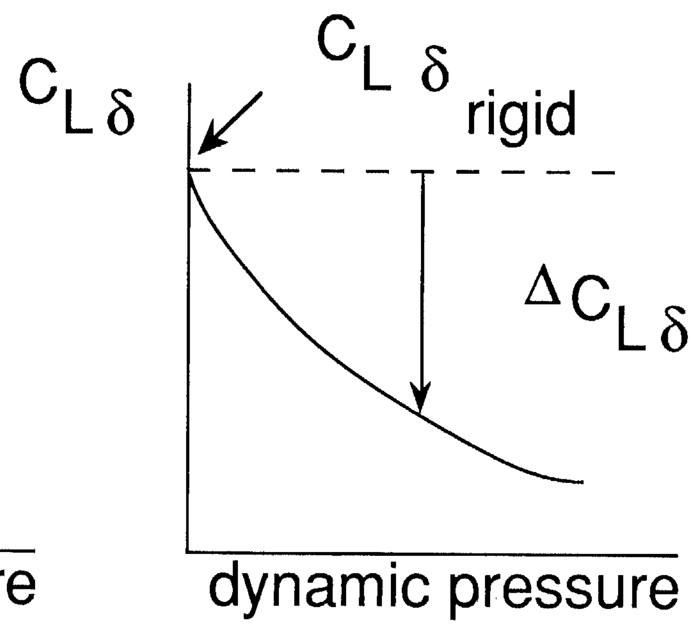
Accurate prediction of control derivatives (such as lift due to control surface deflection) is essential for accurate control law design. In order to improve the analytical predictions of control derivatives (using the doublet lattice code), a procedure was developed for correcting the analytical derivatives using wind-tunnel data. The wind-tunnel data consists of measured static loads induced by control surface deflections at several dynamic pressures and Mach numbers from which effectiveness parameters (derivatives) can be computed and tabulated. The procedure assumes that each effectiveness parameter (function of dynamic pressure) can be separated into a rigid component (at zero dynamic pressure) and an elastic increment which can be added to the rigid component as dynamic pressure (or flexibility) is increased. This assumption is applied to both the analytical and experimental effectiveness parameters from which two sets of correction factors are computed: a ratio of experimental to analytical rigid values, $f_1$, and a ratio of experimental to analytical elastic increments, $f_2$. Note that $f_1$ is a constant and $f_2$ is a function of dynamic pressure. Although these corrections are for static conditions only, they were applied at all dynamic conditions as well.

# LINEAR MATH MODEL DEVELOPMENT
## *Control Surface Effectiveness*

- Analytical control surface derivatives corrected to match experiment

512



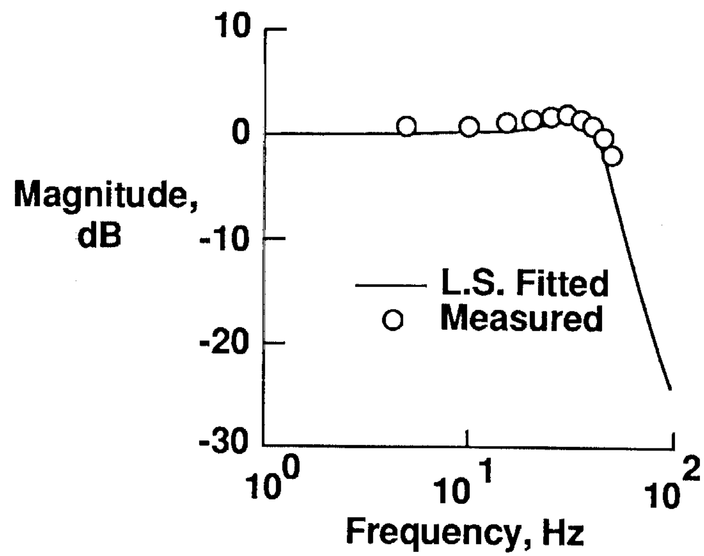



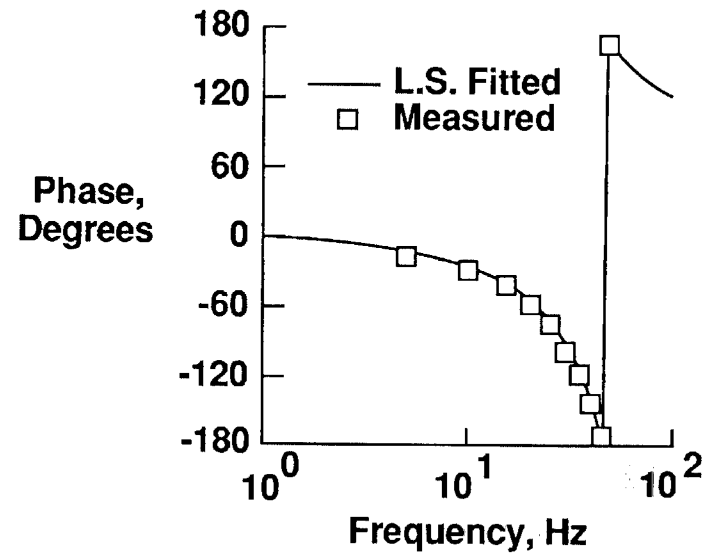

$$C_{L\delta_{corrected}} = f_1\,(C_{L\delta_{rigid}})_{analytical} + f_2(q)\,(\Delta C_{L\delta})_{analytical}$$

## LINEAR MATH MODEL DEVELOPMENT
### Actuator Model

Another important ingredient in the development of an accurate state-space model of the AFW is the modelling of the actuator dynamics. Actuator transfer functions were measured during the GVT for all control surfaces for the aerodynamically unloaded (zero airspeed) case. Analytical transfer functions were generated using a least-squares method to fit the discrete experimental values. A comparison between experimental data and a least-squares fitted model is shown in the figure. The resultant transfer functions are of zeroth order in the numerator and third order in the denominator.

# LINEAR MATH MODEL DEVELOPMENT
## *Actuator Model*




Fitted TF's are $$\frac{K}{(s - p_1)(s^2 + 2\zeta\omega_n s + \omega_n^2)}$$

## LINEAR MATH MODEL DEVELOPMENT
### State-Space Model

Finally, once all of the previously mentioned modelling steps have been taken, a state-space sytem can be created. This is the plant model which is used by the control system designers for their design and analysis work. A Dryden gust mode is included in the equations of motion to model wind-tunnel turbulence (results in two additional states). The loads, consisting of shear, bending moment, and torsion moment at 14 different locations, were computed using the mode displacement method.

# LINEAR MATH MODEL DEVELOPMENT
## *State-Space Model*

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

**States (x):**

| | |
|---|---|
| 10 elastic modes | = 20 |
| 1 aero lag | = 10 |
| 4 3rd order act. | = 12 |
| gust modes | = 2 |
| | 44 |

**Inputs (u):**

| | |
|---|---|
| 4 control surfs | = 4 |
| gust | = 1 |
| | 5 |

**Outputs (y):**

| | |
|---|---|
| sensors | = 8 |
| pilot inputs | = 4 |
| actuators | = 12 |
| loads | = 42 |
| gust | = 1 |
| | 67 |

## NONLINEAR AERODYNAMIC ANALYSIS
## CAP-TSD Code

Before open-loop flutter testing of the AFW was to begin, it was desirable to have analytical predictions of the model's flutter boundary for use as guidance during flutter testing. The range over which testing was to occur included the transonic Mach numbers. Although linear aerodynamics are applicable at subsonic and supersonic Mach numbers, unsteady transonic aerodynamics requires the solution of nonlinear equations. One of these equations is the transonic small disturbance (TSD) equation. A time-accurate, approximate factorization algorithm that solves this equation is the CAP-TSD (Computational Aeroelasticity Program - Transonic Small Disturbance) code developed at the NASA - Langley Research Center. The code can handle realistic configurations that include multiple lifting surfaces with control surfaces, vertical surfaces, bodies (pylons, nacelles, and stores), and a fuselage. The structural equations of motion and the nonlinear aerodynamic equations are coupled and integrated in time. The result of this time stepping is a time history of the generalized displacements of the vehicle.

# NONLINEAR AERODYNAMIC ANALYSIS
## *CAP-TSD Code*

- Computational Aeroelasticity Program-Transonic Small Disturbance
- Uses time-accurate, approximate factorization finite-difference algorithm
- Applied to realistic configurations
- Structural equations of motion and aerodynamic solutions are coupled and integrated in time
- Result is the time history of the generalized displacements of the aeroelastic system

## NONLINEAR AERODYNAMIC ANALYSIS
### Assumptions and Limitations

A full and accurate understanding of the flutter results that are to be subsequently presented requires a knowledge of the assumptions and limitations of transonic small disturbance (TSD) theory and of the CAP-TSD code. TSD theory assumes inviscid, irrotational flow so that the effects of vortices, boundary layer, and separated flow on the aeroelastic behavior of the AFW will not be accounted for. Vorticity and entropy corrections were incorporated into the CAP-TSD code for improved shock modelling but difficulties with this part of the code prevented their use in the AFW analysis.

Bodies, such as the tip-ballast store and the fuselage, are not given any modal definition in the current version of CAP-TSD. That is, bodies serve only as aerodynamic influences on the lifting surfaces. This limitation can and should be corrected in future versions of the code. Another limitation is that only symmetric modes can be analyzed with a half-model of the AFW so that analysis of the antisymmetric modes requires both left and right sides. This is not a limitation of the code but is due to the uncertainty of the loads generated at the centerline of the vehicle due to anti- or asymmetric motions of the vehicle.

# NONLINEAR AERODYNAMIC ANALYSIS
## *Modelling Assumptions and Limitations*

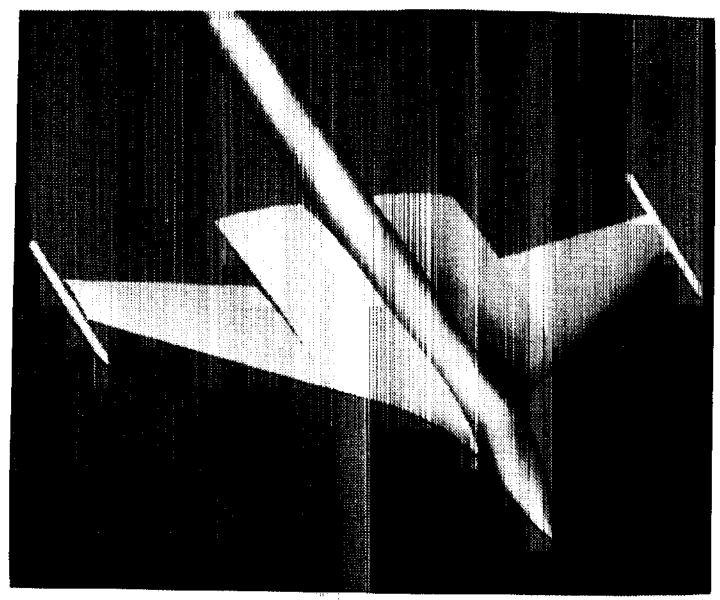
- Bodies do not have modal definition; serve only as influence on lifting surfaces
- Vorticity and entropy corrections were not used
- Symmetric, half-model of the AFW analyzed

## NONLINEAR AERODYNAMIC ANALYSIS
### Model Definition

The computational CAP-TSD model of the AFW consisted of eight symmetric modeshapes (for the coupled case) and the GVT frequencies for those modes. The grid was dimensioned 134 by 51 by 62 grid points in the x-, y-, and z-directions respectively. The grid density was increased in regions where large changes in the flow were expected such as at the leading edge, trailing edge, wing tip, and control surface boundaries. The grid extended ten (10) root chords in the upstream, downstream, positive z- and negative z-directions, and two (2) root chords in the y-direction.

A computer-generated picture of the CAP-TSD model of the AFW is shown on the facing page. The picture shows both left and right sides although only the right side is defined. The modelling of the fuselage and tip ballast store as bodies is clearly seen. In order to model the effects of the wind-tunnel sting mount, the computational fuselage was extended to the downstream boundary of the grid.

# NONLINEAR AERODYNAMIC ANALYSIS
## *Model Definition*



## NONLINEAR AERODYNAMIC ANALYSIS
### Static Aeroelastic Analysis

In linear aeroelastic analyses, the dynamic behavior is independent of static parameters such as airfoil shape and vehicle angle of attack. At transonic Mach numbers, however, this is no longer true as airfoil shape and angle of attack can significantly affect the dynamic response of the vehicle. The AFW has an unsymmetric airfoil shape which induces static aeroelastic deformations. The magnitude of these deformations needs to be known before any transonic dynamic analysis can be performed since the static results are the initial conditions for the dynamic analyses. A procedure was therefore developed to directly compute static aeroelastic deformations using CAP-TSD. This was done by setting the inital values of the generalized displacements to zero and executing the coupled aerodynamic and structural equations, including some viscous damping, for about two thousand time steps. This resulted in convergence of the generalized displacements, which implies static aeroelastic convergence. Static aeroelastic analyses were performed at each Mach number and dynamic pressure of interest.

# NONLINEAR AERODYNAMIC ANALYSIS

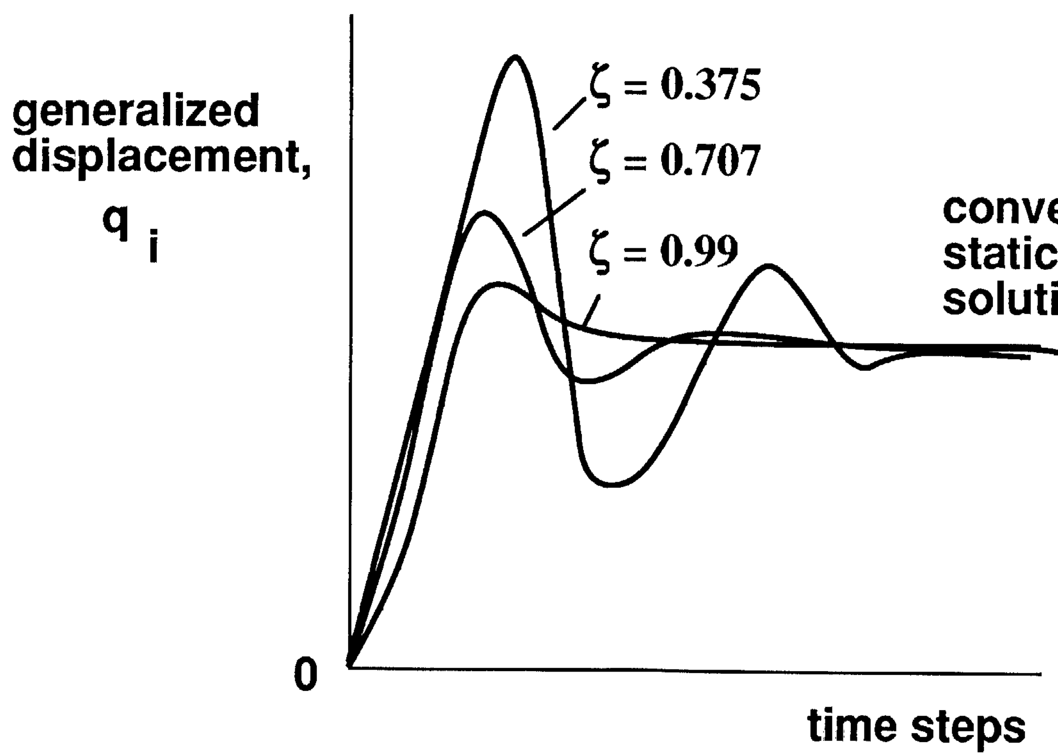
## *Static Aeroelastic Analysis*

- AFW has unsymmetric airfoil shape
- Static aeroelastic deformations are induced
- CAP-TSD used to compute static aeroelastic deformations
- Initial values of generalized displacements set to zero
- Effect of viscous damping variation on static aeroelastic convergence studied

## NONLINEAR AERODYNAMIC ANALYSIS
### Static Aeroelastic Analysis (Cont'd)

Static aeroelastic deformations should, however, be independent of viscous damping. A study was carried out to investigate the effects of different values of viscous damping on the static aeroelastic convergence of the model. The figure shows a representative result of generalized displacement versus computational time steps for three different values of viscous damping. As can be seen, the converged value is indeed independent of viscous damping. However, the larger the damping, the faster the convergence. As a result, all static aeroelastic analyses were performed using a maximum viscous damping value of 0.99. The converged result then becomes the initial condition for the dynamic analysis. In order to dynamically excite the system, generalized velocity excitations are also included.

# NONLINEAR AERODYNAMIC ANALYSIS
## *Static Aeroelastic Analysis (cont'd)*



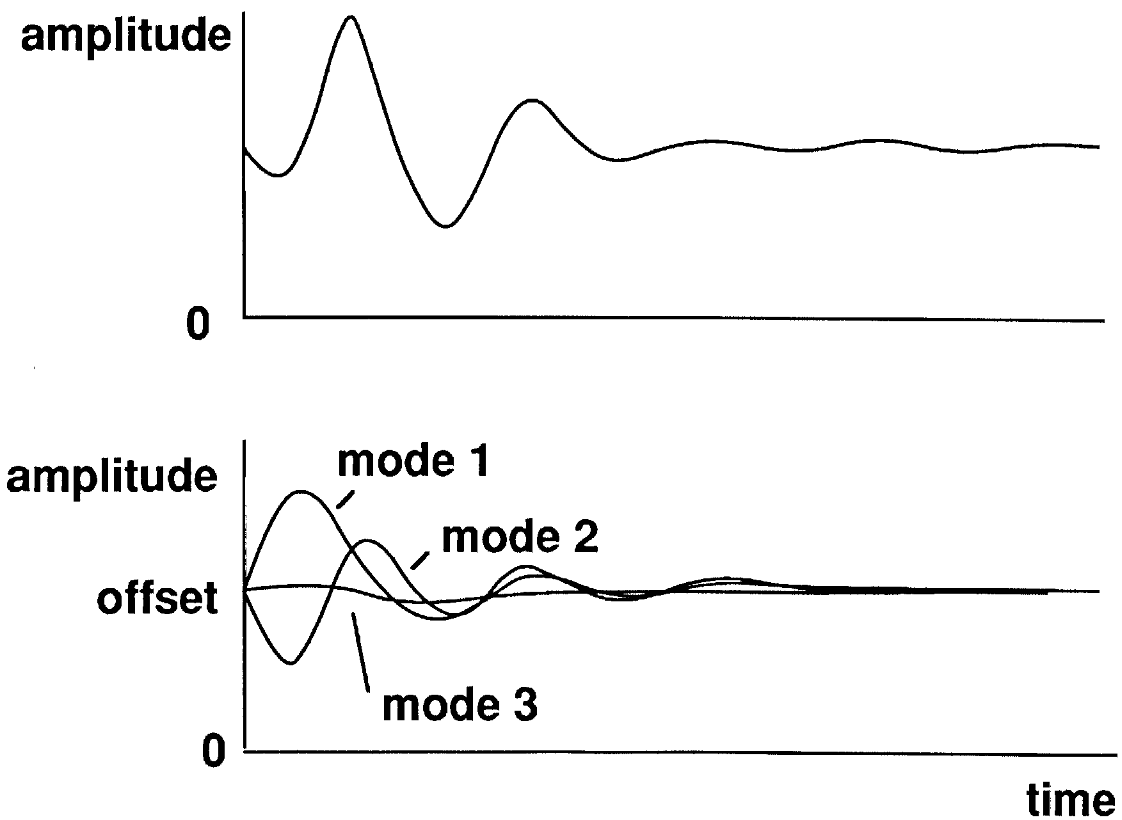

$q_i, \dot{q}_i = 0$ at $t = 0$

- Offset value is initial condition for dynamic analysis in addition to generalized velocity excitations

## NONLINEAR AERODYNAMIC ANALYSIS
### Dynamic Analysis (Modal Identification)

Once the dynamic analysis is executed, the resultant time history that is output from CAP-TSD is processed through a modal identification technique. This technique identifies the modal components of the response in terms of damping and frequency from which stability information can be obtained. If the system is stable, the dynamic pressure is increased. At each dynamic pressure, a static aeroelastic solution is computed followed by the dynamic response and modal identification. This procedure continues until an unstable root (flutter) is encountered. The flutter boundaries are defined at each Mach number by the dynamic pressure for which flutter occurs.

# NONLINEAR AERODYNAMIC ANALYSIS
*Dynamic Analysis (Modal Identification)*

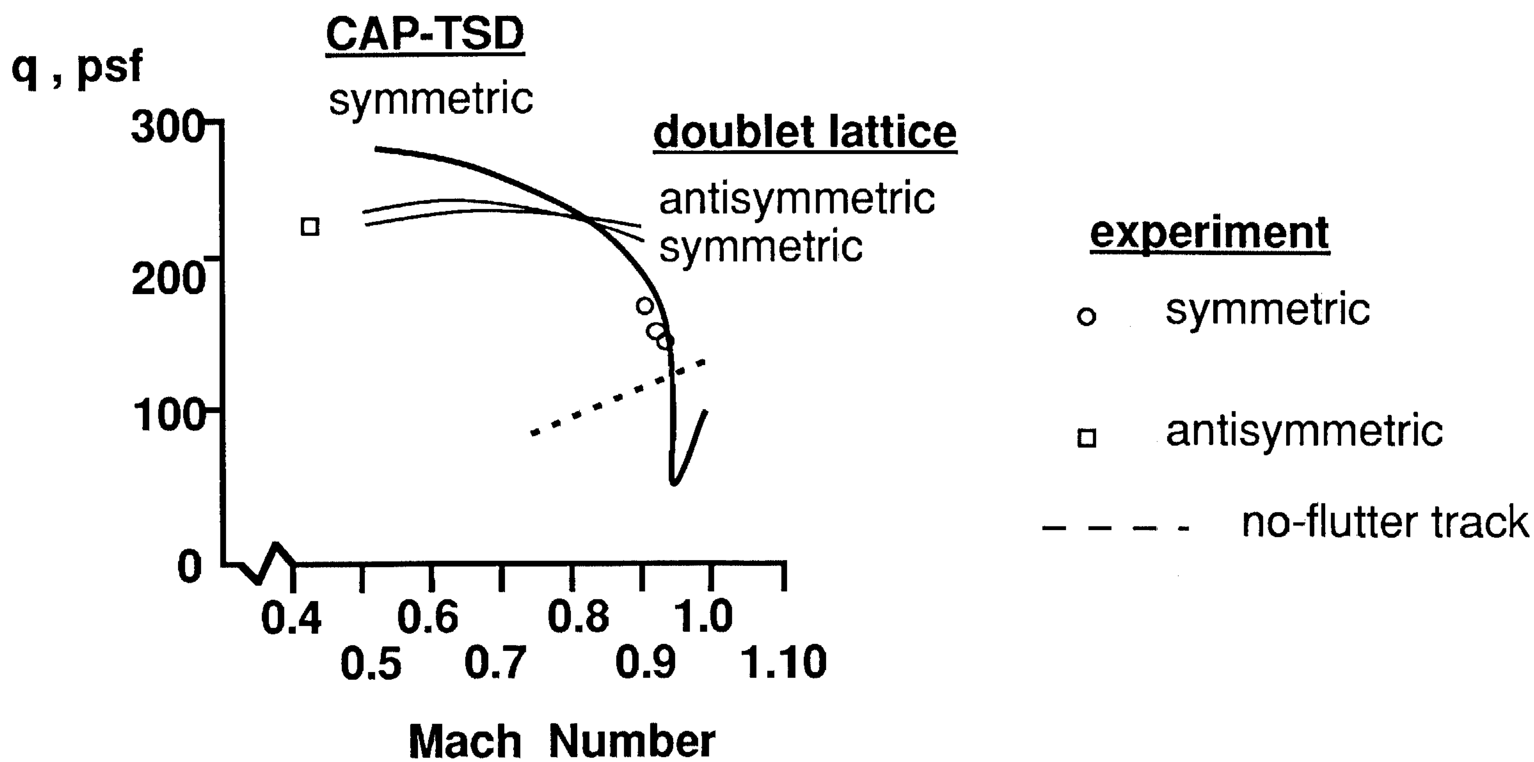



- Time history output from CAP-TSD
- Identified components and static aeroelastic offset

## OPEN-LOOP FLUTTER RESULTS
### Comparison with Experiment

The open-loop flutter results for the doublet lattice (linear aerodynamics) symmetric and antisymmetric models (tip-ballast store coupled configuration), the CAP-TSD symmetric model, and comparisons with experimental results are shown on this figure. At M=0.4, the experimental flutter instability was antisymmetric and as a result cannot be compared with the subsonic CAP-TSD result. Comparison with the doublet lattice antisymmetric prediction, however, is within 14% of the experimental value in terms of dynamic pressure. At M=0.9, M=0.92, and M=0.93, the experimental flutter instabilities were symmetric flutter instabilities, which compare very well with the CAP-TSD predictions for those Mach numbers. Both the symmetric and antisymmetric doublet lattice predictions seem to have missed the overall trend at these higher Mach numbers, as would be expected for linear theories. The crossing of the doublet lattice symmetric and antisymmetric flutter boundaries, however, appears to be an accurate behavior as experimental data defines the antisymmetric, transonic flutter boundary to be above the symmetric one shown on the figure. The no-flutter track on the figure is the path, in terms of Mach number and dynamic pressure, along which the wind tunnel proceeds for which no experimental flutter was encountered. This then implies that the bottom of the experimental transonic flutter dip occurs at M=0.93 and a dynamic pressure of 140 psf. The CAP-TSD predicted bottom of the transonic flutter dip is at 50 psf and M=0.93. This discrepancy may be due to viscous and/or separated flows not accounted for in TSD theory. It is also possible that the lack of modal definition of the bodies in CAP-TSD (specifically the tip-ballast store) has a significant effect on this result. The CAP-TSD flutter boundary was nonetheless very valuable since it was available during the test and warned test engineers of a potentially dangerous and sudden drop in stability at transonic Mach numbers.

# OPEN-LOOP FLUTTER RESULTS
## *Comparison with Experiment*



## CONCLUDING REMARKS

This presentation addressed the primary issues involved in the generation of linear, state-space equations of motion of a flexible wind-tunnel model, the Active Flexible Wing (AFW). The codes that were used and their inherent assumptions and limitations were also presented and briefly discussed. The application of the CAP-TSD code to the AFW for determination of the model's transonic flutter boundary is included as well.

# CONCLUDING REMARKS

- Main ingredients necessary for open-loop aeroelastic equations of motion presented
- ISAC and CAP-TSD codes & applications briefly described
- Experimental data used to improve math model
- Open-loop flutter results for linear, nonlinear, and experimental data presented

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