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**Aeroelastic Modeling for the FIT* Team
F/A - 18 Simulation**

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Abstract

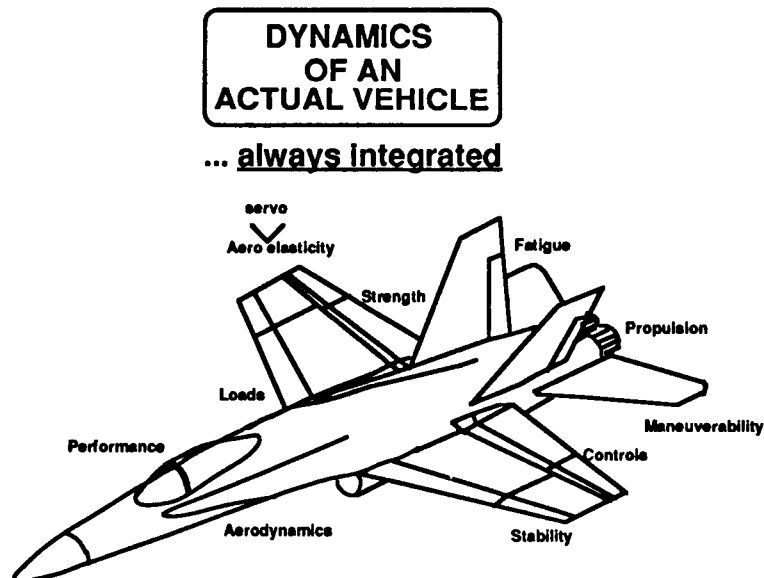
As part of Langley Research Center's commitment to developing multidisciplinary integration methods to improve aerospace systems, the Functional Integration Technology (FIT) team was established to perform dynamics integration research using an existing aircraft configuration, the F/A - 18. An essential part of this effort has been the development of a comprehensive simulation modeling capability that includes structural, control, and propulsion dynamics as well as steady and unsteady aerodynamics. The structural and unsteady aerodynamics contributions come from an aeroelastic model. Some details of the aeroelastic modeling done for the FIT team research is presented in this paper. Particular attention is given to work done in the area of correction factors to unsteady aerodynamics data.

Dynamics of an Actual Vehicle

The dynamics of an actual flight vehicle are always integrated. For better or worse, all the physical elements of the vehicle and its operating environment interact to varying degrees continually and without exception. It is only when we desire to analyze or design a complex physical system that nature's continuum becomes discretized into specialties and segregated into disciplines. It's recognized, of course, that real systems are not so discretized and some "multidisciplines" have emerged and are given due consideration in analysis and design. Aeroelasticity and its descendent, aeroservoelasticity, are examples.

Even where "multidisciplines" have not emerged to deal with complex physical interactions, interdisciplinary communication is still established to analyze and design the vehicle. A structures group will obtain force and pressure data from the aerodynamics, propulsion, and guidance and control groups to define the operating environment and, particularly, loads to which the structure is subjected [1]. In turn, the structures group might provide the guidance and control group with modal dynamics and, more likely, flexible stability derivatives and maneuver constraints.

However, the cross - disciplinary data flow is not always smooth. Each group uses models, methods, theories, and assumptions peculiar to its own discipline. This state of affairs makes one discipline seem remote and even incomprehensible to another discipline even though they are all subject to the same laws of physics and may be involved in designing parts of the same airplane. So, there is still a need for more in-depth integration of multiple disciplinary techniques [2].



FIT Background

In its statement of mission and goals [3], NASA's Langley Research Center lists that one of its major goals is to "develop multidisciplinary integration methods to improve aerospace systems." In pursuit of this goal two working groups were formed in January of 1985. One group, known as ACIG (for Aircraft Configuration Integration Group), was to concentrate on structural and aerodynamic configuration parameters. The other, known as the FIT (for Functional Integration Technology) Team, would work on the integration of vehicle dynamics.

Using an existing configuration, specifically the F/A - 18, the FIT Team has been working toward two major objectives: improving the effectiveness of piloted simulation in the preliminary and conceptual design phases, and removing unfavorable or exploiting favorable dynamic systems interactions. The plan is to eventually merge the activities of the two groups to produce comprehensive, integrated analysis and design methodologies.

- **A NASA/LaRC Major Goal - - "Develop multidisciplinary integration methods to improve aerospace systems"**

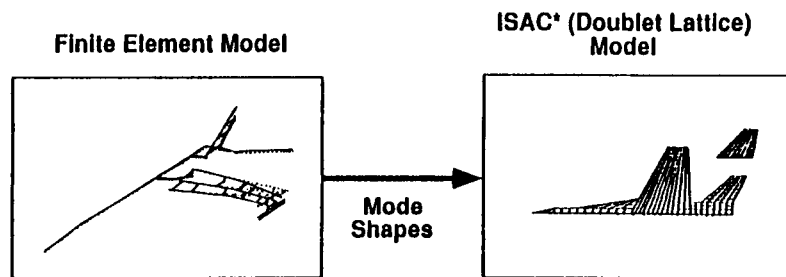
- **Two Working Groups Formed:**
 - **Aircraft Configuration Integration Group (ACIG) - Aero & Structures**

 - **Functional Integration Technology (FIT) - Dynamics Integration**
 - **Improve Effectiveness of Piloted Simulation in Preliminary and Conceptual Design Phases**

 - **{ Remove Unfavorable } Dynamic Systems Interactions**
{ Exploit Favorable }

FIT Aeroelastic Model

An essential part of the FIT effort has been the development of a comprehensive simulation modeling capability that includes structural, control, and propulsion dynamics as well as steady and unsteady aerodynamics [4]. The structural and unsteady aerodynamic contributions come from the aeroelastic model. The aeroelastic model of the F/A - 18 used in the FIT studies consists of a finite element beam model obtained from the manufacturer, and a doublet lattice model constructed using ISAC (Interaction of Structures, Aerodynamics, and Controls, Ref. 5). Mode shapes are determined from the structural model and used with the doublet lattice model for the computation of generalized oscillatory aerodynamic loads. A discussion of some modeling details follows.



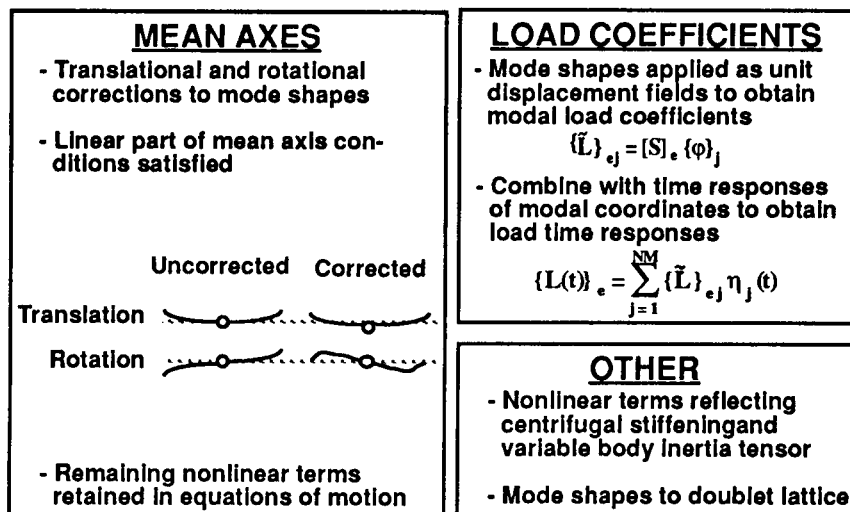
* Interaction of Structures, Aerodynamics, and Controls

Structural Modeling

In the general nonlinear equations of motion of a free-flying aeroelastic aircraft, a great deal of coupling between the body and elastic momenta can occur unless the body reference axes are chosen to be "mean axes" [6, 7, 8]. So, it is advantageous to use vibration modes that satisfy the mean axis conditions. Free vibration modes theoretically satisfy these conditions exactly and the mode shapes for this model were determined for the unrestrained structure. However, computations showed that the conditions were not satisfied exactly [6], likely as the result of computational error. Since the mean axis conditions are known, the mode shapes could, in principle, be modified so as to satisfy the conditions. But the mean axis conditions themselves are nonlinear, making it difficult to determine the modifications. Therefore, only the linear portions of the conditions were satisfied by applying small translational and rotational corrections to the mode shapes. This leaves small nonlinear terms coupling the body and elastic angular momenta. These terms are retained in the nonlinear equations of motion [6, 7]. If the structure were undergoing free vibration in a gravity-free vacuum, a true mean axis system would be observed to be perfectly stationary with respect to an inertial reference. However, since the body frame in the present model is only approximately a mean axis system, it would be seen to undergo small angular oscillations.

Modal load coefficients were determined by applying the mode shapes to the structural model as unit displacement fields [6]. The internal loads within each element resulting from the application of one mode become the load coefficients for that mode. The internal loads are comprised of the six stress resultants: two bending moments; one torsion moment; two shears; and one axial force. The coefficients are combined with time histories of the modal coordinates (which are the generalized coordinates representing the structure in the integrated model) to produce time histories of the internal loads.

As the structure deforms, the inertia tensor of the body changes since mass is being redistributed in space. The structural model is used to compute terms reflecting this effect as well as terms representing centrifugal stiffening, frequencies, and generalized modal masses - all of which are supplied to the integrated simulation model. [6, 7]. Finally, as mentioned previously, the corrected mode shapes are supplied to the doublet lattice model for computation of generalized, unsteady aerodynamic loads.



Unsteady Aerodynamics Modeling

In order to obtain a representation of the unsteady aerodynamic loads in state-space form for the simulation model, a rational function approximation (RFA) is used. The form of RFA used is known generally as Roger's approximation and is shown in the figure. The coefficient \hat{A} matrices are determined by a least - squares fit of the approximation to oscillatory loads tabulated over a range of reduced frequencies [9, 10]. The approximations are only valid for a given Mach number, so sets of coefficient matrices must be calculated to cover the Mach number range of interest. The aerodynamic loads provide the simulation model with incremental loads resulting from elastic and control deflections and from unsteady motion. A total of four (4) lags (the β 's) were used in the FIT F/A - 18 model.

- Unsteady aerodynamic loads in the Laplace domain :

$$F_s(\bar{s}) = q [Q(\bar{s})] X(\bar{s})$$

- Roger's Rational Function Approximation (RFA) :

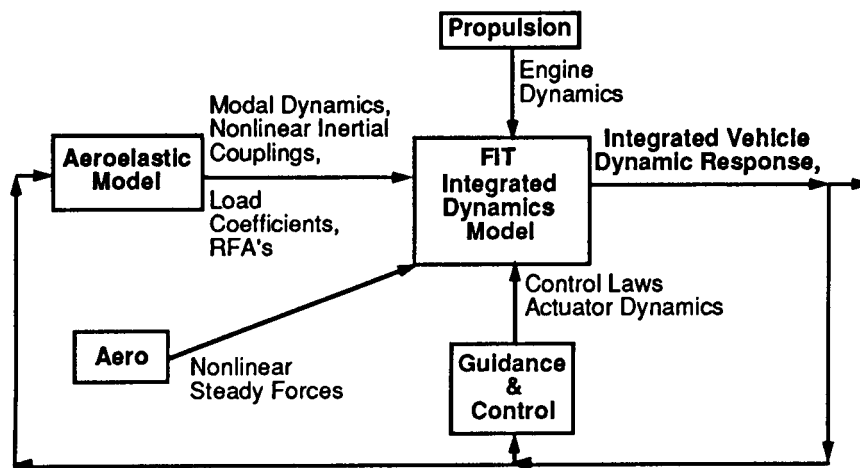
$$Q(\bar{s}) = \hat{A}_0 + \hat{A}_1 \bar{s} + \hat{A}_2 \bar{s}^2 + \sum_{i=1}^{N_L} \frac{\hat{A}_{1+i} \bar{s}}{\bar{s} + \beta_i}$$

- Least-Squares fit of $\hat{Q}_{ij}(k_v)$ to tabulated $Q_{ij}(k_v)$ over a range of k values for given Mach number
- Incremental loads from elastic and control deflections and from unsteady motion

FIT Integrated Dynamics Model

The general, nonlinear equations of motion [6, 7] are implemented in a batch simulation model written in ACSL (Advanced Continuous Simulation Language, Ref. 11). The model incorporates elements from an engine dynamics model, control laws and actuator dynamics, nonlinear steady aerodynamic data, which for the present F/A - 18 model comes from the LaRC Real-Time Simulation Facility's own F/A-18 simulation, and data from the aeroelastic model. As described earlier, this data includes generalized masses and frequencies, nonlinear momentum coupling terms, nonlinear terms representing centrifugal stiffening and the effects of deformation on the body's inertia tensor, and the rational function coefficients for the unsteady aerodynamic loads. Modal load coefficients may also be supplied to the simulation for immediate calculation of load time histories. But since this places an additional computational burden on the simulation, it is more efficient to send the modal coordinate time histories back to the aeroelastic model for a comprehensive evaluation of the loads.

A time history of internal loads for the F/A - 18 model resulting from a roll doublet maneuver was animated using colors to represent various internal load levels. A videotape of the display was prepared and shown as part of the oral presentation of the paper. As it turns out, the nonlinear inertial terms are not a major factor for the F/A - 18 loads and would not likely be important for any conventional aircraft configuration. For rotorcraft, aircraft with stores or high T - tails, or for flexible spacecraft they may become more important [6, 7].



Needs

A future concern for FIT team efforts is improvement in the representation of the unsteady aerodynamic loads. The present form of RFA being used, Roger's approximation, introduces a large number of states into the model [6]. For a formulation including six rigid body modes, twenty elastic modes, and four aerodynamic lags, the number of aerodynamic states alone is 104 [4]. Add to this the rigid body and elastic modes, altitude, quaternion, actuator, and engine states, and the size of the simulation model becomes very large. This substantially affects the run time of the batch simulation limiting its utility. Work is underway to incorporate an updated form of Karpel's Minimum State Method [9, 12] into the options available in the ISAC programs being used for the unsteady aerodynamics. Another concern is the quality of the unsteady aerodynamic data being approximated, particularly for rigid-body motions at low reduced frequencies and near the transonic regime. Work being done in this area with correction factors will occupy the latter part of this paper.

Unsteady Aerodynamics

- **Simpler approximation
(Minimum State Method - Karpel)**
- **Improved quality of unsteady aerodynamics
data near zero reduced frequency and
transonic regime (Correction Factors)**

Correction Factor Methodologies

The Doublet Lattice Method is one method used to calculate unsteady aerodynamics for a wide variety of applications, but it has limitations. It is a linear, subsonic, and small perturbation method [13]. One method to expand the usefulness and the accuracy of the Doublet Lattice Method is the use of correction factors. Correction factors are modifiers of either the pressures or the downwashes calculated with the doublet lattice method. Correction factors can be calculated to match pressure distributions, section properties, or total loads (force and moment derivatives) that are obtained from experiment or CFD calculation [14]. Matching total forces requires solving an optimization problem that can be formulated in one of several ways. One way is to minimize the difference between the experimental and analytical loads with side constraints on the changes in the pressure or downwash distribution. Alternatively, the change in the original pressure or downwash distribution can be minimized subject to constraints on the differences between the experimental and analytical loads [15].

WHY - Doublet Lattice has limitations: linear, subsonic, small perturbation

WHAT - Correction Factors are modifications to pressures and / or downwashes in order to match experimental or CFD data

HOW-

Match Pressure Distributions

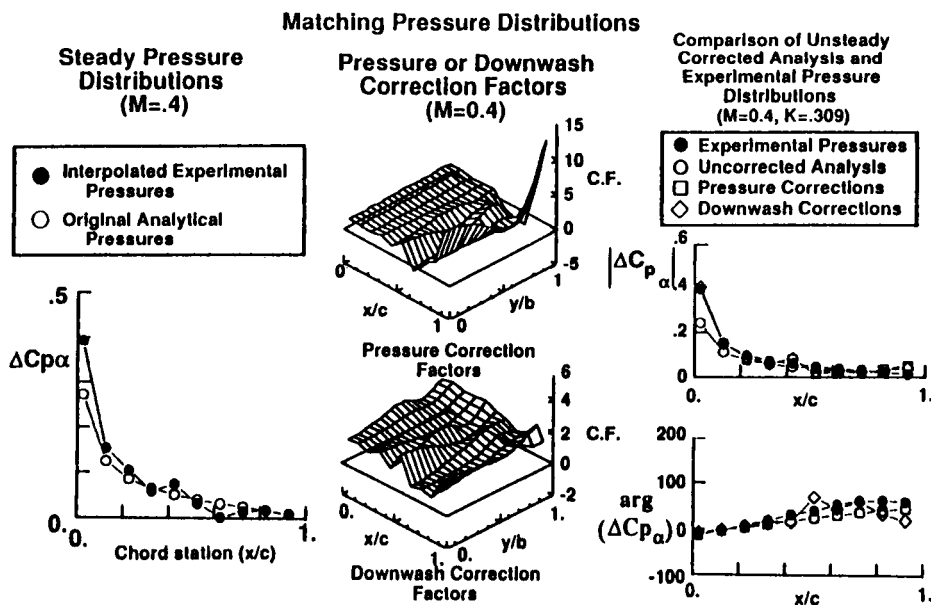
Match Section Properties

Match Total Loads - Force and Moment Derivatives by Optimization

$$\min_{\{\Delta w, \Delta p\}} \{\text{Load error}\}, \text{ subject to } \{\Delta w, \Delta p\} \{\text{Load error}\}$$

Correction Factor Methodologies - Methodology and Results

A brief description of the methodology of matching pressure distributions is presented here. For the purpose of explanation and example, the methodology was exercised on a Rectangular Supercritical Wing that was tested in the NASA Langley Transonic Dynamics Tunnel [16,17]. The steps to calculating these correction factors are as follows. First, experimental pressures are interpolated to analytical locations, which in the case of Doublet Lattice correspond to the quarter-chord and mid-span location of each of the doublet lattice boxes. This is accomplished using one-dimensional spline interpolation in the chordwise direction followed by the spanwise direction. The pressures at each of the analytical locations are then interpolated using splines as a function of angle-of-attack. The analytical first derivative of the spline interpolation curve is evaluated at an angle-of-attack of zero degrees to obtain the quantity which will be matched using correction factors. Correction factors are calculated to modify either the analytical pressures or the downwashes such that the steady pressure distributions are matched. Typical distributions of pressure and downwash correction factors are shown in the center of the slide. These correction factors were then applied to the calculation of the unsteady pressures. The methodology was validated by comparing corrected unsteady analytical aerodynamic data and unsteady experimental aerodynamic data.



Doublet Lattice Modeling of F/A - 18

An aerodynamic model of the F-18 was needed to calculate Doublet Lattice aerodynamics for the FIT integrated dynamics model. In the original aerodynamic model of the F-18, the fuselage was modeled as a flat plate, the horizontal tail and the wing had no dihedral, and the tip missile was not modeled. An initial attempt at calculating correction factors for this model was unsatisfactory, primarily because the pitching moment derivative of the doublet lattice model was of the wrong sign. The method concentrated on improving the pitching moment derivative at the expense of the other stability derivatives, resulting in a poor overall "corrected" model, and unrealistic values for the correction factors. Because of this problem, a parametric study was conducted to evaluate the sensitivities of the stability derivatives to different models of the fuselage and tip missile, the inclusion of wing dihedral, and wing panelling. The fuselage was modeled several different ways as a flat plate or as a slender body with interference panels. The models investigated are shown in the figure. Several tip missile models having different sizes of slender bodies as well as cross sections of interference panels were evaluated as shown. Dihedral was also included in the wing and horizontal tail.

- **Original model**

Flat plate fuselage, no tip missile, no wing dihedral and no horizontal tail dihedral

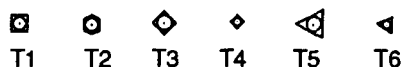
- **Sign of $C_{M\alpha}$ - wrong**

- **Parametric study of doublet lattice model features**

- 1) **Fuselage**



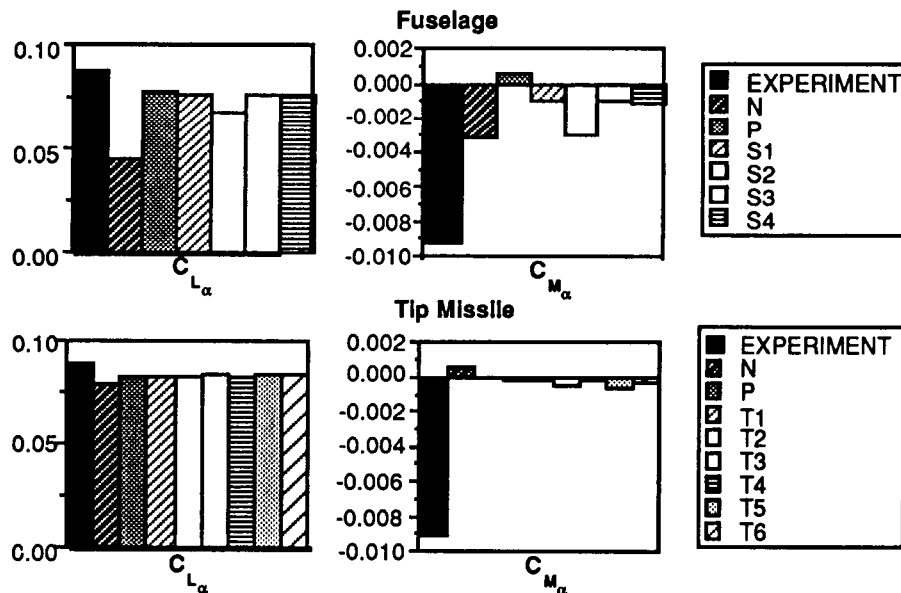
- 2) **Tip missile**



- 3) **Dihedral - Wing (-3 degrees) and horizontal tail (-2 degrees)**

Sensitivities of Stability Derivatives to Modeling

Shown here are some typical comparisons of the effect of modeling the fuselage and the tip missile on the several stability derivatives. The top half of the figure shows the effect of modeling the fuselage. N signifies no fuselage, P signifies a flat plate fuselage, S# identifies the slender body and interference panel model used, shown on the previous figure. Modeling the fuselage as a slender body changes the sign of the pitching moment. Incorporating the slender body fuselage model, however, does not greatly change the lift due to angle of attack. The bottom of the figure shows the effect of different tip missile models. N signifies none, P signifies a flat plate, and T# refers to the tip missile models as shown on the previous figure. The tip missile comparison also shows that the adding a tip missile improves the pitching moment with negligible effect on the lift coefficient due to angle of attack.



Sensitivities of Stability Derivatives to Modeling (cont.)

Summarized here are the results of the parametric study of the effect of modeling on the analytical stability derivatives. Results showed that the modeling the fuselage as a slender body resulted in improving the analytical calculation of the pitching moment due to angle-of-attack and lift coefficient due to pitch rate. There was a small effect on the antisymmetric loads. The tip missile modeling improved the pitching moment due to angle-of-attack and the rolling moment coefficients with respect to the wing trailing edge control surfaces. Implementing dihedral on the wing and the tail affected the antisymmetric derivatives and had a small beneficial effect on the pitching moment due to angle-of-attack. Based on this parametric study, the best starting model for calculating correction factors is one in which the fuselage is modeled as a slender body with interference panels and the tip missile is modeled in the simplest manner. Though the tip missile does not have a great effect on the stability aerodynamic forces for this application, it has been shown that how the tip missile is modeled does affect local loads and flutter [18].

Fuselage modeling	Modeling fuselage as slender body improves C_{M_α} , C_{L_q} Negligible effect on antisymmetric forces and moments
Tip Missile	Negligible effect except for C_{M_α} and rolling moment coefficients with respect to trailing edge flap and aileron
Dihedral Wing (-3 deg) Tail (-2 deg)	Negligible effect on symmetric derivatives except for C_{M_α} Small beneficial effect on C_{Y_β} Small detrimental effect on C_{N_β} and C_{L_β}

Concluding Remarks

This paper has presented some details of an aeroelastic model of the F/A - 18 created for NASA LaRC's Functional Integration Technology team's research in dynamics integration. This model was used to directly incorporate aeroelastic effects, including modal structural dynamics, unsteady aerodynamics, and structural loads, into a comprehensive nonlinear simulation model that combines aeroelasticity, propulsion dynamics, control dynamics, and a nonlinear steady aerodynamics data base. Data passed to the simulation model include modal generalized mass, frequencies, nonlinear inertial coupling terms, nonlinear terms accounting for centrifugal stiffening and variation of the body inertia tensor resulting from deformation, rational function approximation coefficients for generalized unsteady aerodynamic forces, and a limited number of modal load coefficients. The structural model can also be used for a broader loads analysis using output time histories of the elastic modal coordinates from the simulation model.

As a result of experiences with the simulation model, several aeroelastic modeling needs have been identified. These deal with the representation of unsteady aerodynamics. First, it is felt that the Minimum State Method will provide a lower order approximation. Second, correction factor methodologies are being developed to improve the quality of the doublet lattice data being approximated, extending its usefulness. As part of this work, some issues related to fuselage and tip missile modeling and its effects upon efforts to calculate correction factors have been resolved.

- **Aeroelasticity Included directly in an integrated dynamics model**
 - **Structural modal dynamics**
 - **RFA's of modal generalized aerodynamic forces**

- **Have need for improvements in unsteady aerodynamics**
 - **Lower order RFA's needed**
 - **Correction Factor Methodologies developed and tested on Rectangular Supercritical Wing**
 - **Fuselage and tip missile modeling issues resolved**

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