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Working Paper 1439-9

Survey of Existing Aeroservoelastic Models

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1.0 INTRODUCTION

This working paper documents a survey of existing mathematical models of aeroservoelastic aircraft. For the purposes of this working paper, the primary purpose of such models is for control analysis and design. Enhanced validation and simulation (piloted and non-piloted) are also important.

Models that are considered herein include the following:

- X-53 Active Aeroelastic Wing (AAW) Aeroservoelastic Models
- Body Freedom Flutter (BFF) Vehicle State Space Models
- X-56A State Space Models
- Very Flexible Aircraft State Space Model
- B-1-Like Models
- Boeing F/A-18C Linear Model for Aeroservoelastic Analysis

2.0 AEROSERVOELASTIC MODEL DESCRIPTIONS

2.1 X-53 Active Aeroelastic Wing (AAW) Aeroservoelastic Models

2.1.1 Description

This description was taken directly from Ref. 1 and a detailed analysis with these models is documented in Ref 2.

The database contains state space models called Input-to-Output ROMs (IOROMs) where each was constructed using the STI ASETool following the formulation described in Ref. 3. These models are built for use in Matlab.

For each model, a total of 124 sensor nodes are defined on the wing, the fuselage, the vertical tails and the stabilators as indicated in Figure 1.

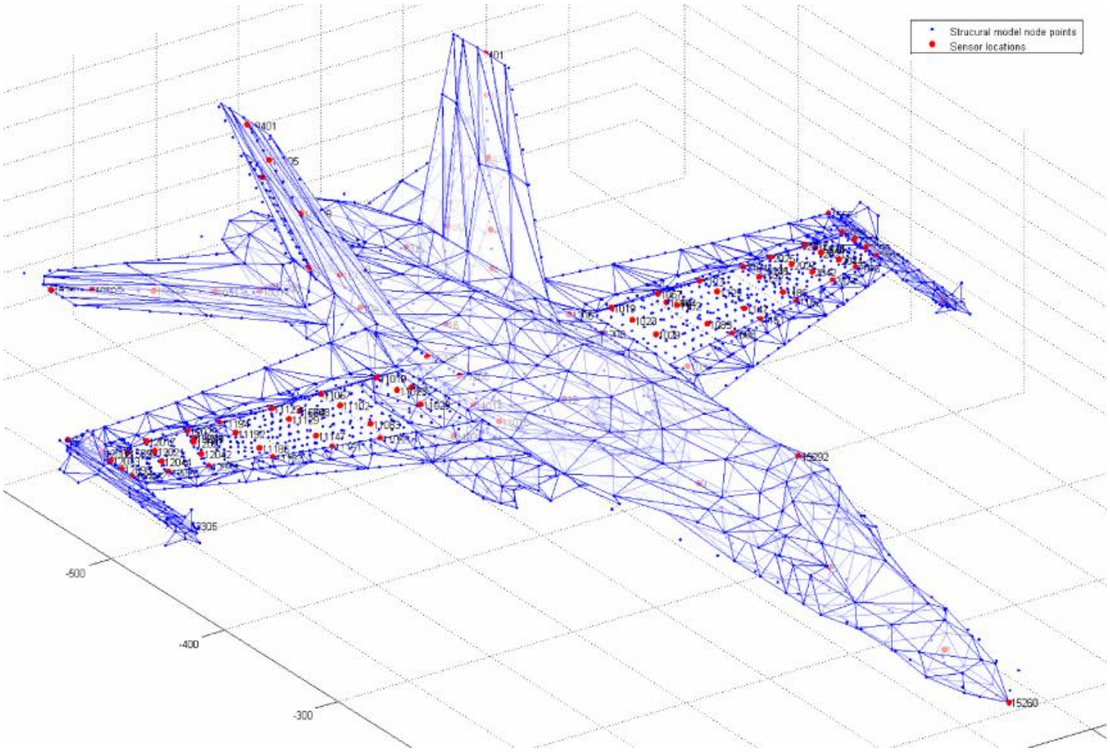

Figure 1: X-53 Structural Model with sensor nodes indicated.

The resulting state space models have 9 inputs in the form of moments and force (units of in-lb and lb). There are 8 control surfaces (two ailerons, two trailing edge flaps, two rudders and two stabilators) which are actuated by equal and opposite moment (in-lb) and a thrust input (lb) actuated by a force applied at a node near the c.g.. Model outputs are in the form of translational and rotational quantities consisting of accelerations (in/s^2, rad/s^2), velocities (in/s, rad/s) and displacements (in, rad) at each node. There are 18 total sensor quantities per node resulting in 2232 total sensor outputs. The outputs are expressed in their local node frame representative of actual sensors.[4]

These models are in the following form shown in Eq. (1). Inputs and outputs are sufficiently labeled but states are not. The state descriptions can be determined using knowledge that there are 21 structural modes, meaning the last 21 states are these modal deflections (u_m), the previous 21 states are the modal deflection derivatives ($\dot{u}_m$), making the remaining states due to the unsteady aerodynamic forces (w).

$$\begin{bmatrix} \dot{w} \\ \ddot{u}_m \\ \dot{u}_m \end{bmatrix} = \begin{bmatrix} -H & -B & -C \\ P & 0 & -\Omega^2 \\ 0 & I & 0 \end{bmatrix} \begin{bmatrix} w \\ \dot{u}_m \\ u_m \end{bmatrix} + \begin{bmatrix} G_w \\ G_{\dot{u}} \\ G_u \end{bmatrix} u$$

$$y = \begin{bmatrix} Z_w & Z_{\dot{u}} & Z_u \end{bmatrix} \begin{bmatrix} w \\ \dot{u}_m \\ u_m \end{bmatrix} + Du \qquad (1)$$

In the above equation H, B, C and P describe the unsteady aerodynamic forces and Ω^2 is a diagonal matrix of the square of the dry structural modal frequencies. The database is made up of 9 models described in Table 1. All models are trimmed to steady level flight with 0 degree flight path angle with a mass of 965.31 slugs.

Table 1: X-53 IOROM database.

Mach	Trim Altitude (ft)	angle of attack (degrees)	stabilator deflection (degrees positive down)	Thrust (lbs)
0.7	0	1.5	0.742	3523.792
0.7	20000	2.82	0.3932	2154.153
0.7	40000	6.8	–0.248	2816.762
0.8	0	1.188	0.7656	4429.370
0.8	20000	2.15	0.518	2455.755
0.8	50000	7.6	–0.135	3362.783
0.9	0	1.02	0.5832	6465.560
0.9	20000	1.68	0.4197	3348.925
0.9	50000	5.25	–0.978	2840.122

2.1.2 Notable Features

- These models are linear state space models in an ideal form for control analysis and design.
- These models are representative of a transonic flight regime.
- These models represent fully coupled rigid body and flexible dynamics.
- These models were created directly from a full order nonlinear CFD/CSD model that is also available for high fidelity validation.
- This model is not restricted for use by ITAR or other.

2.2 Body Freedom Flutter (BFF) Vehicle State Space Models

2.2.1 Lockheed Martin Models

2.2.1.1 Description

This description is taken directly from Ref. 5. Airframe models have frequency adjustments to match GVT and in-flight data at ~34 KEAS. Model speeds range from 40 to 90 KEAS in 2 knot increments at constant altitude of 1000 feet (variable Mach) AGL. Modal damping is from GVT. Actuators include roll-off. Inputs are the 8 individual trailing edge control surface commands in degrees. Outputs include the vehicle body rotational rates, accelerometers at various locations on the aircraft, and sectional lift at span locations of LESP sensors. Figure 2 displays the vehicle planform showing sensors and effectors.

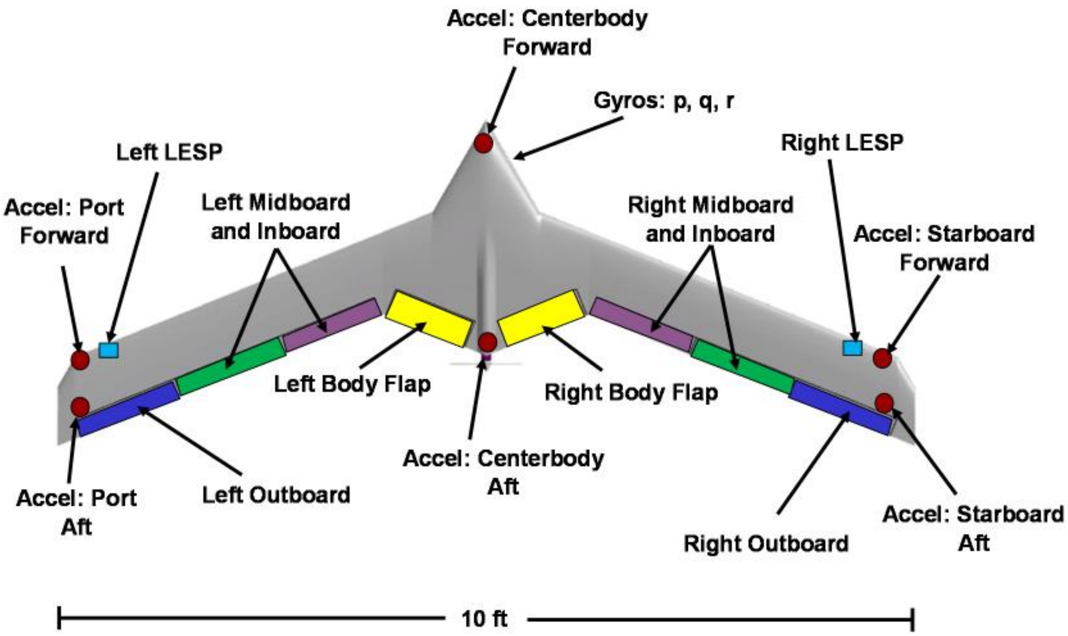

Figure 2: BFF Vehicle planform.

2.2.1.2 Notable Features

- These models are linear state space models in an ideal form for control analysis and design.
- These models have been validated and enhanced with flight test data
- These models represent fully coupled rigid body and flexible dynamics and model a vehicle that displays significant coupling between rigid body and flexible dynamics, similar to the miniMUTT.
- This model is not restricted for use by ITAR or other.

2.2.2 Models Developed Under this Project

2.2.2.1 Description

Airframe models have frequency and modal damping adjustments to match GVT performed at the University of Minnesota. Model speeds range from 35 to 60 KEAS in 5 knot increments at constant altitude of 3000 feet (variable Mach) AGL. Actuators include roll-off. Inputs are the 8 individual trailing edge control surface commands in degrees. Outputs include the vehicle body rotational rates, accelerometers at various locations on the aircraft. The aircraft geometry is that shown in Figure 2. The development of these models is described in Ref. 6.

2.2.2.2 Notable Features

- These models are linear state space models of the vehicle’s longitudinal dynamics, and are in an ideal form for control analysis and design.
- The models describe the vehicle’s motion in terms of translational and rotational velocities defined in the vehicle-fixed coordinate frame, as in traditional rigid-body flight dynamics models.
- These models have been partially validated against the Lockheed Martin models described above.
- These models represent fully coupled rigid body and flexible dynamics and model a vehicle that displays significant coupling between rigid body and flexible dynamics, similar to the miniMUTT.

- These models are not restricted for use by ITAR or other.

2.3 X-56A State Space Models

2.3.1 Description

This description is taken directly from Ref. 7. This is a database of linear state space models representing steady level flight at Mach 0.16 at 50 KEAS to 150 KEAS in 2 KEAS increments at fuel loads of 0 to 80 lbs in 10 lb increments. The core models were created using ZAERO and are in a format for use in Matlab. 20 structural modes were used to create the models (6 rigid body, 14 elastic). Actuator states (including engine dynamics) are included in the model. Sensor Dynamics are also included. Each flight condition has 3 models: the original ZAERO flutter model, the ZAERO model with gust filter and the updated model that includes the phugoid mode. The models have 12 inputs consisting of 10 trailing edge control surface deflections and 2 throttles for the engines. The models each have 22 outputs consisting of 16 IMU measurements as well as vertical acceleration at 6 locations distributed on the structure. Figure 3 displays a planform view with sensors and effectors indicated.

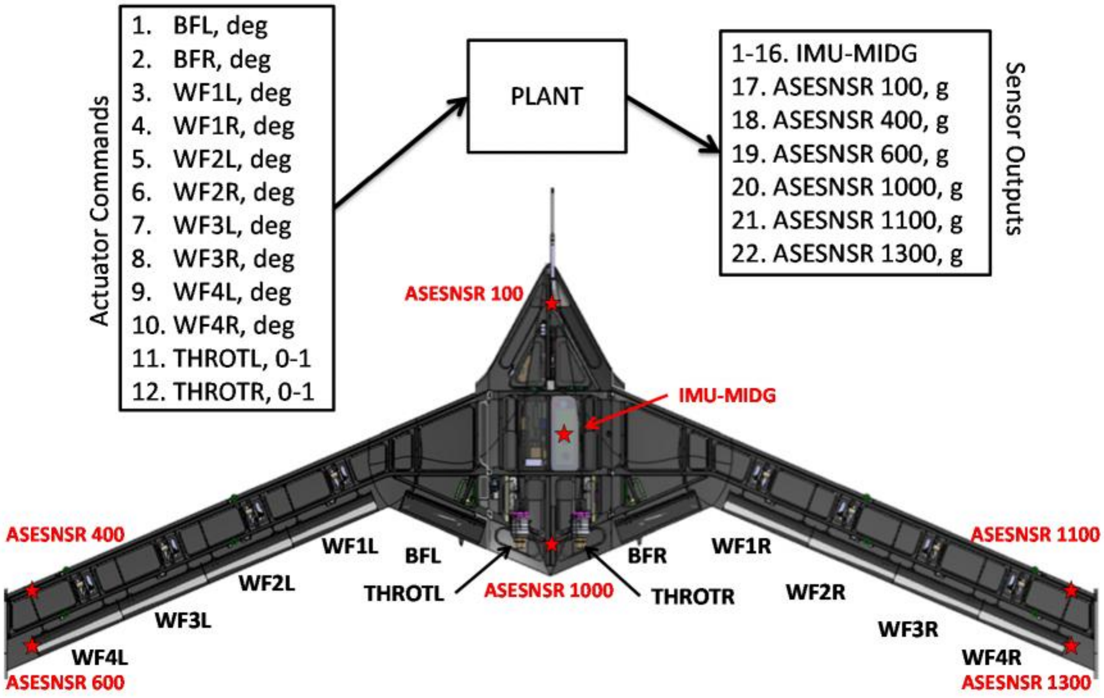

Figure 3: X-56A planform view.

2.3.2 Notable Features

- These models are linear state space models in an ideal form for control analysis and design.
- These models have been partially validated and enhanced with flight test data. Particularly, data from flights with a stiff wing vehicle have been used to update the low frequency (rigid body vicinity) dynamics. The structural model has also been updated to represent data from GVT tests.
- These models represent fully coupled rigid body and flexible dynamics and model a vehicle that displays significant coupling between rigid body and flexible dynamics, similar to the miniMUTT.
- This model is restricted for use by ITAR.

2.4 Very Flexible Aircraft State Space Model

2.4.1 Description

This description was taken from Ref. 8, which is much more comprehensive. Consider the air vehicle based on the DARPA Vulture project shown in Figure 4, which is powered by fifteen forward facing engines and which contains six actuated tail elevators. The elevators are divided into: two tip devices at each end of the span and four tail elevators located at the aft of each of the four vertical tail surfaces called the sails. Four forward facing pods collinear with the sails are used for energy storage and contain air data instrumentation.

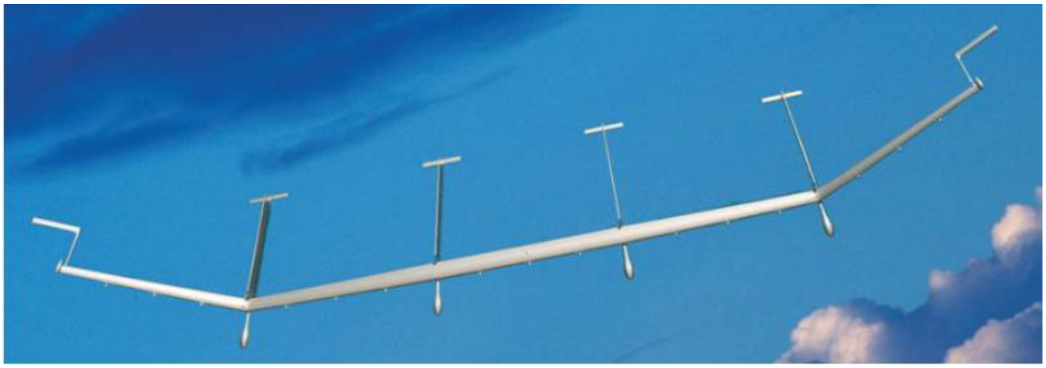

Figure 4: Vulture Very Flexible Aircraft (VFA) Rendering.

The model is in linear state space form of the vehicle trimmed at 34.6 ft/s, altitude of 0 ft., dynamic pressure of 1.42 psf and angle of attack of 0 degrees. The states are represented as:

$$x_{707\times 1} = \begin{bmatrix} x \\ y \\ z \\ \phi \\ \theta \\ \psi \\ \text{aero inflow (1:15)} \\ \text{flex positions (1:340)} \\ u \\ v \\ w \\ p \\ q \\ r \\ \text{flex velocities (1:340)} \end{bmatrix} = \begin{bmatrix} \text{inertial x-position, ft., positive North} \\ \text{inertial y-position, ft., positive East} \\ \text{inertial z-position, ft., positive down} \\ \text{bank angle, rad., positive right wing down} \\ \text{pitch angle, rad., positive nose up} \\ \text{true heading angle, rad., positive nose left} \\ \text{non-dimensional} \\ \text{flex mode positions in body axes, ft.} \\ \text{CG velocity in body axes, fps., positive forward} \\ \text{CG velocity in body axes, fps., positive out right wing} \\ \text{CG velocity in body axes, fps., positive down} \\ \text{roll rate, rps., positive right wing down} \\ \text{pitch rate, rps., positive nose up} \\ \text{yaw rate, rps., positive nose left} \\ \text{flex mode velocities in body axes, fps.} \end{bmatrix}$$

The aero inflow states (lags) are dimensionless and used to capture unsteady aerodynamic effects in the model. The 340 elastic modes come from a full-order finite element model (FEM) using five active degree-of-freedom from 68 nonlinear beam elements, with the x-axial deflection held constant.

The system inputs consist of 15 engine trusts, 18 tail actuators, and 348 gust inputs at various points on the structure. The system outputs consist of 18 wing root measurements, 8 AOA/AOS measurements and 18 measurements at 21 additional sensor locations.

2.4.2 Notable Features

- This model is a single linear state space model in an ideal form for control analysis and design.

- This model represents fully coupled rigid body and flexible dynamics and models a vehicle that displays significant coupling between rigid body and flexible dynamics and is very flexible.
- This model has many inputs and outputs making it control effector rich and sensor rich.
- Given that the vehicle is very flexible and can experience large nonlinear deflections, the validity of a linear model is limited.
- This model is not restricted for use by ITAR or other.

2.5 B-1-Like Models

2.5.1 FLEXSIM

2.5.1.1 Description

This description is taken directly from Ref. 9, which includes a much more detailed description as well as several test cases. The nonlinear aeroelastic simulation model (The Simulation) is based on the Rockwell B-1 aircraft and is in the form of a Matlab Simulink model. The mathematical models used to develop The Simulation was, for the most part, available in the open literature. But some additional aerodynamic modeling was performed, and some modifications were made to the feedback systems incorporated into The Simulation. Consequently, it is important to note that The Simulation is not intended to be a model of the actual B-1 aircraft, but rather a generic aircraft similar to the B-1 (Figure 5).

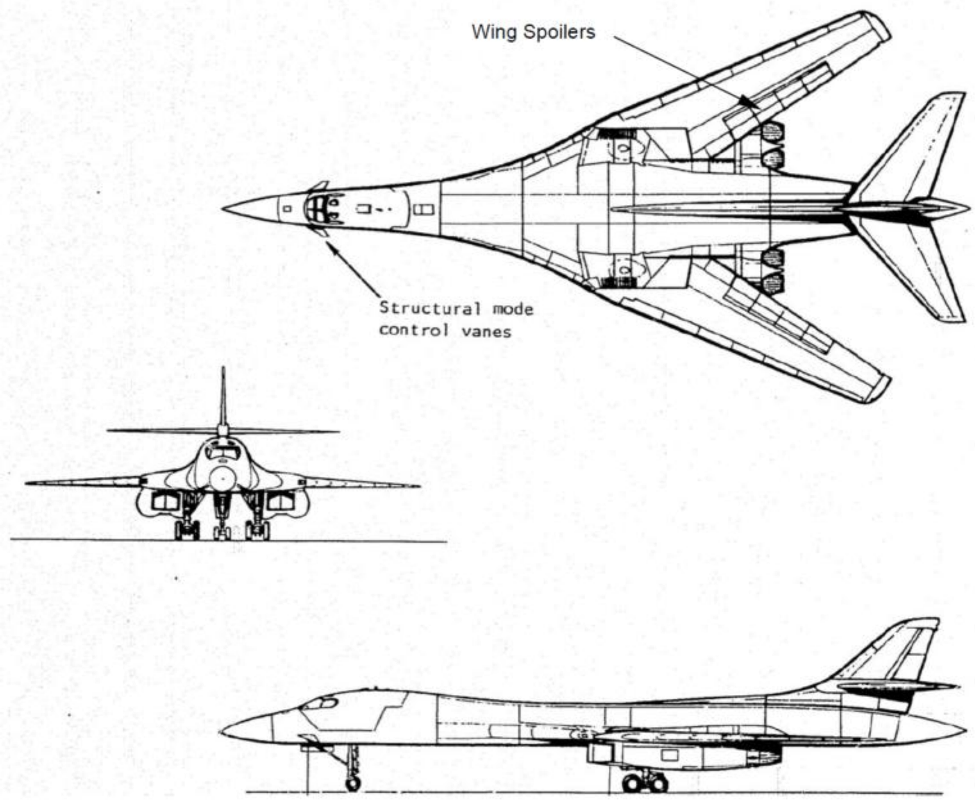

Figure 5: the Rockwell B-1 aircraft.

The resulting non-linear simulation model includes all six rigid-body degrees of freedom, plus five elastic degrees of freedom; expanded aerodynamic models, including the aerodynamic coupling between the rigid-body and elastic degrees of freedom; a non-linear model of the turbojet engine dynamics and limits; models of the measurement set (sensed responses) used on the B-1; and models of the effects of atmospheric turbulence. In addition to the engine, the vehicle configuration, as modeled, includes several control effectors, including symmetric and antisymmetric horizontal tail deflections, wing spoilers, a split rudder, and forward control vanes for structural mode control.

Additionally, the stability-augmentations systems (SAS) and structural-mode-control systems (SMCS) for the B-1 are also described in the open literature. But some modifications have been made to the control laws in these systems, to better meet program objectives, and the resulting feedback systems incorporated into The Simulation. The included systems are longitudinal, lateral, and directional SAS's, and vertical and lateral SMCS's. These systems are also intended to provide benchmarks for further active-control research.

With the aerodynamic database, engine model, and feedback-system gain schedules employed, the simulation should be sufficiently valid over a rather large flight envelope. Based on testing performed to date, this envelope extends from approximately Mach 0.5 to 0.8 and altitudes from 5000 to 30K feet, thus spanning a range of dynamic pressures. Hence The Simulation provides an extensive range of flight environments for research.

2.5.1.2 Notable Features

- This model represents fully coupled rigid body and flexible dynamics.
- This model represents nonlinear rigid body dynamics and linear flexible dynamics and is valid for a large range of varying flight conditions.
- This model also includes controllers in the form of a SAS and SMCS.
- This model is in an ideal form for piloted simulation.
- This model is not restricted for use by ITAR or other.

2.5.2 Piloted Simulation Math Model

2.5.2.1 Description

This mathematical model of a flexible aircraft similar to the B-1 was developed for piloted simulations performed at NASA Langley Research Center, and is described in Ref. 10. This math model is the basis for the FLEXSIM model described above, with a few differences This non-linear simulation model includes six rigid-body degrees of freedom, plus only two elastic degrees of freedom; expanded aerodynamic models, including the aerodynamic coupling between the rigid-body and elastic degrees of freedom; a non-linear model of the turbojet engine dynamics and limits; models of the measurement set (sensed responses) used on the B-1; and models of the effects of atmospheric turbulence. In addition to the engine, the vehicle configuration, as modeled, includes several control effectors, including symmetric and anti-symmetric horizontal tail deflections, wing spoilers, and a split rudder. The stability-augmentations systems (SAS) include the longitudinal, lateral, and directional SAS's. The structural-mode control system is not included in this model

2.5.2.2 Notable Features

- This mathematical model represents fully coupled rigid body and flexible dynamics.
- This model represents nonlinear rigid body dynamics and linear flexible dynamics and is valid for a large range of varying flight conditions.
- This model also includes controllers in the form of SAS's.
- This model was developed for piloted simulation.
- This model is not restricted for use by ITAR or other.

2.5.3 Linear Longitudinal B-1-like Math Model

2.5.3.1 Description

This mathematical model provides sufficient data to develop the linear state-space description of the longitudinal, bare-airframe flight dynamics of a flexible B-1-like aircraft. The derivation of this model, along with data for up to four elastic degrees of freedom, is described in Ref. 11. This model includes fully coupled rigid body and flexible dynamics, and describes the vehicle motion in terms of translational and rotational velocities defined in the vehicle-fixed coordinate frame.

2.5.3.2 Notable Features

- This mathematical model represents fully coupled rigid body and flexible dynamics.
- This model represents linear, longitudinal dynamics and is valid for a large range of varying flight conditions.
- This model is not restricted for use by ITAR or other.

2.6 Boeing F/A-18C Linear Model for Aeroservoelastic Analysis

2.6.1 Description

This description is taken directly from Ref. 12, which provides much more detail.

The flight condition for the linear model is 0.85 Mach, 10,000 ft. The 5.6 Hz configuration includes full 330 gallon tanks on the inboard pylons and MK-84s (i.e., 2,000 lb bombs) on the outboard pylons. A three-view of the aircraft is shown as Figure 1.

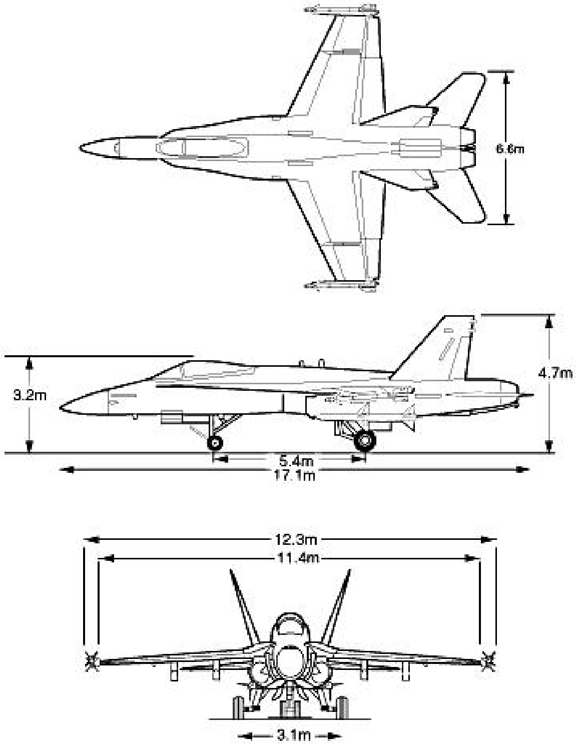

Figure 1. Three-view of the F/A-18C Aircraft.

The lateral-directional model was provided in the form of ABCD matrices for the rigid body airframe, ASE dynamics, control system, plant input time delay, zero order hold, and sensors. A block diagram of the system is shown in Figure 2. The input to the sensor model is the sum of the rigid and ASE dynamics.

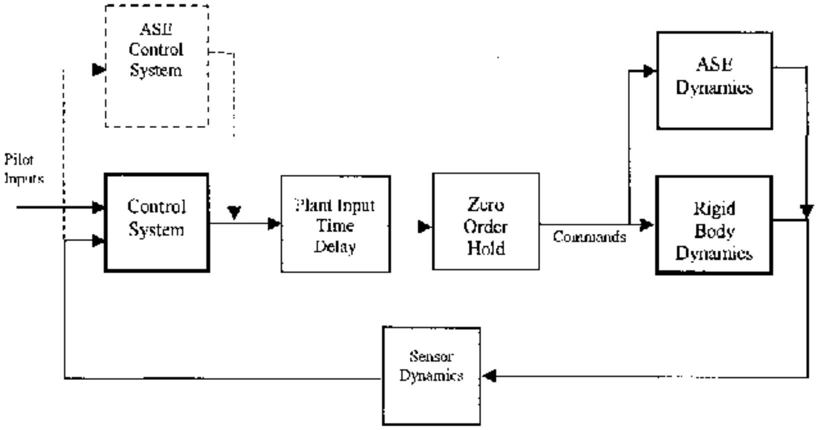

Figure 2. Linear Aircraft Model Structure

The model inputs are lateral stick and rudder pedal, and the feedbacks to the control system are roll rate, yaw rate, and lateral acceleration. Actuator dynamics are embedded in the ASE and rigid body airframe dynamics.

2.6.2 Notable Features

- This model is a single linear state space model in an ideal form for control analysis and design.
- Only lateral-directional dynamics are captured by this model.
- This model includes actuator and sensor dynamics.
- Rigid body and flexible dynamics are decoupled in this model.
- This model is restricted as proprietary to Boeing. Permission from Boeing is required for use.

3.0 DISCUSSION AND RECOMMENDATIONS

3.1 Discussion

- The majority of these models are represented as linear state space. While ideal for control analysis and design, there are limitations to linear models at fixed flight conditions.
- The B-1-like FLEXSIM model and simulation math model are unique in that they represent nonlinear rigid body flight dynamics across a large range of flight conditions. This makes them in an ideal form for piloted simulation where flight condition varies significantly.
- Piloted simulation can be conducted with linear models as well but simulation validity will be limited to small perturbations of the states around the fixed flight condition. If nonlinear kinematics is used, simulations with linear models can represent large ranges of position and orientation as long as velocity perturbation change is minimal (e.g., small angle of attack perturbation, sideslip perturbation, forward velocity perturbation, and rotational rate perturbation). Large orientation change with small body-frame-velocity perturbation such as this represents a large range of standard aircraft operation.

- The X-53 model database is in the exact form as the proposed models to be developed for mAEWing1 and mAEWing2. These are also linear state space models but they include a corresponding nonlinear full order CFD/CSD model that could be used for enhanced validation.
- The unsteady aerodynamic forces for the X-53 models are represented in such a way that they can be used independently, possibly incorporated with a nonlinear flight dynamic model in a form like the B-1-like FLEXSIM.
- The X-56A models are limited for use since they are restricted by ITAR.
- The Boeing F/A-18C model is proprietary and limited for use.

3.2 Recommendations

- Multiple models are desired for control analysis, design, and validation; linear models for control analysis and design, and nonlinear models for validation.
- The ideal model form for control design is a linear parameter varying (LPV) state space model where parameters that define the flight condition are continuous. A database of point models is also acceptable in lieu of LPV models.
- There is potential for the development of a hybrid model where the unsteady aerodynamic forces are generated using CFD (see the X-53 model description) and applied to a nonlinear flight dynamic model (see the B-1-like FLEXSIM model).
- A nonlinear model is ideal for validation.
    - The form of the B-1-like FLEXSIM model is ideal for validation and can also be used for real-time piloted simulation validation that is valid for a large range of flight conditions
    - The nonlinear CFD/CSD model is also useful for validation. It is not real-time capable but it has the potential to be used to capture more detailed flow phenomena (e.g., viscosity, flow separation, etc.).

REFERENCES

[1] Danowsky, B. P., "Description of X-53 ROM Model Database," *Systems Technology, Inc.*, STI WP-1426-11, February 2015.

[2] Danowsky, B. P., "Analysis of CMSoft X-53 ROMs," *Systems Technology, Inc.*, STI WP-1407-14, November 2013.

[3] Danowsky, B. P., Thompson, P. M., Farhat, C., Lieu, T., Harris, C. and Lechniak, J., "Incorporation of Feedback Control into a High-Fidelity Aeroservoelastic Fighter Aircraft Model," *Journal of Aircraft*, Vol. 47, No. 4 (2010), pp. 1274-1282.

[4] Danowsky, B. P. and Thompson, P. M., "Application of Accurate Sensor Measurement Capability for FCS Application in the Virtual Flight Test Suite," *Systems Technology, Inc.*, STI WP-1408-5, May 2012.

[5] Beranek, J., "BFF06 Airframe state space model for UMN," *Lockheed Martin Corp.*, Powerpoint presentation, January 2011.

[6] Schmidt, D.K., "MATLAB®-Based Flight-Dynamics and Flutter Modeling of a Flexible Flying-Wing Research Drone," Working Paper for this NASA NRA project. Oct 2014.

[7] Ouellette, J. and Chin, A., "X-56A MUTT State Model Descriptions- Flex Wing V10 FEM, Version 5.40," *NASA Armstrong Flight Research Center*, Powerpoint presentation, May 2014.

[8] Gadient, R., Lavertsky, E., and Wise, K., “Very Flexible Aircraft Control Challenge Problem,” AIAA Paper 2012-4973, August 2012.

[9] Schmidt, D. K., “A Non-Linear Simulink Simulation Of a Large, Flexible Aircraft – FLEXSIM,” document delivered to MUSYN, Inc. under subcontract, March 2013.

[10] Waszak, M.R., Davidson, J.D., and Schmidt, D.K., "A Simulation Study of the Flight Dynamics of Elastic Aircraft," NASA Contractor Report 4102, Vols I and II, Dec, 1987.

[11] Waszak, M.R. and Schmidt, D.K., "On The Flight Dynamics of Aeroelastic Vehicles," *Journal of Aircraft*, Vol. 25, No. 6, June, 1988.

[12] Smith, D., Thompson, P. M., and Klyde, D. H., “F/A-18C LINEAR MODEL FOR AEROSERVOELASTIC ANALYSIS,” *Systems Technology, Inc.*, STI WP 1339-3.