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FULL ENVELOPE AERODYNAMIC MODELING OF THE HARRIER AIRCRAFT

B. David McNally*
NASA Ames Research Center, Moffett Field, California

Abstract

The status of an ongoing project to identify a full-envelope model of the YAV-8B Harrier using flight-test and parameter identification techniques is described. As part of the research in advanced control and display concepts for V/STOL aircraft, a full-envelope aerodynamic model of the YAV-8B will be identified. Mathematical model structures and parameter identification methods that are being developed for identification of a YAV-8B aerodynamic model are presented. A global-polynomial model structure is being used as a basis for identification of the YAV-8B aerodynamic model. State estimation methods are used to ensure flight data consistency prior to parameter identification. Equation-error methods are being used to identify model parameters. A fixed-based simulator has been used extensively to develop flight test procedures and to validate parameter identification software.

Using simple flight maneuvers, a simulated data set was created covering the YAV-8B flight envelope from about 0.3 to 0.7 Mach and about -5° to 15° angle of attack. A singular value decomposition implementation of the equation-error approach produced good parameter estimates based on this simulated data set.

Nomenclature

α = angle of attack

δ = stabilator deflection

θ = pitch attitude

θ_J = nozzle angle

q = body pitch rate

a_z = normal acceleration

Introduction

In April of 1984 NASA Ames Research Center acquired a YAV-8B Harrier, a subsonic vectored thrust vertical/short takeoff and landing (V/STOL) fighter aircraft. Nearly ten years of research at Ames has resulted in the definition of advanced flight-propulsion control, display, and guidance concepts for V/STOL aircraft.[1-4] These concepts have been defined through analytical studies and ground-based simulation. The YAV-8B will provide an excellent test bed for continuing V/STOL research. The most promising concepts will be configured for flight on the YAV-8B and evaluated throughout the aircraft's entire flight envelope.

The program for flight test and system identification of the NASA YAV-8B is described in this paper. Flight-test and system identification techniques are often used in conjunction with wind-tunnel testing for definition of an aircraft's aerodynamic and propulsive force and moment characteristics. Mathematical models of aircraft are used extensively in the development of aircraft control systems, and play a vital role in real-time aircraft simulation. System identification refers to the complete process of defining a math model from flight-test data using parameter identification methods. With growing interest in vectored-thrust V/STOL aircraft, math model structures, flight-test techniques, and parameter identification methods appropriate for this class of aircraft need to be explored further. Our objective is to identify, through flight test, a full-envelope model of the YAV-8B Harrier. The results of this work will be used to update existing YAV-8B math models for control system design and real-time simulation. System identification studies on the YAV-8B will lead to a better understanding of the dynamics associated with a vectored-thrust aircraft such as the Harrier.

The paper is organized as follows. A background section gives a brief discussion on the origin of the AV-8 family of aircraft, the research associated with the YAV-8B at Ames, and a description of some existing Harrier math models. A section on model structures presents a general discussion on global-polynomial model structures used to develop full-envelope aircraft math models, and describes the model structure that is being used for the identification of a YAV-8B aerodynamics model. A section on parameter identification discusses the equation-error parameter identification method. A section on flight-test procedures covers aircraft instrumentation, test facilities, and envelope coverage. A section on post-flight data processing covers air data calibration, data consistency checking and state estimation, isolation of aerodynamic forces and moments from flight-test data, and preparation of concatenated data sets for parameter identification. The last two sections present a summary of results to date, and the concluding remarks.

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*Research Engineer. Member AIAA.

Background

In mid-1957 a British aircraft company, Hawker Aircraft Limited, entered the field of powered-lift aircraft design. The first hovering flight of the P1127, predecessor to the AV-8 Harrier, was completed in October of 1960. A decade later the vectored-thrust design born from the P1127 had matured. By the early 1970s American interest in this V/STOL concept had resulted in a design and development partnership between Hawker Siddeley Aviation and The McDonnell Douglas Aircraft Company (MCAIR). Of the many subsonic V/STOL designs, the Harrier is the only one that has become operational in the Western world. The Harrier's main engine nozzles can be rotated from 0° for conventional forward flight, to over 90° for hover and low-speed flight. Compressor bleed air is used for attitude control and stabilization during V/STOL operation. Over the past decade the powered lift design, proven by the Harrier, has captured the interest of the military, NASA, and private industry.

The AV-8 family of aircraft began with the McDonnell Douglas AV-8A. By the early 1970's the Marine Corps, the primary user of the AV-8A, wanted to increase the payload radius of the aircraft by at least a factor of two. The AV-8B was designed to meet these requirements. Major changes to the AV-8A included a supercritical wing for improved aerodynamic efficiency and greater fuel capacity, improved engine intake design and trailing edge flaps for better V/STOL performance, and additional lift improvement devices for better performance in ground effect. The YAV-8B aircraft (prototype AV-8B) has an AV-8A airframe with the supercritical wing, a modified inlet design, and added lift improvement devices. Figure 1 shows a comparison of the AV-8A, the YAV-8B, and the AV-8B. The NASA YAV-8B (158394) was one of two prototype AV-8B's to be built by MCAIR. Figure 2 shows the NASA YAV-8B performing a short takeoff at the Ames flight test facility, Crows Landing, California.

The YAV-8B Harrier is currently being used as a test bed for control systems research for the high-performance V/STOL class of aircraft at NASA Ames Research Center. Flight testing of the YAV-8B at Ames is divided into three phases. Phase I experiments are directed towards database development and include determination of supercritical wing/pylon effects, identification and validation of simulation math models, and measurement of reaction control system bleed-flow requirements. Phase II experiments are for implementation and validation, through flight test, of advanced V/STOL control and display concepts. These experiments will validate precision approach guidance concepts, determine advanced V/STOL attitude and velocity control system effects on handling qualities, and validate integrated flight and propulsion control system concepts. Phase III experiments will evaluate the capability of the advanced control concepts during shipboard operation. The ongoing Phase I experiments for full-envelope math model identification and validation are described herein.

The aerodynamics associated with a vectored thrust V/STOL aircraft such as the AV-8 Harrier are highly nonlinear because of the complex interaction between conventional aerodynamics and power-induced aerodynamics. A full-envelope, or global, mathematical model of an aircraft is one that simulates the aircraft motion throughout its entire operational envelope. Full-envelope modeling of any aircraft usually involves either wind-tunnel testing or flight testing. Until recently, modeling of the Harrier has been based entirely on wind tunnel testing. Throughout the design and development of both the AV-8A and AV-8B, MCAIR has collected wind-tunnel data covering the entire operating envelope of the Harrier.[5]

The MCAIR model of the YAV-8B is composed of function tables based on this wind-tunnel data. Wind-tunnel testing included powered and unpowered tests of 15%-scale and full-scale models of the AV-8A and YAV-8B. The MCAIR Model, although accurate, is too slow for real-time simulation on NASA-Ames computers. The bare airframe model alone requires about 70 ms of computer cycle time on the Xerox Sigma-9 general purpose digital computer. The bare airframe model includes the aerodynamic, propulsion, weight and balance, and primary flight control systems, and does not include additional control or display augmentation. The advanced control and display concepts currently under consideration require an additional 20 ms of computer cycle time. The cycle time is the time required for the simulation computer to integrate the differential equations of motion for each position and orientation throughout the simulation. As computer cycle times in aircraft simulations go beyond about 70 ms, pilots begin to perceive quantization (discrete jumps from one state to another) in the visual displays. In addition, the associated time delay begins to affect the dynamics of the closed-loop pilot-airframe system. As a result, the integrity of the simulation can be seriously degraded. Thus, the existing MCAIR model cycle time is unacceptable for real-time simulation.

Most of the research at Ames on advanced V/STOL control and display concepts for the Harrier has been supported by a simple, and fast, model of the AV-8A developed at the Naval Air Development Center.[6] This is a nonlinear function table model that was originally developed to simulate the takeoff and landing of V/STOL aircraft aboard ship. The model is based on wind-tunnel data, and, until recently, was the only model suitable for real-time simulation. This AV-8A model uses a simple first-order model to represent the dynamics of the propulsion system. Although the model has some deficiencies in aero-propulsion interaction, it has proven useful in the development of control and display systems for the

YAV-8B. The cycle time for the bare airframe AV-8A model is about 35 ms.

Systems Control Technology (SCT), under contract to the Naval Air Test Center and NASA, has recently developed a global-polynomial aerodynamic model for the AV-8B.[7-9] This model is based on flight-test data and system identification. The cycle time for the SCT aerodynamics routine alone is about 4 ms, as compared to the MCAIR function table aerodynamic routine of about 19 ms. The SCT longitudinal aerodynamic model incorporates a 37 term global-polynomial structure which includes conventional aerodynamics, jet-induced aerodynamics, and gross thrust effects.[9] The general purpose Harrier simulation math model at Ames now uses the original MCAIR YAV-8B model, but incorporates the SCT AV-8B aerodynamic routine in place of the MCAIR aerodynamic routine. This so called "New YAV-8B Model" runs in about 50 ms. The first part of our Phase I effort will be to update the AV-8B aerodynamic model based on YAV-8B flight data.

Math Model Formulation

A full-envelope aerodynamic model is a set of nonlinear functions of state and control variables which, when multiplied by the identified model parameters, represents aircraft force or moment coefficients. This set of functions is referred to as the model structure. A YAV-8B model structure must include both conventional and power-induced aerodynamic terms. Prior to a parameter identification run, the functions that make up the model structure are computed based on measured or estimated data. A complex structure that attempts to model every aspect of a physical system may be impractical to implement and/or difficult to understand intuitively. A simple structure however, may not adequately model some important aspect of the physical system. At NASA Ames we are considering using global and/or piecewise polynomials to model the YAV-8B aerodynamics.

A polynomial function of one or more state and control variables (independent variables) may be used to define a force or moment coefficient (dependent variable). The general polynomial model structure given by Eq. (1) is used to represent a force or moment coefficient at the ith data frame.

$$\sum_{j=1}^{N} a_j(z_i)x_j = b_i \tag{1}$$

where b_i is the coefficient value at the ith frame, z_i is a vector of state and control values at the ith frame, $a_j(z_i)$ is the jth polynomial function, and x_j is the jth parameter value.

Each function $a_j(z_i)$ may be any nonlinear combination of state and control variables; it may be valid over the entire envelope, or valid in only a portion of the envelope. For a full envelope model, the family of functions a_{ij} must be chosen so that the force and moment coefficients are valid over the entire entire operational envelope. For example, the untrimmed lift characteristic portion of the SCT AV-8B lift model is given by

$$C_L(\alpha,M) = x_1 + x_2\bar{\alpha} + x_3\bar{\alpha}^2 + x_4\bar{\alpha}^3 + x_5M^2 + x_6M^4 + x_7M^2\bar{\alpha} + x_8M^4\bar{\alpha} \tag{2}$$

where $\bar{\alpha}$ is the normalized alpha and M is the Mach number. Curves of lift as a function of α for M = 0.1, 0.5, and 0.9 are shown in Fig. 3. The parameters x1-x8, as identified by SCT from AV-8B flight-test data, are given in Table 1.

If a global polynomial does not adequately represent a dependent variable over the entire range of independent variables, then piecewise polynomials may be in order. Piecewise polynomials (sometimes called splines) are used to define a functional relationship using two or more polynomials connected together at their end points.[10] The range of independent variables is divided into regions separated by knots (selected values of the independent variable). A single polynomial of the form in Eq. (1) may be used to define the function between knots. End-point constraints are imposed at the knots to ensure a smooth transition from one polynomial to another. A global polynomial is simple to implement, but a piecewise polynomial may be required to model a complex nonlinearity. Each term in a global polynomial is active over the entire range of independent variables. This may be undesirable in a rapidly changing function. Piecewise polynomials may be more appropriate since they are made up of low-order components which are active over a specific range of the independent variables. Piecewise polynomials require extra coding to implement since the region of the independent variable must be determined before the function can be computed.

We are presently using the SCT AV-8B polynomial structure as a basis for identification of a YAV-8B aerodynamic model. The SCT longitudinal aerodynamic model structure and the AV-8B model parameters are shown in Table 1a.[7] The model terms in Table 1a are based on normalized values of the aircraft state and control variables. The nonlinear functions, XALF, etc. that make up the model structure will lie approximately within the interval of 0 to 1. Table 1b lists the normalizing equations. Each of the coefficients CL, CD, and Cm use a different subset of terms within this structure. Note that there are 18 active terms in the lift model, 16 in the drag model, and 27 in the pitching moment model. Active terms are those which have nonzero model parameters.

The first 8 terms in the model represent aerodynamic effects as a function of alpha and Mach only. Terms 9-12 represent flap effects. Terms 13-22 represent power-induced aerodynamic effects as a function of power setting, nozzle angle, flap deflection, and angle of attack. Terms 23-27 represent stabilator effects. Term 28 is the aileron droop term. When "V/STOL mode" is selected in the YAV-8B control system, the ailerons are deflected (drooped) 15° down. The V/STOL mode also deflects the flaps 25° and engages the flap-nozzle interconnect schedule.[11] Terms 28 and 29 are speed brake terms. The YAV-8B does not have a speed brake so these terms can be left out of the YAV-8B model. Terms 31 and 32 represent landing gear effects, terms 33 and 34 represent pitch rate effects, and terms 35-37 account for direct thrust effects.

Parameter Identification

We are using the equation-error parameter identification (PID) method for identification of a YAV-8B math model. The equation-error method is well-suited to a system identification effort where the model structure may be modified several times throughout the course of the study. With this approach, the aerodynamic force and moment models are naturally decoupled from one another and therefore may be identified independently. Terms within the model structure can be easily added, modified, or removed through simple modifications to the aerodynamic structure alone. The time channel is insignificant in equation-error PID since the method does not require solution of any differential equations of motion. This property represents an important advantage of the equation-error method, especially for full-envelope model identification. Selected time segments from unrelated flight-test maneuvers may be concatenated to make up a complete data set for PID processing. Flight-test procedure does not require a continuous time sequence covering the full range of interest. Frames of data where telemetry dropouts have occurred may be removed without causing numerical problems in the PID routine. The relatively straightforward numerical requirements of the equation-error approach allow the analyst to concentrate on the model rather than on the intricacies of the parameter identification procedure.

The input to the PID program is computed by evaluating Eq. (1) for every frame in the data set. The resulting set of equations can be written as

$$Ax = b \tag{3}$$

where the m-row by n-column model matrix A has as many rows as there are frames of data and as many columns as there are terms in the model structure. Each column in A may be any nonlinear function of the measured or estimated state and control variables. The dependent variable vector b is composed of the force or moment coefficient for each frame. The vector x represents the model parameters $\{x_j\}$.

The identification procedure is based on a model error formulation where the "equation error" is the difference between the left and right sides of Eq. (3), i.e.,

$$e = Ax - b \tag{4}$$

The performance measure is the sum of the equation error squared for each frame in the data set, and can be written as

$$J = e^T e \tag{5}$$

where the superscript T represents the transpose operation. Model parameters are computed such that J is a minimum. The solution to this simple least-squares problem is given by solving the set of linear simultaneous equations

$$(A^TA)x = A^Tb \tag{6}$$

The Optimal Subset Regression (OSR) program is one implementation of the equation-error method. The OSR program incorporates a systematic model structure determination procedure into the parameter identification process.[12,13] OSR uses a multistep procedure where candidate model terms are added and removed from the model based on their correlation with the dependent variable. One term is added or removed at each step in the procedure until the program converges. At each step in the process the set of x-simultaneous equations represented by Eq. (6) are solved directly for the model parameters $\{x_j\}$. The object of the model structure determination procedure is to obtain the best fit to the data with the fewest number of model terms.

Singular Value Decomposition (SVD) is another implementation of the equation-error approach. This method is closely related to the eigenvalue-eigenvector decomposition of the symmetric matrix A^TA of Eq. (6). In fact, each singular value is the square root of the corresponding eigenvalue of A^TA. The singular values are arranged in a descending order that reflects the degree of independent excitation of model terms. A singular value that is small compared to the largest singular value indicates a linear dependency between model terms.[14,15] A subroutine from the IMSL subroutine library[16] has been used to implement the SVD method. The OSR and SVD methods solve Eq. 6 in a different way. Unlike the SVD method, the OSR method computes A^TA directly, which may result in the loss of some numerical precision.

Flight Test Procedures

The NASA YAV-8B is equipped with a 10-bit digital data acquisition system. All data are telemetered (TM) to a ground station where it is recorded. The pulse code modulation (PCM) format is set up to transmit 156 mainframe channels and 160 subframes. Mainframe channels are sampled at 120 Hz, and subframes are sampled at 30 Hz. Third-order Butterworth anti-aliasing filters with cut-off frequencies set at one fifth of the sample rate are used on all analog signals.

Flight testing of the YAV-8B will be done at the NASA-Ames test facility at Crows Landing, California. A laser tracker provides range and elevation information that is merged and recorded along with the TM data. Figure 4 shows the Crows test facility with the laser tracker mounted on a mobile Nike radar system. The facility has five eight-channel strip chart recorders and three color monitors (for status information) for real-time display of the TM data. Figure 5 shows the flight-test control room. The runway and hover pad are visible from the control room at Crows Landing. Flight tests at Crows can be monitored from a control room at Ames through a real-time link that transmits TM data from Crows to Ames.

Flight testing of the YAV-8B will cover the operational envelope of the aircraft as completely as possible. The objective is to gather data which reflect independent excitation of all state and control variables. Flight-test maneuvers are to be large amplitude subject to operational limitations and pilot acceptance. Large amplitude maneuvers are appropriate when flight data is to be used for global model identification. If the objective is to use flight data to identify a linear perturbation model about some trim point, then one must be careful not to let the aircraft states exceed the linear bounds during flight test. However, if the objective is to identify a nonlinear model, as in this study, maneuvers should be in as large an amplitude as possible in order to cover the flight envelope. Flight data will be gathered at a series of Mach numbers covering the envelope from hover to 0.9 Mach. Flight-test control inputs include stick and rudder doublets and frequency sweeps, and pulses in nozzle and throttle.

Post Flight Data Processing

A flow chart of the flight data-processing scheme to be used for identification of a YAV-8B aerodynamic model is shown in Fig. 6. An interactive data processing package, developed in support of the YAV-8B system identification effort, may be used to display measured or estimated data at any point in the processing. The package, called DSPAUG, runs on the DEC VAX computer and makes extensive use of the DISSPLA plotting library.[17] Flight or simulated data files are converted to a common keyed access format for quick interactive access. Data channels may be interactively selected and plotted in either x-y or strip-chart format. Cross plots show data from one or more time segments within a data file and offer a convenient way to evaluate data coverage. A "Show Status" option identifies all data in the cross plotting arrays by file name and time segment.

During flight test, aircraft TM data from the onboard system are merged with range and elevation data from the laser tracker and recorded. A partial list of the variables measured on-board the YAV-8B is given in Table 2. The variables in Table 2 are sufficient for parameter identification. Time segments of data are selected from raw flight (or simulated) data sets for further processing. Wildpointing, flow angle calibration, and air data computations are done next. Reference 18 discusses flow-field effects, such as vane position error and angular rate errors, which need to be considered. Variables such as Mach number, true airspeed, and altitude must be computed based on measurements of total pressure, static pressure, and total temperature. Reference 19 gives the basic equations necessary for computing these variables from onboard measurements of pressure and temperature. In addition, the effects of power setting and thrust-vector angle must be considered when performing air data corrections and flow angle calibrations.

State estimation as a means of checking instrument accuracy and data consistency is now used by many flight-test groups. The field of state estimation follows from the pioneering work of Otto Gerlach in the 1960s at the Delft Technological University, the Netherlands. Gerlach's work[20,21] called "flight path reconstruction," was primarily concerned with accurate determination of angle of attack, pitch angle, and vehicle velocity during dynamic maneuvers. As Gerlach pointed out, the technique of state estimation provides both a check on instrument accuracy and data consistency, and estimates of unmeasured or poorly measured variables. The SMACK (Smoothing for Aircraft Kinematics) algorithm, a general purpose state estimation program developed at NASA Ames,[22] is used to obtain a consistent set of smoothed time-histories for parameter identification. SMACK uses a six-degree-of-freedom-kinematic model to fit all of the aircraft body rate, attitude, position, and air data measurements. In order to avoid erroneous parameter estimates, it is essential that good state time-histories are input to the PID program. This necessitates the use of a state estimation program such as SMACK. Once a consistent, smoothed data set is available, the analyst may concentrate on developing a proper aerodynamic model.

Aerodynamic forces and moments acting on the aircraft during flight test must be isolated before flight data can be used for parameter identification. A nominal propulsion model of the YAV-8B engine (Rolls Royce YF402-RR-404 Pegasus)[11] is used to separate engine and reaction-control system (RCS) forces and moments from total measured forces and moments. Fan dynamics need not be included in the model since fan speed is measured in flight. The total force acting on the aircraft is computed based on measurements of body axis accelerations and aircraft weight. Aircraft weight is computed based on measurements of the remaining fuel and water. The aerodynamic forces and moments are obtained by subtracting the engine contributions from the total measured forces and moments. It is important to note that only pure thrust contributions are subtracted from the total measured forces and moments. Aerodynamic forces and moments are composed of both conventional aerodynamics and power-induced aerodynamics which are a strong function of power setting and nozzle angle. Although the emphasis of this paper is on identification of an aerodynamic model, identification of an accurate Pegasus engine model should not be overlooked. Any identified aerodynamic model can be only as accurate as the engine model that is used to isolate the aerodynamic forces. As a follow-on study the YAV-8B engine model will be validated through flight test. It is expected that we will have a fully instrumented Pegasus engine later this year. This should aid greatly in verification of not only the engine model but the aerodynamic model as well.

The equation-error PID method allows segments of data, noncontinuous in time, to be concatenated for use in PID analysis. Time segments of data must be chosen so that the complete data set reflects independent variation of all variables in the model structure. Consider the lift formulation in Eq. (2). If a flight-data set had very little variation in Mach number, a PID program would have trouble identifiying the second, seventh, and eighth parameters in the model structure of Eq. (2). With no variation in Mach, all of these terms would behave like linear terms in alpha. The "concatenate" option in the data processing package creates a formatted "map" file that contains the file name and the time segment information necessary to create a concatenated data set. At the beginning of a parameter identification run a "read-map" subroutine is called which creates a concatenated data file based on file name and time segment information stored in the map file. Concatenated data files are created as scratch files for each PID run.

Simulator Evaluation

This section describes the use of a fixed-base real-time simulator to develop flight-test procedures and validate parameter identification software. The simulator is equipped with standard stick and rudder controls as well as throttle and nozzle control levers. The visual display provides a forward field of view and includes a basic Harrier heads-up display. The AV-8B aerodynamic model defined in Table 1 is used to drive the simulator. When a known model is used to create a simulated data set, a parameter identification scheme should reproduce the known model parameters provided that the simulated data set adequately covers the flight envelope. Flight-test maneuvers must produce enough variation in the aircraft states and control variables so that all the terms in the model structure are identifiable. Table 2 lists the variables that were recorded and used for aerodynamic parameter identification.

The simulator was used to create a data set representative of actual flight-test data. The primary flight-test objective was to exercise all the control inputs, using simple maneuvers, at as wide a range of Mach numbers as possible. Maneuvers include using stick pumping and doublets in pitch and roll, and doublets in yaw. Nozzle pulses and throttle pulses are also included. Data were recorded at fixed-flap settings of 5°, 15°, and 25°, and with the stability augmentation system off. Figure 7 shows a time-history of a typical set of pitch maneuvers that do not require precise control inputs. Note the frequency sweep sequence in the stabilator trace. Figure 8 shows cross plots of alpha vs Mach and stabilator vs alpha for the concatenated data set. The cross plot in Fig. 8a shows the boundaries of data coverage (about 0.3-0.7 Mach), and a void in the data set in the 0.55 Mach region. Fourteen time segments were selected from three different simulated data files. These segments were concatenated to make a total of 4 min and 20 sec of data in 4500 data points. The concatenated set was processed by a data windowing routine which removed all frames where alpha was out of the bounds from -5° to +25°. 160 frames were removed leaving 4340 frames for parameter identification. The data set was noise free.

The results of the SVD identification of the longitudinal model are given in Table 3. The model terms in Table 3 correspond to those in Table 1a. All of the identified model parameters are in close agreement with the SCT model parameters used to create the data. Similar results were obtained for the lateral model. The results suggest that relatively simple, imprecise flight test maneuvers such as those in Fig. 7 may be used for full envelope aerodynamic model identification using the SVD equation-error procedure.

Concluding Remarks

Based on work to date using real-time simulated flight data, the singular value decomposition implementation of the equation-error method is a promising candidate method for identification of a YAV-8B aerodynamic model. The results indicate that simple flight-test maneuvers provide adequate data coverage for full-envelope model identification. However, simulated data are noise-free and in that sense are not representative of actual flight-test data. The complete identification process must be tested using data contaminated by measurement noise. By adding noise to the simulated data set, data consistency checking and state estimation processes may be validated.

Adaptation of the YAV-8B propulsion system model for use in aerodynamic parameter identification is nearly complete. However, the validity of this model is also in question, and plans are being made to verify the propulsion system using flight test and system identification techniques.

As experience is gained in modeling AV-8 aerodynamics, a simpler aerodynamic model structure for the YAV-8B will be developed. A spline model for the YAV-8B is currently being investigated at Ames.

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Table 1a AV-8B Global Polynomial Model Longitudinal Aerodynamics and Identified Lift, Drag, and Pitching Moment Model Parameters

	Normalized model terms	Lift parameters, C_L	Drag parameters, C_D	Pitching moment parameters, C_m
1	1.0	0.0	0.03	0.010
2	X_{ALF}	1.465	-0.147	-0.315
3	$(X_{ALF})^2$	0.307	0.168	0.133
4	$(X_{ALF})^3$	-0.456	0.171	-0.197
5	$(X_{MACH})^2$	0.0	-0.116	0.0
6	$(X_{MACH})^4$	0.179	0.174	0.053
7	$(X_{MACH})^2 \cdot X_{ALF}$	-0.698	0.649	0.0
8	$(X_{MACH})^4 \cdot X_{ALF}$	0.638	-0.596	-0.169
9	X_{DF25}	0.328	0.036	-0.034
10	$X_{DF25} \cdot X_{ALF}$	-0.172	0.086	0.228
11	X_{DFMAX}	0.667	0.186	-0.032
12	$X_{DFMAX} \cdot X_{ALF}$	-0.305	0.158	0.276
13	$X_{PWR} \cdot (1-X_{TJ})$	0.112	0.0	-0.027
14	$X_{PWR} \cdot (1-X_{TJ}) \cdot X_{ALF}$	0.0	0.0	-0.282
15	$X_{PWR} \cdot (1-X_{TJ}) \cdot X_{DFO}$	-0.510	0.0	-0.092
16	$X_{PWR} \cdot (1-X_{TJ}) \cdot X_{DFO} \cdot X_{ALF}$	0.0	0.0	0.769
17	$X_{PWR} \cdot X_{TJ}$	0.0	0.0	0.173
18	$X_{PWR} \cdot X_{TJ} \cdot X_{ALF}$	-0.758	0.0	0.0
19	$X_{PWR} \cdot X_{TJ} \cdot X_{DFMAX}$	0.0	0.0	0.0
20	$X_{PWR} \cdot X_{TJ} \cdot X_{DFMAX} \cdot X_{ALF}$	0.0[a]	0.0[a]	0.0[a]
21	$X_{PWR} \cdot X_{TJ} \cdot X_{DFO}$	0.0[a]	0.0[a]	0.0[a]
22	$X_{PWR} \cdot X_{TJ} \cdot X_{DFO} \cdot X_{ALF}$	0.0[a]	0.0[a]	0.0[a]
23	X_{DH}	0.0934	0.0	-0.075
24	$X_{DH} \cdot X_{DFO}$	0.0	0.0	-0.040
25	$X_{DH} \cdot X_{ALF}$	0.0[a]	0.032	0.0[a]
26	$X_{DH} \cdot X_{PWR} \cdot (1-X_{TJ})$	0.0	0.0	-0.420
27	$X_{DH} \cdot X_{PWR} \cdot X_{TJ}$	0.0	0.0	-0.210
28	X_{DROOP}	0.111	0.0	-0.097
29	X_{SB}	0.021	0.024	0.0094
30	$X_{SB} \cdot X_{ALF}$	0.0[a]	0.0[a]	0.0[a]
31	X_{GEAR}	0.022	0.043	-0.0047
32	$X_{GEAR} \cdot X_{ALF}$	0.0	-0.018	0.0165
33	X_Q	0.0	0.0	-8.0
34	$X_Q \cdot X_{DFO}$	0.0	0.0	-5.0
35	$(1-X_{TJ}) \cdot F_G/\bar{q}_1 S$	0.0	0.0[b]	0.026
36	$X_{TJ} \cdot F_G/\bar{q}_1 S$	0.0[b]	0.0	0.0
37	$(1-X_{PWR}) \cdot X_{TJ} \cdot F_G/\bar{q}S$	-0.274	0.0	0.081

Note: $S = 230$ ft^2, reference wing area
$\bar{q}_1 = \bar{q}$ for $\bar{q} \geq 0.01$ PSF
$= 0.01$ for $\bar{q} < 0.01$ PSF

[a]These parameters were not identified because of insufficient test data. Other zero value parameters were identified to be at or close to zero.

[b]These parameters are set to zero because they have the same effect as gross thrust correction factors, which are implemented elsewhere in the simulation.

Table 1b Definition of Normalized Model Terms for AV-8B
Longitudinal Aerodynamic Model

Normalized model terms	Definition	Notes
X_{ALF}	$\alpha/20°$	Corrections to alpha: $\alpha = \alpha$ for $V_J \geq 0.1$ $= \theta + (\alpha - \theta)\cdot K$ for $0.05 \leq V_J \leq 0.1$ $= \theta$ for $V_J < 0.05$ $K = (V_J - 0.05)/0.05$ $V_J = (13\cdot\bar{q}/F_G)^{1/2}$ V_J is the jet velocity ratio $\bar{q}$ = free stream dynamic pressure
X_{MACH}	MACH	
X_{DFO}	$(25°\text{-DF})/25°$	Computed only when DF < 25° DF = (DFL + DFR)/2
X_{DFMAX}	$(\text{DF-}25°)/36.7°$	Computed only when DF ≥ 25°
X_{DF25}	$1 - X_{DFO}$ $1 - X_{DFMAX}$	For DF < 25° For DF ≥ 25°
X_{PWR}	$0.2/(V_J + 0.2)$	
X_{TJ}	$\text{SIN}(\theta_J + 1.5°)$	
X_{DH}	$(\text{DH-}2°)/10°$	
X_{DROOP}	DA/15°	Active only when ailerons are drooped. DA = (DAL + DAR)/2
X_{SB}		No speed brake on YAV-8B
X_{GEAR}	0/1	Landing gear flag up/down
X_Q	$Q\cdot\bar{C}/2V_1$	$\bar{C}$ = 8.316 ft, reference mean aerodynamic cord $V_1 = V$ for $V \geq 1.0$ ft/s $= 1.0$ for $V < 1.0$ ft/s $V \equiv$ true airspeed

Table 2 Measurement Set for Parameter Identification

Channel name	Channel description	Units
ALPHA	angle of attack	deg
BETA	angle of sideslip	deg
PHI	roll angle	deg
THETA	pitch angle	deg
PSI	heading angle	deg
P	body roll rate	rad/s
Q	body pitch rate	rad/s
R	body yaw rate	rad/s
AX	}	
AY	} body axis accelerations	ft/s/s
AZ	}	
DH	stabilator position	deg
DAL	left aileron position	deg
DAR	right aileron position	deg
DR	rudder position	deg
DFL	left flap position	deg
DFR	right flap position	deg
THETAJ	nozzle angle	deg
PAMB	ambient pressure	psf
PTOT	total pressure	psf
TTOT	total temperature	degc
RN1	fan rpm	rpm
WFUEL	fuel quantity	lbs
FUELFLO	fuel flow	lbs/hr
WWAT	water quantity	lbs
PPH	compressor discharge pressure	psi
AFPJ	forward pitch	
ARPJ	rear pitch	
ALURJ	left up-blowing	
ALDRJ	left down-blowing RCS valve	sqin
ARURJ	right up-blowing areas	
ARDRJ	right down-blowing	
AYAWJ	yaw	

Table 3 SVD Identification of Longitudinal Model Coefficients Based on Real-Time Simulated Data

	Lift		Drag		Pitching moment	
Model term	Model	Estimate	Model	Estimate	Model	Estimate
1	-	-	0.030	0.030	0.010	0.010
2	1.465	1.463	-0.147	-0.148	-0.315	-0.316
3	0.307	0.308	0.168	0.168	0.133	0.133
4	-0.456	-0.457	0.171	0.170	-0.197	-0.197
5	-	-	-0.116	-0.116	-	-
6	0.179	0.181	0.174	0.174	0.053	0.053
7	-0.698	-0.685	0.649	0.652	-	-
8	0.638	0.616	-0.596	-0.598	-0.169	-0.167
9	0.328	0.328	0.036	0.036	-0.034	-0.034
10	-0.172	-0.172	0.086	0.087	0.228	0.228
13	0.112	0.116	-	-	-0.027	-0.027
14	-	-	-	-	-0.282	-0.281
15	-0.510	-0.530	-	-	-0.092	-0.091
16	-	-	-	-	0.769	0.765
17	-	-	-	-	0.173	0.138
18	-0.758	-0.751	-	-	-	-
23	0.0934	0.0934	-	-	-0.075	-0.075
24	-	-	-	-	-0.040	-0.040
25	-	-	0.032	0.032	-	-
26	-	-	-	-	-0.420	-0.417
27	-	-	-	-	-0.210	-0.255
28	0.111	0.112	-	-	-0.097	-0.097
33	-	-	-	-	-8.0	-8.0
34	-	-	-	-	-5.0	-5.0
35	-	-	-	-	0.026	0.024
37	-0.274	-0.285	-	-	0.081	0.16

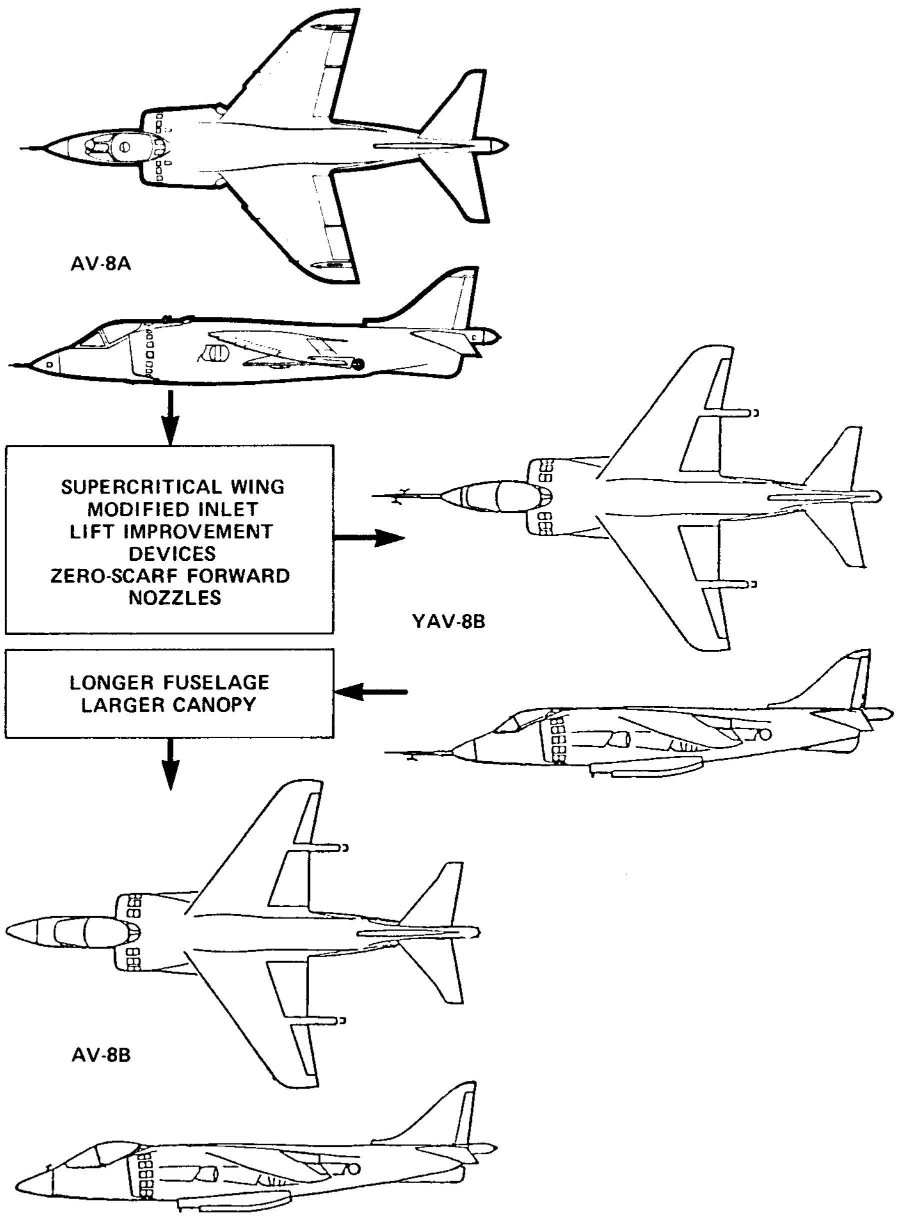

Fig. 1 Comparison of AV-8A, YAV-8B, and AV-8B.

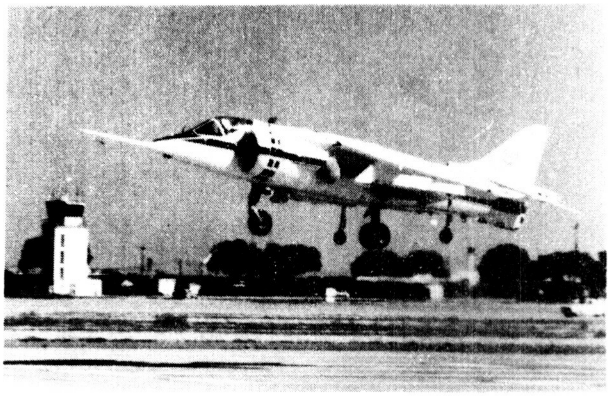

Fig. 2 NASA YAV-8B performing a short takeoff at the Ames Flight Test Facility, Crows Landing, California.

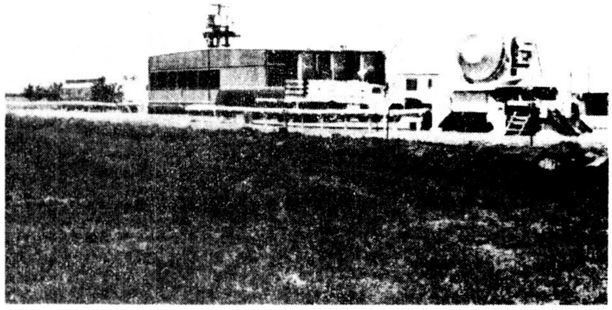

Fig. 4 Crows Landing, CA Flight Test Facility showing nike radar and laser tracker.

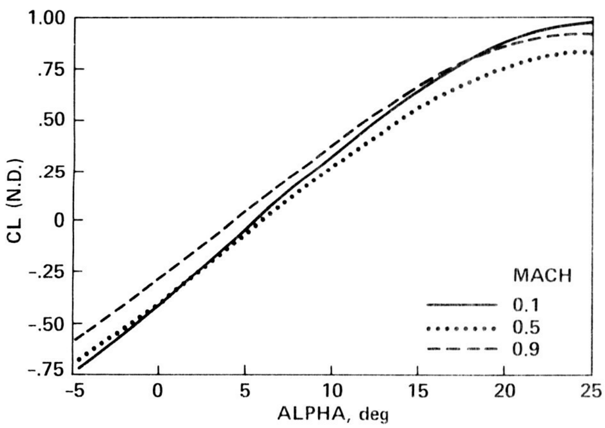

Fig. 3 Untrimmed lift coefficient vs alpha. AV-8B longitudinal model.

Fig. 5 Flight test control room at Crows Landing.

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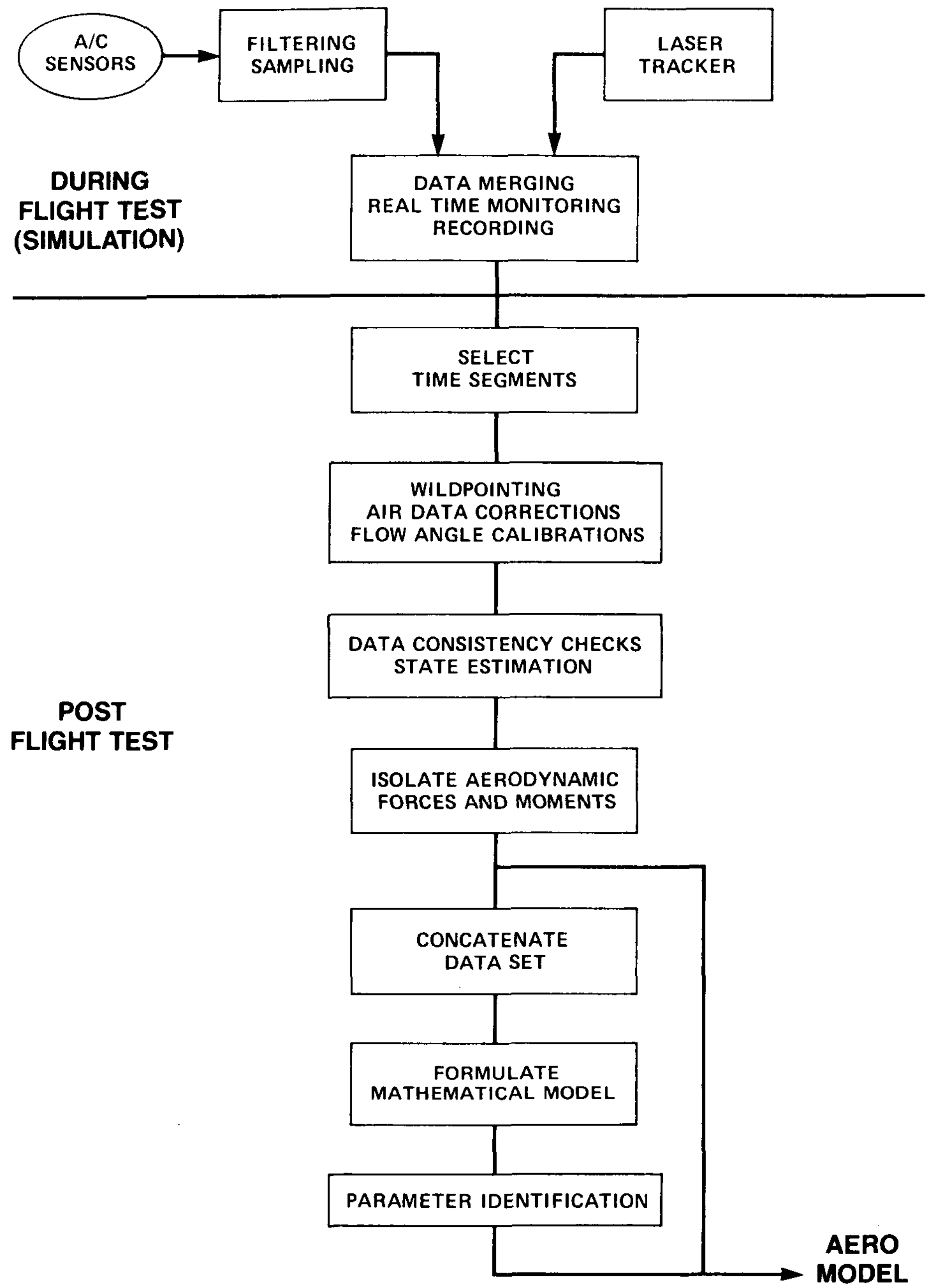


Fig. 6 Data processing scheme for YAV-8B aerodynamic model identification.

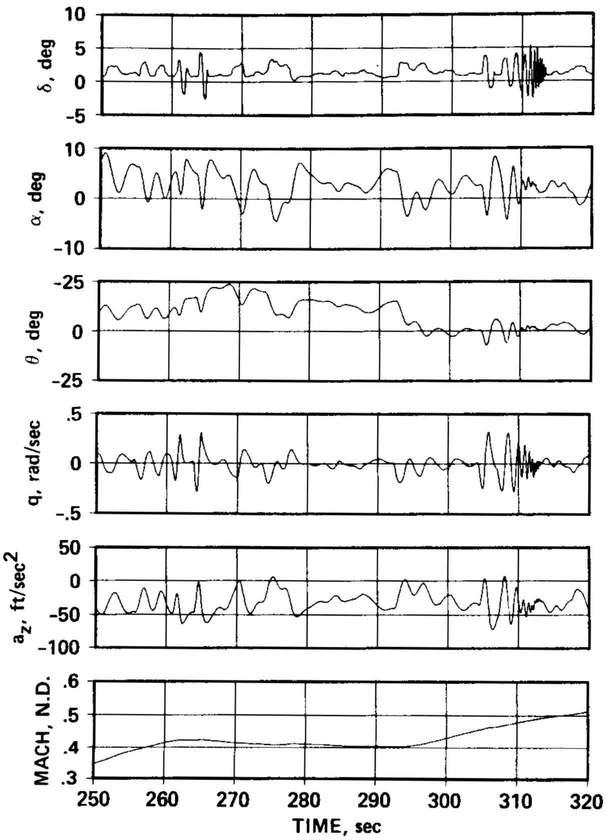
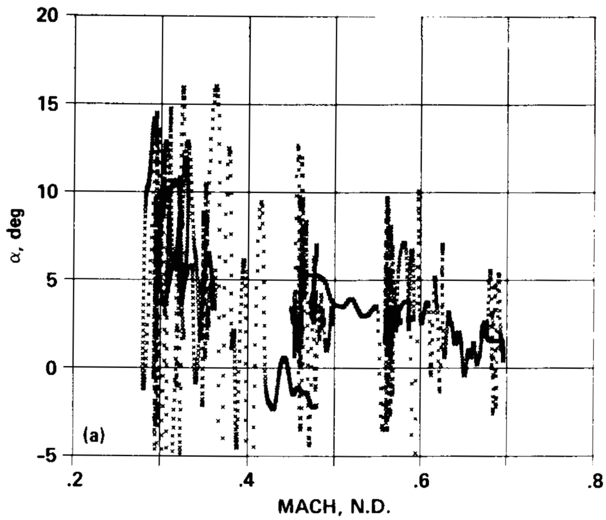
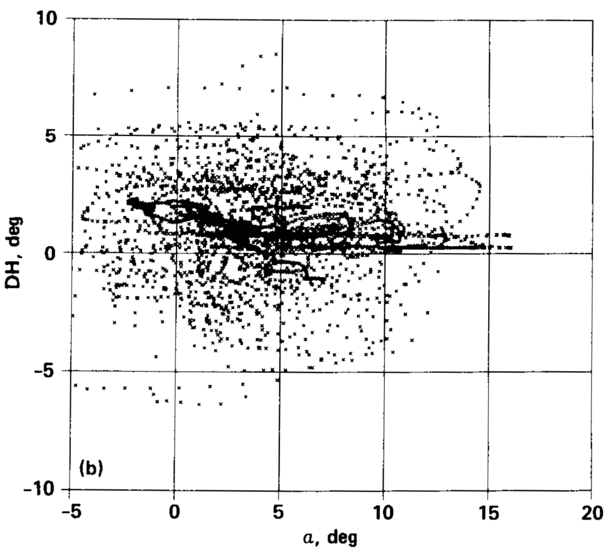


Fig. 7 Typical flight maneuvers developed on simulator.



a) α vs Mach.



b) DH vs α.

Fig. 8 Cross plots showing composite of 14 concatenated simulated data segments.

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Point of Contact: B. David McNally, Ames Research Center, M/S 210-9
Moffett Field, CA 94035 (415) 694-5440 or FTS 464-5440

16. Abstract

The status of an ongoing project to identify a full-envelope model of the YAV-8B Harrier using flight-test and parameter identification techniques is described. As part of the research in advanced control and display concepts for V/STOL aircraft, a full-envelope aerodynamic model of the YAV-8B will be identified. Mathematical model structures and parameter identification methods that are being developed for identification of a YAV-8B aerodynamic model are presented. A global-polynomial model structure is being used as a basis for identification of the YAV-8B aerodynamic model. State estimation methods are used to ensure flight data consistency prior to parameter identification. Equation-error methods are being used to identify model parameters. A fixed-based simulator has been used extensively to develop flight test procedures and to validate parameter identification software.

Using simple flight maneuvers, a simulated data set was created covering the YAV-8B flight envelope from about 0.3 to 0.7 Mach and about -5° to 15° angle of attack. A singular value decomposition implementation of the equation-error approach produced good parameter estimates based on this simulated data set.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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