N-08
64543

NASA Technical Memorandum 110228

Design of a Mixer for the Thrust-Vectoring System on the High-Alpha Research Vehicle

W. Thomas Bundick
Langley Research Center
Hampton, Virginia

Joseph W. Pahle
Dryden Flight Research Center
Edwards, California

Jessie C. Yeager and Fred L. Beissner, Jr.
Lockheed Engineering & Sciences Company
Hampton, Virginia

June 1996

National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23681-0001

Summary

As part of NASA's High Alpha Technology Program, advanced control technology concepts for enhancing the performance of supermaneuverable aircraft are being evaluated through flight testing on the High-Alpha Research Vehicle (HARV). One of the concepts being investigated on the HARV, a highly modified pre-production F/A-18, is multi-axis thrust vectoring using an experimental thrust-vectoring (TV) vane system.

One technique for interfacing the flight control laws with the thrust-vectoring vanes is the use of a Mixer to translate the pitch, roll, and yaw- TV commands into appropriate vane commands for distribution to the actuators. A computer-aided optimization process was developed to perform the inversion of the thrust-vectoring effectiveness data used by the Mixer to perform this command translation. This process was then utilized to design a new Mixer for the HARV.

An important element of the Mixer is the priority logic, which determines priority among the pitch-, roll-, and yaw-TV commands when the TV system is not capable of satisfying those commands simultaneously. The new HARV Mixer normally assigns first priority to pitch, and the effects of this logic on airplane performance are discussed.

Performance of the new Mixer design has been evaluated via a specialized Mixer test program (simulation of the HARV engine-TV vanes-Mixer combination), by batch and piloted simulations of the HARV, and in flight tests. Although the new Mixer does require more flight computer memory, the new design is an improvement over the previous HARV Mixer in terms of a command priority system and the accuracy with which it achieves the commanded thrust vectoring moments.

Introduction

Background

Future supermaneuverable fighters will need to employ rapid nose-pointing maneuvers to be successful in air combat. These maneuvers, compared with those of current fighters, will require the aircraft to operate throughout significantly expanded angle-of-attack and sideslip ranges and to have unprecedented maneuvering capabilities, particularly at low speed and high angles of attack. However, the effectiveness of conventional aerodynamic control effectors is often inadequate to meet these requirements under the conditions of high angle of attack and low dynamic pressure. One technique that can potentially provide the desired control moments is multi-axis thrust vectoring.

Thrust-vectoring technology and its benefits for supermaneuverable aircraft is a key part of several current research programs including the Defense Advanced Research Project Agency X-31 (ref. 1), the U.S. Air Force short takeoff and landing (STOL) and maneuver technology demonstrator (ref. 2), the NASA High-Angle-of-Attack Technology Program (HATP), and more recently the F-16 Multi-Axis Thrust Vectoring (MATV) program. As part of the HATP, advanced technology concepts for enhancing the performance of supermaneuverable aircraft, such as advanced control effectors and advanced control laws, are being evaluated via flight testing on the High-Alpha Research Vehicle (HARV), a highly modified pre-production F/A-18 (refs. 3 and 4) extensively instrumented for high angle of attack. One of the concepts being investigated on the HARV is multi-axis thrust vectoring (ref. 5).

The F/A-18 propulsion system is comprised of two General Electric F-404 turbofan engines with afterburners. To implement thrust vectoring (TV) on the HARV within a modest budget, a TV-vane system consisting of three hydraulically actuated vanes, or paddles, per engine (figs. 1 and 2) was developed by McDonnell Aircraft Company (McAir). The divergent nozzles of the engines were removed, and the TV vanes and actuators were mounted directly on the aircraft structure. These vanes are deflected into the engine exhaust plume to vector the thrust and thus produce the desired pitching and yawing moments. The size, shape, and spacing of the vanes were designed after considerable study by McAir to meet the moment requirements within aircraft structural constraints.

A key element of any future supermaneuverable aircraft will be the Flight Control System (FCS). Since relaxed static stability is expected to be a characteristic of these aircraft, the FCS will be essential to provide stability augmentation, improve flying qualities, and enhance performance. With conventional aerodynamic control effectors in current aircraft it is typical that the FCS generate commands which are sent directly to the effector servo actuators. For an aircraft with multiple redundant effectors, Lallman (refs. 6 and 7) has developed a technique called relative control effectiveness, or pseudo controls, which can be used to design an interface, or distributor, between the FCS and the effectors. Using this technique the number of channels in the FCS can be reduced, typically to three - pitch, roll, and yaw. The distributor, a block of software code in the flight computer, then uses relative control effectiveness to develop a control mixing strategy, that is, to distribute the command signals from the FCS to the most effective control effectors in a near optimal proportion. As will be discussed subsequently, a variation of Lallman's relative control effectiveness technique has been used on the HARV to distribute the pitch and yaw commands from the FCS to the six TV vanes, although his procedure was not used explicitly in the design.

The Mixer

The HARV Flight Control System converts pitch, roll, and yaw moments commanded from the control laws into vane deflections through a distributor function known as the "Mixer". Although it is possible to command the six TV vanes individually from within the control laws (similar to aerodynamic surfaces), a mixer function was designed to accomplish the complex task of computing the proper thrust vane deflections required to achieve the desired moments. This was done to:

- separate the TV and engine functions into a generic module that could be used in future control law designs.
- reduce control law design effort and the associated verification testing.
- allow minor modifications and updates to the TV effectiveness (for example, from flight test) without modification to the inner-loop control laws.

The original HARV TV-command distributor, called a mixer/predictor (MPre), was designed by McAir. The structure and complexity of the original design made it difficult to modify. Additionally, this Mixer did not provide roll vectoring, nor did it include the capability to prioritize pitch and yaw vectoring when the combination of these commands were not simultaneously achievable. These factors motivated the development of a new Mixer for the HARV.

A computer-aided procedure for designing a thrust vectoring Mixer interface between the control laws and the TV-vane system has been developed. An integral part of this procedure is the use of an optimization scheme to process, or "invert", the thrust vectoring effectiveness data. This report will discuss the requirements and design procedure for the Mixer. Results from several designs will be used to illustrate the resulting TV effectiveness. Included are results from flight tests of the Mixer design flown on the HARV.

Symbols

	Scalars are in italics; vectors and matrices are in boldfaced italics.
$A8$	convergent nozzle area, in ^{2}
$F(\boldsymbol{x})$	objective function in optimization problem
F_U	unvectored thrust, lbs
F_x	force (thrust) along x-axis, lbs
F_y	force (thrust) along y-axis, lbs
F_z	force (thrust) along z-axis, lbs
$g_i(\boldsymbol{x})$	function defining i-th equality constraint in optimization problem
h	altitude, ft
$h_j(\boldsymbol{x})$	function defining j-th inequality constraint in optimization problem
$Mach$	Mach number
NPR	nozzle pressure ratio
PLA	power lever angle, deg or percent
$P56$	turbine discharge pressure, lbs/in^2
R^n	set of n-dimensional real vectors
$R8$	convergent nozzle radius, in
T_L	thrust loss factor
$\boldsymbol{x}$	n-dimensional real vector
$\delta_A, \delta_B, \delta_C$	deflection angle of vane A, B, C, respectively, deg
$\delta_{A_{nom}}, \delta_{B_{nom}}, \delta_{C_{nom}}$	nominal deflection angle of vane A, B, C, respectively, deg
δ_p	effective pitch thrust-vectoring angle, deg (positive nose down)

δ_{p_c}	commanded pitch thrust-vectoring angle from FCS, deg (positive nose down)
δ_y	effective yaw thrust-vectoring angle, deg (positive nose left)
δ_{y_c}	commanded yaw thrust-vectoring angle from FCS, deg (positive nose left)
θ	polar coordinate measured clockwise from the negative z-axis of the thrust vector projected on the yz-plane, deg
δ_{M_c}	thrust-vectoring magnitude measured as the angle between the z-axis and the thrust vector, deg

Abbreviations:

DB	deadband
FCS	Flight Control System
HARV	High Alpha Research Vehicle
Max A/B	maximum afterburner throttle setting
McAir	McDonnell Aircraft Company
Mil Pwr	military power throttle setting
MixPre, MPre	Mixer designed by McDonnell Aircraft Company and flight tested with the NASA-0 control law
M4, M/P	variable grid with internal deadband compensation
NASA-0	control law designed by McDonnell Aircraft Company and Dryden Flight Research Center and flight tested on the HARV
NASA-1A	control law designed by Langley Research Center and Dryden Flight Research Center and flight tested on the HARV
RMS	root-mean-square
TLU	table look-up
TV	thrust vectoring
TVS	Thrust Vectoring System
1x1DB	one-degree-by-one-degree grid with external deadband compensation
1x1NDB	one-degree-by-one-degree grid with no deadband compensation
2x2DB	two-degree-by-two-degree grid with external deadband compensation
2x2NDB	two-degree-by-two-degree grid with no deadband compensation

Design Requirements

Functional Requirements

The primary functional requirement for the Mixer is to translate the pitch-, yaw-, and roll-TV-moment commands from the control laws into vane actuator commands throughout the HARV flight envelope. This command translation and distribution should be done in an optimal or near-optimal manner; that is, the commanded moments should be achieved with as little error as practicable within the capabilities and constraints of the thrust-vectoring system (TVS) and the aircraft. In order to minimize surface deflection and reduce vane heating, the Mixer should also place the vanes at the minimum deflection required to generate the commanded moments.

Since the moment achieved from TV is a function of the thrust level as well as the TV angle, the FCS calculates the pitch-, yaw-, and roll-TV-moment commands in terms of degrees of vectored-thrust deflection on the basis of a reference thrust. The Mixer must then adjust the TV-angle commands to produce the desired control moments based on an estimate of the current gross-thrust level, which is provided to the Mixer as an input. The TV commands should be further adjusted to account for losses in thrust due to thrust vectoring and limited as a function of flight condition to avoid excessive structural loads. These adjusted TV commands must then be translated into suitably scaled vane-deflection commands for distribution after rate and position limiting to prevent overdriving the actuators.

Thrust-Vectoring Systems designed for different engines and specific aircraft will not all have the same thrust-vectoring capabilities; that is, a map of the achievable TV angles in the pitch-vectoring/yaw-vectoring plane will vary for different TVS designs. For any aircraft it is likely that there will be instances when the FCS will command TV angles that are outside of the achievable range. In such instances the Mixer must resolve the conflict by mapping the desired pitch-yaw-vectoring angles into achievable TV angles by assigning priority to pitch, yaw, roll, or some combination of the three. The philosophy behind this mapping will depend on the aircraft departure characteristics, control power available from the aerodynamic effectors, design criteria, and flight safety considerations. For the HARV the mapping philosophy is, in general, to assign first priority to pitch vectoring over yaw and roll and secondary priority to yaw vectoring over roll. As will be seen there are regions in pitch-vectoring/yaw-vectoring space where these priorities were modified. It will also be seen from HARV simulation and flight results that these priorities can have important effects on aircraft performance.

The HARV TVS vectors thrust by deflecting into the plume only two of the three vanes on each engine. Proper positioning of the third, or inactive, vane is a function of the Mixer. Proper inactive vane positioning is desired to minimize vane heating, minimize thrust losses, and reduce excessive vane travel. To reduce heating and thrust losses, inactive vane placement should be away from the plume. To reduce the distance a vane travels when it switches from being the inactive vane to becoming the active vane and vice versa (vane switching), the inactive vane should be placed close to the plume. (This vane switching is most problematic when small changes in TV angles near zero TV are being commanded.) A compromise that satisfies these conflicting requirements is to position

Figure 1.- Photo of HARV Thurst-Vectoring System.

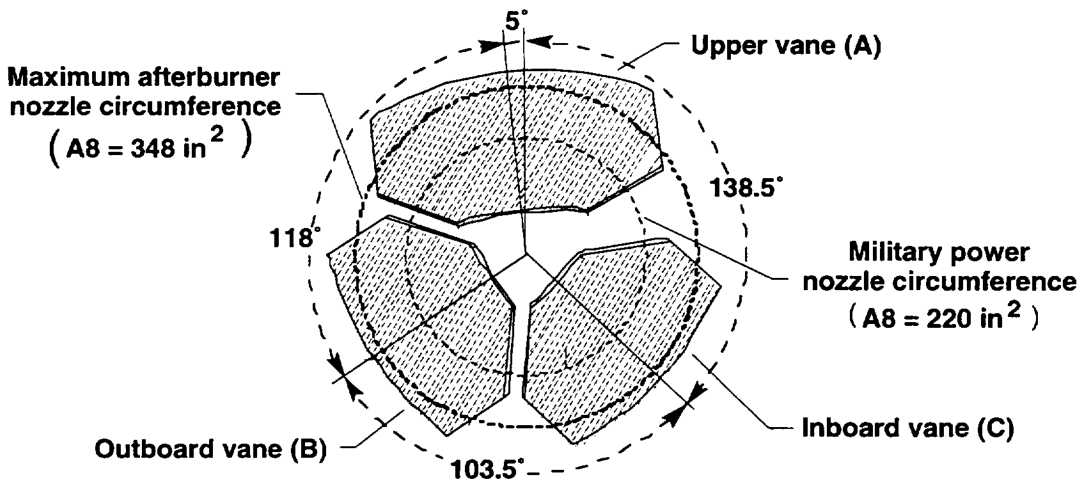


Figure 2. - HARV left engine nozzle and vane geometry

the inactive vane at a "ready" position immediately adjacent to the plume. The vane deflection at this "ready" position at the edge of the plume is referred to as the vane deadband (DB) position.

Implementation Requirements

The Mixer is an integral part of the inner-loop control laws. Therefore, the memory requirements and execution time must be minimized so that the Mixer, the control laws, and any other necessary software will not exceed the memory and throughput capacity of the flight hardware. This requirement has been one of the major factors in the design of the Mixer data tables and the table look-up method.

TV-Effectiveness Data

HARV Thrust-Vectoring System

As noted previously, the HARV TVS consists of two sets of three TV vanes mounted on the aft end of the HARV to deflect the engine exhaust plumes. A photograph of the vanes and associated actuator mechanism is shown in figure 1. Note that the TVS design is strictly an experimental design and does not represent a production prototype.

The geometry of the vanes for the left engine is shown in figure 2. The placement of the vanes is determined, at least in part, by the location of the supporting structure and the vane clearance requirements. The top vane (vane A) is larger than the outboard and inboard vanes (vanes B and C, respectively) to balance the available pitch-up and pitch-down TV moments. The vanes, whose exhaust sides are biconcave, have surface areas of 359.7 in^2 for the top vanes and 262.8 in^2 for the others. The TVS for the right engine is a mirror image of that for the left engine.

The vanes can be deflected from -10 ° (stowed position) to 25° (fig. 3). The TV-vane actuators are F/A-18 aileron actuators with enlarged damper orifices to reduce the hydraulics-off retract time.

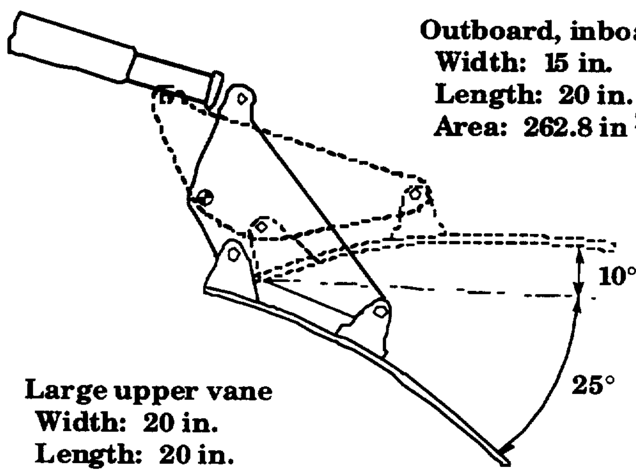


Figure 3. - HARV vane deflection

Test Setup for Cold-Jet Data

Data used in the Mixer design to relate the thrust-vectoring effectiveness to the TV-vane positions was obtained in the static test, or Cold Jet, facility of the Langley 16-Foot Transonic Tunnel (ref. 8). High pressure cold air was exhausted into a propulsion simulation system which included a 14.25-percent-scale model of the F/A-18 convergent-divergent nozzle. Just as on the HARV the divergent section of the nozzle was removed and a scale model of the HARV three-vane TV system for the left engine was mounted in its place. The model vanes accurately represented the HARV vanes in terms of size, shape, curvature, and location, but they were deflected into the exhaust plume manually rather than hydraulically. No effort was made to model the vane mounting and deflection mechanism since these were static tests with no air flow external to the simulated engine. Two nozzle configurations were tested: one represented a maximum afterburner-power condition (Max A/B) of the engine and the other represented a military-power (Mil Pwr) condition.

Forces and moments on the model were measured with a strain-gauge balance to determine the amount of thrust vectoring. Pressure measurements were made to determine the nozzle-pressure ratio.

Test Conditions

Tests were conducted to obtain the cold-jet data as a function of vane deflection (δ_A, δ_B, δ_C), engine nozzle-pressure ratio (*NPR*), and convergent nozzle area (*A8*). To obtain a complete set of data, tests were performed at the following data points: all combinations of two vanes deflected at 5° increments between -10° and 30°, inclusive, with intermediate points at 17.5° and 22.5° while the third vane was stowed at -10°. These matrices of data were desired at *NPR*'s of 2, 3, 4, 5, and 6 and at values (full scale) of *A8* of 220 in^2 corresponding to Mil Pwr and 348 in^2 corresponding to Max A/B. These combinations of

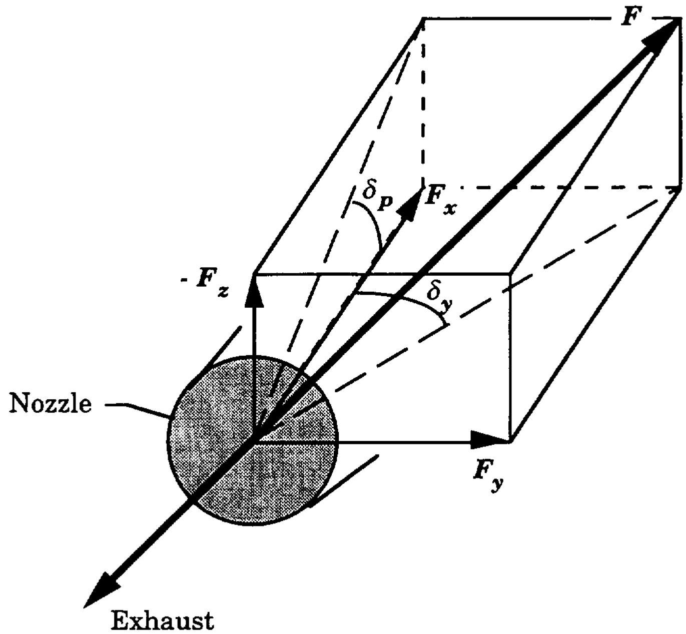


Figure 4.- Thrust-vectoring angles for left engine.

conditions would have required that tests be performed at a total of 3630 points, clearly a formidable task. As a compromise, data was taken at 790 test conditions at Max A/B and at 268 test conditions at Mil Pwr. A numerical relaxation method was used to compute values for the missing data points (ref. 9).

From the basic force measurements the effective pitch-TV angle δ_p and yaw-TV angle δ_y were computed for each data point using the following expressions:

$$\delta_p = tan^{-1}\left(\frac{-F_z}{F_x}\right) \tag{1}$$

$$\delta_y = tan^{-1}\left(\frac{F_y}{F_x}\right) \tag{2}$$

where F_x = force along x-axis
F_y = force along y-axis
F_z = force along z-axis.

The axes are defined in figure 4. The sign convention used on the left engine is positive δ_p for nose down and positive δ_y for nose left. The values for δ_p and δ_y were the basic thrust-vectoring data used in the Mixer design.

The cold-jet data, including the estimates calculated using the relaxation method, were stored in pairs of square arrays of dimension 11×11, one array of δ_p values and one of δ_y values. The eleven rows and columns corresponded to the eleven values of deflection angles for Vane A and Vane B (δ_A and δ_B), respectively, with Vane C (δ_C)

stowed. Ten such array pairs contained the data for the five values of *NPR* and the two values of *A8*. There were ten similar arrays for Vane B stowed and ten for Vane A stowed.

The other primary TV data are values for the thrust loss T_L calculated from the basic force measurements according to the following:

$$T_L = \frac{F_x}{F_U} \tag{3}$$

where F_U = undeflected thrust, or force along x-axis when $\delta_A = \delta_B = \delta_C = -10$ (no thrust vectoring). The thrust-loss data are stored in arrays in the same format as the TV-vane-effectiveness data.

Problem Statement

The problem then is to design a Mixer based on the TV effectiveness and thrust loss data which meets the functional requirements previously described, is implementable on the HARV, and is relatively easy to modify. The remainder of this report describes the techniques used to accomplish such a design, the details of the resulting design, and some data demonstrating the performance of the resulting Mixer.

Design Process

The Mixer design process is illustrated in figure 5. First the desired performance of the Mixer and the constraints upon the design are determined. The primary design requirement was to achieve the commanded TV moments with as small an error as practicable. The desired performance includes pitch/yaw/roll priority and structural limit considerations. The deflection limits of the vanes and flight computer memory capacity are constraints which also had to be incorporated into the design.

The second step is to invert the cold-jet TV-effectiveness data into a form that can be efficiently used by the Mixer while allowing the desired performance to be achieved. Inversion is necessary because the basic cold-jet data is formulated with vane deflections as the independent variables and the effective pitch- and yaw-TV angles as the dependent variables. Since the control laws command TV pitch and yaw angles, the Mixer requires that these be the independent variables and the vane deflections be the dependent variables. As will be discussed later the inversion process can involve more than just the execution of a data inversion computer program. Considerable additional processing may be required to assure that the arrays of inverted data are filled, that all entries meet the required performance, and that transversing between data points does not produce excessive vane chatter or jumps. A significant portion of this step was to design software to accomplish the requirements with as little manual processing as practical.

The third step is to design the Mixer algorithms and logic that will implement the functional requirements and meet the desired performance. A major element of this logic was the implementation of the priority philosophy. The second and third steps of the process will be discussed in considerable detail in subsequent sections.

The last step in the design process is to compare the design results against the desired performance and detect any constraint violations. If the performance is not satisfactory,

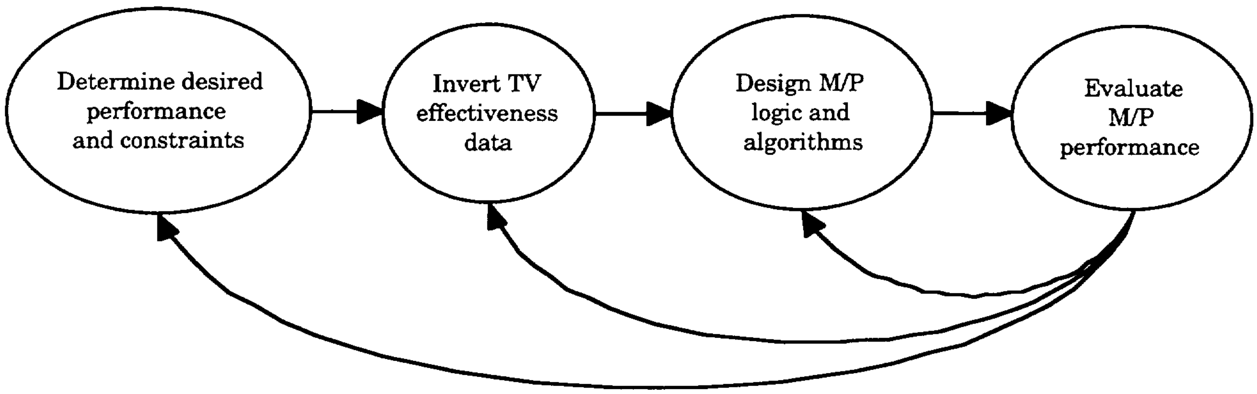


Figure 5.- Mixer design process.

one or all of the previous steps may have to be repeated. It should be recognized that the process requires compromises or tradeoffs. For example, one of the factors affecting the accuracy of the achieved TV moments is the density of the inverted TV-effectiveness data. Thus, tradeoffs must be made between the accuracy of the design results and the size of the flight computer memory required to store the data. Furthermore, the last step in the design process takes place during the evaluation of the entire control law (including the Mixer) using aircraft simulations. Such simulations may reveal performance inadequacies that change the functional requirements and desired performance of the Mixer, which would necessitate repeating the steps of the Mixer design process.

Data Inversion

The overall problem of obtaining a set of inverted-TV-effectiveness data required considerable data processing as previously mentioned. Figure 6 illustrates the automatic and manual processing required to produce the final arrays of inverted data used by the Mixer.

The heart of the inversion process, the actual data inversion, was accomplished by casting the problem as an optimization problem with nonlinear inequality constraints. Mathematically, the problem was to find the minimum of the objective function $F(\boldsymbol{x})$, where $\boldsymbol{x}$ is an n-dimensional Real vector, $\boldsymbol{x} \in \{R^n\}$, subject to the m equality constraints

$$g_i(\boldsymbol{x}) = 0 \qquad i = 1, 2, ..., m \tag{4}$$

and the l inequality constraints

$$h_j(\boldsymbol{x}) \geq 0 \qquad j = 1, 2, ..., l. \tag{5}$$

The current problem is three dimensional (n = 3), and the variables (components of $\boldsymbol{x}$) are the vane positions δ_A , δ_B and δ_C . The objective function $F(\boldsymbol{x})$ was chosen to

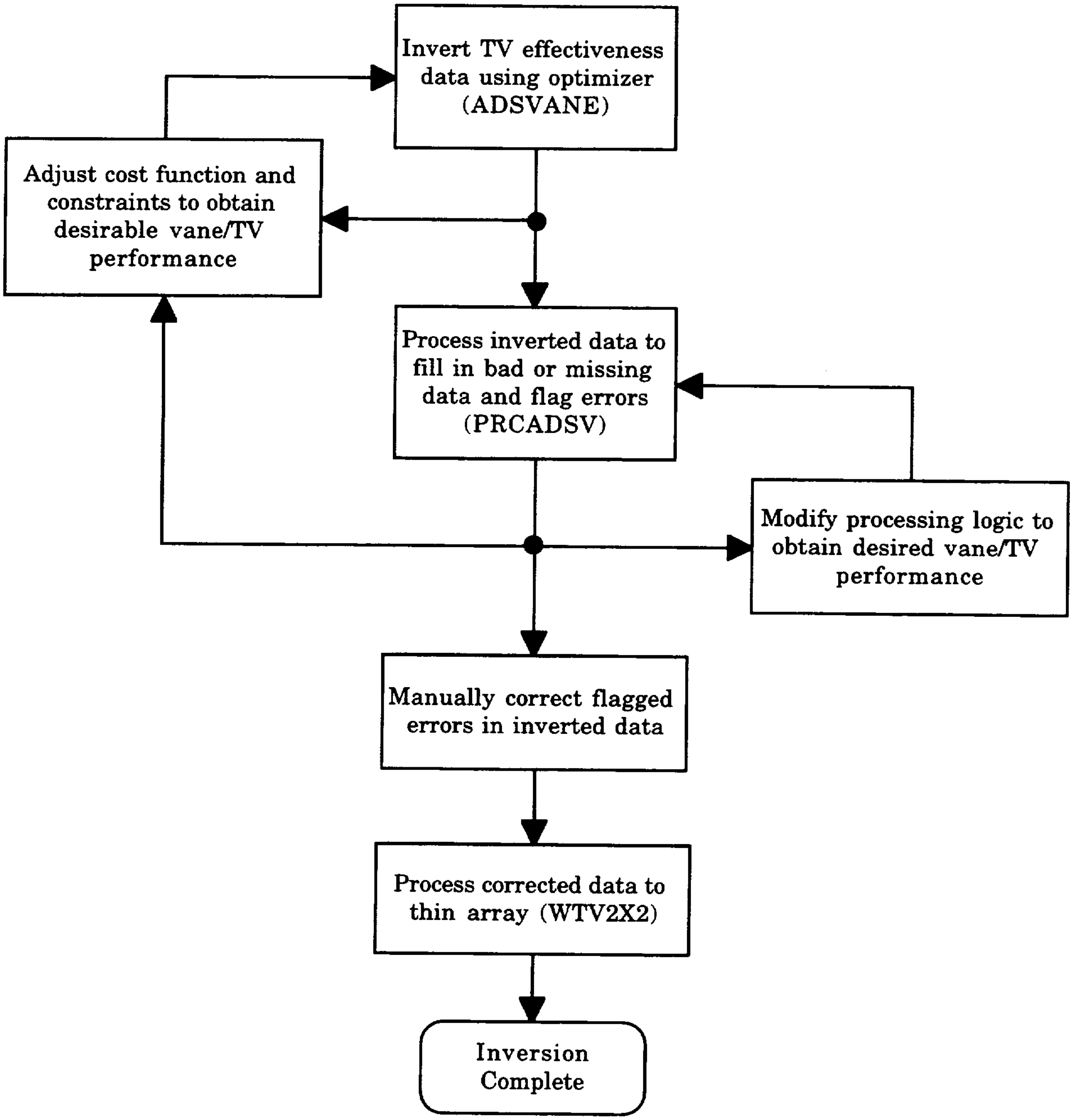


Figure 6.- Data inversion procedure.

minimize vane deflections from a "nominal" position $\delta_{i_{nom}}$ where the vanes were placed to initialize the optimization. For small deflections in pitch and yaw, the nominal position was at the edge of the plume for all vanes. Placing the inactive vane at the deadband position during data inversion will be referred to as internal deadband compensation. For large plume deflections, the nominal position was the stowed position (-10.0 degrees) for the vane toward which the plume was to be deflected, and at the plume edge for the remaining vanes. The stowed position minimizes plume interference.

Specifically, the objective function was

$$F(x) = \sqrt{(\delta_A - \delta_{A_{nom}})^2 + (\delta_B - \delta_{B_{nom}})^2 + (\delta_C - \delta_{C_{nom}})^2}\,. \tag{6}$$

A solution for the desired TV was assured by utilizing two equality constraints (m = 2) to force the difference between the desired (commanded) TV $\delta_{p_c}, \delta_{y_c}$ and the achieved TV δ_p, δ_y to zero; that is,

$$\delta_p - \delta_{p_c} = 0 \tag{7}$$

$$\delta_y - \delta_{y_c} = 0\,. \tag{8}$$

The desired solution is forced through the use of the constraints (eq. 7 and 8), while the objective function (eq. 6) is used to impose a local "unique" solution. Six inequality constraints (l = 6) were used to keep the solution within the usable values of vane deflection; that is,

$$\delta_i \geq -10^\circ \qquad i = A, B, C \tag{9}$$

$$\delta_i \leq 25^\circ \qquad i = A, B, C. \tag{10}$$

The optimization problem was solved using a general purpose numerical optimization FORTRAN subroutine called by an executive program created for the problem. The executive sequenced through the data points, determined the initial conditions, established the objective function and the constraints, calculated the error in the achieved TV angles, and iteratively tried different initial conditions to reduce the error if necessary. The optimization subroutine used an augmented Lagrange technique to find an optimal solution. The solutions are arrays of vane positions δ_A, δ_B, and δ_C indexed by the desired pitch- and yaw-TV angles. These solutions for δ_A, δ_B, and δ_C produce the desired TV angles while minimizing the objective function and satisfying the constraints, including placing the inactive vane at the deadband position when appropriate. These data were produced for a $1^\circ \times 1^\circ$ ($\delta_p \times \delta_y$) grid, that is, at one degree increments in pitch and yaw.

Not all of the solutions returned by the optimization met the accuracy requirement imposed by the constraints (eq. 7 & 8). Furthermore, solutions were not always found for all of the desired TV angles without violating the vane deflection constraints (eq. 9 & 10). The maximum envelope of pitch-yaw-TV angles achievable by the HARV TVS is not rectangular in the δ_p/δ_y plane because of the limits imposed by only three vanes, and the non-symmetric axial placement of the vanes. Typically, for a given *NPR* and *A8*, the achievable region of pitch- and yaw-TV angles is an irregular, somewhat diamond shape referred to as a "shield", as illustrated in figure 7 (*NPR* = 3 and *A8* = 348 in^2). Furthermore, the shape of the shield varies with *NPR* and *A8*. The irregular shape and variation considerably complicated the computerized inversion process and resulted in the decision to seek solutions for all of the points within a "standard" shield, also illustrated

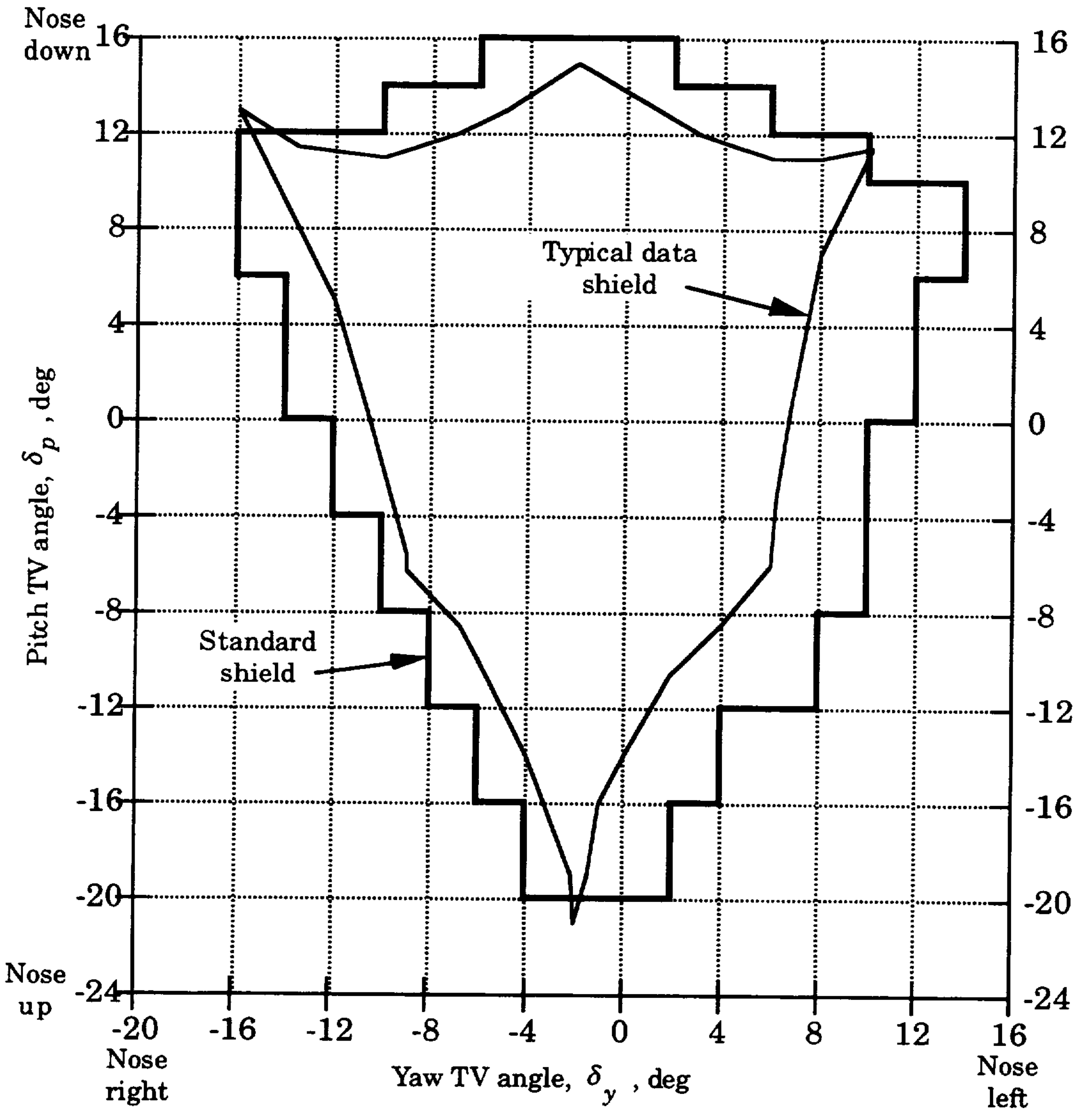


Figure 7.- Typical irregular shield and standard shield for left engine.

in figure 7. This standard shield was incorporated into the inversion program, but the optimization was still unable to find solutions in all cases.

Post-Inversion Processing

Several steps were required to process the data produced by the inversion program and ensure its suitability for use in the Mixer. Processing software was developed to read the inverted data produced by the inversion program, including the errors in the achieved TV angles, and insert missing data points. Inserting the missing data points required considerable complexity in the software logic since individual points, a sequence of points, or even entire rows of data could be missing. The general philosophy was to fill missing points with the nearest good data at a smaller yaw-TV angle and at the same pitch-TV

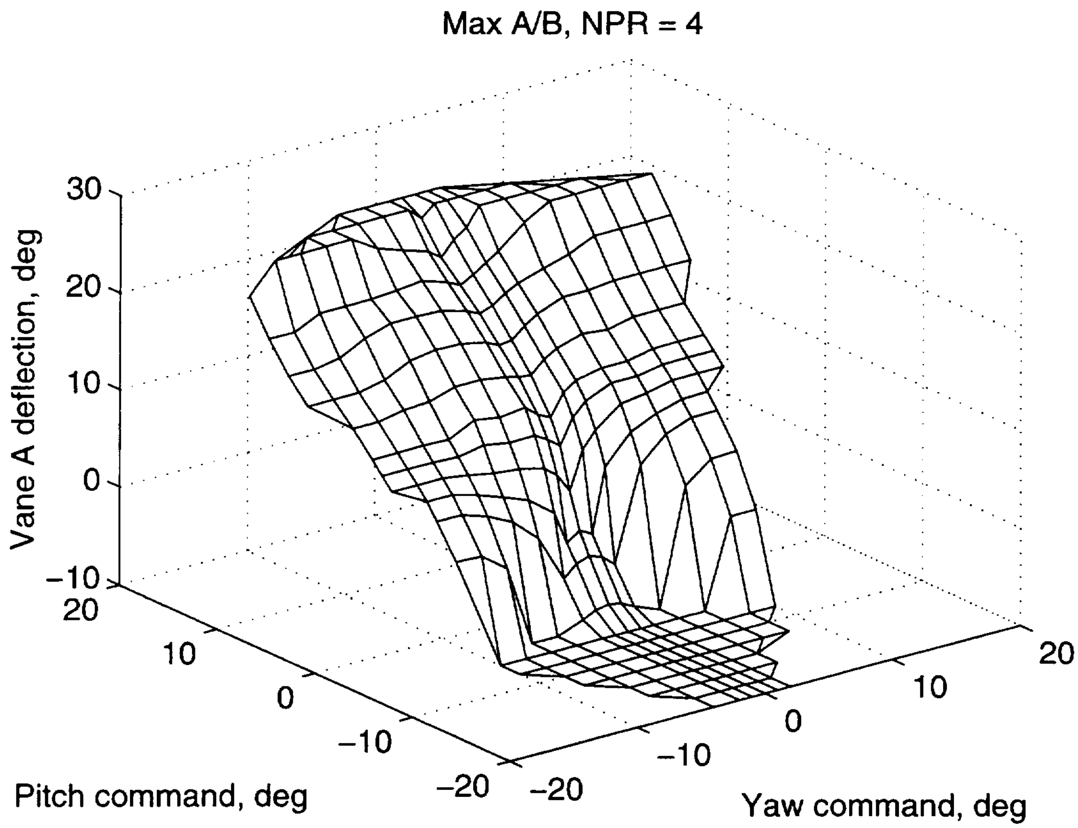


Figure 8.- Plot of Vane A deflection commands.

angle. This philosophy became more complex very quickly in some situations, for example, near the tip of the irregular shield where data was sparse.

The processing software also flagged data points where the error in the achieved TV angles exceeded the accuracy requirement and flagged points when no vane was at the stowed (-10°) position. The flags were identified points which required subsequent manual processing and engineering judgment to ensure valid data. Then the arrays were checked for internal consistency and continuity in order to provide smooth commands to the vanes when transitioning within an array or between arrays. Figure 8 shows an example surface plot of the top vane (Vane A) deflection commands as a function of desired pitch and yaw vectoring. Surface plots like this were examined to detect any discontinuities within an array.

The HARV Mixer Design

Following the procedure described above and in figure 5 a new Mixer was designed for the HARV. An initial set of requirements was established, which have previously been discussed in the Design Requirements section. The cold-jet TV data was inverted on a uniform 1° × 1° grid using the numerical optimization routine, and then the inverted data was processed by computer and manually.

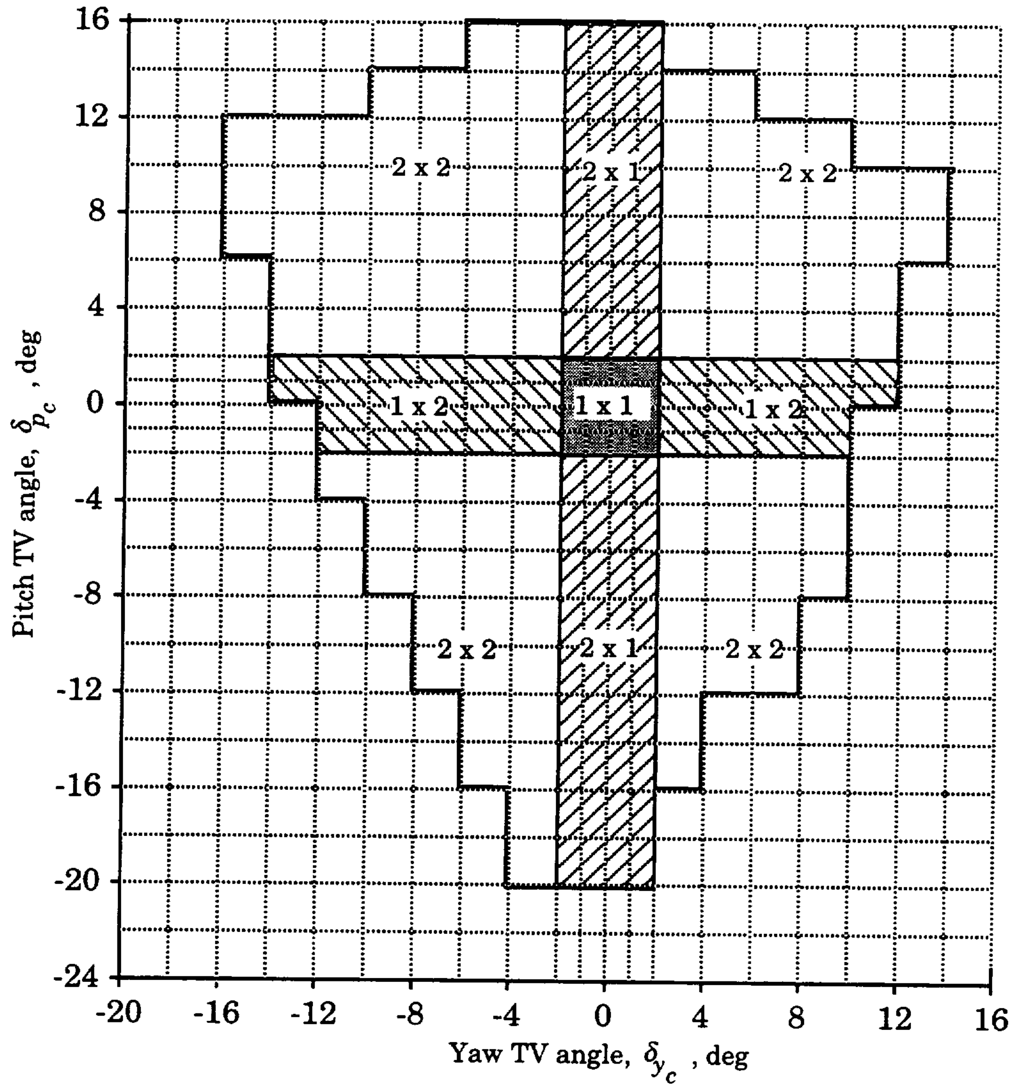


Figure 9.- Asymmetric, variable-resolution-grid array for one vane.

Data Storage

Designing the Mixer to use inverted data on a uniform rectangular $1° \times 1°$ grid in the pitch - yaw plane for pitch-TV angles from -20° to 16° and for yaw-TV angles from -16° to 16° would require 36630 data points (vane positions δ_A , δ_B , and δ_C) to command the three vanes throughout all 10 combinations of *NPR* and *A8*. To reduce the memory required in the flight computer while maintaining adequate accuracy in the achieved TV angles, other data storage options were examined.

Variable grid.- One of the options investigated was a uniform rectangular $2° \times 2°$ grid, which reduced the memory required to store the inverted data by nearly a factor of four. To further conserve memory, another option explored was the use of a variable resolution grid illustrated in figure 9. As shown in the figure most of the variable grid is $2° \times 2°$, but within ±2° in pitch the grid is only 1° in pitch. Likewise, within ±2° in yaw the grid is only

1° in yaw. Thus, in the area where small vane deflections will occur, the accuracy is improved compared to the uniform rectangular 2° × 2° grid with only a slight increase in memory requirements.

Non-rectangular arrays.- Most of the area in the pitch - yaw-TV plane outside the standard shield shown in figure 7 corresponds to pitch - yaw-TV combinations which cannot be achieved due to limitations of the HARV TVS. Therefore, to further conserve memory, a decision was made to store data only for those points within or on the boundary of the standard shield. Thus, the final Mixer design utilized a variable-grid, non-rectangular array to store the inverted data, as shown in figure 9 which represents the grid for one vane at selected values of *NPR* and *A8*. This configuration, illustrated in figure 10 for all the data points for one vane, increased the complexity of the table look-up and interpolation scheme, but it required a total of only 8100 data points for the three vanes, which is a reduction of 78 percent compared with the uniform rectangular 1° × 1° grid. In these arrays the grid intersections in the pitch-TV-yaw-TV plane, which are the breakpoints in the table look-up, are at integer values of pitch-TV command δ_{p_c} and yaw-TV command- δ_{y_c}. The independent variables are pitch-TV command δ_{p_c}, yaw-TV command δ_{y_c}, nozzle pressure ratio *NPR*, and nozzle radius $R8\ (=\sqrt{A8/\pi})$.

Table look-up.- The use of non-rectangular, variable-grid arrays considerably complicated the table look-up (TLU) process. The arrays of inverted data, which can be visualized as in figure 10, are actually three one-dimensional arrays, one for each vane, of length 2700. Since the TLU is four dimensional (four independent variables), 16 data points from the table are required for the interpolation process. The complexity in the TLU arises primarily in determining the indices of the dependent variables corresponding to these 16 data points. In the TLU implementation, determining the indices begins by locating the base point, which is the table location for which the independent variables are closest to, but less than, their values at the desired interpolated point. Conversion of engine *NPR* and *R8* to integer values determines which of the ten shields in figure 10 contain the base point. Conversion of δ_{p_c} and δ_{y_c} to integer values locates the base point within the shield. The indices of the 15 neighboring points in the 4-D space needed for interpolation are then determined. A key element in determining the indices is knowing the number of yaw data points on each pitch grid line of the array in figure 9.

Once the indices are known, the 16 data values can be extracted from the array for each of the vanes, and linear interpolation is performed to compute the vane commands. The entire TLU process is repeated for the other engine.

Thrust-Vectoring Priorities

As noted previously, there will be instances when the FCS will command a combination of pitch-, roll-, and yaw-TV angles that are outside of the achievable range. In such instances the Mixer must resolve the conflict by mapping the desired pitch-yaw-vectoring angles into achievable TV angles; this is done by assigning priority to pitch,

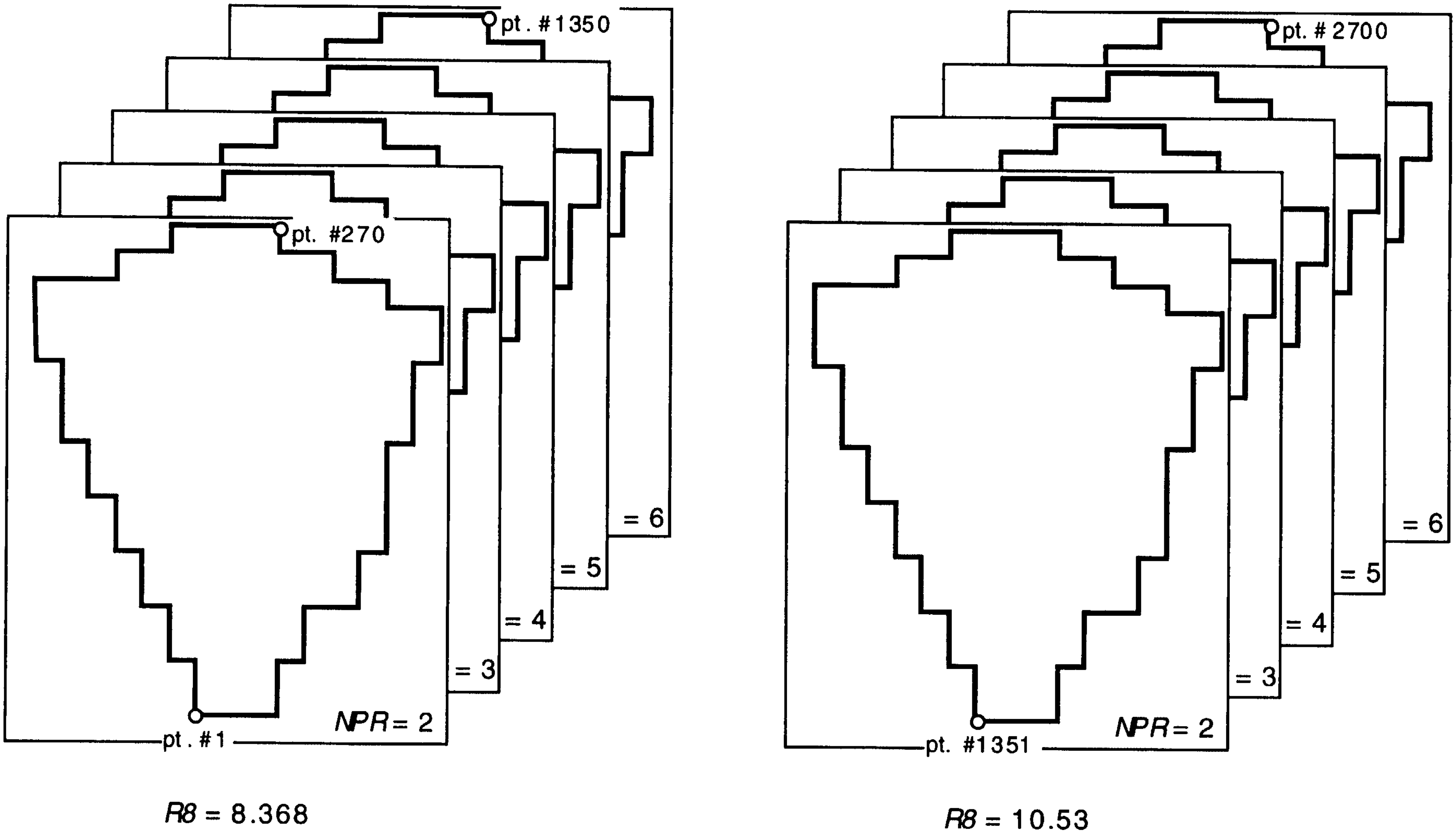


Figure 10.- Asymmetric array for one vane.

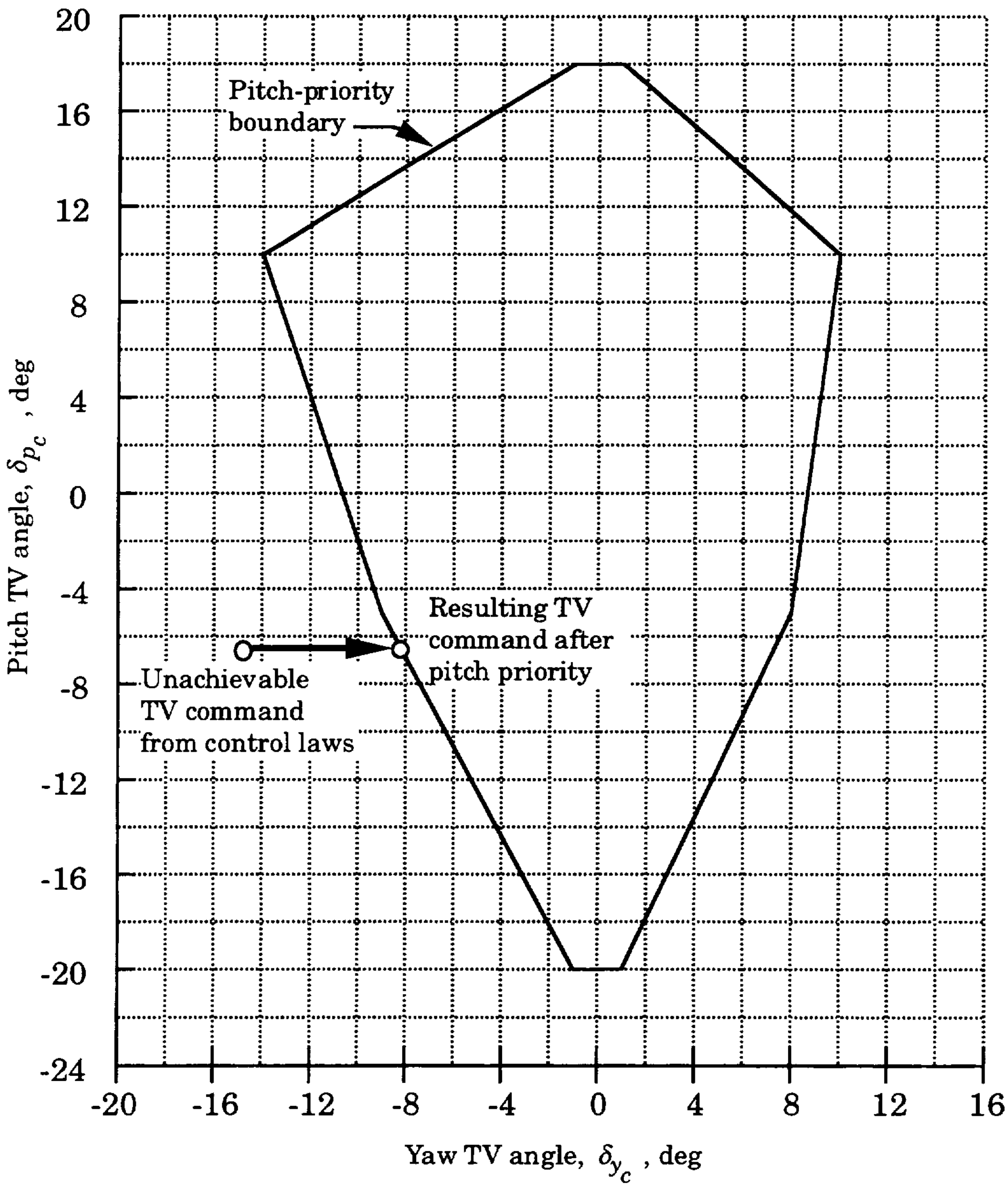


Figure 11.- Pitch-priority function.

yaw, roll, or some combination of the three. The mapping philosophy for this design is, in general, to assign first priority to pitch vectoring over yaw and roll vectoring and secondary priority to yaw vectoring over roll vectoring. Pitch is assigned first priority to assure adequate nose-up and nose-down control at high angles of attack.

Pitch-priority.- Pitch-priority is assigned using the pitch-priority boundary shown in figure 11. Whenever a TV command is outside this boundary, the command is adjusted in yaw at constant pitch to reach the boundary in figure 11. In this way pitch-priority is achieved by maintaining the desired pitch-TV command while sacrificing yaw-TV. To assure that unachievable pitch-TV is not commanded, a variable pitch limiter function is first applied to the commands. This function will be discussed in the next subsection.

***Yaw-priority*.-** On a twin engine airplane roll moment can be generated by differential pitch thrust vectoring. On the HARV the roll moment arm (distance between the engines) is much smaller than the yaw and pitch moment arms, causing the roll moment to be significantly less than the pitch and yaw moments. For this reason pitch and yaw were given priority over roll so that the ability to generate large body-axis pitch and yaw moments would not be sacrificed by the generation of a small body-axis roll moment.

The yaw-priority was accomplished by limiting the commanded roll-TV angle as a function of the commanded pitch and yaw thrust vectoring. This limit is plotted in figure 12 as a function of the pitch-TV command for several values of yaw-TV command. Figure 13 shows the boundary in the commanded pitch - yaw plane outside of which the roll command is limited to zero.

As previously mentioned the pitch-TV command is limited to prevent commanding unachievable pitch-TV angles. Initially these limits were constant at -20° and 16°, determined from an average of the maximum pitch vectoring capability for all the tested values of *NPR* and *A8*. However, for large negative pitch-TV commands, the achievable range of TV angles is very narrow in yaw leaving limited body-axis yaw (stability-axis roll) control at high angles of attack. Simulation experience in this area led to the development and use of the variable pitch limiter shown in figure 14. This variable limiter still allowed reasonable pitch-TV authority while maintaining at least a moderate amount of yaw thrust vectoring at high angles of attack.

Figure 15 is a composite plot which shows the relationship among the inverted-data-array boundary, the variable pitch limiter, the zero-roll-TV boundary of the yaw-priority function, and the pitch-priority function.

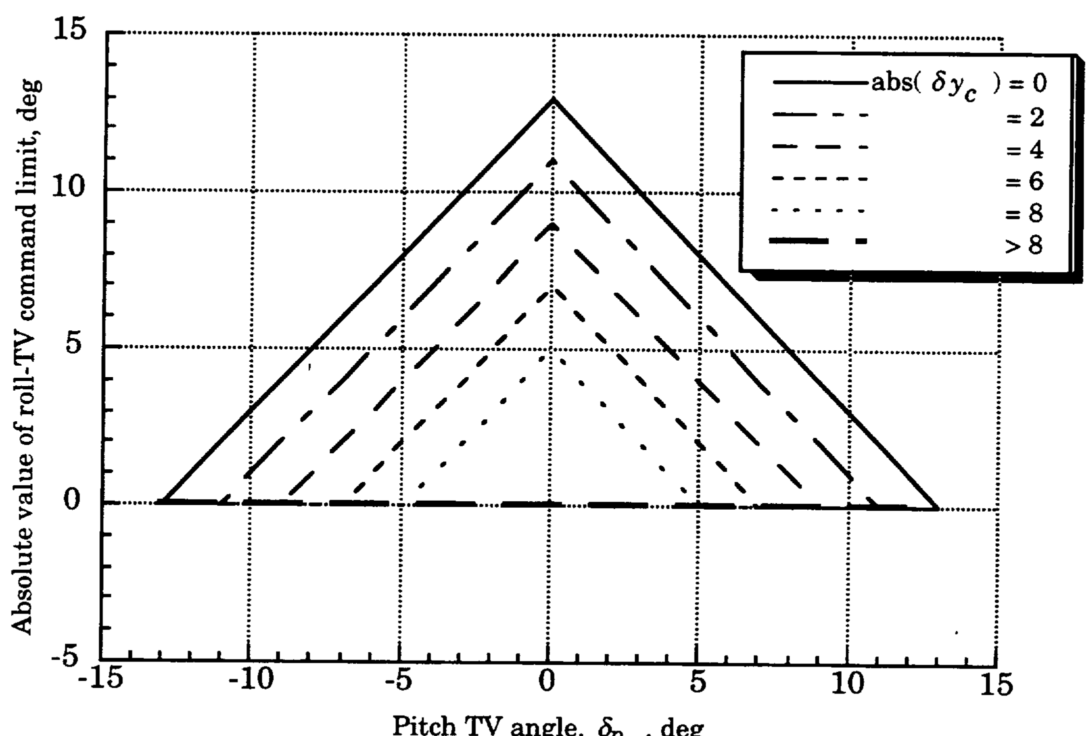


Figure 12.- Absolute value of roll-TV limit.

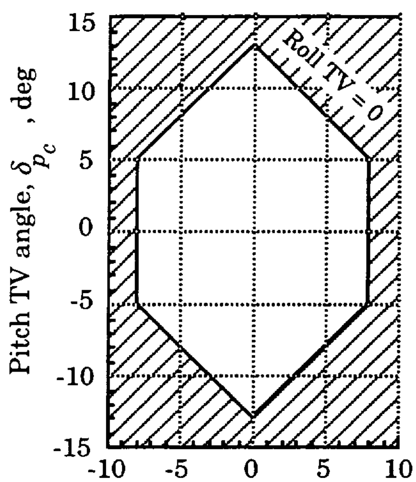


Figure 13.- Roll-TV boundary.

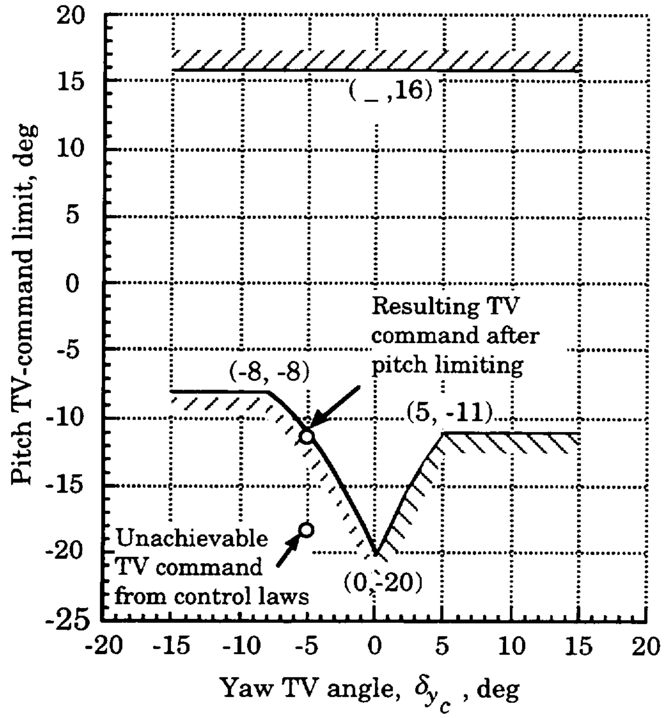


Figure 14.- Variable pitch TV-command limits.

Block Diagram

A block diagram of the Mixer is shown in figure 16. Inputs to the Mixer are roll-, pitch-, and yaw-TV commands from the control laws; estimated gross thrust, nozzle pressure ratio, and nozzle radius from each engine; and measurement of Mach and altitude. Outputs are the six vane deflection commands in inches of actuator travel.

Thrust-vectoring commands from the control laws are based on a reference thrust of 7500 lbs per engine. The Mixer adjusts the TV commands using the thrust-adjustment factor plotted in figure 17 to produce the desired control moments based on an estimate of the current gross thrust. Pitch and yaw commands are adjusted on the basis of the estimated thrust for the engine involved, while the roll command is adjusted on the basis of the average thrust adjustment for the two engines. The thrust-adjustment factor is essentially a piecewise-linear approximation of the ratio 7500/gross thrust, but it is substantially reduced at low thrust levels to reduce excessive vane motion.

As can be seen in the block diagram the thrust-adjusted commands are passed through the appropriate priority functions. The roll-TV command is then implemented by adding to and subtracting from the left/right pitch-TV commands. The resulting pitch and yaw commands are further adjusted to compensate for thrust losses due to thrust vectoring using the thrust-loss factor plotted in figure 18. This factor, based on the root-sum-square of the TV commands, is an approximation to the thrust loss due to vectoring measured in the cold-jet facility and in full-scale thrust stand tests (ref. 10). The adjusted pitch and yaw commands are then input to the table look-up process, producing actuator commands

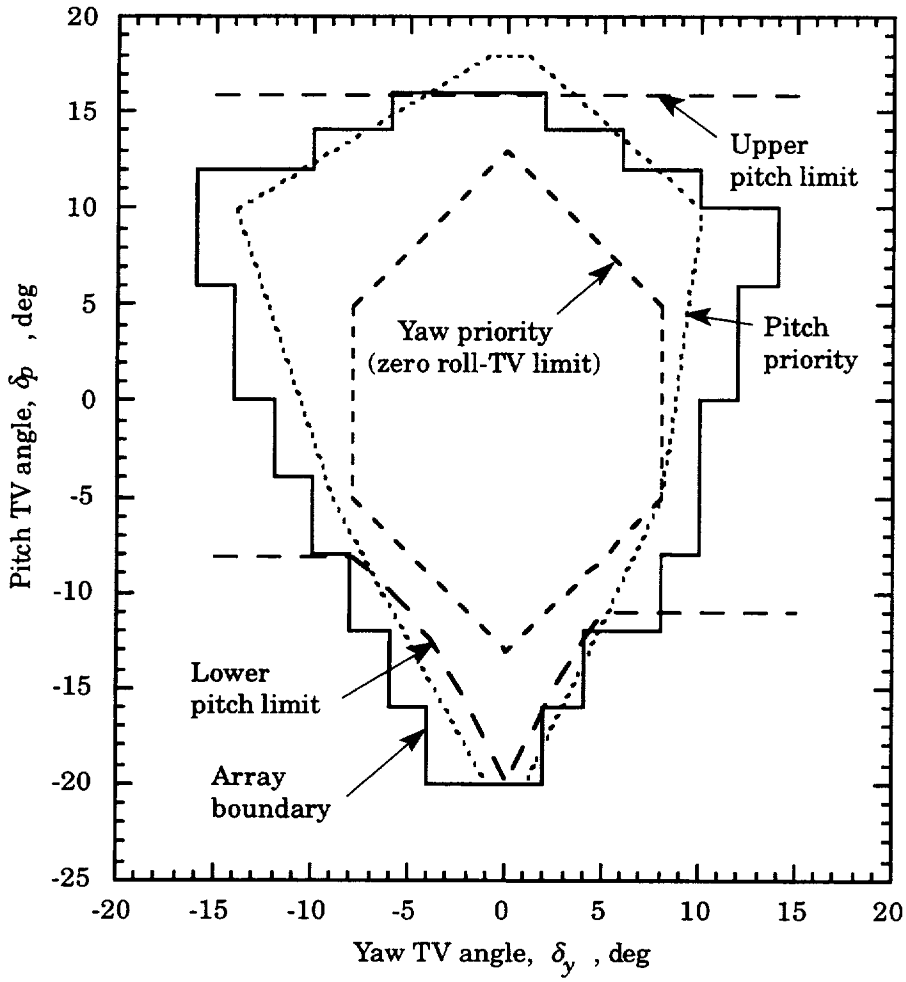


Figure 15.- Boundaries, limits, and priorities.

for all six vanes. Finally, the vane-actuator commands are limited for flight conditions where excessive vane loads could be produced.

Results

Mixer Test Program Results

The accuracy with which the Mixer commands the TV vanes to reproduce the TV angles commanded by the FCS was evaluated in simulation using the Mixer software, the models of the HARV engine and TVS from the HARV aircraft simulations, and an executive to run the tests.

Simulated FCS pitch and yaw-TV commands δ_{p_c} and δ_{y_c} ,were input to the Mixer at specified values of power lever angle *PLA*, speed *Mach*, and altitude *h*. Along with *PLA* and static pressure, engine turbine discharge pressure *P56* and nozzle area *A8* from the

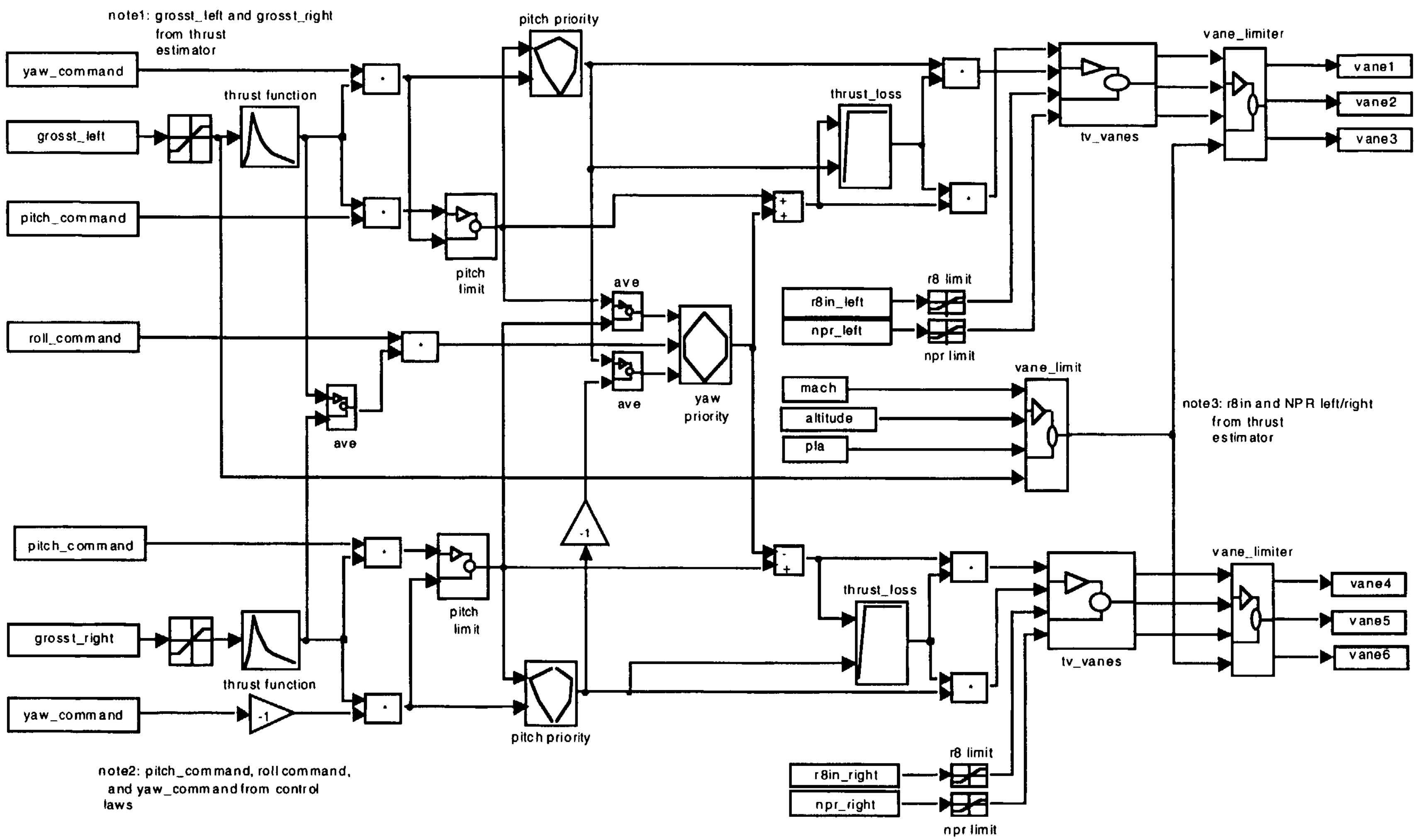


Figure 16.- Mixer block diagram.

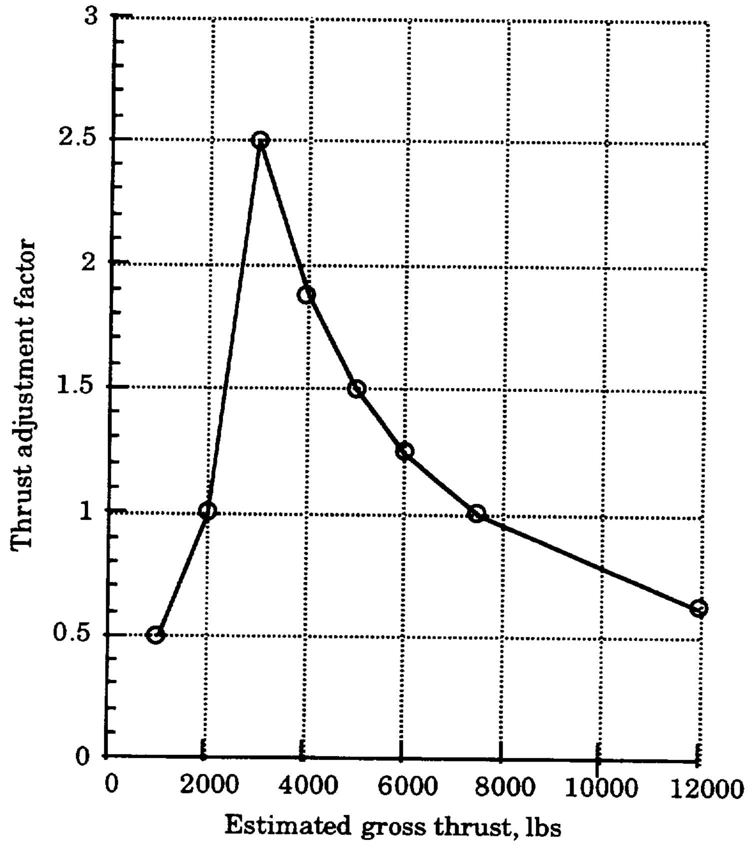


Figure 17.- Thrust adjustment factor.

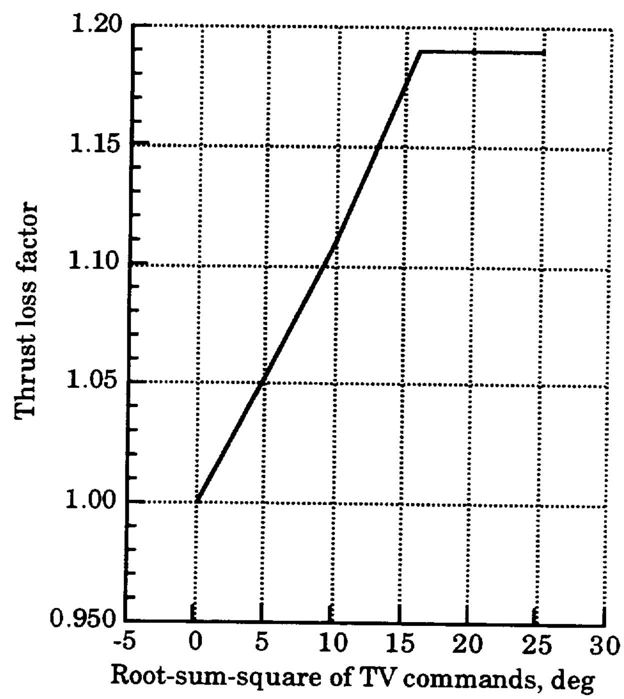


Figure 18.- Thrust loss factor.

engine simulation were input into a thrust estimator to obtain estimates of the engine thrust needed by the Mixer. Vane commands from the Mixer were input into the engine/TVS simulation which computed the "truth", or achieved, values of pitch and yaw thrust vectoring angles δ_p and δ_y . These achieved angles were then compared with the commanded values from the FCS, after adjustment for thrust level, to obtain the error.

A series of runs called theta sweeps were conducted. In theta sweeps the commanded pitch and yaw-TV angles δ_{p_c} and δ_{y_c} were programmed to vary in direction as measured by a polar coordinate θ while the magnitude δ_{M_c} of the TV was held constant. The magnitude δ_{M_c} is the magnitude of the TV angle, that is, the angle of the thrust vector with respect to the engine axis, while θ is the angle from the z-axis of the projection of the thrust vector on the yz-plane. Mathematically, δ_{M_c} and θ are defined by

$$\delta_{M_c} = \sqrt{\delta_{p_c}^2 + \delta_{y_c}^2} \tag{11}$$

$$\theta = \cot^{-1}\left(\frac{\delta_{p_c}}{-\delta_{y_c}}\right) \tag{12}$$

Actuator dynamics were bypassed during these runs, so the vanes were positioned at the commanded location without time lag.

The series of theta sweeps consisted of test runs using the new Mixer design (M4), which includes the variable-grid, non-rectangular array of inverted data with internal deadband compensation. For comparison, theta-sweep simulation runs were also made with five other Mixer designs. Two of the designs used a $1 \times 1°$ data grid, one of these with external deadband compensation and the other without deadband compensation. Two other designs used a $2 \times 2°$ data grid, again one with external deadband compensation and the other without deadband compensation. The fifth comparative design was the original McAir Mixer/Predictor (MPre), which incorporated external deadband compensation. "Without deadband compensation" means that the inactive vanes were always placed at the stowed position of -10°. "With external deadband compensation" means that the active vanes were deflected to the same position as "without deadband compensation", but the inactive vanes were then placed at the deadband position instead of stowed position, if appropriate.

The theta sweeps were made with TV magnitude δ_{M_c} values of 2, 4, 6, 10, and 15 degrees. Results are shown in figures 19 through 22 as plots of the average achieved pitch-TV angle versus the average achieved yaw-TV angle, where average refers to the average of the TV angles for the two engines. Note that if the commanded TV angles were exactly achieved for all θ, the plots would consist of circles of radii equal to δ_{M_c} , that is, radii equal to 2, 4, 6, 10, and 15 degrees. Figure 23 shows bar graphs of the RMS error for the different designs, where the error (difference between achieved and commanded TV angles) is RMS averaged over θ. The flight conditions in these simulations were h = 25,000 ft, *Mach* = 0.3, and *PLA* = 125.455° (from a range of 31° to 130°). This *PLA* setting produced an engine thrust (7499.87 lbs) approximately equal to the reference thrust level such that the thrust adjustment factor was essentially unity.

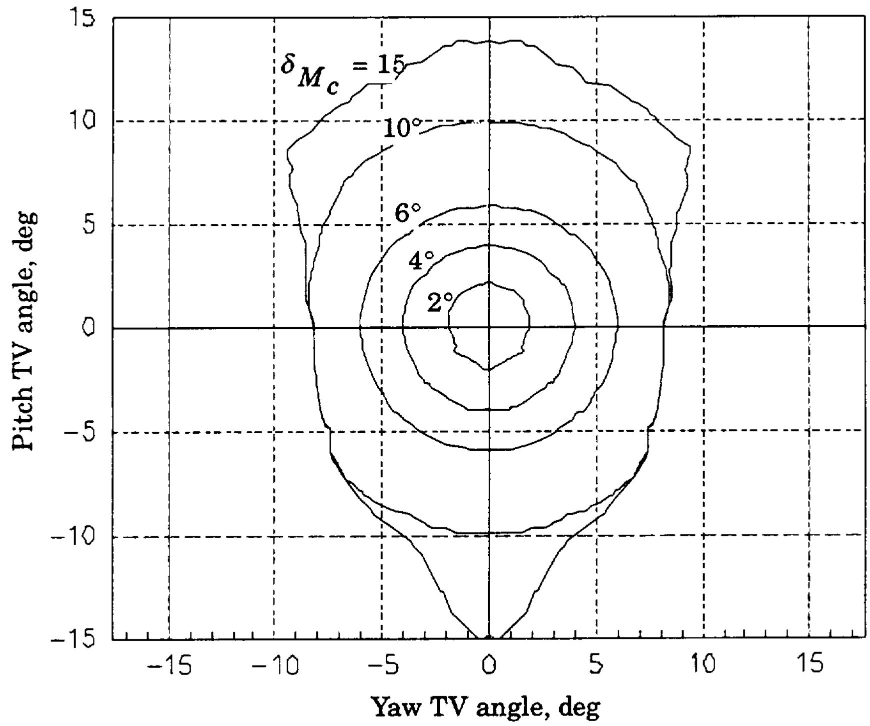
Effects of grid size.- Looking first at the designs without deadband compensation, the effect of the inverted-data grid size on the accuracy of the achieved TV angles can clearly be seen by comparing the shape of the plots for $\delta_{M_c} = 2°$ for the $1° \times 1°$ grid and the $2° \times 2°$ grid in figures 19a and 20a, respectively. Clearly the accuracy is degraded for the 2° x 2° grid. Some degradation in accuracy can also be seen in the plots for $\delta_{M_c} = 4°$. The plots in figure 21a show that the TV accuracy when using the variable grid is comparable to that of the $1° \times 1°$ grid. These conclusions are also reflected in the bar graphs of RMS TV error in figure 23 which show that the error for the $2° \times 2°$ grid (2x2DB, 2x2NDB) is larger than for the $1° \times 1°$ grid (1x1DB, 1x1NDB) , but, in general, the errors for the $1° \times 1°$ grid and the variable grid (M4) are comparable. When external deadband compensation is used (figs. 19b and 20b), the improvement offered by the $1° \times 1°$ grid is not evident.

Although the accuracy of the $2° \times 2°$ grid with no deadband compensation (2x2NDB) is the worst of the three grids just discussed, the errors are not large for any of these cases. When considering the accuracy of these results, it should be remembered that "truth" in these cases is the engine and TVS simulation and the cold-jet TV-effectiveness data. It should not be expected that the accuracy of the achieved TV angles in flight would be as good as these simulation results, where the errors are relative to the cold-jet data. An analysis to determine what grid size to use for the inverted data should take into account the accuracy and the grid size of the basic TV-effectiveness data to be inverted.

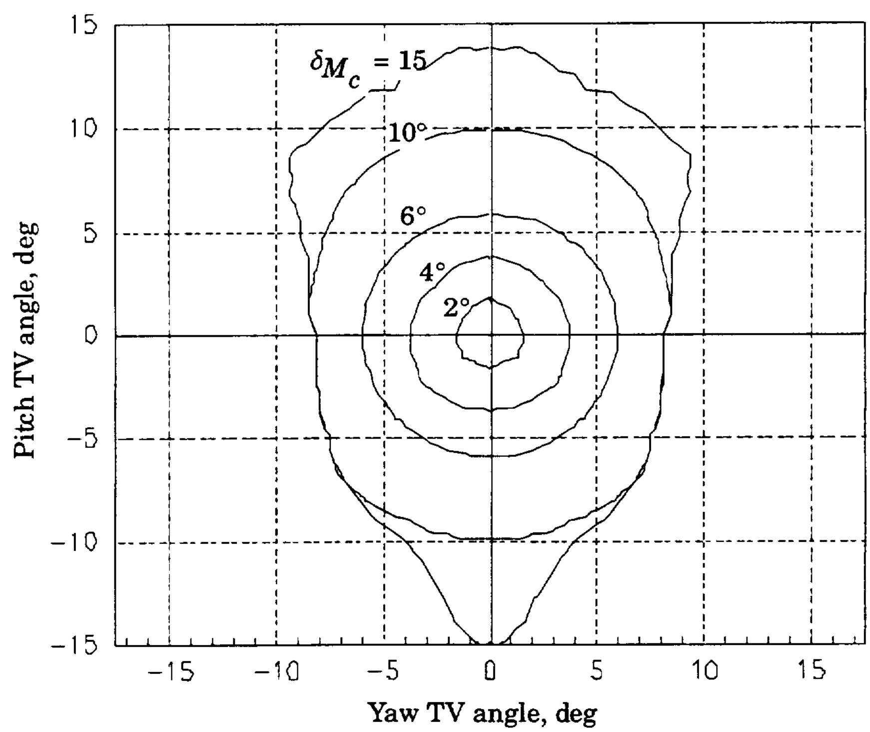
Effects of deadband compensation.- Comparison of results in figure 19a with 19b and figure 20a with 20b show that external deadband compensation, that is, placing the unused vane on the edge of the exhaust plume, degrades the TV accuracy considerably by decreasing the amount of TV achieved. In these cases the inverted data assumes that the unused vane is stowed at -10°. In figure 23 the errors with external deadband compensation are seen to be 1.5 to 2.5 times as large as the errors with no deadband compensation. Of course, this discussion applies to TV magnitudes of 2° and 4° in the plots because deadband compensation is not used for $\delta_{M_c} \geq 6°$ in these Mixer designs. Notice in figures 19 and 20 that the plots for $\delta_{M_c} \geq 6°$ are identical. Likewise, in figure 23 note that the RMS errors for the same design with and without external deadband compensation are identical for $\delta_{M_c} \geq 6°$. In figures 21 and 23 it can be seen that the accuracy lost when external deadband compensation is employed is nearly all recovered when internal deadband compensation is utilized. At δ_{M_c} equal to 2° and 4°, using internal deadband compensation reduces the RMS error by a factor of 2 or 3 relative to the 1° x 1°-grid-with-external-deadband design, although the errors are small in both cases.

Thrust-Vectoring-priority System

Achievable thrust vectoring and pitch-priority.- As mentioned previously, if the commanded TV angles were actually achieved, the plots in figures 19 through 22 would consist of concentric circles of radii equal to δ_{M_c}. This is certainly true in these figures for thrust-vectoring magnitudes δ_{M_c} of 10 and 15 degrees. The curves for $\delta_{M_c} = 15°$ look more like the data shields in figure 7. This effect is due to the characteristics of the TV available from the HARV TVS and to the pitch-priority implemented in the Mixer designs in figures 19 through 21. Due to these factors considerably larger pitch-TV angles were

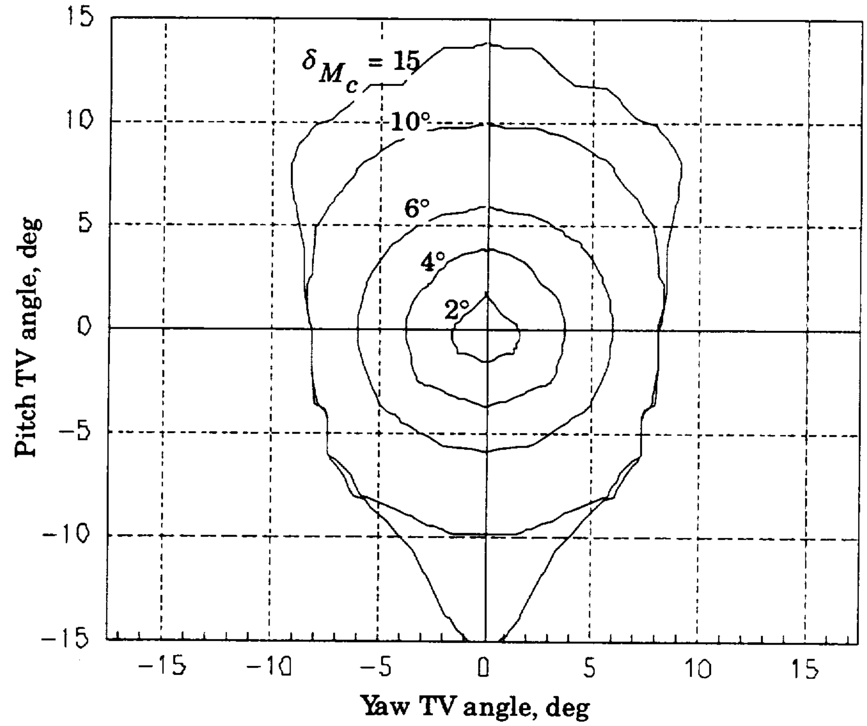


a.- No deadband compensation

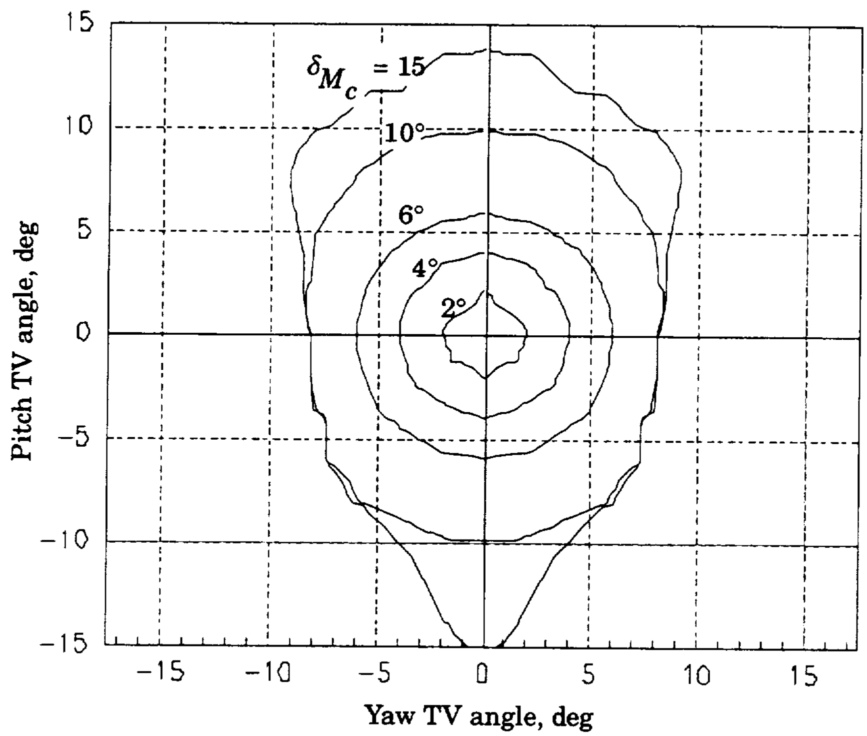


b.- With external deadband compensation

Figure 19.- Theta-sweep results for 1° × 1° grid.



a.- No deadband compensation



b.- With external deadband compensation

Figure 20.- Theta-sweep results for 2° × 2° grid.

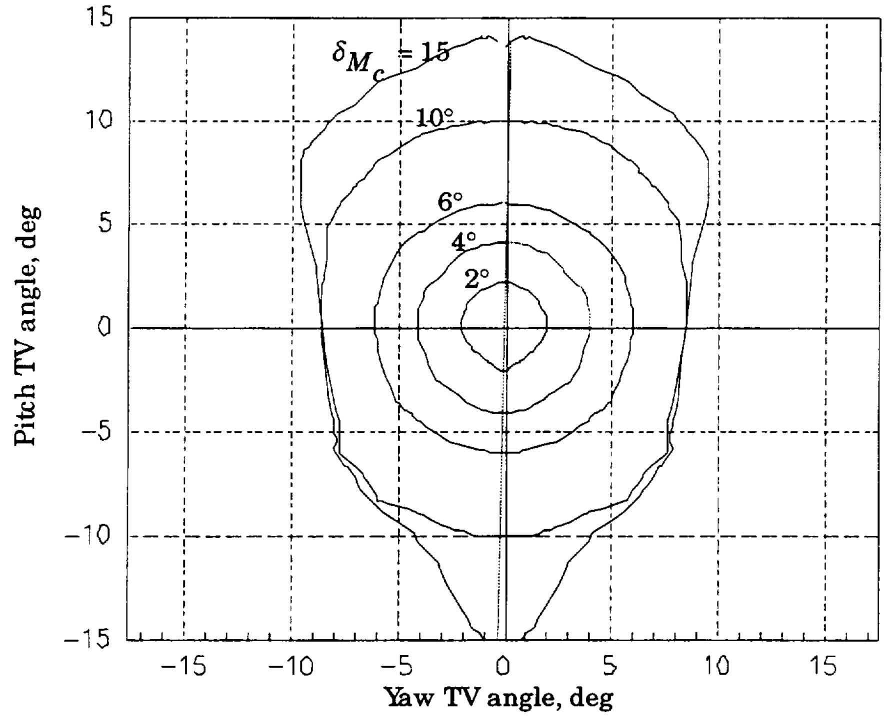


Figure 21.- Theta-sweep results for final asymmetric variable grid with internal deadband compensation (M4).

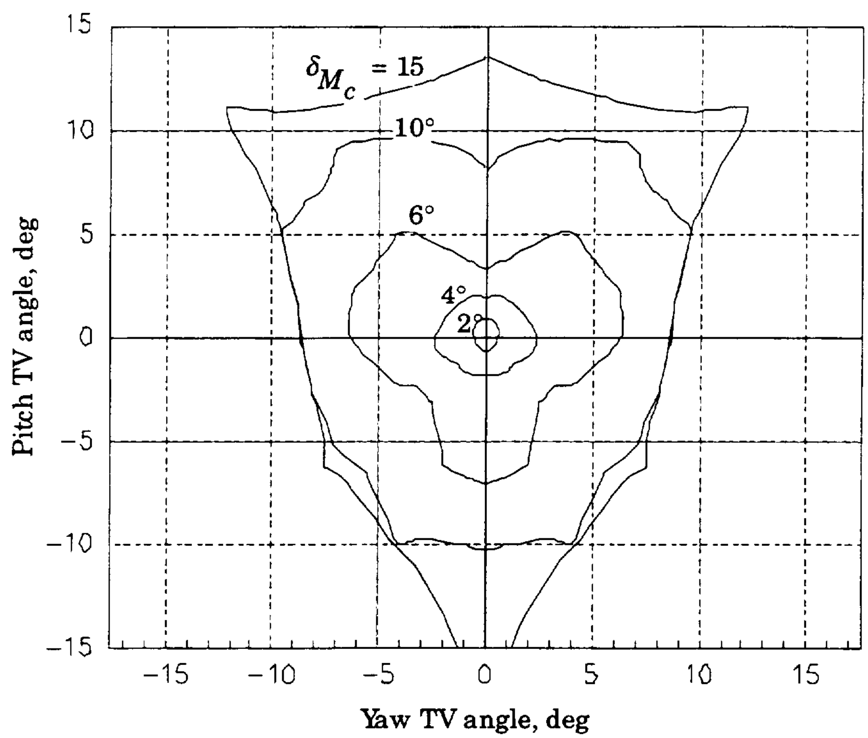
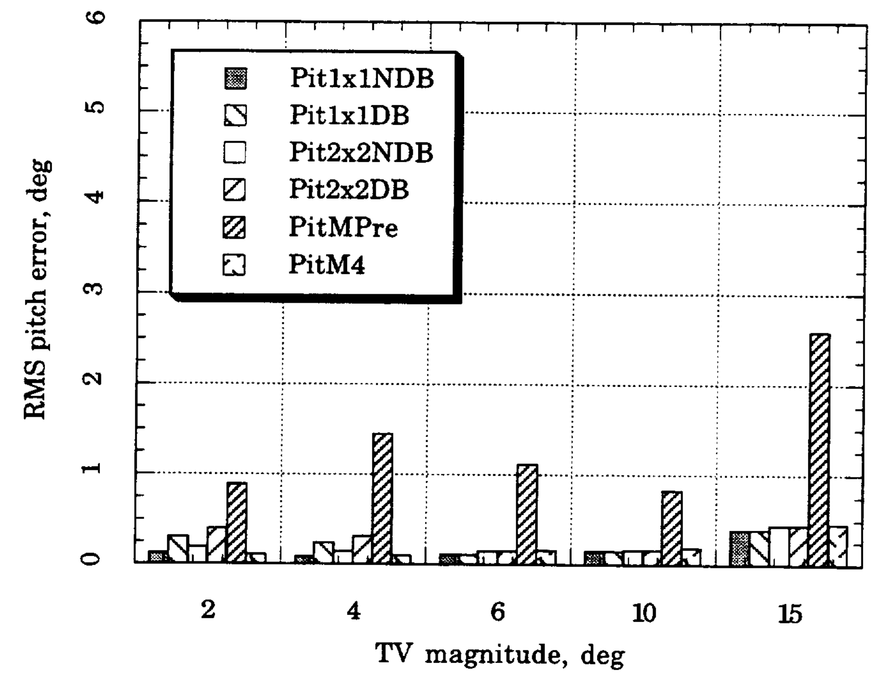
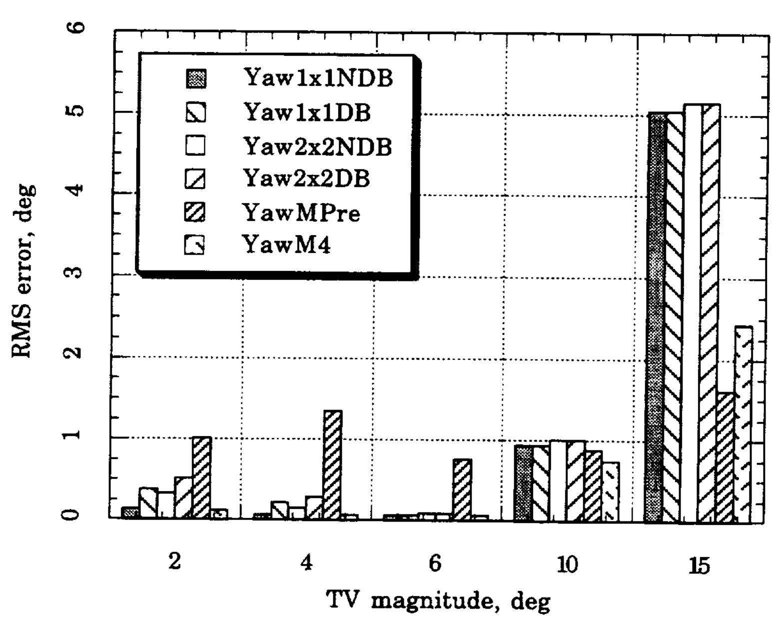


Figure 22.- Theta-sweep results for original Mixer/Predictor with deadband compensation (MPre).

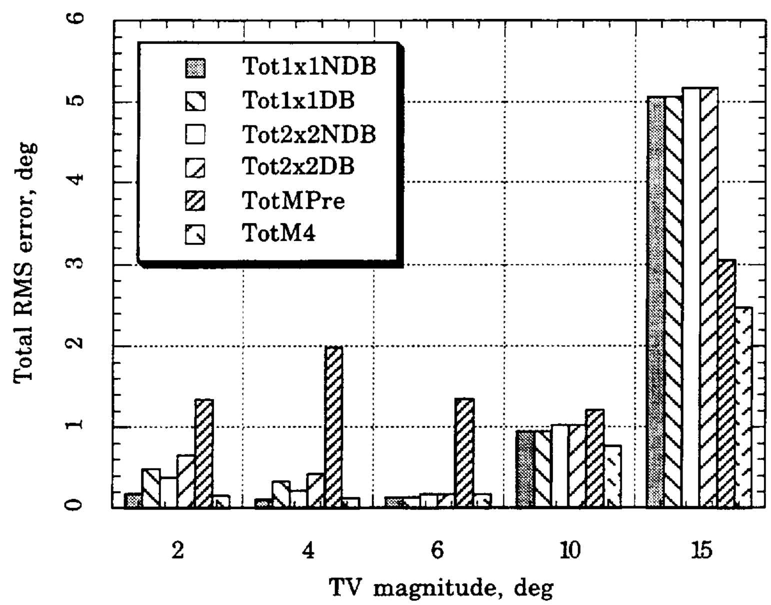


(a).- Pitch-TV error



(b).- Yaw-TV error

Figure 23.- RMS error in achieved thrust vectoring during theta sweeps for different Mixer designs.



(c).- Total-TV error
Figure 23.- Concluded.

achievable than were yaw-TV angles when using the three new designs (1° × 1° grid, 2° × 2° grid, and variable-grid). Note in figure 23b that at $\delta_{M_c} = 15°$ the RMS yaw-TV errors for the three new designs are larger than the comparable error for the original MPre. The original MPre had much larger pitch error because the design had no pitch-priority function. Note also that the total RMS TV error for the final variable-grid, non-rectangular array design is smaller than the comparable error for the original MPre except at $\delta_{M_c} = 15°$. The primary factor in this difference is that the piece-wise linear approximation to the cold-jet data used in the MPre design is not as accurate as the optimally inverted data used in the new designs.

Comparison of the theta-sweep results in figures 19 through 23 show that all of the new designs have superior accuracy compared with the original MPre because they more accurately follow the commanded TV than the original MPre. The lone exception is that the yaw-TV accuracy for large yaw-TV commands is more accurate for the original MPre.

Variable pitch limiting and yaw-over-pitch-priority.- The general philosophy in the design of the new M4 Mixer was that pitch-TV should have the highest priority. However, as discussed earlier, a variable pitch limiter was included in the design to override this pitch-priority and retain some yaw-vectoring capability when large negative (nose-up) TV is being commanded. Results from the HARV batch simulation illustrate this effect (fig.

24). These results are for the airplane trimmed at $h = 25{,}000$ feet and $\alpha = 66°$. At this trim condition $Mach = 0.285$, $PLA = 130°$ (max A/B), and $\delta_p = -17.5°$.

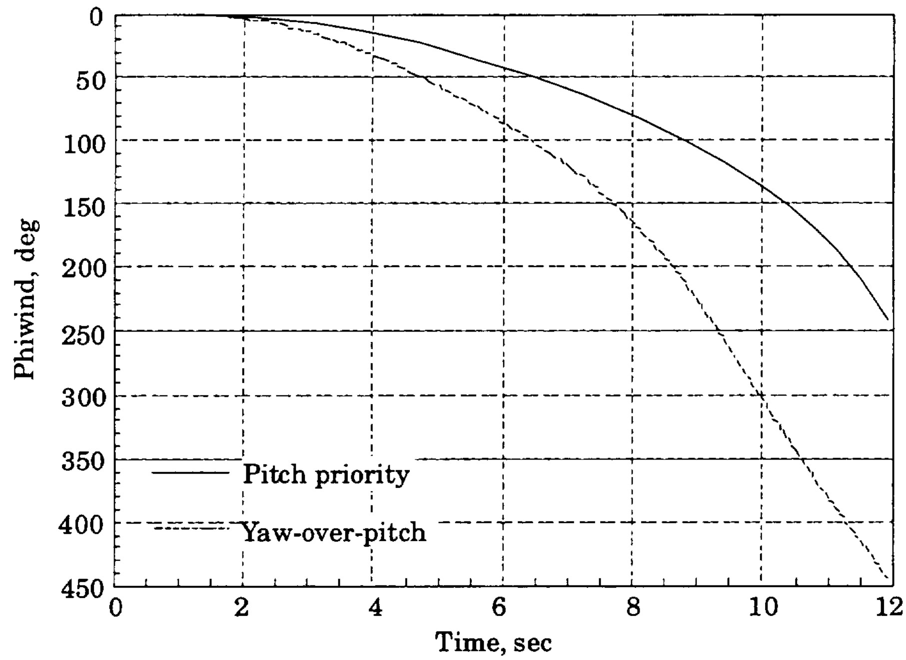
At $t = 1$ second, a full-lateral-stick roll was commanded. The resulting wind-axis roll angle and the angle of attack are plotted in figure 24 for two cases: with variable pitch limiting (yaw-over-pitch-priority) and no variable pitch limiting (pitch-priority). In figure 24(a) note the higher roll rate achieved for the yaw-over-pitch-priority case because of the increased yaw-TV available. With yaw-over-pitch-priority the airplane rolls to 180° in 8.2 seconds, while it takes 11 seconds to roll to 180° with pure pitch-priority. This increased roll performance is not achieved without paying a price, however. Immediately after the roll is commanded, the achieved pitch-TV is reduced in magnitude to -8.5° on one engine and -12° on the other because of the commanded yaw-TV. The result, shown in figure 24(b), is that angle-of-attack regulation is not as good with yaw-over-pitch-priority .

Yaw-priority.- As noted previously, a yaw-priority function was included in the final M4 design to give yaw-TV priority over roll-TV when the combination of yaw- and roll-TV commanded by the FCS cannot simultaneously be achieved; that is, the resulting commands are outside of the shield of achievable TV in the pitch-yaw plane. The Mixer test program was used to illustrate the effect of yaw-priority, and the results are plotted in figure 25. For these runs the simulated flight conditions were $h = 25{,}000$ feet, $Mach = 0.3$, and $PLA = 125.455°$. The resulting gross thrust was 7499.87 lbs per engine as with the theta sweeps.

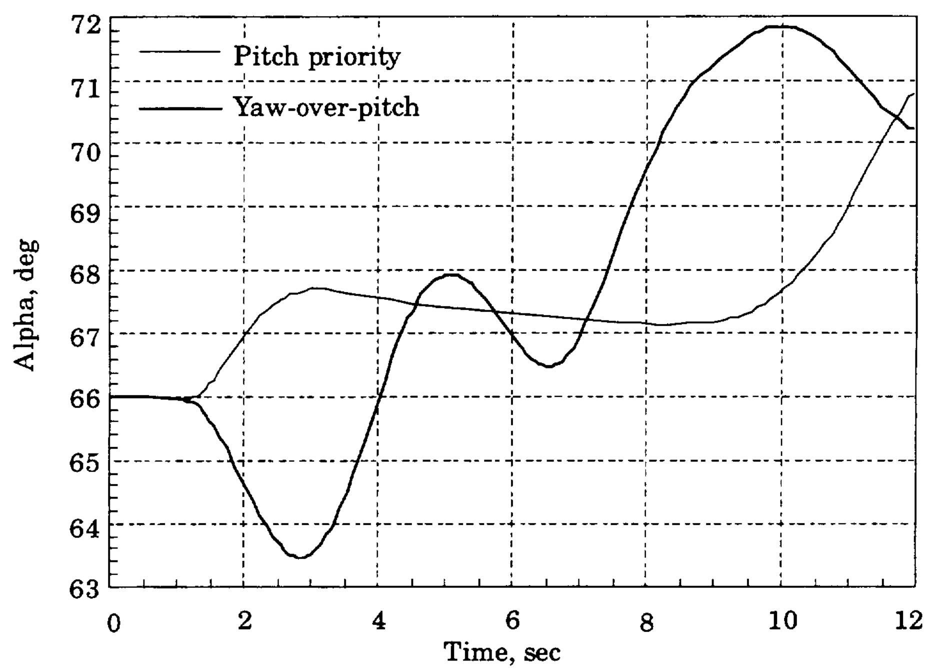
The pitch- and roll-TV commands into the M4 were held constant at 6° pitch and 12° roll (prior to thrust-loss adjustment). The yaw-TV command was swept from - 15° to +15° to show the effects of commanded roll-TV on the achieved yaw-TV. As with the theta sweeps, actuator dynamics were by-passed. The resulting achieved yaw-TV angle for the left engine and the total body-axis roll moment and yaw moment for both engines are plotted in figure 25 versus the commanded yaw-TV angle.

In figure 25(a) note that without yaw-priority the minimum and maximum yaw-TV angles achieved by the left engine are -6.0° and +0.7°, respectively, because the combination of commanded pitch-, roll-, and yaw-TV is outside the shield of achievable TV. Yaw-TV is sacrificed for pitch-TV and, hence, for roll-TV, since roll-TV is just differential pitch-TV. In contrast, with yaw-priority the left engine achieves minimum and maximum values of yaw-TV of -12.1° and +7.1°, respectively, as shown in figure 25(a). Figure 25(b) shows similar results for the achieved yaw moment, where values in the range of ±43,000 ft-lbs are achieved with yaw-priority, but only -21,500 to 29,900 ft-lbs are achieved without yaw-priority.

The cost of using yaw-priority to increase yaw capability is decreased roll moment, as can be seen in figure 25(c). A maximum of 2800 ft-lbs of roll moment was achieved with yaw-priority, whereas 4400 ft-lbs was achieved without yaw-priority. Note that with yaw-priority approximately 1600 ft-lbs of roll moment was traded for over 13,000 ft-lbs of yaw moment. With yaw-priority it can be seen in figure 12 that no roll-TV is allowed for yaw-TV commands above 7° when the pitch-TV command is 6°. This effect can be seen in figure 25(c). The approximately ±1000 ft-lb roll moment outside of the ±7° range of yaw-TV is the result of the product of 2100 lbs of TV force in the $\pm y$-direction and the 0.45 ft distance in the z-direction between the engine centerline and the airplane center of gravity.

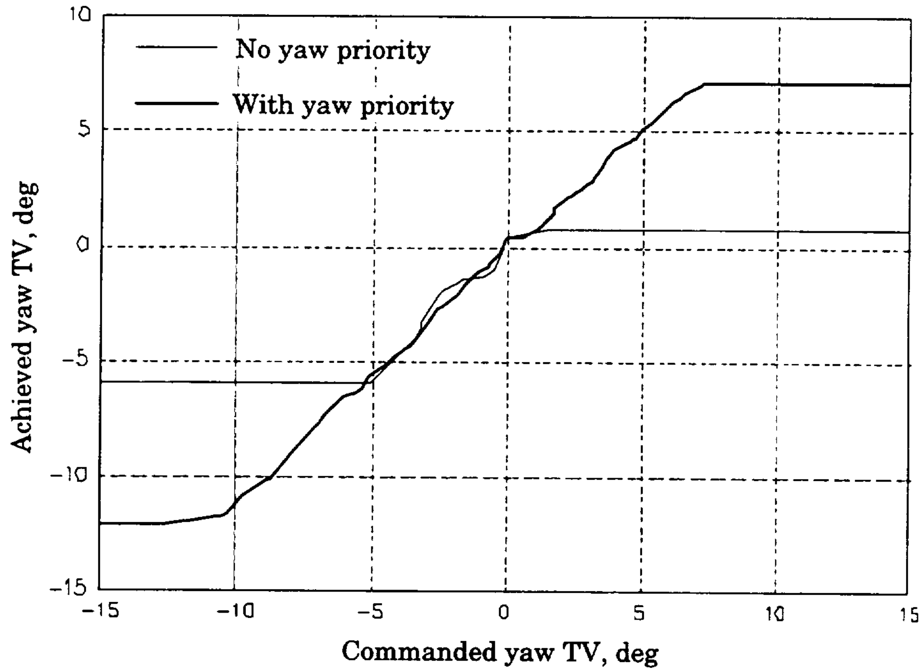


(a).- Wind-axis roll angle

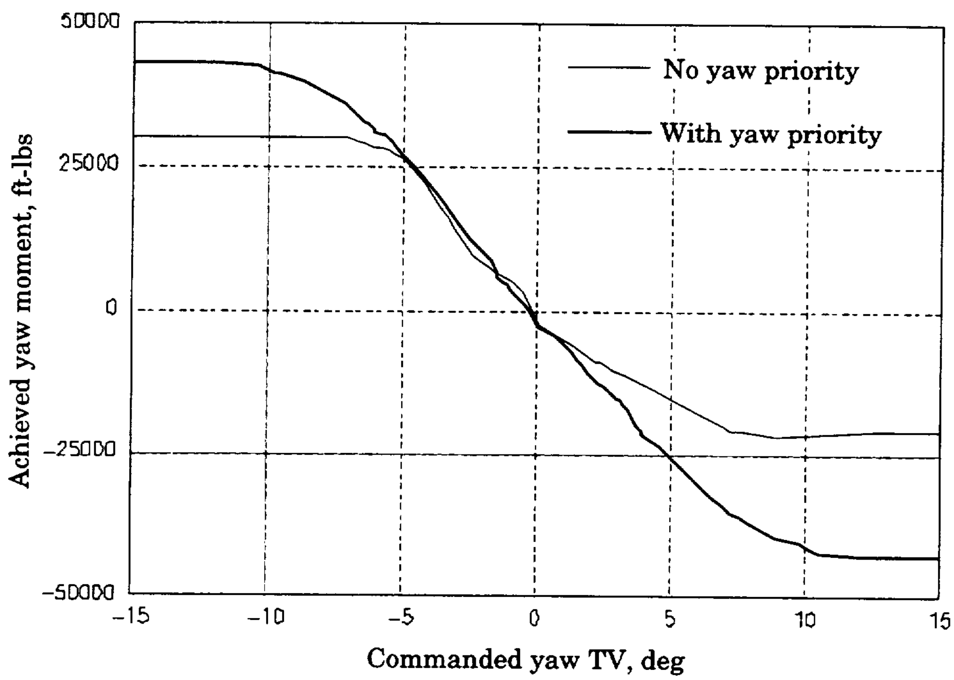


(b).- Angle of attack

Figure 24.- Effects of pitch priority and variable pitch limiter on roll rate and angle-of-attack regulation.

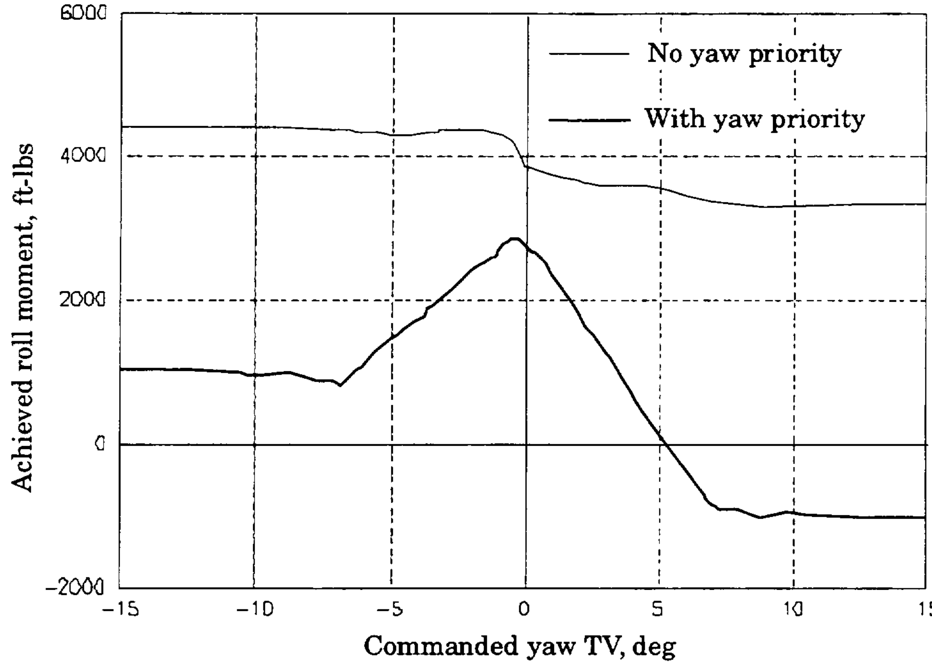


(a).- Achieved yaw thrust-vectoring angle for left engine.



(b).- Achieved yaw moment for both engines.

Figure 25.- Effects of yaw priority on achievable thrust vectoring.



(c).- Achieved roll moment for both engines.

Figure 25.- Concluded.

Flight results.- The new Mixer design (M4) was flown on the HARV in the summer of 1994, when an advanced control law design known as NASA-1A was flight tested. In general, the Mixer performed well in flight and as expected; however, it is not the purpose here to present a comprehensive review of the results of these flight tests for the Mixer or the flight control laws. Some maneuvers performed during the flights, though, illustrate a couple of key points about priority logic for thrust vectoring systems. Results for a typical maneuver will be presented.

On Flight 260 a 360° stability-axis roll to the left was attempted at 60° angle of attack. As shown in figure 26 the aircraft reached a peak body-axis yaw rate at about 7.5 seconds into the maneuver, and then the stability-axis roll-rate began to diminish. At about 12.5 seconds the stability-axis roll reversed direction, and the aircraft began to roll to the right. In the roll to the left a maximum wind-axis roll angle of approximately 65° was achieved. If additional roll control power had been available from ailerons, differential tail, rudder, and thrust vectoring, the 360° roll could have been completed.

Figure 27(a) shows time-history plots of the body-axis yaw thrust-vectoring angles computed from flight data for this maneuver. The desired thrust vectoring is simply the yaw vectoring angle commanded by the flight control law after adjustment for thrust level. The achieved yaw thrust-vectoring angles were calculated by putting appropriate flight data into a simulation of the engine , TVS, and two Mixer/Predictor designs, namely, the original Mixer (MPre) and the new NASA-1A design (M4). Note that because of TVS limitations the desired yaw vectoring cannot be achieved with either Mixer for much of the maneuver. However, the original Mixer, which did not include priority logic, produces

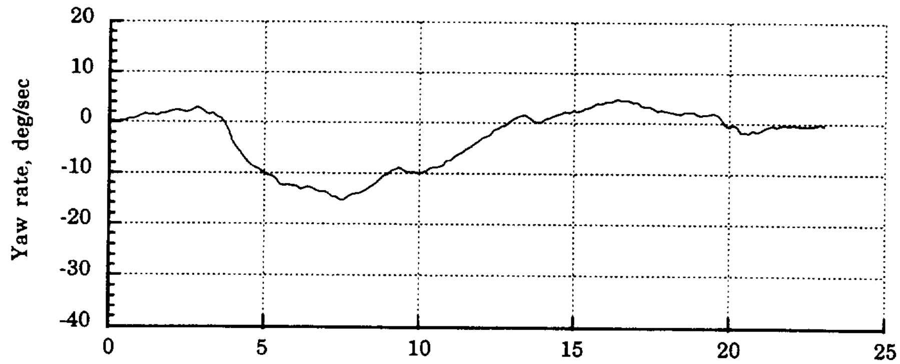


Figure 26.- HARV flight data showing yaw rate during roll maneuver.

more yaw vectoring than does the new design. This is not to say that the roll could have been completed using the original Mixer, but more yaw-TV would have been available.

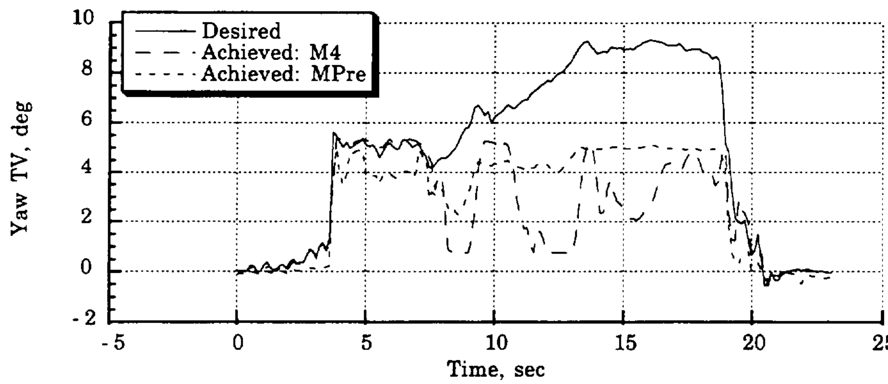
Figure 27(b) shows time-history plots of the pitch thrust-vectoring angles for this maneuver. Note that the original Mixer does not produce as much pitch vectoring as does the new design. Thus, with the original design the angle-of-attack regulation may not have been as good. This data illustrates the trade-off between achievable pitch- and yaw-TV that the designer must make in developing the priority logic.

Concluding Remarks

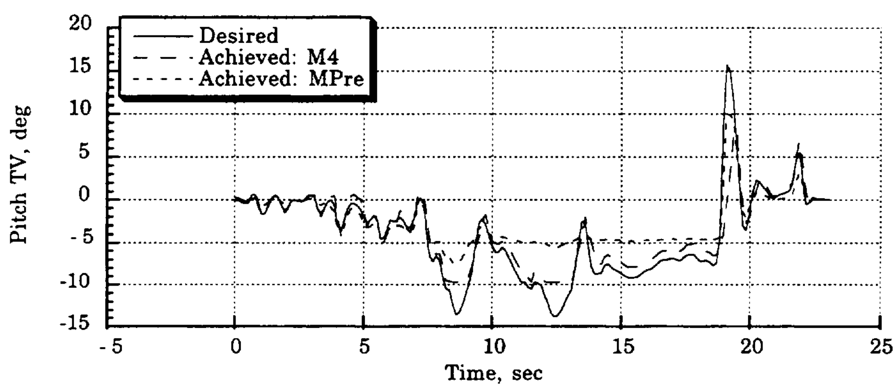
A new Mixer (M4) has been developed for the High-Alpha Research Vehicle to distribute pitch, yaw, and roll commands from the Flight Control System to the six thrust-vectoring vanes. This new Mixer is an improvement over the original HARV Mixer in terms of a command priority system and the accuracy with which it achieves the commanded thrust vectoring moments, although it does require more flight computer memory.

A new computer-aided process for designing a Mixer was also developed. This process includes the use of a numerical optimization technique to invert the TV-effectiveness data and thus obtain the TV-vane commands as functions of the commanded pitch- and yaw-TV angles. These vane positions are optimum in the sense of minimizing the total vane deflection while obtaining the desired TV accuracy.

The new design demonstrates the importance of incorporating a priority system to prioritize the pitch-, yaw-, and roll-TV commands from the FCS when all of the TV commands cannot be achieved simultaneously. The new design generally establishes pitch-TV as top priority over yaw and roll-TV to meet the high-alpha nose-up and nose-down requirements at high angles of attack while establishing yaw-TV as higher priority than roll-TV. Simulation and flight test results show that airplane performance tradeoffs can be made among the longitudinal, lateral, and directional axes by adjusting the TV priority logic, and these tradeoffs should be carefully considered during the Mixer design.



(a).- Yaw-TV angle.



(b).- Pitch-TV angle.

Figure 27.- TV angles calculated from flight data.

In the new design the inverted TV-effectiveness data places the third TV vane on the edge of the exhaust plume instead of in the stowed position when small TV angles are being commanded. The optimizer was useful in positioning the third vane on the plume without sacrificing TV accuracy as did the original Mixer. The use of variable-grid, asymmetrical arrays to store the inverted data proved valuable in significantly reducing the flight computer memory required by the new M4 Mixer.

The new Mixer (M4) design has successfully flown with two thrust-vectoring control laws on the F/A-18 HARV.

References

1. Siuru, Bill: Agile Aircraft: The Search for Supermaneuverability,. *Mechanical Engr.,* Dec. 1988, p.28.

2. Roberts, F.D.: *The F-15 STOL and Maneuver Technology Demonstrator (S/TMD) Program.* SAE 87-2383, Dec. 1987.

3. Foster, John V.; Bundick, W. Thomas; and Pahle, Joseph W.: Controls for Agility Research in the NASA High-Alpha Technology Program. *SAE Aerospace Tech. Conf. and Expos.,* SAE Paper-912148, Sept. 1991.

4. Pahle, Joseph W.; et al: *Research Flight Control System Development for the F-18 High Alpha Research Vehicle.* NASA TM 104232, 1991.

5. Bowers, Albion H.; et. al.: *Multiaxis Thrust Vectoring Using Axisymmetric Nozzles and Postexit Vanes on an F/A-18 Configuration Vehicle,'.* NASA TM-101741, 1991,

6. Lallman, Frederick J.: *Relative Control Effectiveness Technique With Application to Airplane Control Coordination.* NASA TP-2416, April 1985.

7. Lallman, Frederick J.: *Preliminary Design Study of a Lateral-Directional Control System Using Thrust Vectoring*. NASA TM-86425, November 1985.

8. Mason, Mary L.; Capone, Francis J.; and Asbury, Scott C.: *A Static Investigation of the Thrust Vectoring System of the F/A-18 High-Alpha Research Vehicle.* NASA TM-4359, June 1992.

9. Gerald, Curtis F.: *Applied Numerical Analysis*. Second ed. Addison Wesley, 1978.

10. Johnson,, Steven A.: *Aircraft Ground Test and Subscale Model Results of Axial Thrust Loss Caused by Thrust Vectoring Using Turning Vanes*,. NASA TM-4341, 1992.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1996	Technical Memorandum

4. TITLE AND SUBTITLE
Design of a Mixer for the Thrust-Vectoring System on the High-Alpha Research Vehicle

5. FUNDING NUMBERS
WU 505-68-30-05

6. AUTHOR(S)
W. Thomas Bundick (Langley), Joseph W. Pahle (Dryden Flight Research Center), Jessie C. Yeager (LE&SC), and Fred L. Beissner Jr. (Formerly LE&SC)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, Va 23681-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
NASA TM 110228

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unclassified-Unlimited

Subject Category - 08

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

One of the advanced control concepts being investigated on the High-Alpha Research Vehicle is multi-axis thrust vectoring using an experimental thrust-vectoring (TV) system consisting of three hydraulically actuated vanes per engine. A Mixer is used to translate the pitch-, roll-, and yaw-TV commands into the appropriate TV-vane commands for distribution to the vane actuators. A computer-aided optimization process was developed to perform the inversion of the thrust-vectoring effectiveness data for use by the Mixer in performing this command translation. Using this process a new Mixer was designed for the HARV and evaluated in simulation and flight. An important element of the Mixer is the priority logic, which determines priority among the pitch-, roll-, and yaw-TV commands.

14. SUBJECT TERMS
Flight control systems, thrust-vectoring, high angle of attack, control design

15. NUMBER OF PAGES
39

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified		