NASA TM-87344

NASA Technical Memorandum 87344

NASA-TM-87344 19860020596

HYTESS II—A Hypothetical Turbofan Engine Simplified Simulation With Multivariable Control and Sensor Analytical Redundancy

Walter C. Merrill
Lewis Research Center
Cleveland, Ohio

June 1986

NASA

HYTESS II - A HYPOTHETICAL TURBOFAN ENGINE SIMPLIFIED SIMULATION WITH MULTIVARIABLE CONTROL AND SENSOR ANALYTICAL REDUNDANCY

Walter C. Merrill
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-3014

SUMMARY

A hypothetical turbofan engine simplified simulation with a multivariable control and sensor failure detection, isolation, and accommodation logic (HYTESS II) is presented. The digital program, written in FORTRAN, is self-contained, efficient, realistic, and easily used. Simulated engine dynamics were developed from linearized operating point models. However, essential non-linear effects are retained. The simulation is representative of a hypothetical, low bypass ratio turbofan engine with an advanced control and failure detection logic. Included is a description of the engine dynamics, the control algorithm, and the sensor failure detection logic. Details of the simulation including block diagrams, variable descriptions, common block definitions, subroutine descriptions, and input requirements are given. Example simulation results are also presented.

INTRODUCTION

This report is a user's manual for the hypothetical turbofan engine simplified simulation with multivariable control and sensor failure detection logic (HYTESS II). This simulation builds upon the technology reported in reference 1. Essentially, the simulation developed in reference 1 (HYTESS) has been modified to incorporate a control law and sensor failure logic. Additionally, some improvements have been incorporated. In particular some routines have been eliminated to simplify the program flow. Also, some information transfer between routines is now accomplished explicitly using subroutine arguments rather than implicitly using large common blocks. This makes following and understanding program flow much easier. Finally, in HYTESS scaled (unitless) variables were used extensively in the simulation along with unscaled variables. This inconsistency often led to confusion. In HYTESS II all variables are now unscaled and therefore consistent from one routine to the next. Performance scaling, however, is still a feature of the program. It now takes place, once, during program initialization.

This digital simulation exists as FORTRAN source code and was designed for use on the NASA Lewis Research Center's IBM 3033 AP computer running under the TSS/370 operating system. The program is self-contained and was developed to offer those interested in engine dynamics and controls research an efficient, realistic, and easily used engine simulation.

Typically turbine engine simulations incorporate detailed nonlinear descriptions of both steady-state and dynamic engine operation throughout the engine's flight envelope. These detailed nonlinear simulations are very accurate and realistic and, when implemented in a digital computer, require relatively large amounts of computer storage and computer processing time.

This makes these detailed simulations difficult and costly to use. HYTESS II was developed as an alternative. It is structurally simpler than a full nonlinear engine simulation and therefore has reduced storage and processing requirements. HYTESS II retains the essential nonlinear effects inherent in the engine's operation. This is accomplished by modeling the engine using a linear state space formulation, and incorporating the nonlinear characteristics by representing the matrix elements within the linear state space structure as nonlinear functions of various engine variables. The compromise implied in this process is that, although the fidelity of HYTESS II is maintained for the variables considered, it is very difficult to identify individual component behavior as in a detailed simulation. Also HYTESS II is restricted to operation in regions about the normal operating line of the engine. The engine characteristics simulated by HYTESS II, although hypothetical, are qualitatively similar to those of realistic advance turbofan engines. Typical applications for this simulation would include open-loop engine dynamics studies, closed-loop controls analysis, and sensor failure detection performance studies.

This report begins with a description of the engine control and failure logic simulated by HYTESS II. Descriptions of the mathematical model of the engine and the simulation are given. Finally some results are given. Flow charts and variable definitions are also included.

SYMBOL LIST

Acronyms	Description
ADIA	advanced detection, isolation, and accommodation
HYTESS	hypothetical turbofan engine simplified simulation
LQR	linear quadratic regulator
MVC	multivariable control
PI	proportional-integral
SFS	sensor failure simulator
WSSR	weighted sum of squared residuals

Variables	Description
AJ	nozzle jet area
ALT	altitude
BLC	compressor bleed flow
D	feed forward system matrix.
F	state system matrix
f	engine nonlinear state function vector

$F^{-1}G$	gain system matrix
FGV	fan guide vane angle
FNMX	thrust
FTIT	fan turbine inlet temperature
<u>Variables</u>	<u>Description</u>
G	control system matrix
g	engine nonlinear output function vector
H	output system matrix
$\mathscr{H}$	log likelihood ratio
K	Kalman gain matrix
N	number of past residual samples
N1	fan speed
N2	compressor speed
PLA	power lever angle
PT2	engine face pressure
PT4	burner pressure
PT6	augmentor pressure
PO	ambient pressure
S	switching matrix
SMHC	compressor surge margin
SMN	Mach number
SVA	high compressor stator vane angle
TT2	engine face temperature
TT25	fan discharge temperature
TT4PLO	burner exit slow response temperature
TT45	inter-turbine temperature
TT45LO	fan turbine inlet slow response temperature
t	time

U	engine control vector
v	value
W	residual weighting factor
WFMB	main burner fuel flow

Variables	Description
X'	engine state vector
Y	engine output vector
δ	corrected face pressure
ε	residual vector
θ	corrected face temperature
λ	detection/isolation threshold
Φ	environmental variables

Subscripts	Description
b	base point
H	hard failure
I	isolation
i	hypothesis number
m	measured
RP	reference point
S	soft failure
SS	steady-state
TR	trajectory control
0	normal mode

SYSTEM DESCRIPTION

The system described by this report consists of a hypothetical turbofan engine, sensors, actuators, control system, sensor failure simulator (SFS), and sensor failure detection, isolation, and accommodation (DIA) logic. These components are connected as shown in figure 1. Note that sensors for three classes of variables are shown: (1) control variables, (2) environmental variables, and (3) engine outputs. Note also that the sensor failure logic applies only to the engine output variable sensors. A description of each of these components and its respective model follows.

ENGINE DESCRIPTION

The engine simulated by HYTESS II is representative of current high technology engines and is shown schematically in figure 2. It is a low bypass ratio, twin-spool, axial-flow turbofan engine, consisting of the following components:

(1) Low-speed fan driven by a turbine (spool 1)

(2) High-speed compressor driven by a turbine (spool 2)

(3) Main burner

(4) Annular fan duct that surrounds the basic gas generator and discharges air into the mixed flow augmentor

(5) Variable area nozzle

Variable inlet guide vanes are used ahead of the fan to improve inlet distortion tolerance and fan efficiency. Variable stators in the high compressor improve starting and high Mach number characteristics. Airflow bleed is extracted at the compressor exit to improve starting. The exhaust nozzle variable geometry enables all three nozzle performance parameters (nozzle area, expansion ratio, and boattail drag) to be simultaneously near optimum throughout the operating range. A list of engine inputs and outputs is given in the next section.

Engine Model

A detailed nonlinear engine model can be written in vector differential equation form

$$\left.\begin{aligned} \dot{X} &= f(X,U,\Phi) \\ Y &= g(X,U,\Phi) \end{aligned}\right\} \qquad (1)$$

where X is a state vector, U is the vector of controls, Y is the output vector, and Φ is a vector of environmental conditions. Detailed nonlinear engine relations are represented by the functions $f(\cdot)$ and $g(\cdot)$. At a base point, that is a steady-state point on the operating line,

$$\left.\begin{aligned} f(X_b,U_b,\Phi_b) &= 0 \\ Y_b &= g(X_b,U_b,\Phi_b) \end{aligned}\right\} \qquad (2)$$

In HYTESS the state space description of the model of equations (1) and (2) is implemented as

$$
\left.\begin{aligned}
X_{ss} &= X_b - F^{-1}G(U - U_b) \\
\dot{X} &= F(X - X_{ss}) \\
Y &= Y_b + H(X - X_b) + D(U - U_b)
\end{aligned}\right\} \qquad (3)
$$

The subscript b is used to denote base points. The subscript ss is used to denote the steady-state value of X for a given U. The matrices F, $F^{-1}G$, H, and D are the typical system matrices. The states, inputs, and outputs were chosen to be typical of those variables used in dynamics and controls analysis in modern turbofan engines and consist of the following variables.

States:

X_1 fan speed (N1), rpm
X_2 compressor speed (N2), rpm
X_3 burner exit slow response temperature (TT4PLO), K
X_4 fan turbine inlet slow response temperature (TT45LO), K

Engine inputs:

U_1 main burner fuel flow (WFMB), kg/sec
U_2 nozzle jet area (AJ), m^2
U_3 fan guide vane position (FGV), deg
U_4 high compressor variable stator vane angle (SVA), deg
U_5 customer compressor bleed flow (BLC), percent

Engine outputs:

Y_1 fan speed (N1), rpm
Y_2 compressor speed (N2), rpm
Y_3 burner pressure (PT4), N/m^2
Y_4 augmentor pressure (PT6), N/m^2
Y_5 fan turbine inlet temperature (FTIT), K
Y_6 thrust (FNMX), N
Y_7 compressor surge margin (SMHC)

Operating conditions:

Φ_1 ambient pressure (PO)
Φ_2 engine face pressure (PT2), N/m^2
Φ_3 engine face temperature (TT2), K
Φ_4 fan discharge temperature (TT25)

The system matrices were determined in the following manner. Linearized system matrices at several base points were found from a representative detailed nonlinear simulation using perturbational techniques. The elements of each of these matrices were regressed upon selected engine variables or elementary functions of these variables (elements of Y and Φ). As a result, nonlinear polynomial functions were found that fit the change in these matrix elements for the full range of engine power through the flight envelope as shown in figure 3. An example of some typical regression polynomials for the system matrices is given in table 1. Rewriting equation (3) with a more explicit functional notation yields

$$\left.\begin{aligned} X_{ss} &= X_b(Y,\Phi) - [F^{-1}G](Y,\Phi)[U - U_b(Y,\Phi)] \\ \dot{X} &= F(Y,\Phi)[X - X_{ss}] \\ Y &= Y_b(Y,\Phi) + H(Y,\Phi)[X - X_b(Y,\Phi)] + D(Y,\Phi)[U - U_b(Y,\Phi)] \end{aligned}\right\} \qquad (4)$$

Note, that in the list of engine variables, TT25 was defined as an operating condition variable. Although strictly an engine output, TT25 (Φ_4) is being called an environmental or operating condition variable for three reasons. First the only place TT25 is used in the control logic is to schedule the SVA. Thus, TT25 is used only in a fashion similar to that for the other environmental variables. Second, TT25 is not covered by the sensor failure logic as are all of the listed engine output variables. Finally, in this simulation TT25 is modeled as

$$TT25 = \left(0.2308 \frac{PT6}{PT2} + 0.82\right) TT2$$

Thus, TT25 is linearly related to TT2, an environmental variable.

Control Description

The control law used here is a multivariable proportional-integral (PI) control law. The control used is a modification of an existing control (ref. 2) designed for a high performance turbofan engine. This engine has a similar input-output structure to HYTESS II, and thus, the existing control was a logical starting point for the HYTESS II control. A block diagram of the HYTESS II control is given in figure 4. Also shown are the subroutines that correspond to the various blocks. The reference point schedules establish the desired steady-state performance of the engine and essentially are an implementation of equation 2. The reference point schedules are followed by the transition control which limits the rate of change of the commanded variables during changes in operating point. The variables, U_{TR}, serve as feed forward controls, while Y_{TR} serves as a command trajectory to be followed by the control law. The PI control acts upon differences between Y_{TR} and the engine output estimates which are obtained from the DIA logic. The PI gains are scheduled as a function of Φ and the compressor speed component of Y_{TR}. Finally, the maximum and minimum values of the control are limited by the engine protection logic to ensure safe engine operation.

Sensor Failure Logic Description

Also, incorporated in the simulation is logic based upon the principle of analytical redundancy (ref. 3) to detect, isolate, and accommodate (DIA) sensor failures. The DIA logic incorporated in this simulation is a modification of a recently developed algorithm (ref. 4) called the Advanced Detection, Isolation, and Accommodation (ADIA) algorithm. The ADIA as originally developed incorporates advanced filtering and detection methodologies. The ADIA logic was modified for use with HYTESS II by incorporating the HYTESS II model in the ADIA logic. Thus, in the simulation there are two identical copies of the engine dynamics. The first engine model is combined with a multivariable control and DIA logic to form the simulation. The DIA logic portion of the simulation itself contains the second copy of the engine model which is used to estimate engine outputs.

The DIA logic consists of four elements: (1) hard failure detection and isolation logic, (2) soft failure detection logic, (3) soft failure isolation logic, and (4) an accommodation filter. The algorithm detects two classes of sensor failures, hard and soft. Hard failures are out-of-range or large bias errors that occur instantaneously in the sensed values. Soft failures are small bias errors or drift errors that accumulate relatively slowly with time. The algorithm inputs are the measured engine inputs, $U_m(t)$, and the measured engine outputs, $Y_m(t)$. The algorithm outputs are optimal estimates, $\hat{Y}(t)$, of the engine outputs, $Y(t)$.

The algorithm has two modes of operation, normal and failure. During normal mode operation, i.e., when no sensor failure is present, the normal mode accommodation filter uses all the measured information to determine $\hat{Y}(t)$. In failure mode operation, one of the five sensors has failed. Simultaneous multiple sensor failures are rare events and are not considered. A threefold process takes place once the failure has occurred. First the failure is detected. Once a failure is known to have occurred, the specific faulty sensor must be isolated. Finally, when isolation has occurred, the failure is accommodated by reconfiguring the normal mode accommodation filter which generates the estimates, $\hat{Y}(t)$. This threefold procedure takes place for both hard and soft failures.

The normal mode accommodation filter logic, shown in figure 5, generates the estimates of the engine outputs, $\hat{Y}(t)$. In the Kalman filter equations, the matrices F, G, H, and D are typical state space system matrices where $\hat{X}(t)$ is the 4 by 1 vector of estimates of the engine's state variables and $\varepsilon(t)$ is the 5 by 1 vector of residuals. The matrix K is the Kalman gain matrix, and S is a switching matrix. The diagonal elements of S, s_{ii}, are either 1 or 0. All the system matrices as well as the Kalman gain matrix are scheduled as a function of operating point to model variations in engine dynamics.

The hard failure detection and isolation logic, shown in figure 6, performs a straightforward threshold check on each sensor residual, ε_i. Threshold values are determined from sensor and process noise values as well as sensor range considerations. If a residual value is greater than the threshold, λ_H, hard failure detection and isolation follow immediately.

If a hard failure has not occurred, then a soft failure check is performed. The soft failure detection logic, shown in figure 7, first calculates an average weighted sum of squared residuals (WSSR). A soft failure is detected when the weighted sum is greater than a prespecified soft failure detection threshold, λ_S. The number, N, of past residuals summed to obtain the average, the weighting factor, W, and the detection threshold, λ_S, are design parameters that are chosen to provide an acceptable tradeoff between false alarms and missed detections.

Once a soft failure has been detected, the soft failure isolation logic, shown in figure 8, is used to isolate the failed sensor. Six different isolation filters generate six different sets of residuals, one for each possible failed sensor, and one based on no failed sensors. A log likelihood ratio, $\mathcal{H}_i$ is generated for each set of residuals. A test is then performed which determines the most probable set of residuals by finding the maximum $\mathcal{H}_i$. When this maximum $\mathcal{H}_i$ is above an isolation threshold, λ_I, the faulty sensor is isolated.

Once a hard or soft failure is detected and isolated, the accommodation filter is reconfigured by an appropriate change of its Kalman gain matrix, K, to remove the failed sensor from consideration. This is shown conceptually as a modification of the switching matrix S. For example if a failure in sensor 3 has been isolated then $s_{33} = 0$ and $s_{ii} = 1$, $i = 1,2,4,5$. That is

$$S = \begin{vmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{vmatrix}$$

For a soft failure of sensor i, the accommodation filter is also reinitialized to the current value of $\hat{Y}_i(t)$ and $\hat{X}_i(t)$ from the appropriate isolation filter. Reinitialization is necessary since a significant amount of time may have elapsed between failure and isolation.

The output of the algorithm, $\hat{Y}$, is directed to the PI control law. Thus, although the filter reconfigures due to sensor failures no control mode reconfiguration is required. All DIA logic is contained within the subroutine FDIA. Filter dynamics are calculated by the subroutine FILTER.

Program Description

HYTESS II contains all the subroutines necessary to execute the program. There are no system library routines required. The program is written in FORTRAN 66, and it is anticipated that few modifications, if any, will be required to execute the program on any system of adequate size that supports FORTRAN. Additionally, the program is entirely compatible with the ANSI 77 FORTRAN standard except for the use of the NAMELIST feature in the following subroutines GCNTL, INCNTL, MODEL, READIN, SCURVE, and TRCNTL. The NAMELIST statements in all the routines, except READIN, could be trivially removed without changing program operation. Changes to eliminate the use of the NAMELIST feature in READIN would be straightforward but substantial.

The program itself consists of a main program and 46 subroutines and 5 block data routines. (See table II for program hierarchy.) There are a total of eight levels with a maximum of seven levels of nested subroutines. For example at level III the subroutine INLET (called by STDST8) calls four subroutines: ALTABL, PRCMB, HFTA, and TFHA. Subsequently, PRCMB, HFTA, and TFHA all call PVAL. Subroutines are listed in the order of their first occurrence in the calling program. Several of the subroutines may be called more than once by the calling routine. No attempt has been made to show multiple calls in table II. In table III a description of the purpose of each subroutine and block data is given.

Basic program flow is shown in figure 9. Essentially, the program initializes, reads input data, calculates a steady-state point, and if required, calculates a user-specified transient. The program accepts as steady-state or transient input either of the following two sets of inputs:

Input set 1 (IS1)

Altitude (Alt)
Mach number (MN)
Power level angle (PLA)

Input set 2 (IS2)

Altitude (Alt)
Mach number (MN)
Fuel flow (WFMB)
Nozzle area (AJ)
Fan guide van angle (FGV)
High compressor stator vane angles (SVA)
Bleed flow (BLC)

Input set 1 is used to simulate engine response to pilot (PLA) requests. Engine response to PLA is the typical mode of operation for the simulation. Input set 2 overrides the engine inputs calculated by the control logic and replaces them with user supplied values. This mode of operation might be useful for a study of engine dynamics, for example. Also included in the input information are program control parameters which control steady-state and transient execution of the program. Input requirements are completely specified in the next section. This is followed by descriptions of the steady-state and transient options of the main program.

Input Requirements

HYTESS II uses the FORTRAN input mode called NAMELIST to accept values for input parameters. There are six namelists used in subroutine READIN to define input parameters: INPUT, SCALE, MVCIN, INTRAN, PLOT, and FSNS. To help illustrate data entry two examples of program input which correspond to IS1 and IS2 are given in tables IV and V, respectively. Note that although program output is available in both English and metric units, program input must be specified in English units.

Namelist INPUT

The namelist INPUT is used to define the steady-state input as well as for program control. All of the variables used to define a steady-state engine condition as well as some option control parameters are contained in namelist INPUT. The variable names, their default values, and descriptions are given in table VI. For example in table IV the namelist INPUT is used to (1) indicate that a transient is required (TRAN = 1.0); (2) indicate that plotting variables are to be saved (IPLOT = 1); (3) indicate that sensor failures are to be detected (SFAIL = 1.0); (4) define the initial conditions for IS1(SALT = 0.0, SMACH = 0.0, SPLA = 20.0); and (5) indicate that the program output is to be in metric units.

Namelist SCALE

The namelist SCALE is used to change the program's scale factors. These scale factors can be changed to modify engine simulated performance. The variable names, their default values, and descriptions are given in table VII. The default values are selected to yield a performance that is typical of modern, high performance turbofan engines.

Namelist MVCIN

The namelist MVCIN is used to control the modification of the multivariable control. The variable names, their default values, and descriptions are given in table VIII.

Namelist INTRAN

The namelist INTRAN is used to define the input necessary for an engine transient. This namelist is only read if TRAN = 1.0 in the namelist INPUT. All of the parameters entered via this namelist are entered in the following array format

$$\text{ARRAY} = t_1,v_1,t_2,v_2, \ . \ . \ ., t_n,v_n$$

where ARRAY represents the respective variable array and t_i,v_i is a time/value pair. Up to seven pairs may be entered for each array variable, i.e., $n \leq 7$. The INTRAN namelist parameters are accepted as either step or ramp inputs. Since the particular array variable is specified at n discrete time points, the intervals between time points need to be further specified. This is accomplished by defining step and ramp inputs. For a step input the array value in any interval, say t_i to t_{i+1}, is equal to the preceding time point array value v_i. For a ramp input, the array value in any interval lies on a straight line defined by the two points t_i,v_i and t_{i+1},v_{i+1}. Variable names, default values, and descriptions for the transient input namelist INTRAN are given in table IX. For example in table IV namelist INTRAN is used to define the print interval, the user specified PLA transient, and the sampling rate of the control. In this case the PLA input is specified as shown in figure 10.

Namelist PLOT

The namelist PLOT is used to specify plotted variables. This namelist will only be read if IPLOT = 1 in the namelist INPUT. Namelist PLOT contains three array variables, IPVAR1, IVPAR2, and IPVAR3 as defined in table X. These array variables are used to specify the variables to be stored for plotting. A certain variable is specified for plotting by including its associated integer value (channel number) as defined in appendix A in the variable IPVAR1, in appendix B in IPVAR2 and in appendix C in IPVAR3. For example in table IV, IPVAR1 contains the channel numbers 1, 4, 22, and 23. Referencing these numbers with appendix A, it can be seen that TIME(1), PLA(4), engine fan speed(22), and engine compressor speed(23) are specified for plotting. From table IV, IPVAR2 specifies sensed fan and compressor speed for plotting while

IPVAR3 specifies the accommodation filter residuals that correspond to fan and compressor speed.

Namelist FSNS

The namelist FSNS is used to define various performance parameters (detection thresholds, e.g.) for the sensor failure detection logic as well as specifying simulated failures. Sensor failures are simulated in the subroutine FSENS as

$$YFAILED = SF*YSENSED + BIAS + NOISE \quad (5)$$

Default values (SF = 1.0, BIAS = 0.0, NOISE = 0.0) are for the no failure (normal mode) case. The variable NAMP is used to specify noise amplitude. The variables that begin with SN are used to define the scale factors (SF in eq. 5), and the variables that begin with BI define the bias failure values. A complete description is given in table XI. In the IS1 example of table IV a bias failure is simulated on the PT6 sensor. The failure is plotted versus time in figure 11.

Steady-State Program

After the main program is initialized and the input conditions are specified, a steady-state operating point must be established. This is accomplished by a call to subroutine STDST8. Basic program flow through this subroutine is shown in figure 12. First the subroutine INLET is used to calculate engine face conditions. For example given ALT and SMN (see appendix A), INLET calculates PO, TO, PT2, VO, and ETARAM. This subroutine is based upon a table of altitude, pressure, and temperature data taken from the 1962 Geometric Standard. Next, PLA is determined, either explicitly or implicitly from the user specified input. Then nominal engine operation is calculated by RPSCH for this value of PLA. Next, the multivariable control and the sensor DIA logic is calculated for the nominal engine response by MVCNT. Next, engine model base points (eq. 2) and system matrices are calculated by EMODEL. Finally, the actual engine model response is simulated by SIMUL using the control information obtained from MVCNT and the parameters obtained from EMODEL. A convergence test is applied to fan speed. If the fan speed predicted by SIMUL (model response) is equal to the fan speed (nominal response) used in the initial call to RPSCH (within 0.01 percent) then convergence to a steady-state point is achieved. The steady-state values of the engine states, controls, and outputs are used as initial conditions in any subsequent transient calculation.

Transient Program

After a steady-state operating point is established, the main program determines if a transient calculation was requested (TRAN = 1.0). If requested, the transient is simulated by the subroutine TRANS. A block diagram of the basic program flow through TRANS is given in figure 13. Here the program flow is similar to that of STDST8. First model base points and system matrices are computed (EMODEL). Next, engine dynamics are simulated (SIMUL). The data is printed if the print time specified by the user is equal to the simulated time. Next, a call to NUTIME updates the simulated time and updates all the user requested transient input information that was entered through the namelist INTRAN. If simulated time is greater than the stop time there is a final data print before the return to the main program. Next, new engine face conditions are calculated (INLET) and the control and sensor DIA logic are simulated (MVCNT). The program then returns to the call to EMODEL and continues the iteration through the program. Each iteration represents an update of the Euler integration scheme (in SIMUL) and the iteration continues until the specified final time is reached.

Program Output

Figure 14 shows a sample of some of the printout for the test case of table IV. The program first prints the number of iterations required to reach a steady-state point. This output is controlled by the subroutine STDST8. The main program output is generated by calls to the subroutine PRINT. For both steady-state and transient data subroutine PRINT prints the variables from the common ENGOUT (appendix A), common MVCOUT (appendix B), and common DIAOUT (appendix C). The ENGOUT variables are labeled ENGINE RESPONSE VARIABLES' with four subheadings. The MVCOUT variables are labeled 'CONTROL RESPONSE VARIABLES' with sixteen subheadings, and the DIAOUT variables are labeled 'DIA RESPONSE VARIABLES' with seventeen subheadings. The subroutine PRINT uses a 10-column format. Each column corresponds to a time at which routine PRINT was called. The program also creates an unformatted binary data file written on unit 10. This file contains all the transient data that was specified by the user for plotting. Figures 15 to 17 are time plots of the variables specified for plotting in the example of table IV. The plot of PLA is already given in figure 9. Routines for plotting transient data are not included in the HYTESS II program. Thus, the user must interface his own plotting capability to the program.

CONCLUDING REMARKS

A hypothetical turbofan engine simplified simulation with control and sensor failure DIA logic is presented. The program is suitable for dynamics and control analysis. The engine simulation is structurally simpler than a detailed performance digital simulation. However, it does retain the essential nonlinearities of the engine and accurately simulates qualitative engine operation. The engine is modeled using a state space structure. Elements within the state matrices are defined by polynomials whose independent variables are functions of engine environment and engine operation. Storage and execution time requirements are significantly less than those for a detailed nonlinear simulation and are quite reasonable for typical dynamics and control analysis studies. The control is a multivariable proportional plus integral controller. The control represents advanced engine control technology. Also simulated is sensor failure detection, isolation, and accommodation logic. This DIA logic is based upon state of the art decision making and control theories. Thus, HYTESS II represents a realistic, technically advanced, test bed for a variety of research objectives within the dynamics and controls arena.

APPENDIX A

ENGINE SIMULATION VARIABLES IN ENGOUT

The following is the list of engine variables used in the simulation. These variables are all in the COMMON called ENGOUT and are also printed as a portion of the hard copy output of the program.

Channel number	Variable	Units	Description
1	T	sec	Time
2	ALT	m	Altitude
3	SMN	-------	Mach number
4	PLA	deg	Power level angle
5	PO	N/M^2	Ambient pressure
6	TO	K	Ambient temperature
7	DPO	N/m^2	Adder to ambient pressure
8	DTO	K	Adder to ambient temperature
9	PT2	N/m^2	Engine face pressure
10	TT2	K	Engine face temperature
11	VO	m/sec	Airspeed at the inlet
12	ETARAM	-------	Ram efficiency
13	WFMBH	kg/sec	Fuel flow
14	AFCD	m^2	Nozzle area
15	FGVPOS	deg	Fan guide vane angle
16	SVAPOS	deg	High compressor stator angle
17	BLC	Percent	Bleed flow
18	SNFAN	rpm	Fan physical speed, engine state
19	SNCOM	rpm	Compressor physical speed, engine state
20	TT4PLO	K	Burner exit slow response temperature, engine state
21	TT45PLO	K	Fan turbine inlet slow response temperature, engine state
22	SNFM	rpm	Fan physical speed, engine output
23	SNCM	rpm	Compressor physical speed, engine output
24	PT4	N/m^2	Burner pressure, engine output
25	PT6	N/m^2	Augmentor pressure, engine output
26	TT45	K	Fan turbine inlet, engine output
27	FNMX	N	Thrust, engine output
28	SMHC	-------	Compressor surge margin, engine output
29	XTRA1	-------	Extra dummy variable
30	XTRA2	-------	Extra dummy variable

APPENDIX B

CONTROL SIMULATION VARIABLES IN MVCOUT

The following is a list of control variables used in the simulation. These variables are all in the common called MVCOUT and are also printed as a portion of the hard copy output of the program.

Channel number	Variable	Units	Description
1	PLAMV	deg	PLA input
2	ALTMV	m	Altitude input
3	SMNMV	-------	Mach number input
4	TT2MV	K	Ambient TT2
5	PT2MV	kPa	Ambient PT2
6	PLASN	deg	Sensed PLA
7	TT2SN	K	Sensed TT2
8	PT2SEN	N/m^2	Sensed PT2
9	SMNSEN	-------	Sensed Mach number
10	PMODE	-------	Extra variable
11	SNFSEN	rpm	Sensed fan speed
12	SNCSEN	rpm	Sensed compressor speed
13	TT25SN	K	Sensed TT25
14	FTITSN	K	Sensed FTIT
15	PT4SEN	N/m^2	Sensed PT4
16	PT6MSN	N/m^2	Sensed PT6
17	RINP1	-------	Extra variable
18	RINP2	-------	Extra variable
19	RINP3	-------	Extra variable
20	RINP4	-------	Extra variable
21	WFMBFB	kg/sec	Sensed fuel flow
22	AJFB	m^2	Sensed nozzle area
23	SVAVFB	deg	Sensed high compressor stator angle
24	FGVVFB	deg	Sensed fan guide vane angle
25	BLCFB	percent	Sensed bleed flow
26	PLAEST	deg	Estimated PLA
27	TT2EST	K	Estimated TT2
28	PT2EST	N/m^2	Estimated PT2
29	SMNEST	-------	Estimated Mach number
30	PMDEST	-------	Extra variable
31	SNFEST	rpm	Estimated fan speed
32	SNCEST	rpm	Estimated compressor speed
33	T25EST	K	Estimated TT25
34	FTIEST	K	Estimated FTIT
35	PT4EST	N/m^2	Estimated PT4
36	PT6EST	N/m^2	Estimated PT6
37	REST1	-------	Extra variables
38	REST2	-------	Extra variables
39	REST3	-------	Extra variables
40	REST4	-------	Extra variables
41	WFMBES	kg/sec	Estimated fuel flow
42	AJEST	m^2	Estimated nozzle area
43	SVAVES	deg	Estimated stator vane angle

Channel number	Variable	Units	Description
44	FGVVES	deg	Estimated fan guide vane angle
45	BLCEST	percent	Estimated bleed
46	PLASS	deg	Steady state schedule value of PLA
47	TT2SS	K	Steady state schedule value of TT2
48	PT2SS	N/m^2	Steady state schedule value of PT2
49	SMNSS	-------	Steady state schedule value of SMN
50	PMDSS	-------	Extra variable
51	SNFSCH	rpm	Steady state schedule value of fan speed
52	SNCSCH	rpm	Steady state schedule value of compressor speed
53	T25SCH	K	Steady state schedule value of TT25
54	FTISCH	K	Steady state schedule value of FTIT
55	PT4SCH	N/m^2	Steady state schedule value of PT4
56	PT6MSH	N/m^2	Steady state schedule value of PT6
57	TT4P	K	Steady state schedule value of TT4PLO
58	TT45P	K	Steady state schedule value of TT45PLO
59	FNMXSH	N	Steady state schedule value of THRUST
60	SMHCSH	-------	Steady state schedule value of compressor surge margin
61	WFMBSH	kg/sec	Steady state schedule value of fuel flow
62	AJSCH	m^2	Steady state schedule value of nozzle area
63	FGVVSH	deg	Steady state schedule value of fan guide vane angle
64	SVAVSH	deg	Steady state schedule value of stator vane angle
65	BLCSH	percent	Steady state schedule value of bleed
66	PLATR	deg	Transition control value of PLA
67	TT2TR	K	Transition control value of TT2
68	PT2TR	N/m^2	Transition control value of PT2
69	SMNTR	-------	Transition control value of Mach number
70	PMDTR	-------	Extra variable
71	SNFTR	rpm	Transition control value of fan speed
72	SNCTR	rpm	Transition control value of compressor speed
73	T25TR	K	Transition control value of TT25
74	FTITR	K	Transition control value of FTIT
75	PT4TR	N/m^2	Transition control value of PT4
76	PT6MTR	N/m^2	Transition control value of PT6M
77	RTR1	-------	Extra variable
78	RTR2	-------	Extra variable
79	RTR3	-------	Extra variable
80	RTR4	-------	Extra variable
81	WFMBTR	kg/sec	Transition control value of fuel flow
82	AJTR	m^2	Transition control value of nozzle area
83	FGVVTR	deg	Transition control value of fan guide vane angle
84	SVAVTR	deg	Transition control value of stator vane angle
85	BLCTR	percent	Transition control value of bleed
86	DELN1	rpm	Regulator error, fan speed
87	DELN2	rpm	Regulator error, compressor speed
88	DELPT6	N/m^2	Regulator error, PT6
89	DELTIT	K	Regulator error, FTIT
90	DELPT4	N/m^2	Regulator error, PT4
91	DLQWF	kg/sec	Regulator control contribution, fuel flow
92	DLQAJ	m^2	Regulator control contribution, nozzle area
93	DLQSVA	deg	Regulator control contribution, stator vane angle
94	DLQFGV	deg	Regulator control contribution, fan guide vanes

Channel number	Variable	Units	Description
95	DLQBLC	percent	Regulator control contribution, bleed
96	XINFER	rpm	Integral error, fan speed
97	XIEPER	-------	Integral error, EPR
98	XISVER	deg	Integral error, stator vane
99	XIFGER	deg	Integral error, fan guide vanes
100	XIBLER	percent	Integral error, bleed
101	XIFTER	K	Integral error, FTIT
102	XIPHER	N/m^2	Integral error, high burner pressure
103	XIPLER	N/m^2	Integral error, low burner pressure
104	XTRAA1	-------	Extra variable
105	XTRAA2	-------	Extra variable
106	DITWF	kg/sec	Euler difference value of WFMBH
107	DITAJ	m^2	Euler difference value of AJCD
108	DITSVA	deg	Euler difference value of SVAPOS
109	DITFGV	deg	Euler difference value of FGVPOS
110	DITBLC	percent	Euler difference value of BLC
111	XIWFMB	kg/sec	Integral control contribution of WFMBH
112	XIAJ	m^2	Integral control contribution of AJCD
113	XISVAV	deg	Integral control contribution of SVAPOS
114	XIFGVV	deg	Integral control contribution of FGVPOS
115	XIBLC	percent	Integral control contribution of BLC
116	WFMBCL	kg/sec	Unlimited control output for WFMBH
117	AJCL	m^2	Unlimited control output for AJCD
118	SVAVCL	deg	Unlimited control output for SVAPOS
119	FGVVCL	deg	Unlimited control output for FGVPOS
120	BLCCL	percent	Unlimited control output for BLC
121	WFCOM	kg/sec	Commanded control output for WFMBH
122	AFCOM	m^2	Commanded control output for AJCD
123	SVAVCM	deg	Commanded control output for SVAPOS
124	FGVVCM	deg	Commanded control output for FGVPOS
125	BLCCM	percent	Commanded control output for BLC
126	WFABSH	-------	Unused variable
127	WFABTR	-------	Unused variable
128	WFABCL	-------	Unused variable
129	WFABCM	-------	Unused variable
130	WFABFB	-------	Unused variable
131	WFABES	-------	Unused variable
132	XSEGLT	-------	Unused variable
133	XLOD	-------	Unused variable
134	DLQWAB	-------	Unused variable
135	XIWFAB	-------	Unused variable
136	XIABER	-------	Unused variable
137	DITWAB	-------	Unused variable
138	ABS5	-------	Unused variable
139	ABS6	-------	Unused variable
140	ABS7	-------	Unused variable
141	XWFFLG	-------	Fuel flow limit flag (1 = Max limit, -1 = Min limit
142	XAJFLG	-------	AJ limit Flag (1 = Max limit, -1 = min limit)
143	XRCFLG	-------	SVAPOS limit flag (1 = Max limit, -1 = Min limit)
144	XCVFLG	-------	FGVPOS limit flag (1 = Max limit, -1 = Min limit)
145	XBLFLG	-------	BLC limit flag (1 = Max limit, -1 = Min limit)
146	XABFLG	-------	Unused variable

Channel number	Variable	Units	Description
147	XNFFLG	-------	Integral control (=1, fan speed control)
148	XFTFLG	-------	Integral control flag (=1, FTIT control)
149	XPHFLG	-------	Integral control flag (=1, Max PT4 control)
150	XPLFLG	-------	Integral control flag (=1, Min PT4 control)
151	XMTRAN	-------	Transient indication flag
152	SPR2	-------	Unused variable
153	SPR3	-------	Unused variable
154	SPR4	-------	Unused variable
155	SPR5	-------	Unused variable
156	SPR6	-------	Unused variable
157	SPR7	-------	Unused variable
158	SPR8	-------	Unused variable
159	SPR9	-------	Unused variable
160	SPR10	-------	Unused variable
161	SPR11	-------	Unused variable
162	SPR12	-------	Unused variable
163	SPR13	-------	Unused variable
164	SPR14	-------	Unused variable
165	SPR15	-------	Unused variable
166	WASH	kg/sec	Maximum airflow
167	WFMIN	kg/sec	Minimum fuel flow
168	WFMAX	kg/sec	Maximum fuel flow
169	WABMX	-------	Unused variable
170	WABMN	-------	Unused variable
171	FTITMX	K	Maximum FTIT
172	PBMIN	N/m^2	Minimum PT4
173	PBMAX	N/m^2	Maximum PT4

APPENDIX C

DIA SIMULATION VARIABLES IN DIAOUT

The following is a list of DIA variables used in the simulation. These variables are all in the common called DIAOUT and are also printed as a portion of the hard copy output of the program.

Channel number	Variable	Description
1 to 11	SF	Scale factor failure values for the eleven sensed variables
12 to 22	BI	Bias failure values for the eleven sensed variables
23 to 33	V	Noise failure values for the eleven sensed variables
34 to 38	Z	The vector of measurements used as the accommodation filter input
39 to 43	ZUL	The vector of unlagged (no sensor dynamics) estimates of Z
44 to 48	ZH	The vector of estimates of Z (with sensor dynamics)
49 to 53	GAMDHO	The vector of accommodation filter residuals
54	DTHRSH	Unused
55	DFLAGH	Hard detection flag
56	KI	Normalized and squared sum of residuals
57	ETA	Weighted sum (over time) of squared residuals
58	DTHRSS	Unused
59	DFLAGS	Soft detection flag
60 to 64	ZIO	Output vector of hypothesis 0
65 to 69	GAMIHO	Residual vector of hypothesis 0
70 to 74	ZI1	Output vector of hypothesis 1
75 to 79	GAMIH1	Residual vector of hypothesis 1
80 to 84	ZI2	Output vector of hypothesis 2
85 to 89	GAMIH2	Residual vector of hypothesis 2
90 to 94	ZI3	Output vector of hypothesis 3
95 to 99	GAMIH3	Residual vector of hypothesis 3
100 to 104	ZI4	Output vector of hypothesis 4
105 to 109	GAMIH4	Residual vector of hypothesis 4
110 to 114	ZI5	Output vector of hypothesis 5
115 to 119	GAMIH5	Residual vector of hypothesis 5
120	HIOO	Likelihood value for hypothesis 0
121 to 125	HI	Likelihood value for hypothesis 1 to 5
126 to 130	HOMHI	Log likelihood ratios
131	ITHRSH	Unused
132 to 136	ICHAN	Isolated channel flags
137	ISOLT	Isolation flag
138	ACCOM	Accommodation flag
139 to 145	ZACCOM	Accommodation filter outputs
146 to 200	DOUT	Extra variables

REFERENCES

1. Merrill, W.C., et al.: HYTESS - A Hypothetical Turbofan Engine Simplified Simulation. NASA TM-83561, 1984.

2. Lehtinen, B., et al.: F100 Multivariable Control Synthesis Program - Results of Engine Altitude Tests. NASA TM S-83367, 1983.

3. Merrill, W.C.: Sensor Failure Detection for Jet Engines Using Analytical Redundancy. Journal of Guidance, Control, and Dynamics, vol. 8, no. 6, Nov.-Dec. 1985, pp. 673-682.

4. DeLaat, J.C.; and Merrill, W.C.: A Real-Time Implementation of an Advanced Sensor Failure Detection, Isolation, and Accommodation Algorithm. AIAA Paper 84-0569, Jan. 1984.

TABLE I. - TYPICAL REGRESSION POLYNOMIALS FOR THE ELEMENTS OF THE SYSTEM MATRICES

System matrix	Element	Polynomial[a]
F	(1,1)	$-\frac{0.0968}{\delta} - \frac{0.0019\ PT6^2}{\delta^2} - 2.463$
$F^{-1}G$	(4,1)	$\frac{0.000933\ PT6}{\delta} - \frac{0.97\times10^{-9}\ N1}{\sqrt{\theta}} \cdot \frac{PT6^2}{\delta^2} - 0.03606$
H	(5,3)	$0.0311\theta + 0.5486\times10^{-4}\ \frac{TT45}{\theta} - 0.3612$
D	(5,1)	$-0.0354\theta + \frac{31.35\delta}{PT4} + 0.04914$

[a] δ = P1/14.696; θ = T1/518.67

TABLE II. - HYTESS II ROUTING HIERARCHY

Level							
I	II	III	IV	V	VI	VII	VIII
MAIN	SETUP						
	MSET						
	READIN	SCURVE	UNBAR				
		GCNTL	UNBAR				
		TRCNTL	MODEL	UNBAR			
			UNBAR				
		INCNTL	UNBAR				
	STDST8	INLET	ALTABL				
			PRCMB	PVAL			
			HFTA	PVAL			
			TFHA	PVAL			
		SNFMAP	UNBAR				
		SN1SCH	SCURVE	UNBAR			
		N2TABL	SCURVE	UNBAR			
		RPSCH	N2TABL	SCURVE	UNBAR		
			SCURVE	UNBAR			
			SPRINT				
			FGVCAL				
		MVCNT	SENSOR	XLAGX			
			FSENS	GRAND	RANDU		
			EMODEL	SNFMAP	UNBAR		
				RPSCH	N2TABL	SCURVE	UNBAR
					SCURVE	UNBAR	
					SPRINT		
					FGVCAL		
			FDIA	FILTER	SUB		
					MUL		
					ADD		
					DMINV		
					SCA		
					XLAGX		
				NORMAL	MUL		
				WSSR			
				XLAGX			
			RPSCH	N2TABL	SCURVE	UNBAR	
				SCURVE	UNBAR		
				SPRINT			
				FGVCAL			
			TRCNTL	MODEL	UNBAR		
				UNBAR			
			GCNTL	UNBAR			
			LQR				
			INCNTL	UNBAR			
			EPRTKT	SCURVE	UNBAR		
			ACTUAT				
		EMODEL	SNFMAP	UNBAR			
			RPSCH	N2TABL	SCURVE	UNBAR	
				SCURVE	UNBAR		

TABLE II. - Concluded.

Level							
I	II	III	IV	V	VI	VII	VIII
				SPRINT			
				FGVCAL			
		SIMUL	SUB				
			MUL				
			SCA				
			ADD				
	PRINT						
	TRANS	PRINT					
		NUTIME					
		INLET	ALTABL				
			PRCMB	PVAL			
			HFTA	PVAL			
			TFHA	PVAL			
		MVCNT	SENSOR	XLAGX			
			FSENS	GRAND	RANDU		
			EMODEL	SNFMAP	UNBAR		
				RPSCH	N2TABL	SCURVE	UNBAR
					SCURVE	UNBAR	
					SPRINT		
					FGVCAL		
			FDIA	FILTER	SUB		
					MUL		
					ADD		
					DMINV		
					SCA		
					XLAGX		
				NORMAL	MUL		
				WSSR			
				XLAGX			
			RPSCH	N2TABL	SCURVE	UNBAR	
				SCURVE	UNBAR		
				SPRINT			
				FGVCAL			
			TRCNTL	MODEL	UNBAR		
			GCNTL	UNBAR			
			LQR				
			INCNTL	UNBAR			
			EPRTKT	SCURVE	UNBAR		
			ACTUAT				
		EMODEL	SNFMAP	UNBAR			
			RPSCH	N2TABL	SCURVE	UNBAR	
				SCURVE	UNBAR		
				SPRINT			
				FGVCAL			
		SIMUL	SUB				
			MUL				
			SCA				
			ADD				

TABLE III. - HYTESS II ROUTINE DESCRIPTIONS

ACTCRV	- Block Data, contains data for stator vane angle schedule
ACTUAT	- Simulates actuators
ADD	- General matrix addition
ALTABL	- Calculates temperature and pressure corrections at various altitudes
DIAPNT	- Block Data, contains names of DIA variables to be printed
DMINV	- General matrix inversion
EMODEL	- Calculates engine model matrices and basepoints and Kalman filter gain matrix
ENGPRN	- Block Data, contains names of engine variables to be printed
EPRTKT	- MVC engine protection logic
FDIA	- DIA analytical redundancy algorithm
FGVCAL	- Calculates fan guide vane angle scheduled value
FILTER	- DIA Kalman filter calculation
FSENS	- Simulates sensor failures
GCNTL	- Calculates proportional and integral gains
GRAND	- Converts uniformly distributed random numbers to Gaussian distributed random numbers
HFTA	- Calculates enthalpy as a function of temperature
INCNTL	- Integral control logic
INLET	- Solves for engine inlet conditions from ambient conditions
LQR	- Linear Quadratic Regulator (proportional) control logic.
MAIN	- Main program for HYTESS II
METRIC	- Converts from English to metric units or vice versa
MODEL	- Used by the transition control to generate trajectory value of states and outputs
MSET	- Initializes program control parameters
MUL	- General matrix multiply
MVCGAN	- Block Data, contains data for PI gain matrices
MVCNT	- Control system structure including sensors, DIA logic, multivariable PI logic, and actuators
MVCPRN	- Block Data, contains names of control variables to be printed
NORMAL	- Computes normalized dot product of a vector
NUTIME	- Finds print interval and values of ramp functions
N2TABL	- Calculates N2 as a function of PLA and TT2, or PLA as a function of N2 and TT2
PRCMB	- Calculates specific heat as a function of temperature
PRINT	- Formats and prints output
PVAL	- Evaluates a given polynomial
RANDU	- Generates uniformly distributed random numbers
READIN	- Reads input data
RPSCH	- Calculates steady-state operating point values for state, output, and control variables
SCA	- Multiply elements of a matrix by a constant
SCURVE	- Contains data (curves) for steady-state operating points
SENSOR	- Simulates sensors
SETUP	- Initialization routine
SIMUL	- Updates engine state space model equations using Euler integration
SNFMAP	- Finds PLA as a function of N1, TT2, and SMN
SN1SCH	- Finds N1 as a function of TT2, SMN, and PLA
SPRINT	- Table lookup routine

TABLE III. - Concluded.

STDST8 - Controls execution during steady-state convergence
SUB - General matrix subtraction
TFHA - Calculates temperature as a function of enthalpy
TRANS - Controls execution during a transient.
TRCNTL - Transition control logic
UNBAR - Table lookup routine
WSSR - DIA weighted sum of squared residuals calculation
XLAGX - First order lag

TABLE IV. - IS1 EXAMPLE INPUT TEST CASE

```
&INPUT
  TRAN=1.0, IPLOT= 1,SFAIL=1.0,
  SALT =0.0, SMACH=0.0,SPLA=20.0
  IMTRC= 1,
&END
&INTRAN
  PNTBLK = 0.0, 0.1,   10.0, .1,
  PLABLK = 0.0,20.0,   .5,  20.0,   1.0,83.0,   10.0,83.0,
  SMPBLK = 0.0,0.02,   0.04,0.02,   10.0,.02,
&END
&PLOT
  IPVAR1 = 1, 4,22,23
  IPVAR2 = 11,12
  IPVAR3 = 49,50
&END
&FSNS
  BI11BK = 0.0,0.0,   2.5,0.0,   7.502,250.,
&END
```

TABLE V. - IS2 EXAMPLE INPUT TEST CASE

```
&INPUT
  SMACH=0.,SALT=0.,SPLA=52.,TRAN=1.,
  SFGVV=-25.,SSVAV=6.0,
&END
&INTRAN
  PNTBLK=0.,.1,10.,.1,
  FGVBLK=0.0,-25.0,0.1,-25.0,.2,-22.5,10.,-22.5,
  SVABLK=0.0,6.0,5.0,6.0,5.1,5.4,10.,5.4,
&END
```

TABLE VI. - DESCRIPTION OF STEADY-STATE NAMELIST INPUT

Variable name	Default	Description
TRAN	0	If TRAN=1 then transient run desired
IPLOT	↓	If IPLOT=1 then plotting desired
ISCL	↓	If ISCL=1 then enter new engine scale factors
SFAIL	↓	If SFAIL=1 then include sensor DIA logic
MFLAG	↓	If MFLAG=1 then enter new control logic parameters
SALT	-999	Altitude, m
SMACH	↓	Mach number
SPLA	↓	Power level angle, deg
STAM	↓	Ambient temperature, K
SPAM	↓	Ambient pressure, N/m^2
SDTAM	↓	Adder to ambient temperature, K
SDPAM	↓	Adder to ambient pressure, N/m^2
SPT2	↓	Engine face total pressure, N/m^2
STT2	↓	Engine face total temperature, K
SWF	↓	Fuel flow, kg/sec
SAJ	↓	Nozzle jet area, m^2
SFGVV	↓	Fan guide vane angle, deg
SSVAV	↓	Compressor stator vane angle, deg
SBLC	↓	Bleed flow, percent
IMTRC	0	If IMTRC=1 then convert output from English to metric units

TABLE VII. - DESCRIPTION OF NAMELIST SCALE

Variable name	Default value	Variable description
SCL(1)	10 000 rpm	Scale factor for engine state 1(SNFAN)
SCL(2)	15 000 rpm	Scale factor for engine state 2(SNCOM)
SCL(3)	1 600 °F	Scale factor for engine state 3(TT4PLO)
SCL(4)	1 600 °F	Scale factor for engine state 4(TT45LO)
SCL(5)	10 000 rpm	Scale factor for engine output 1(SNFN)
SCL(6)	15 000 rpm	Scale factor for engine output 2(SNCM)
SCL(7)	550 psi	Scale factor for engine output 3(PT4)
SCL(8)	130 psi	Scale factor for engine output 4(PT6)
SCL(9)	1 600 °F	Scale factor for engine output 5(TT45)
SCL(10)	25 000 lb	Scale factor for engine output 6(FNMX)

TABLE VIII. - DESCRIPTION OF NAMELIST MVCIN

Variable name	Default	Description
XMVC	Defined in routine MSET	Equivalenced to the 81 variables in the common MVCCON
SSCH	0.0	If SSCH≠0.0 then read new steady-state schedule data
GAININ	0.0	If GAININ≠0.0 then read new PI control gains
TCNIN	0.0	If TCNIN≠0.0 then read new transition control rate data
XINTIN	0.0	If XINTIN≠0.0 then read integral control dead zone data

TABLE IX. - DESCRIPTION OF TRANSIENT NAMELIST INTRAN

Variable array name	Default	Description
Step input		
PNTBLK	-999	Print interval
SMPBLK	-999	Control sampling interval
Ramp inputs		
PLABLK	-999	PLA ramp input
ALTBLK	↓	Altitude ramp input
XMNBLK	↓	Mach number ramp input
WFBLK	↓	Fuel flow ramp input
AJBLK	↓	Nozzle area ramp input
FGVBLK	↓	Fan guide vane ramp input
SVABLK	↓	Compressor stator vane angle ramp input
BLCBLK	↓	Bleed flow ramp input

TABLE X. - DESCRIPTION OF NAMELIST PLOT

Variable name	Default	Variable description
IPVAR1	-1	Integer array that defines those variables in the common ENGOUT that are to be saved for plotting. See appendix A
IPVAR2	-1	Integer array that defines those variables in the common MVCOUT that are to be saved for plotting. See appendix B.
IPVAR3	-1	Integer array that defines those variables in the common DIAOUT that are to be saved for plotting. See appendix C.

TABLE XI. - DESCRIPTION OF NAMELIST FSNS

Variable name	Default	Variable description
GMEANO(1)	0	Noise mean for DIA variable 1
(2)	↓	Noise mean for DIA variable 2
(3)	↓	Noise mean for DIA variable 3
(4)	↓	Noise mean for DIA variable 4
(5)	↓	Noise mean for DIA variable 5
GSDO(1)	350	Noise standard deviation for DIA variable 1
(2)	400	Noise standard deviation for DIA variable 2
(3)	30	Noise standard deviation for DIA variable 3
(4)	5	Noise standard deviation for DIA variable 4
(5)	250	Noise standard deviation for DIA variable 5
NHIST	3	The number of past values used in the calculation of the WSSR statistic
THRH	0.2	Heal threshold factor
THRDI	2.0	Hard failure detection/isolation threshold factor
THRD	1.6	Soft failure detection threshold
THRI	3.0	Soft failure isolation threshold
TAU	.1	Time constant used for smoothing hypothesis log likelihoods
FSPRT	0	If FSPRT=0.0 then write the failure detection data and failure scenario data
NAMP(1)	0	Noise amplification factor for PLASN
(2)	↓	Noise amplification factor for TT2SN
(3)	↓	Noise amplification factor for PT2SN
(4)	↓	Noise amplification factor for SMNSN
(5)	↓	Noise amplification factor for EXTRA
(6)	↓	Noise amplification factor for SNFSEN
(7)	↓	Noise amplification factor for SNCSEN
(8)	↓	Noise amplification factor for TT25SN
(9)	↓	Noise amplification factor for FTITSN
(10)	↓	Noise amplification factor for PT4SEN
(11)	↓	Noise amplification factor for PT6MSN
SN1BLK	-999	Data for simulated step change in PLASN scale factor
SN2BLK	↓	Data for simulated step change in TT2SN scale factor
SN3BLK	↓	Data for simulated step change in PT2SN scale factor
SN4BLK	↓	Data for simulated step change in SNMSN scale factor
SN5BLK	↓	Data for simulated step change in EXTRA scale factor
SN6BLK	↓	Data for simulated step change in SNFSEN scale factor
SN7BLK	↓	Data for simulated step change in SNCSEN scale factor
SN8BLK	↓	Data for simulated step change in TT25SN scale factor
SN9BLK	↓	Data for simulated step change in FTITSN scale factor
SN10BLK	↓	Data for simulated step change in PT4SEN scale factor
SN11BLK	↓	Data for simulated step change in PT6MSN scale factor
BI1BLK	-999	Data for simulated ramp change in PLASN bias factor
BI2BLK	↓	Data for simulated ramp change in TT2SN bias factor
BI3BLK	↓	Data for simulated ramp change in PT2SN bias factor
BI4BLK	↓	Data for simulated ramp change in SMNSN bias factor
BI5BLK	↓	Data for simulated ramp change in EXTRA bias factor
BI6BLK	↓	Data for simulated ramp change in SNPSEN bias factor
BI7BLK	↓	Data for simulated ramp change in SNCSEN bias factor

TABLE XI. - Concluded.

Variable name	Default	Variable description
BI8BLK	-999	Data for simulated ramp change in TT25SN bias factor
BI9BLK	↓	Data for simulated ramp change in FTITSN bias factor
BI11BLK	↓	Data for simulated ramp change in PT4SEN bias factor
BI11BLK	↓	Data for simulated ramp change in PT6MSN bias factor

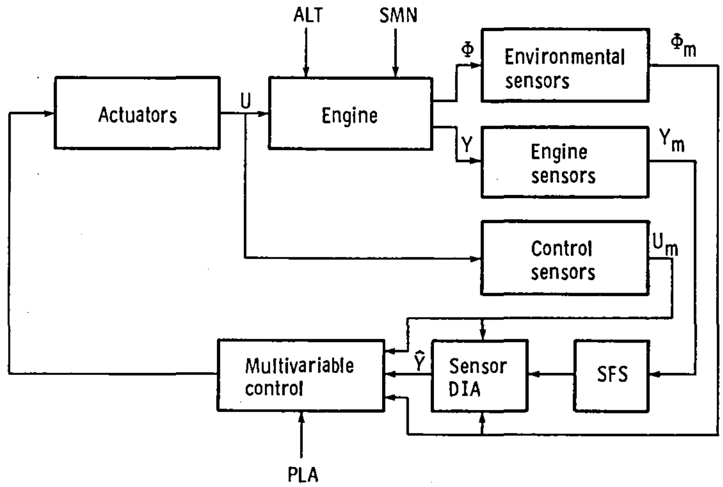

Figure 1. - HYTESS II system block diagram.

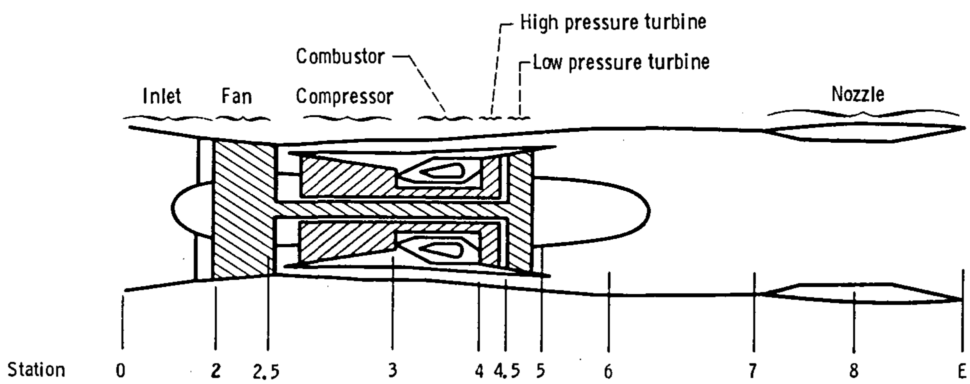

Figure 2. - Schematic representation of a hypothetical turbofan engine.

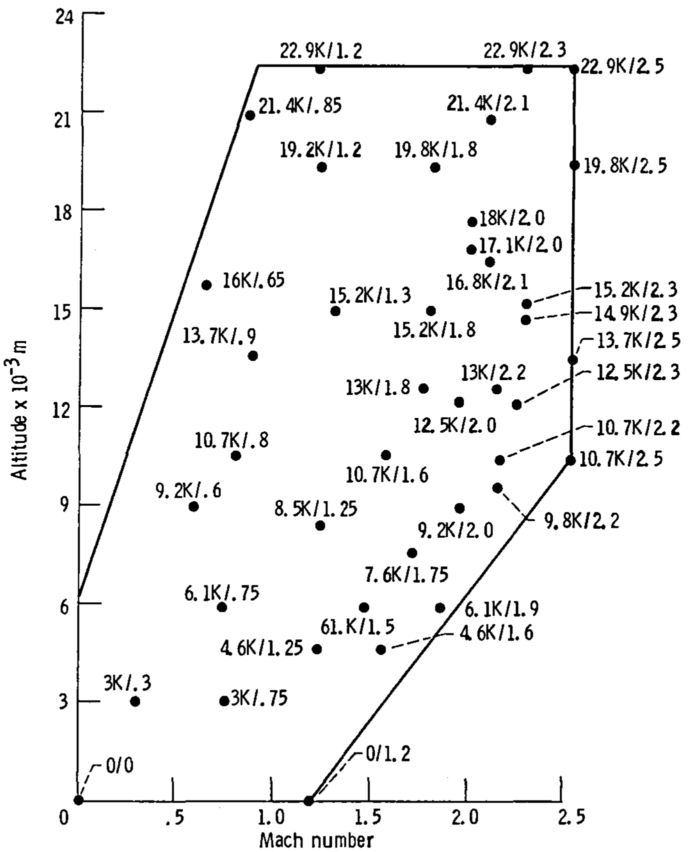

Figure 3. - Engine flight envelope with engine operating points.

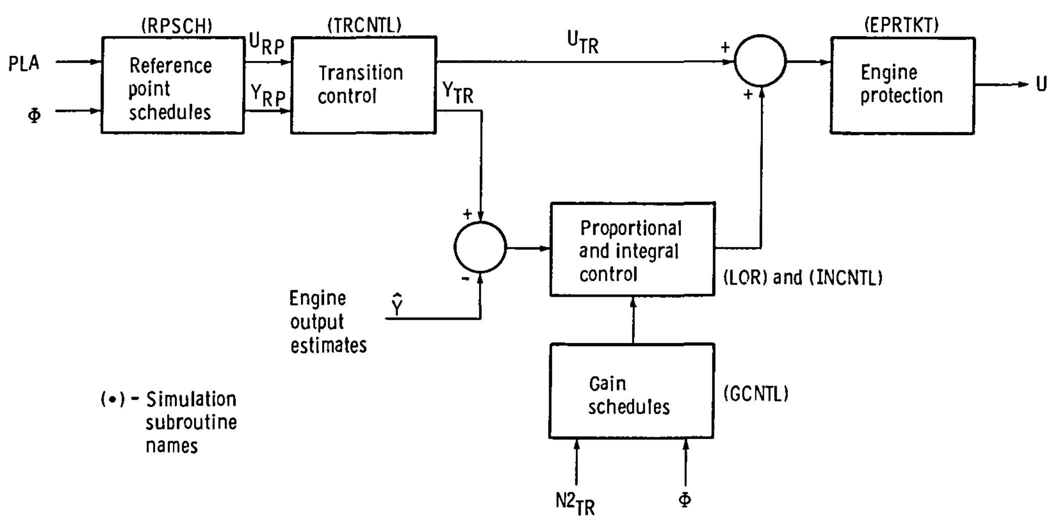

Figure 4. - HYTESS II control block diagram.

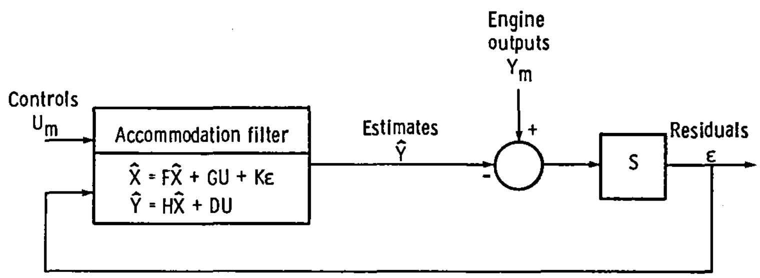

Figure 5. - Sensor DIA normal mode accommodation filter.

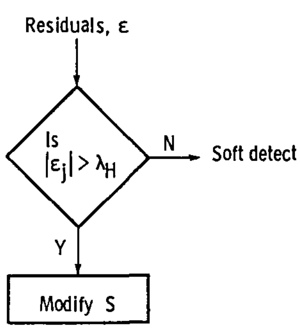

Figure 6. - DIA hard failure detection and isolation logic.

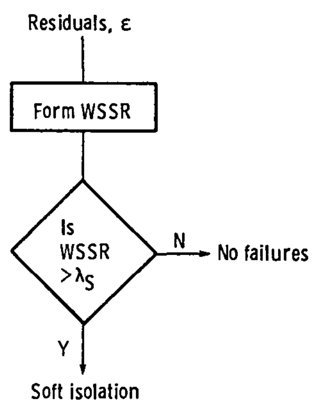

Figure 7. - DIA soft failure detection logic.

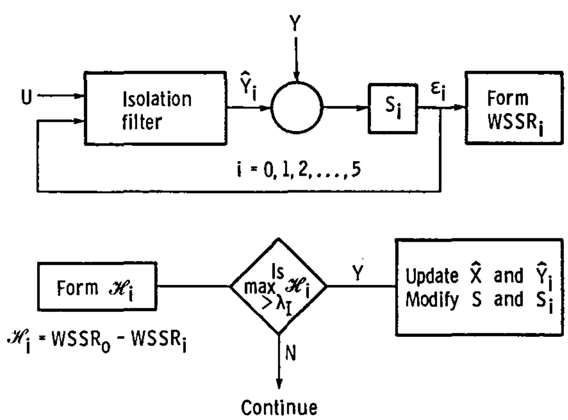

Figure 8. - DIA soft failure isolation logic.

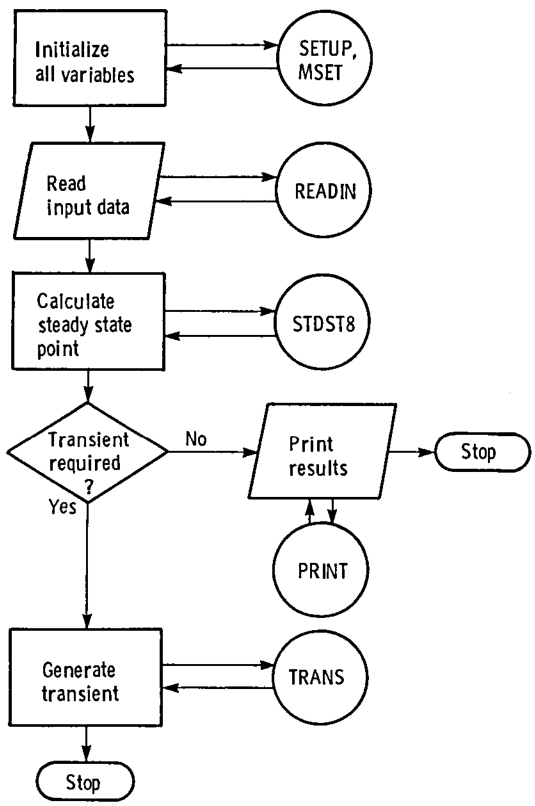

Figure 9. - Basic program flow through MAIN.

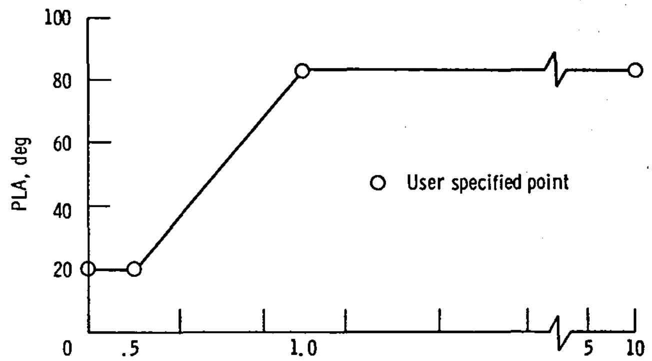

Figure 10. - User specified PLA input transient - IS1 example test case. (See table IV.)

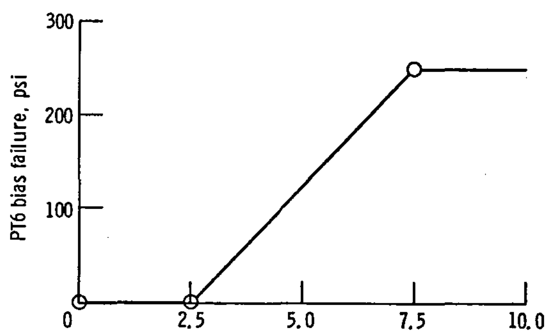

Figure 11. - PT6 bias failure versus time.

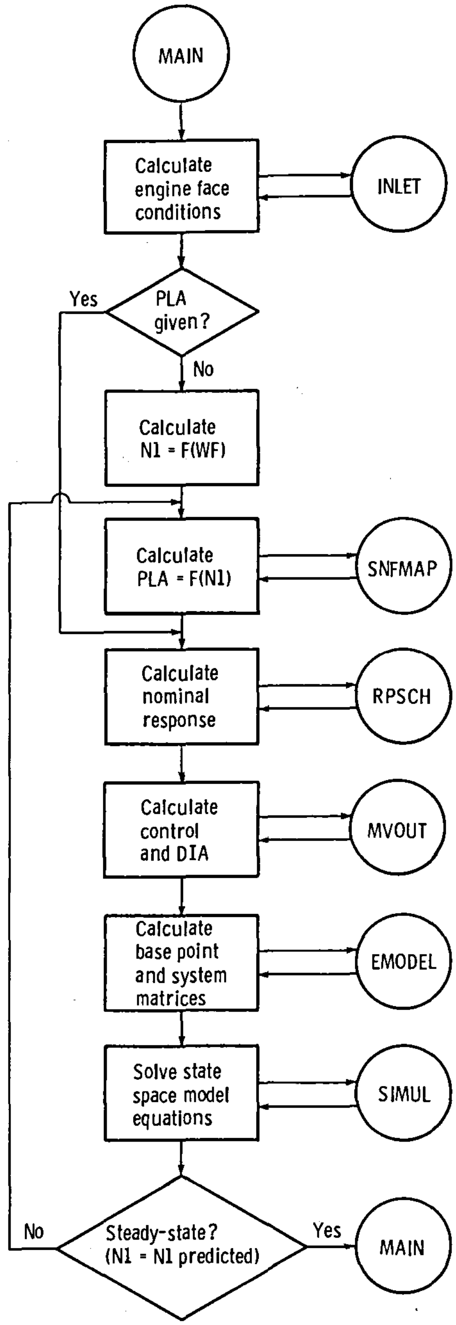

Figure 12. - Basic program flow through STDST.

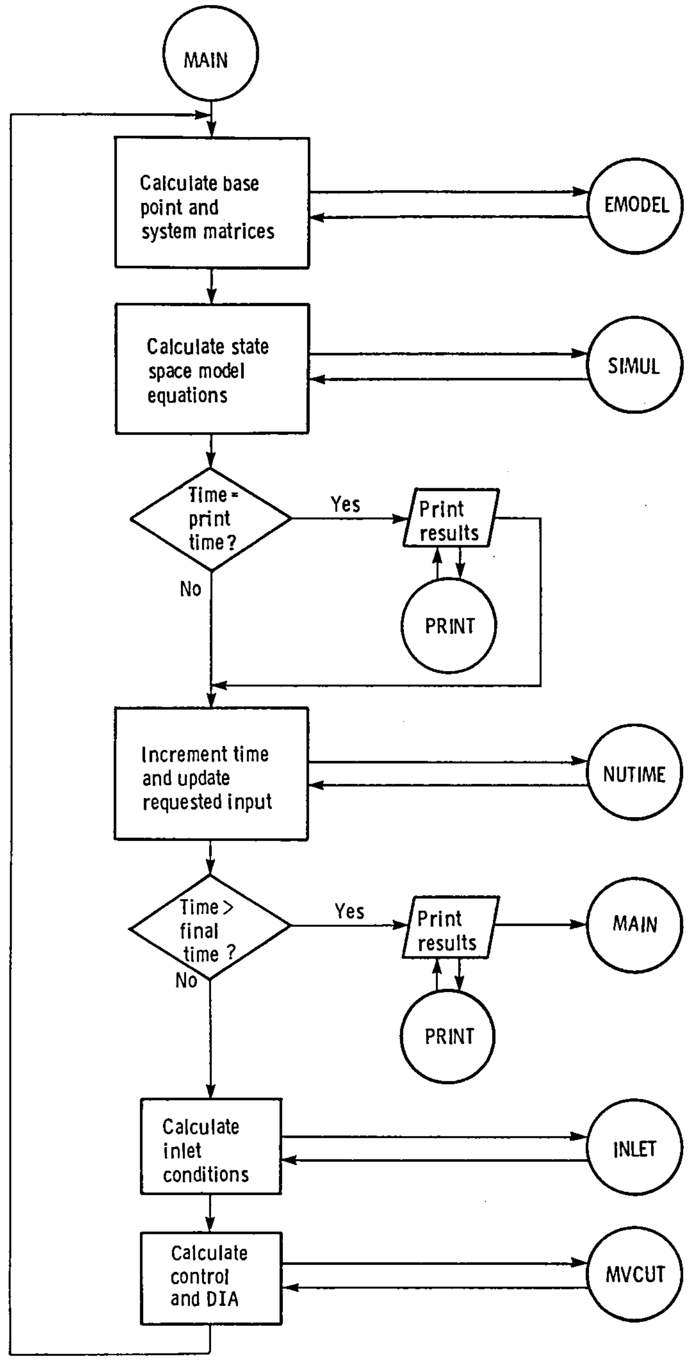

Figure 13. - Basic program flow through TRANS.

HYPOTHETICAL TURBOFAN CONTROLLER

	*** ENGINE RESPONSE VARIABLES ***									
1 TIME	0.00000	0.10000E 00	0.20000	0.30000	0.40000	0.50000	0.60000	0.70000	0.80000	0.90000
	AMBIENT CONDITIONS									
2 ALT	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3 SMN	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
4 PLA	20.000	20.000	20.000	20.000	20.000	20.000	32.600	45.200	57.800	70.400
5 P0	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696
6 T0	518.69	518.69	518.69	518.69	518.69	518.69	518.69	518.69	518.69	518.69
7 DP0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
8 DT0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
9 PT2	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696
10 TT2	518.67	518.67	518.67	518.67	518.67	518.67	518.67	518.67	518.67	518.67
11 V0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
12 ETARAM	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	ENGINE INPUTS									
13 WFMBH	1133.1	1133.1	1133.3	1133.6	1133.8	1134.0	1227.9	1358.4	1469.6	1564.7
14 AJCD	3.0000	2.9500	2.9500	2.9500	2.9500	2.9500	3.0062	3.0084	3.0058	2.9995
15 FGVPOS	-25.000	-25.000	-25.000	-25.000	-25.000	-25.000	-24.857	-24.711	-24.562	-24.452
16 SVAPOS	-39.033	-39.033	-39.033	-39.033	-39.029	-39.018	-38.821	-38.608	-38.281	-37.748
17 BLC	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	ENGINE STATES									
18 SNFAN	3540.9	3536.8	3534.1	3531.9	3530.1	3528.6	3536.2	3557.1	3592.7	3642.6
19 SNCOM	8695.4	8693.8	8692.5	8691.4	8690.4	8689.6	8702.2	8743.5	8809.1	8892.1
20 TT4PLO	87.559	87.504	87.467	87.439	87.418	87.404	87.813	89.101	91.143	93.731
21 TT45LO	61.513	61.472	61.450	61.439	61.437	61.439	61.998	63.712	66.290	69:368
	ENGINE OUTPUTS									
22 SNFAN	3540.9	3536.8	3534.1	3531.9	3530.1	3528.6	3536.2	3557.1	3592.7	3642.6
23 SNCOM	8695.4	8693.8	8692.5	8691.4	8690.4	8689.6	8702.2	8743.5	8809.1	8892.1
24 PT4	65.498	65.470	65.448	65.429	65.414	65.403	66.643	68.749	71.097	73.646
25 PT6	13.516	13.617	13.613	13.610	13.608	13.606	13.520	13.576	13.656	13.758
26 TT45	974.43	975.04	975.51	975.94	976.29	976.55	1015.4	1065.2	1100.9	1125.1
27 FNMX	1363.9	1381.2	1380.2	1379.4	1378.7	1378.2	1373.3	1399.1	1430.1	1465.9
28 SMHC	0.77921	0.77891	0.77861	0.77834	0.77809	0.77785	0.76993	0.76486	0.76730	0.77496

Figure 14. - Sample of program printout for test case of table IV.

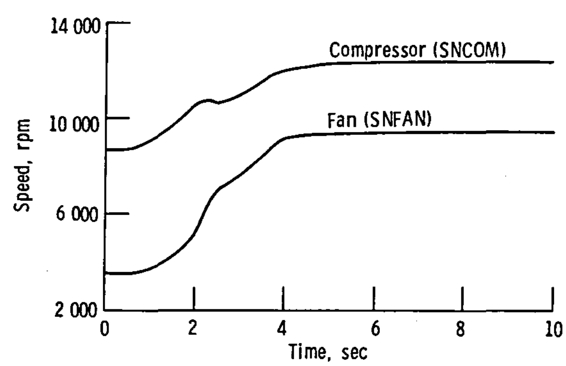

Figure 15. - Fan and compressor speed versus time (IPVAR1).

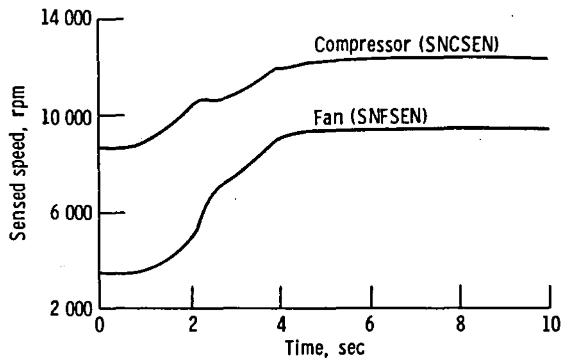

Figure 16. - Sensed fan and compressor speed versus time (IPVAR2).

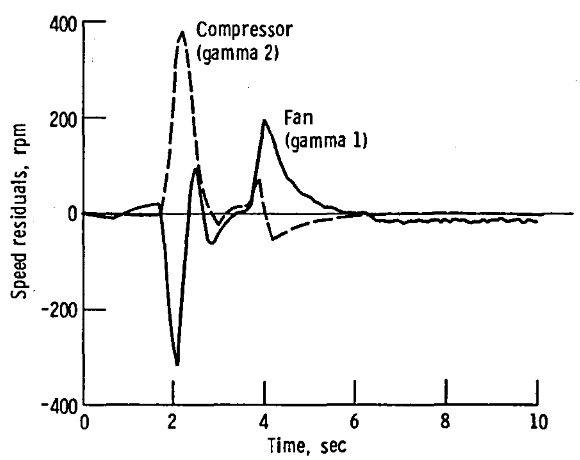

Figure 17. - Fan and compressor speed residuals versus time (IPVAR3).

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-87344		

4. Title and Subtitle	5. Report Date
HYTESS II - A Hypothetical Turbofan Engine Simplified Simulation With Multivariable Control and Sensor Analytical Redundancy	June 1986
	6. Performing Organization Code 505-62-01
7. Author(s) Walter C. Merrill	8. Performing Organization Report No. E-3014
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A hypothetical turbofan engine simplified simulation with a multivariable control and sensor failure detection, isolation, and accommodation logic (HYTESS II) is presented. The digital program, written in FORTRAN, is self-contained, efficient, realistic, and easily used. Simulated engine dynamics were developed from linearized operating point models. However, essential nonlinear effects are retained. The simulation is representative of a hypothetical, low bypass ratio turbofan engine with an advanced control and failure detection logic. Included is a description of the engine dynamics, the control algorithm, and the sensor failure detection logic. Details of the simulation including block diagrams, variable descriptions, common block definitions, subroutine descriptions, and input requirements are given. Example simulation results are also presented.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Turbofan engine; Multivariable control; Simulation; Analytical redundancy	Unclassified - unlimited STAR Category 33

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

End of Document