LESSONS LEARNED IN THE APPLICATION OF SIMULATION TO JET ENGINE MAINTENANCE TRAINING

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ABSTRACT

Technical training and the isolation and diagnosis of jet engine malfunctions has traditionally been accomplished using operational engine hardware, which has limited malfunction training. Simulated aircraft maintenance training (SAMT) devices are being increasingly employed by the military to achieve more efficient and controlled instruction in maintenance procedures. The F-16 engine diagnostic SAMT is comprised of simulated aircraft cockpit and test equipment control panels, an instructor station, and a computer simulation of the Pratt & Whitney F-100 engine. The math model, which consists of a data base of engine variables, with transients provided by simple algorithms, was found to provide completely realistic engine performance for maintenance training. Through the model, students can practice trimming procedures, and diagnosis of a variety of engine component failures. Valuable lessons were learned in regards to sources of data for data base and algorithm development, data base fidelity, and approaches to malfunction model development.

BACKGROUND

Technical training in jet aircraft engine trimming procedures and in the isolation and diagnosis of jet engine malfunctions has traditionally been accomplished by using operational engine hardware; either a complete aircraft or the engine assembly.

The use of "Hot Mockups" for teaching engine trimming has the drawbacks of (1) a noisy teaching environment, (2) exposing the student to hazards which are not a vital part of learning how to trim an engine, (3) the always-present competition with other groups for aircraft hardware; historically, training usually has a lower priority than operations and maintenance, and (4) trimming an engine burns a substantial amount of fuel and results in significant wear on the engine. Data from recent USAF engine trim courses indicate that it requires 30,000-40,000 lbs of fuel and approximately 8 hours of engine time to train each student.

For these reasons, simulated aircraft maintenance training devices are being increasingly employed by the military to reduce costs and achieve more efficient and controlled instruction in maintenance procedures.

THE F-16 ENGINE DIAGNOSTICS SAMT

An example of this new approach to maintenance training is the F-16 Engine Diagnostic Simulated Aircraft Maintenance Trainer (SAMT), comprised of two 3' x 8' panels, an instructor station and a computer simulation of the Pratt and Whitney F-100 engine. The two panels contain aircraft cockpit instruments, engine drawings and blowups of selected components as well as relevant test equipment control panels. They also contain a set of 130 action switches, which allow the student to simulate the taking of various actions; for example, an action switch is used for applying ground power. A set of 70 element switches are distributed within the panels which allow the student to designate particular components; for example, an element switch is used to designate the engine alternator as a defective component.

The instructor's station is comprised of a CRT display and keyboard which allows the instructor to choose one of a set of engine malfunctions for the current lesson and to record student information relevant to the training. An instructional feature of the software prompts the student with caution and hazard messages, and records student performance as the lesson progresses.

SAMT training has been well accepted, saving 30,000-40,000 lbs of fuel per student and 50% of student training time over flight line training; also, to show the current emphasis on malfunction training, the students in the six day USAF F-100 Engine trim course spend four days on the SAMT diagnosing malfunctions.

THE MATH MODEL

The key to successful simulation of the jet engine, cockpit instruments and engine test sets is the math model which underlies the computer-driven display panels. Through the model, students can practice time consuming, tedious and expensive trimming procedures at substantially reduced cost. Selectable malfunctions allow for diagnosis and isolation of a variety of engine component failures.

The engine model and test set models interact to form a totally free-play environment. The student is free to make mistakes on both engine operation and test set operation, and the system is designed to give the appropriate response. A simple real time monitor is included in the simulation to detect and flag student operational and procedural errors.

Traditional approaches to jet engine modeling have involved mathematical description of complex mechanical and thermodynamic processes. This approach when applied to maintenance trainers is both costly and unnecessary.

THE ENGINE MODEL

A new approach was chosen for the math model of the engine which is driven by a data base of engine variables that describe the steady-state behavior of the engine. The transient responses are provided by simple algorithms. This approach was found to provide completely realistic engine performance for maintenance training.

The engine data base consists of 22 tables which describe the engine variables in normal and diagnostic modes. The normal engine parameters data consist of tabulated values for nine observable parameters; fuel flow, nozzle position, variable vane position, compressor and turbine RPM, two temperatures, and two pressures. In addition to the normal engine tables, data is tabulated for the engine operatinng without the engine electronic controller (EEC) and with the back-up controller (BUC). Seven different engine trim tables and 12 malfunction tables complete the set.

Each of the tables (Refer to Table 1) is composed of three sub-tables; one for each of three values of outside air temperature. For a given outside air temperature, the steady-state value of each of the nine parameters is tabulated for incremental values of throttle setting. The tabulated values were obtained using the manufacturer's comprehensive non-real-time engine simulation program.

Refinements to the tabulated values are then made to the nine parameters to simulate the function of six trim screws, engine electronic controller, back-up controller, ambient air temperature, air source selector, anti-ice switch, starting fuel switch (lean/rich), false parameters introduced by various engine test sets, and parameter perturbations due to simulated malfunctions. (Refer to Figures 1 & 2.)

The model includes 32 classifications of malfunctions which fault isolate to 75 unique problems. The malfunction models are either table-driven, algorithm-driven or are a combination of the two. Referring to Figure 1, the malfunction symptoms are either inserted during throttle movement, incorporated into the engine controller algorithms (BUC or EEC), absorbed in the steady-state tables or added at the time of engine transient response. Figure 2 is included to show what is involed in calculating a typical parameter in real time.

Engine transients involve the time behavior of parameters toward the steady-state values corresponding to throttle position. A satisfactory and simple method which we use to model these transients proved to be an exponential response for each engine parameter of the form. (Refer to Figure 3.)

$$X(T) = Ae^{-\frac{T}{TC}} + B(1 - e^{-\frac{T}{TC}}) \qquad (1)$$

Where

A = Steady-state value of the parameter at initial throttle setting A.

B = Steady-state value of the parameter at final throttle setting B.

X(T) = Value of the parameter at time T.

TC = Time constant

Note that the classical form of the response in eq (1) is computationally difficult and involves the evaluation of exponentials. A more efficient form is found by developing a recursion relationship:

From (1) letting $t = N\Delta T$

TABLE 1

TYPICAL DATA BASE TABLE

Parameter	Throttle (Degree)	Ambient Temperature 0 deg	45 deg	100 deg
RPM	20	-	-	-
	23	-	-	-
	26	-	-	-
	35	-	-	-
	44	-	-	-
	50	-	-	-
	68	-	-	-
	80	-	-	-
	83	-	-	-
NOZZLE	20	-	-	-
	23	-	-	-
	38	-	-	-
	50	-	-	-
	53	-	-	-
	65	-	-	-
	80	-	-	-
	91	-	-	-
	109	-	-	-
	115	-	-	-
	127	-	-	-
	130	-	-	-
TEMPERATURE	20	-	-	-
	23	-	-	-
	26	-	-	-
	32	-	-	-
	35	-	-	-
	42	-	-	-
	45	-	-	-
	51	-	-	-
	59	-	-	-
	68	-	-	-
	79	-	-	-
	83	-	-	-

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(etc for all 10 Parameters)

FIGURE 1. ENGINE DIAGNOSTICS SIMPLIFIED FUNCTIONAL DIAGRAM

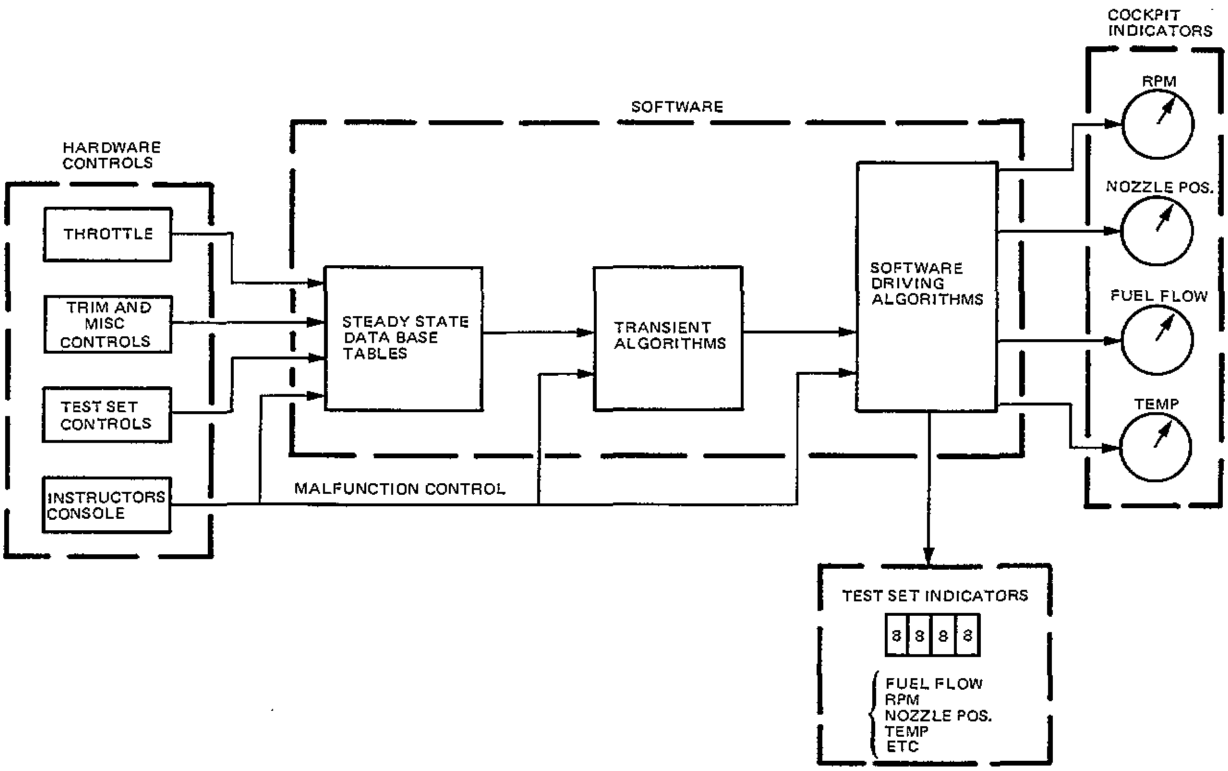


FIGURE 2. ENGINE DIAGNOSTICS SIMULATION
(CALCULATION OF A TYPICAL PARAMETER)

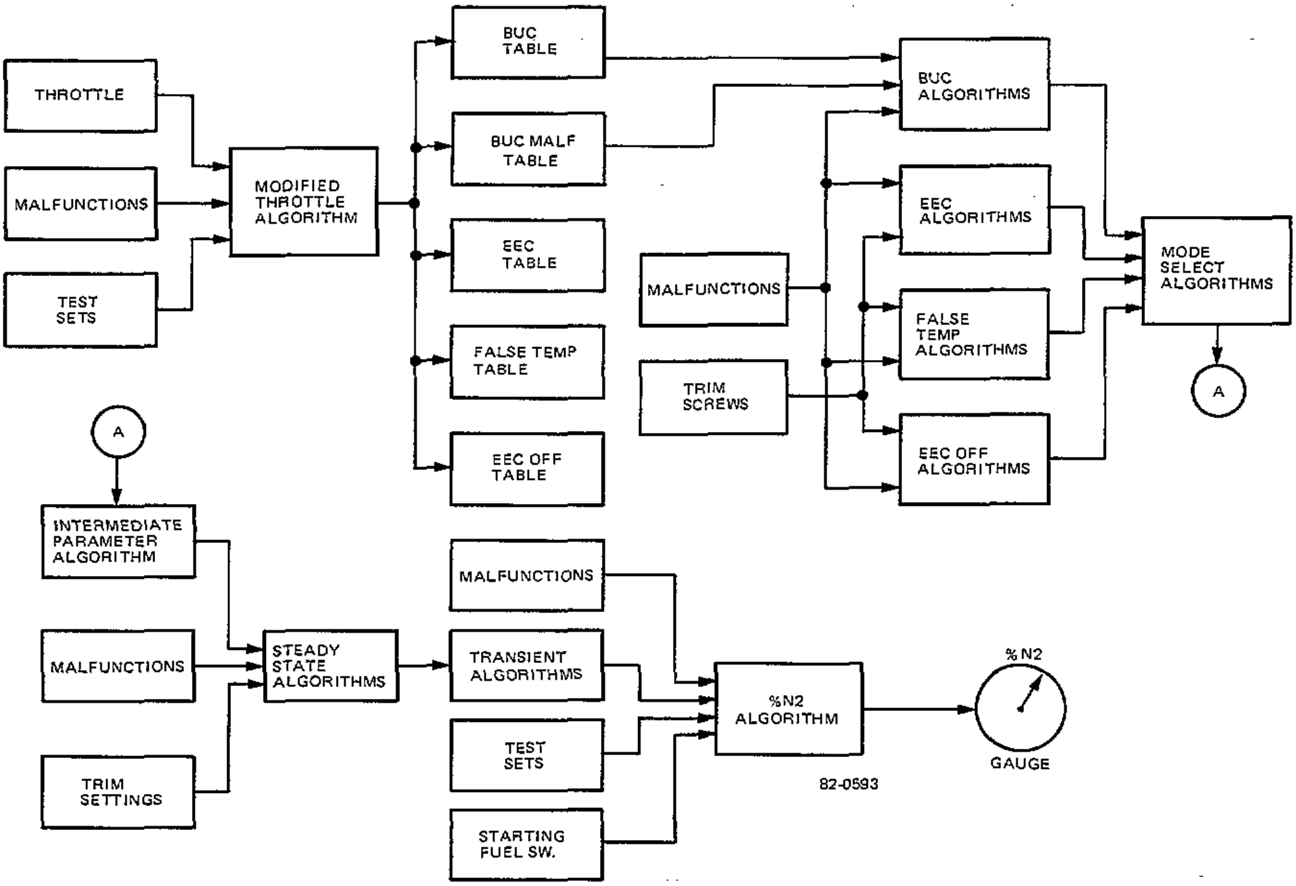
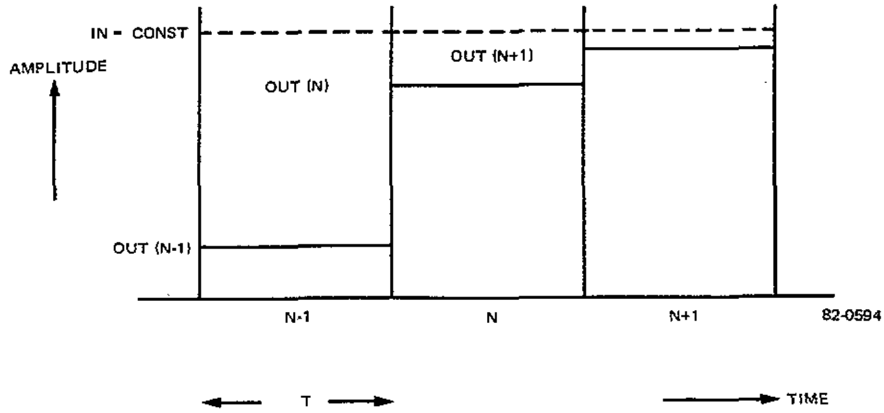


FIGURE 3. EXAMPLE OF EXPONENTIAL RESPONSE



1. A constant input, IN(N-1), is applied at time step N-1.

2. The output at the Nth time step, OUT(N), is 100K% of the interval IN(N-1) - OUT(N-1).

3. The output at the N+1st time step, OUT(N+1), is 100K% of the interval IN(N+1) - OUT(N).

4. The process repeats for subsequent time steps, thus generating an exponential rise from OUT(N-1) to IN(N-1).

$$X(N) = Ae^{-\frac{N\Delta T}{TC}} + B\,[1 - e^{-\frac{N\Delta T}{TC}}]$$

By substitution from (1) and collecting terms

$$X(N+1) = e^{-\frac{\Delta T}{TC}}\,X(N) + B(1 - e^{-\frac{\Delta T}{TC}}) \quad (2)$$

Equation (2) can be written in a more computationally efficient form:

$$OUT(N+1) = OUT(N) + [IN(N+1) - OUT(N)]*K$$

Where

OUT(N+1) = Current value of the parameter

OUT(N) = Value of the parameter computed at the last ΔT time step

IN(N+1) = Current steady state value parameter (a function of throttle setting)

K = K(ΔT,TC)
TC = Time constant

ΔT = Calculating increment (0.1 second in our case)

This form is arrived at by using the Laplace transform of the exponential.

$$\frac{1}{TC*S+1}$$

and Euler's numerical integration formula

$$X(N+1) = X(N) + \dot{X}\Delta T$$

to obtain,

$$IN = TC*\frac{d(OUT)}{dT} + OUT$$

Which leads to

$$OUT(N+1) = OUT(N) - [IN(N+1) - OUT(N)]\,\frac{\Delta T}{TC}$$

In other words, for each time step, the current value is determined by adding K times the difference between the forcing function, IN(N+1), and the last parameter value, OUT(N), to the last parameter value (Refer to Figure 3). If the forcing function (throttle position) remains constant, this is a classical exponential response to a stimulus.

LESSONS LEARNED

Things We Did Wrong

Improved Malfunction Definition. In the early stages of trainer development, not enough attention was paid to malfunction definition. Since our model does not directly employ the basic physical principles of the engine, but rather relies on a data base for symptomatic description, the secondary malfunction responses are not inherent in the model. (An example of a primary response is an oscillating exhaust nozzle, whereas the secondary responses are the changes to the other engine parameters which occur as a consequence of the fluctuating nozzle.) The modeling of these minor (but important to diagnostic training) responses must be carefully specified. However, because of their secondary nature, it is difficult to obtain general agreement on what these responses should be. The manufacturer's data was generally accepted as the most reliable and tended to resolve the differences. In retrospect, the manufacturer should have been consulted in more detail. We also we should have relied more heavily on F-15 engine data, since the two aircraft have the same engine and F-15 had been operational for some time.

Added Audio and Visual Cues? No provisions were made for special diagnostic audio responses and we discovered at a rather late date that the engine Job Guides require the maintenance man to listen for igniter plug noises. He is also required to look for fire coming from the tips of the igniter plugs, and visual indications of igniter firing were not provided for. Adding these special audio and visual effects might be desirable.

Things We Did Right

Exponential response proved to be Simple and Effective. The selection of this type of response to describe engine transient phenomena proved to be a wise choice. We employed more complicated approaches (notably series and parallel networks of exponential responses) in other trainers. Where these approaches were tried on the Engine Diagnostics SAMT the improvements were negligible even when instrumentation was employed.

Improved Method of Tracking Equipment Changes. As the engine and test sets evolve and new operational hardware appears, the problem is ever-present on how often to retrofit the trainers and what to do to accommodate the missing hardware in the meantime. A very workable and inexpensive method was devised consisting of software "bridges", which are a CRT message to the student to describe equipment responses. For example, if a voltage is to be measured and a voltmeter is not included on the trainer, the message "Voltmeter reads 22 Volts" appears at the proper time in the lesson.

Model Accommodates Other Jet Engines. Since transient responses are not of primary importance in the teaching of engine diagnosis, (readings are always taken after the engine stabilizes) the use of the exponential response is probably adequate for any jet engine. It is therefore likely that the model can accommodate most any jet engine by changing the data base (and using appropriate engine parameters) and some time constants.

Things We Should Have Done Better

Reduced Computation Time. Since the engine model as well as the test set models are table-driven, the basic trade-off's in table structure are:

(1) Polynomial fits to the data with no breakpoints - the table consists of coefficients of the polynomials.

(2) Breakpoint logic - only the vertices are retained and the parameters are computed by linear interpolation. (Refer to Table 1)

(3) Slope/Intercept form - the vertices are retained as in breakpoint logic but the slope and intercept are pre-computed and stored as table entries.

Method (1) was ruled out because we were unsure of the fidelity necessary for training and high fidelity requires a very high degree of polynomial to adequately describe the data. Since a polynomial of degree N requires N multiplications and N additions for each evaluation, high degree polynomials are precluded because of real time constraints.

Method (2) requires about three times the computational time of that of method (3) in order to compute a parameter value but requires only half the table size, however, Method (2) was chosen because at the time of model design (1978 time frame) computer memory was considerably more expensive than it is today.

As it turned out, some of the actual data differed significantly from the breakpoint data employed and proved to be entirely satisfactory. Since the actual breakpoint data provided realistic performance, we now think that we could achieve a significant improvement by employing various data compression methods and still not degrade training effectiveness.

Reduced Memory Requirements. A similar trade-off exists in the data base structure. The current method of employing different engine parameter tables for various cockpit switch combinations and malfunctions, leads to large memory requirements, which could be sharply reduced by restructuring the data base to include one primary table of engine parameters and judiciously adding switch-dependent polynomial fits of deltas to these basic parameters. In fact, we suspect that the one remaining table could be significantly reduced by opting for a coarser data structure as noted above.

Missing Cockpit?. All engine maintenance procedures are a two man operation: One man is in the cockpit and the other is operating the test equipment. One of the difficulties facing recent engine training class graduates is how to locate the many cockpit switches that must be placed in the OFF or SAFE position in order to make the aircraft safe for maintenance. (This procedure must preceed any maintenance action.) It may be advantageous to include a simulated cockpit with many of the switches dead-ended but moveable. All engine related switches would be operational.

SUMMARY

The simple model consisting of a data base of steady-state engine parameters, coupled with an exponential response for engine transients proved to be a very effective approach.

We feel now that we could go back and make substantial improvements in table structure (data resolution and data base compression) and computation time.

The manufacturer should be consulted more at the start of the program, particularly in the area of malfunction definition. In doing so we could have avoided the problems of partially- defined and ill-defined malfunctions.

ABOUT THE AUTHORS

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