The Role of Modern Control Theory in the Design of Controls for Aircraft Turbine Engines

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Introduction

CONTROL systems for early aircraft turbine engines performed a rather simple task: metering the fuel to the combustor at the proper fuel-to-air ratio for both transient and steady-state operating conditions. More recently, however, things have changed significantly. To achieve higher thrust-to-weight ratios and to improve specific fuel consumption, many additional manipulated engine inputs have been added. Figure 1 shows the trend in complexity in terms of the number of controlled engine variables. Noted are a number of operational engines that have been put into service. Typical of the added engine manipulated inputs are afterburner fuel flow, variable compressor-inlet guide vanes, variable compressor stators, and variable exhaust-nozzle area.

The task of designing a control algorithm for an engine having a number of inputs and outputs now becomes a formidable problem. Traditional single-input/single-output techniques can be used, but are often inadequate and require many judgmental interactions to get even close to a suitable engine control law. The designer would really like a direct, straightforward method for handling the multivariable problem. This procedure should be able to eliminate unwanted interactions between the different variables, while bringing into play those interactions that are favorable. Faced with these needs, in the early 1970s the engine control community began to investigate what new design methodologies were available. As a result, a number of researchers began to apply to the engine control design problem tools from the evolving methodology generally termed "modern control theory" (MCT).

This paper reviews what has been accomplished in applying MCT to the aircraft turbine engine control design problem over the last 10 or so years and what work yet remains to be done. This review is organized as follows: first is a brief discussion of the evolution of control design methodology, followed by a description of the problems that must be faced in applying MCT to the engine control design task. The past accomplishments in applying MCT to engine control is the subject of the third and most detailed section. The paper concludes with a discussion of the future requirements for advanced engine control design.

Evolution of Control Design Methodology

In the early 1960s, control theoreticians began to use linear state-space methods to design closed-loop controls for large complex physical systems. At the same time, computers that could easily solve the numerical problems associated with large linear system problems were rapidly evolving and becoming readily accessible. Thus began the era of "modern control theory." This terminology was used to differentiate the new methods from the traditional linear system, single-

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input/single-output (SISO), frequency domain design methods in widespread use at that time. These traditional methods employed such tools as Nyquist diagrams, Bode plots, root locus plots, etc. D'Azzo and Houpis[1] and Raven[2] are representative of the many texts describing the traditional methods.

Prior to the era of MCT when a designer was faced with designing a control for a complex multi-input/multi-ouput (multivariable) physical process, the approach was as follows. First, the designer would put together an analytical representation of the physical process to be controlled. This analytical model usually consisted of a number of algebraic and differential equations, which in most cases were nonlinear. To use the traditional linear methods, a linearized, transfer function representation about one or more process operating points would be obtained for this family of nonlinear equations. A control system structure was defined, closing one loop for each system output. Then, using SISO transfer functions relating each system input to each system output, one of the frequency domain SISO design methods mentioned earlier was used one loop at a time. If the results were not satisfactory, this loop-at-a-time design was done iteratively in a trial-and-error process to eventually produce a satisfactory multivariable control. In those cases where more than one linear operating point model was needed to describe the process, this complex iterative procedure would have to be done for each operating point. Finally, the resulting family of linear controllers would have to be tied together in some manner.

The first MCT techniques developed to handle multivariable systems were based upon a state-space matrix formulation of the differential equations describing the process. This approach formulated the problem directly in the time domain. The key paper by Kalman[3] is generally acknowledged to have stimulated initial work using these methods. Early work in this area is summarized in the book by Athans and Falb.[4] One of the most highly developed time domain methods is that of the linear quadratic regulator (LQR). Reference 5 contains a comprehensive bibliography of LQR activities and contributions. Many of the early applications involved flight controls, space vehicle guidance, and some industrial process controls. In addition, a large number of purely analytical endeavors and numerous doctoral dissertations were produced.[5] Beginning in the late 1960s, a second school of throught developed in Great Britain that can also be categorized under MCT. This system retained the frequency domain formulation of the describing equations, but extended the methodology to cover multivariable systems. Methods such as the inverse Nyquist array of Rosenbrock[6] and the characteristic locus of MacFarlane[7] typify the multivariable frequency domain approaches.

Aircraft Turbine Engine Control Design Problem

Multi-input aircraft turbine engines can be modeled analytically by a set of nonlinear differential and algebraic equations,

$$\dot{x}=f(x,u,\Phi) \tag{1}$$

$$y=g(x,u,\Phi) \tag{2}$$

where u, x, and y are the input, state, and output vectors, respectively, and Φ is a vector of environmental conditions. These equations typically represent an aggregation of lumped models of engine components[8] such as fans, compressors, combustors, and turbines. Engine inputs include fuel flows and variable geometries associated with various engine components (for example, combustor fuel flow and variable compressor inlet guide vanes). Engine outputs include component temperatures and pressures as well as the angular velocities of the rotating components (rotor speeds). The environmental conditions of the engine are determined by aircraft altitude and Mach number.

In general, the control performance requirement is to define engine thrust performance in response to a pilot command (PC). This requirement has to take into consideration several factors:

1) Desired response characteristics (e.g., engine acceleration rate).

2) Component operating point matching to provide high operating efficiency.

3) Environmental conditions Φ.

4) Engine physical constraints: a) thermal material limits for the combustor and turbine blades; b) mechanical strength limits for the rotating machinery; c) engine stability constraints such as airflow limits and stall avoidance; and d) component performance limitations such as maximum actuator slew rates.

The control law translates the PC into the appropriate engine input vector u. This input causes the engine to generate the requested thrust performance while observing the limitations imposed by factors 1-4. The control law can thus be written as

$$u=h(PC,y,\Phi) \tag{3}$$

where the constraints are implicit.

In the past, engine control algorithms [Eq. (3)] have been implemented using hydromechanical hardware. Over the years these hydromechanical controls have matured into very reliable units. However, increased performance requirements and engine complexity have resulted in complex control laws that can no longer be reliably or efficiently implemented in such hardware. These new control laws are now being im-

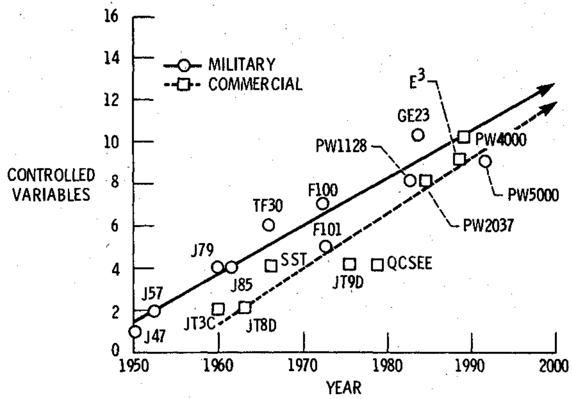

Fig. 1 Trends in control complexity of aircraft turbine engines.

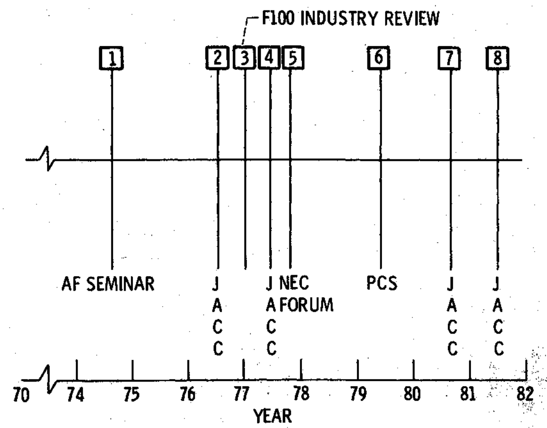

Fig. 2 Major meetings where turbine engine control papers were presented.

plemented using digital electronic (especially microprocessor-based) hardware. Digital controls not only allow for the implementation of complex control laws, they also present the opportunity to easily implement new types of control algorithms. The need to more efficiently and reliably design complex engine control laws, coupled with the inherent flexibility of the digital electronic control, has motivated research into improved engine controls and control design procedures.

Multivariable Turbine Engine Control Design

This section reviews reports and papers published during the last decade that applied MCT to the turbine engine control design problem.

Historical Highlights

In conducting the review of turbine engine control applications, eight significant meeetings held in 1974-1982 are emphasized. At these meetings (denoted in Fig. 2), experiments on turbine engine controls were presented and discussions held that helped to shape ongoing research efforts.

The first meeting (No. 1 in Fig. 2) was a seminar sponsored by the U.S. Air Force Office of Scientific Research (AFOSR) in August 1974. At this meeting G.J. Michael (then of United Technologies Research Center) and C.R. Stone (of Honeywell Corporate Research) presented their results on MCT, and specifically on LQR methods, as applied to aircraft turbine engines. These two efforts[9-11] are regarded as foundational. One outcome of the 1974 meeting was a recommendation that a program be initiated to engine test an LQR-designed control. The Air Force Wright Aeronautical Laboratories (AFWAL) and NASA Lewis Research Center jointly implemented this recommendation by cosponsoring the F100 Multivariable Control Synthesis (MVCS) Program, a major effort that will be discussed further in a subsequent section.

The second, fourth, seventh, and eighth meetings were Joint Automatic Control Conferences (JACC). The July 1976, June 1977, August 1980, and June 1981 meetings each included a session devoted exclusively to the problems of turbine engine control at which many results of MCT as applied to turbine engines were presented. The third meeting, in January 1977, was the industry review of the F100 MVCS program presenting results of the control design and computer evaluation phases.

The fifth meeting was the International Forum on Alternatives for Linear Multivariable Control sponsored by the National Engineering Consortium (NEC) in October 1977. This meeting is significant because a majority of the presentations included an application of MCT to a model of the F100 engine. This not only allowed comparisons between different theories when applied to a practical problem, but it also broadened the reported scope of engine control research.

The sixth meeting, the Propulsion Controls Symposium (PCS) in May 1979, took place at the NASA Lewis Research Center in Cleveland and included presentations by researchers from government, academia, and industry who assessed the state-of-the-art of aircraft propulsion control. Also, several presentations outlined the future needs and problem areas of propulsion control systems. A round-table workshop and an open discussion session that concluded the symposium helped to establish the direction of future research and the appropriate roles of government, industry, and academia.

In discussing MCT applications to turbine engine control, it is convenient to divide the work into a number of categories. For this paper, the categories selected were: 1) linear quadratic regulator (LQR) methods; 2) frequency domain methods; 3) identification, estimation, and model reduction; 4) detection, isolation, and accommodation; and 5) miscellaneous papers on engine control.

For each category, report or paper availability dates have been plotted on a separate time-line figure similar to Fig. 2. Each figure also includes meeting dates in order to provide a visual picture of the quantity and relative timing of the various reports. To be consistent, the reference list has also been subdivided into these five categories.

Linear Quadratic Regulator (LQR) Methods

The application of LQR methods to turbine engine control design is by far the most active area of modern control theory applications, with over 40 papers published. Figure 3 shows a time-line array of these papers for the period 1970-1982. Seven of these papers have been selected to serve as highlights of the activity in this area and will be discussed below.

The earliest application of LQR methods to engine control was by Michael and Farrar in 1973[9] and 1974.[10] Under sponsorship from the U.S. Office of Naval Research, they developed a control structure for handling large signal inputs and applied their control to a simulation of the F100 engine at sea level static conditions. The linear models used in the design were developed from the simulation via a curve-fitting procedure. As mentioned previously, this work was summarized at the 1974 AFOSR Seminar.

Other early work included a report by Stone et al.[11] and an MS thesis[12] by Bowles. Stone et al. documented the design and sea level testing of an LQR-based control for the GE J-85 engine. The primary control variable was fuel flow, with limited control of the exhaust nozzle area and scheduled control of the compressor bleed and inlet guide vane angles. This work was also reported at the 1974 AFOSR Seminar.

In 1975, Merrill[13] documented the use of a discrete output regulator to control a simple turbojet engine simulation. He investigated further applications of the output feedback regulator to the F100 engine.[14,15] Other work in the 1975 time period was that at Bendix by Elliot and Seitz[16] and at AFWAL by Weinberg.[17] In particular, Weinberg developed a now widely used procedure for generating linear-state variable models from a nonlinear (F100) simulation by using perturbation techniques. He also developed an operating line control for the F100 at sea level static. Spurred on by these developments, in 1975 the F100 MVCS program was initiated.

In 1976, the first of a number of special sessions on turbine engine control was held at that year's JACC. A key paper was one by Beattie and Spock[18] that described an LQR control for a variable-cycle engine. Although the study was conducted on a simulation at sea level static, the work was significant because it dealt with more control inputs than had previous studies. At the same conference was a paper by Slater[19] on the use of integrators in an LQR engine control and one by DeHoff and Hall[20] on the preliminary results of the F100 MVCS program (see also DeHoff and Hall).[21] The complete results of the design and simulation evaluation phase of the MVCS program were presented at the January 1977 F100 industry review.

As previously indicated, the F100 MVCS program was a jointly funded effort attempting to demonstrate that LQR theory could be successfully applied to design a practical engine control[22,23]. A control law capable of operating an F100 over its complete flight envelope was designed under an Air Force contract and the control laws were implemented by NASA on a minicomputer and used to control a real-time hybrid F100 simulation. The control was extensively evaluated on the hybrid and the results of both the design process and the hybrid evaluation were reported at the industry review. The information presented is documented in a contractor's final report[24] and also in NASA reports by Szuch et al.[25,26] Other reports[27-32] document various aspects of the MVCS program. Partially as a result of the MVCS program, a number of alternative methods for designing multivariable controls for a typical turbine engine were compared and contrasted at a special NEC forum in 1977. The F100 engine, operating at a sea level static, intermediate power condition, was chosen as the theme problem.[33] Seven papers were presented, each of which used some type of LQR method to

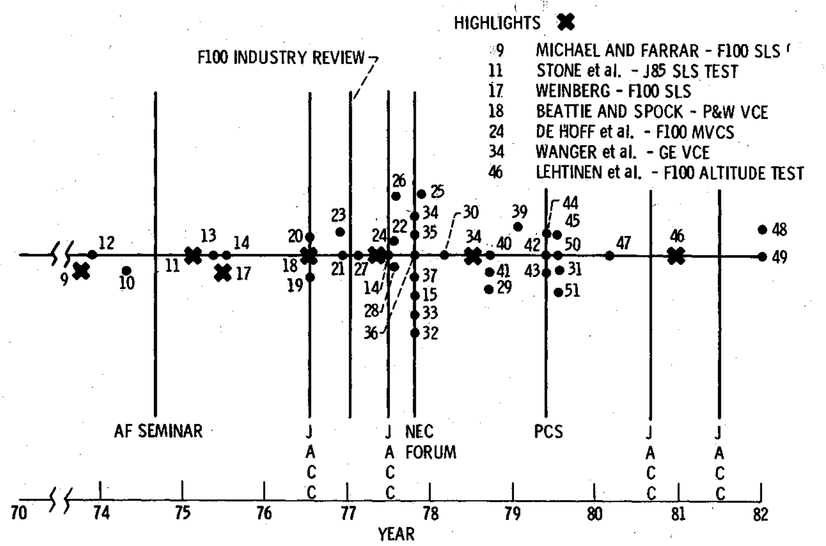

Fig. 3 Papers applying linear quadratic regulator methods to aircraft turbine engine control design.

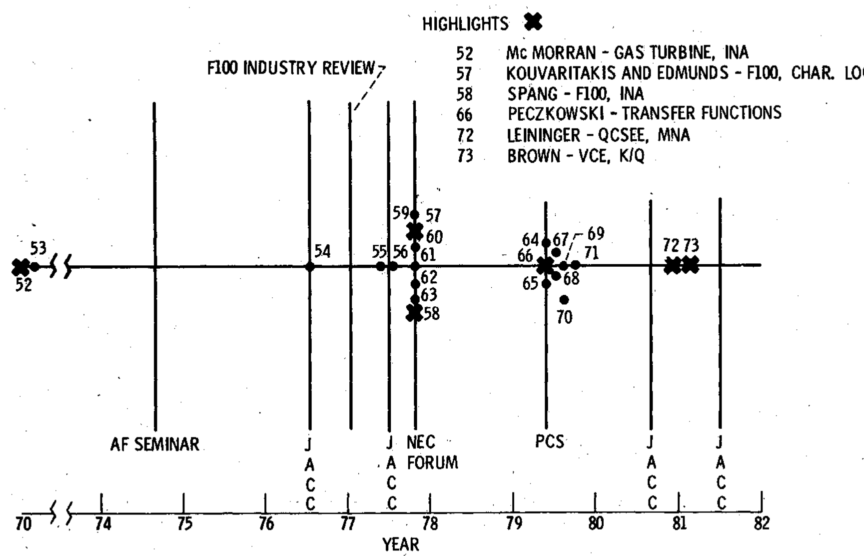

Fig. 4 Papers applying frequency domain design methods to aircraft turbine engine control design.

design an F100 control.[15,32-37] While only the linear regulator portion of the control system was addressed, much valuable insight into the application of multivariable theories was gained and the importance of aircraft turbine engine control problems was conveyed to a wide audience of control theorists and practitioners.

As a result of the success of the F100 MVCS program, AFWAL initiated a program with Systems Control Inc. and General Electric (Evendale) directed toward designing a control for a variable-cycle engine (VCE) using the LQR theory. Wanger et al.[38] documented the preliminary results of the program. Multivariable-control design results were reported by Rock and DeHoff.[39] The general control structure for the VCE was a refinement of that developed for the F100 MVC. Additional details of the design were documented in Refs. 40 and 41. An evaluation of the control was subsequently conducted using a detailed nonlinear VCE simulator.

Further developments in applied LQR theory were presented at the 1979 Propulsion Control Symposium. The subjects covered included integrated inlet/engine control,[42] the AFWAL VCE program,[43] and the results of the altitude test phase of the F100 MVCS program.[44]

The altitude tests of the F100 MVC had been conducted at NASA Lewis during 1978. They successfully demonstrated that the MVC logic could control an actual engine in an altitude test facility throughout the engine's normal flight envelope. The results of the tests are summarized in papers by Lehtinen, DeHoff, and Hackney.[45,46] Additional details of this phase of the program are available in Refs. 47-49.

Continuing activity in applying LQR methods to the engine control problem is evidenced by the appearance of two LQR-related papers in a special session at the 1979 JACC. Chung and Holley[50] extended their previous work on triangular decomposition and Rock and DeHoff[51] discussed the use of output feedback as was used in a VCE control.

Frequency Domain Methods

Multivariable frequency domain control design methods have not been applied to the aircraft engine control problem to the same degree that LQR methods have. However, the frequency domain has been receiving increasing attention in recent years. Figure 4 shows that over 20 reports and papers have been published since 1970 dealing with frequency domain methods applied to turbine engine control problems. Six of these papers will be highlighted here.

One of the earliest applications of the well-known INA (inverse Nyquist array) method of Rosenbrock was to a gas turbine.[52] A related paper by MacFarlane et al.[53] presented results of applying INA and characteristic locus methods to an aircraft turbine engine problem. Other than these two efforts, little else was published on engine applications until 1976 when a paper by Sain et al.[54] described the application of MacFarlane's characteristic locus method to a simple turbofan engine model. In 1977, Leininger[55] reported on work using the multivariable Nyquist array (MNA) and Gejji and Sain[56] applied matrix polynomial design techniques to engine control, which was a somewhat different frequency domain approach. These preliminary efforts in areas other than LQR, plus the increasing interest shown by other control theorists in the turbine engine control problem, led to the establishment of the 1977 NEC forum, where 7 out of 14 papers addressing the theme problem used frequency domain techniques.

Notable among the NEC papers was one by Kouvaritakis and Edmonds[57] in which they described how both multivariable root locus and characteristic locus techniques were used to design a three-input/output controller for the F100. In addition, they considered a three-input problem in which estimates of key unmeasurable variables (thrust, airflow, and turbine inlet temperature) were used as the feedback variables. A paper by Spang[58] discussed the use of an INA computer-aided design package to obtain a diagonal dominance-producing compensator for both three- and four-input F100 designs.

Other frequency domain papers were presented at the NEC by Holfmann, Teper, and Whitbeck,[59] Leininger,[60] Peczkowski and Sain,[61] Rosenbrock and Munro,[62] and Schafer and Sain.[63] The success of these frequency domain approaches indicated that using frequency domain methods might lead to the development of control systems that are simpler than those produced using LQR methods. This conjecture was not substantiated at the NEC because all of the proposed control designs were valid for only one operating point and not over the full F100 operating envelope.

A number of papers on engine control based on the frequency domain were presented at the 1979 Propulsion Control symposium. One by Leininger[64] discussed the MNA method, in which an optimization procedure is used to achieve system diagonal dominance. Sain and Schafer[65] described the use of so-called CARDIAD plots to map regions in the Nyquist plane where dominance-producing compensators can exist. A key paper at this symposium was by Peczkowski[66] describing a direct transfer function matrix approach. A desired closed-loop transfer function matrix was defined and a feedback compensator computed that allowed the desired closed-loop relationship to be achieved. Peczkowski refined and extended his procedure and presented it at the 1979 JACC.[67] Also at this meeting, Schaefer and Sain[68] described a four-input design for the F100 engine using CARDIAD plots.

During 1979, Leininger further elaborated his work on dominance optimization and sharing.[69-71] An application of dominance-sharing concepts appears in a 1981 report[72] covering the MNA design of a two-input control for the GE quiet clean shorthaul experimental engine (QCSEE). The design was evaluated over the full engine power range at sea level static conditions on both linear engine models and a nonlinear simulation.

In the most recently published report on frequency domain design applications, Brown[73] describes the use of MacFarlane's CLADP package to design multivariable regulators for an advanced variable-cycle engine for a V/STOL aircraft. The engine is quite complex, having 12 input variables. Approximate diagonalization was achieved through use of the so-called K/Q method and the resultant designs were evaluated on a nonlinear digital simulation.

Identification, Estimation, and Model Reduction

The topics of identification, estimation, and model reduction are closely related and are important to the overall engine modeling and control problem. In identification, the determination of a usable parametric model for control design (typically a state-space model) is the goal. In estimation, a model is required to predict the response of desired engine variables. In model reduction, the complexity of high-order state-space models identified from engine simulations must be reduced to a less complex, low-order model that is usable in a control design process. The following discusses the important work in these three areas as applied to aircraft turbine engines. The time-line plot of the published papers in this category is given in Fig. 5.

In the identification area, three papers are highlighted. The first is by Michael and Farrar[74] where an algorithm based on least squares estimation and nonlinear dynamic filtering was used to identify the parameters of an F100/F401 turbofan model. The model was multivariable and noise was introduced to simulate stochastic input/output data. Parameters in the multivariable model were identified from simulated stochastic input/output open-loop engine data. The second paper is by DeHoff,[75] where a single-input engine model was determined from closed-loop flight data using a maximum likelihood parameter search of dynamic engine simulation parameters. It was assumed that there was no process noise and the parameter search was accomplished off-line. The third paper is by Merrill,[76] in which the multivariable engine dynamics of an F100 engine were identified using actual closed-loop input/output engine altitude test data. Both bill of material and multivariable control test data histories were used in the identification process. The parameters were identified using a recursive instrumental variable approach that, although applied off-line, could be implemented in a real-time or on-line mode to continually update the model parameters as the engine test evolves. In two other identification papers, a two-input model was identified using the "method of models"[77] and this model form was then used for engine condition monitoring studies.[78] DeHoff and Hall determined F100 engine models from an engine simulation using an offset derivative approach and an output error identification technique.[79] Leonard and Arnett used an equation error approach to obtain models of the QCSEE engine.[80] A multivariable model for the QCSEE was obtained by Merrill as a time domain realization of single-input/single-output transfer functions.[81] The realization was constructed by retaining the system's centralized fixed modes and eliminating all others. The single-input/single-output transfer functions were identified by the extended, adjustable parameter vector recursive identification technique. In another paper, Merrill used a time series analysis method to find the model structure and model equivalent Kalman filters for a single-input engine.[82]

In the area of estimation, Michael and Farrar have authored three papers[83-85] that essentially developed, investigated, and applied a Kalman estimator/filter with model mismatch compensation. This filter was applied to an F100/F401 turbofan engine. Sahgal et al.[86] developed a real-time F100 engine simulation that was used in conjunction with Kalman estimation to dynamically estimate high turbine and fan turbine inlet temperatures in an F100 engine to improve engine protection.

Finally, a number of different approaches to reducing the complexity of state-space models have been investigated.[87-90] However, in each case, the equilibration of high-frequency modes was the principle used to obtain order reduction.

Detection, Isolation, and Accommodation

An important category is one involving the application of MCT to the detection, isolation, and accommodation (DIA) of sensor failures in aircraft turbine engines. The time line of the published papers in this category is given in Fig. 6. The papers can be grouped into four areas, as discussed below.

The first group is made up of two papers[91,92] representing original contributions to the field. Although MCT techniques were not used directly in these papers, they do represent the initial work in applying analytical redundancy to the DIA of sensor failures.

Papers in the next group all involve DIA applications to the F100 engine. The highlighted papers by Beattie et al.[93] and

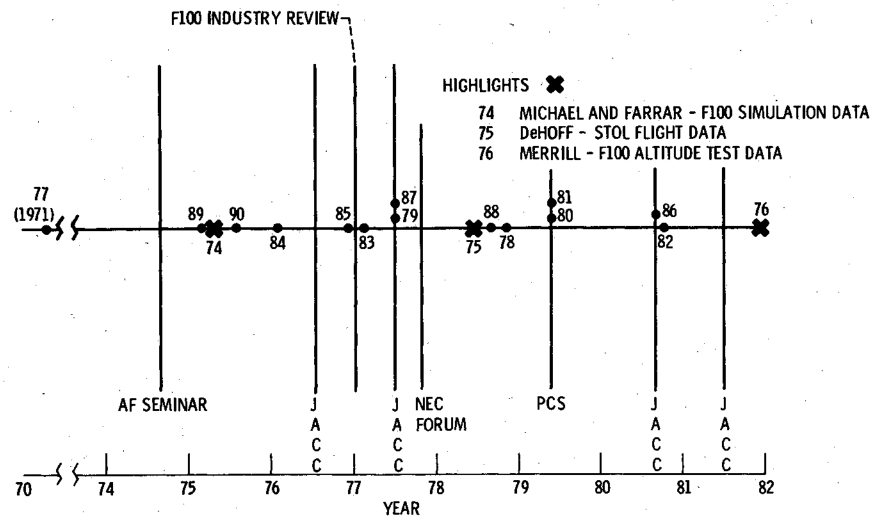

Fig. 5 Papers applying identification, estimation, and model reduction methods to aircraft turbine engines.

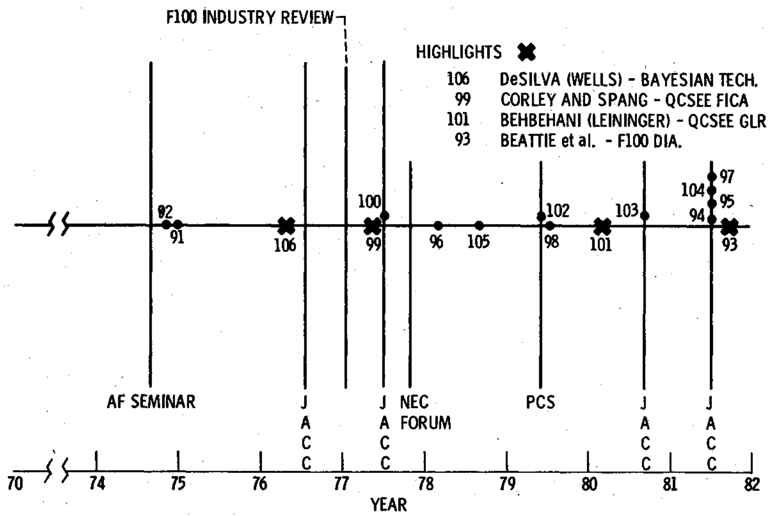

Fig. 6 Papers applying detection, isolation, and accommodation methods to aircraft turbine engines.

two closely related papers[94,95] describe a three-part program consisting of: 1) a careful definition of the extent and criticality of the sensor failure problem, 2) a competitive comparison of five different DIA concepts, and 3) a detailed evaluation of the best concept using a digital F100 engine simulation. The best concept consisted of range checks for the detection and isolation of "hard" failures and a weighted sum of the squared residuals test to detect "soft" failures. "Soft" failure detection is followed by hypothesis testing of filter residuals to isolate the soft failure. Failures are accommodated by reconfiguring a Kalman filter to produce estimates of all sensor outputs based upon the set of available, or unfailed, sensor outputs. The work of DeHoff and Hall[96] served as partial background for these studies. A failure-sensitive filter approach was applied by Meserole to the DIA problem for the F100 engine.[97] Detection and isolation were accomplished by associating the directions of measured residual vectors with a set of known direction vectors associated with the various system components. Sahgal and Miller[98] used a real-time microprocessor-based F100 engine simulation to reconstruct fan turbine inlet temperature in the accommodation of thermocouple failures.

A number of researchers applied DIA techniques to the QCSEE engine. Important and highlighted work here was accomplished by Corley and Spang[99,100] under NASA's QCSEE program. The work is referred to as FICA (failure indicating and corrective action), in which a simplified QCSEE simulation and extended fixed-gain Kalman filters provide estimates of the state based upon the sensor outputs available to the control. The FICA logic detected and isolated failures by simple range checks on the filter residuals since the residual elements were assumed independent. In the work by Behbehani[101] and two related papers,[102,103] a generalized likelihood ratio approach was taken for the detection and isolation of sensor failures. The resultant algorithm was applied to a QCSEE simulation to evaluate its usefulness. Leininger[104] studied the effects of mismatch between the plant and the model (which is used to generate the residuals) on sensor failure detection, both analytically and by application to a QCSEE example. A simple procedure based upon student's t distribution was presented to detect and remove the effect of this model mismatch.

Finally, two related papers by Wells[105] and DeSilva[106] represent the first applications of modern estimation techniques to the DIA problem for turbine engines. In both papers, a Bayesian hypothesis testing approach was studied for the detection of sensor failures. This technique required statistical information generated by a bank of Kalman filters that also reconstructed the failed sensor outputs.

Miscellaneous Papers on Engine Control

Included here are papers that did not fall conveniently into any of the previously discussed categories. The time line for the material is given in Fig. 7. Although this is a miscellaneous category, some grouping is possible.

The first group consists of those papers in which techniques were applied to an F100 engine model. These include papers

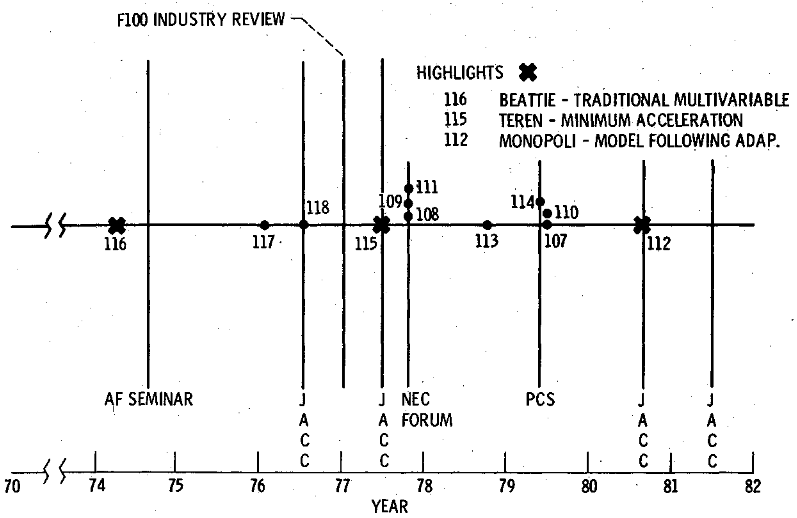

Fig. 7 Miscellaneous turbine engine control papers.

that used the F100 theme problem example of the 1977 NEC Forum,[107-111] including adaptive control,[107,111] state-space[109,110] and optimization approaches.[108] Additionally, in the highlighted paper by Monopoli,[112] a model following adaptive control was applied to a full nonlinear simulation of an advanced technology turbofan engine (similar to the F100 engine). The adaptive control law was designed using Liapunov's direct method and applied to the multivariable (two-input) simulation.

The second group includes three papers that attempt to improve the performance of an engine relative to a performance criterion. For Jordan and Michael[113] and Seldner,[114] the performance criterion was the minimization of the thrust specific fuel consumption. Jordan and Michael[113] applied a sequential univariate search technique to an F100/F401 engine. This technique was selected because of its minimal storage and calculation time requirements. Seldner[114] compared four advanced optimization techniques (including conjugate gradient and conjugate direction search techniques) as applied to the QCSEE engine Teren[115] developed a new computer algorithm based upon nonlinear programming, which was applied to a model of the F100 engine to generate open-loop, minimum-time acceleration control trajectories.

The final group of these papers has no real common denominator. Beattie[116] designed a multivariable engine control for a variable-cycle engine using traditional methods. This paper is included as a point of reference for comparing controls designed by traditional methods with those designed by MCT. Michael and Sogliero[117] developed an analytical assessment procedure to determine the relative importance of each control variable in a multivariable system. The assessment is based upon a modal interpretation of multivariable system dynamics and was applied to an F100 engine model. Finally, Sain et al.[118] discussed some frequency domain and algebraic methods for the design of turbine engine controls.

Future Requirements

There remain a number of perceived requirements that must be met in order to successfully apply MCT to future aircraft turbine engines. These requirements fall generally into three broad areas: control design, modeling, and reliability.

Control Design

Work in this area will emphasize the computer-aided design (CAD) of control systems. Interactive programs that incorporate the latest numerical techniques, command and menu-driven input, user-friendly aids and diagnostics, as well as improved graphics and the latest in display technology can play a significant role in the efficient and reliable design of engine control systems. Recent developments in robust multivariable control design methodology also need to be applied to the engine control problem. Robust design methods allow modeling imprecision to be handled in a rational way and can produce controls that are both simpler and more reliable. In addition, work needs to be done in the areas of microprocessor implementation of modern control algorithms, the effect of sample- and multiple-rate sampling on system performance, and the direct design of controls in the discrete-time domain rather than digitizing continuous-time domain designs. Also, the role of MCT in designing integrated controls for the total airframe/propulsion system needs to be established. Finally, new nonlinear control design techniques are needed to allow for direct design using nonlinear models. These nonlinear techniques should include adaptive control, nonlinear feedback control, self-optimizing or performance-seeking control, and improved optimal trajectory generation. Many of these techniques, however, require improvements in nonlinear engine modeling before nonlinear engine control design results can be achieved.

Modeling

It is generally agreed that the most significant gains in engine control will be achieved by improving the engine modeling process. One important aspect of the modeling process is the identification of dynamic models from the data. Of particular interest is the real-time identification of a model with time-varying parameters using closed-loop data. This would allow the identification of real-time updates to an engine model as the engine moves from one flight point to another. This kind of research could eventually lead to a self-tuning or adaptive engine control. The structure of such a control would be fixed, but the nominal model parameters within the structure would be constantly updated based upon real-time knowledge of specific engine dynamics. Also of importance will be the development of analytically tractable nonlinear models. Important here will be the development of appropriate nonlinear engine model structures and the identification of parameters within these model structures. Nonlinear models will be required both for the successful application of nonlinear control design techniques and for the study of grossly nonlinear engine phenomena such as compressor stall and surge.

Reliability

Work to improve engine system reliability is required. In particular, techniques that incorporate analytical redundancy need to be pursued. The evaluation and demonstration of the detection, isolation, and accommodation of sensor failures on a full-scale engine are needed. The robustness properties of analytically redundant algorithms need to be more completely understood to predict maximum achievable performance. The extension and integration of analytically redundant techniques to multiple-engine systems and to fully integrated airframe/engine systems needs to be studied. Finally, better procedures for modeling system reliability performance is required.

Conclusion

Modern control theory has clearly established a role in the design process of controls for advanced aircraft turbine engines. Organized, systematic methods for designing turbine engine control laws have been demonstrated, using both time and frequency domain techniques. A multivariable control design using LQR methods has been experimentally validated under the F100 MVCS program. Theoretical techniques such as model parameter identification, state estimation, and analytical redundancy for failure accommodation have all been successfully applied to the turbine engine problem.

The field of control theory continues to be a very active one. The body of knowledge comprising modern control theory is thus a growing one and will continue to provide the engine control system designer with powerful tools. The challenge is to apply these tools effectively to the complex engines of the future.

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