JOURNAL OF PROPULSION AND POWER
Vol. 16, No. 5, September–October 2000

Survey of Advancements in Jet-Engine Thermodynamic Simulation

Vivek Sanghi,* B. K. Lakshmanan,† and V. Sundararajan‡
Gas Turbine Research Establishment, Bangalore 560 093, India

The art of engine simulation has come into existence with the advent of analog and digital computers and has become an integral part of any engine development program. It has attracted considerable attention from researchers because of the tremendous benefits it offers not only in terms of cost reduction, but also because of the confidence it induces into the behavior of gas turbine being designed. A substantial number of works have been carried out in the field of engine simulation and its design applications during the past 50 years. The present paper intends to give a comprehensive overview of the attempts that have been made by the earlier researchers, and the considerable amount of knowledge, database, and the expertise that has been made available.

Nomenclature

A = area
H = enthalpy
M = Mach number
N = spool rotational speed
P = total pressure
p = static pressure
R = gas constant
T = total temperature
t = time
W = mass flow rate
W_F = fuel flow rate
γ = ratio of specific heats
Δ = change/error in a quantity
η_m = spool mechanical efficiency
σ = total pressure loss coefficient

Subscripts

ACC = engine accessories
BP = bypass duct
H, HP = high-pressure spool
HPC = high-pressure compressor
HPT = high-pressure turbine
L, LP = low-pressure spool
LPC = low-pressure compressor
LPT = low-pressure turbine
nz = nozzle
α = ambient conditions
1, 2, 3, 4, 5, 6, ... = engine stations

Introduction

WITH increasing levels of aircraft performance and resulting complexity of propulsion system caused by the stringent demands placed on it, the development cost and time of a modern gas-turbine hardware have increased considerably. Thus, prior to developing the hardware, it is necessary to have sufficient confidence in its reliability, handling, and performance in the early design stage itself.

It is equally necessary to design a control system that governs engine response to throttle inputs, defines the safe operational limits, and provides a trouble free automated engine operation during the entire mission, while simultaneously meeting the aircraft performance.

An accurate understanding and prediction of engine dynamic and steady-state performance is a very important input for the definition, development, and refinement of an engine control system, prior to making the control system hardware. It reduces the cost, time, and the risk involved. Deriving inputs for control system design by actual engine testing will not only be very expensive and time consuming, but it will also pose a high level of operational and accident hazards associated with developmental engines.

With the advent of computers, computer simulation techniques have been very useful for predicting engine response. Simulation is the process of studying system behavior by observing the behavior of its representative model. It permits an in-depth understanding of engine dynamic and steady-state behavior in the early design phase, without simplification of complicated logic flow and can be carried out at a low cost, without endangering the engine.

A large number of computer simulations have been reported, in a quest to predict engine dynamic and steady-state behavior with high accuracy and greater reliability. The present paper attempts to recognize the contributions that have played a prominent role in advancing the state of the art. Prior to that, the paper outlines the sequence of developments in a simulation program, simulation requirements, engine thermodynamic modeling, and computer considerations.

Aerospace Abstracts Database was a major source of the relevant literature. The references marked with ISSN and a numerical code in the bracket are in Chinese, the English version of which is available from AIAA Technical Library.

Simulation Sequence

An engine simulation program begins with the development of a nonlinear detailed thermodynamic mathematical model for predicting its dynamic and steady-state performance. Because of large-scale computations, it usually works in a non-real-time environment. For testing and evaluation of control system hardware, the model is required to develop a real-time engine simulation. It is a transient performance computer program whose engine outputs are generated at a rate commensurate with the response of the physical system it represents.

Subsequent to the development of control system software, its functional feasibility is evaluated by studying its interactions with engine, by integrating it with engine system software, i.e., the close-loop simulation.

Until this stage, both the engine and control system are in the software form and need to be translated into a hardware. The development of engine hardware takes much longer than the control system hardware. The real-time simulation is of utmost importance

Received 21 August 1998; revision received 7 June 1999; accepted for publication 28 June 1999.
*Scientist, Engine Simulation Division. Member AIAA.
†Head, Engine Simulation Division.
‡Director.

Table 1 Errors description for engine balancing using MDNR scheme

Error	Description	Station description
1	$(UW_{21} - W_{21})/W_{21}^{a}$	21: high-pressure compressor entry
2	$(UW_{42} - W_{42})/W_{42}^{a}$	42: high-pressure turbine throat
3	$(UW_{52} - W_{52})/W_{52}^{a}$	52: low-pressure turbine throat
4	$(W_{26}^{b} + W_{61} - W_{62})/W_{62}^{c}$	26: cold-stream main-mixer entry
5	$(\eta_{m,LP}{}^{*}\mathrm{WRK}_{LPT} - \mathrm{WRK}_{LPC})/\mathrm{WRK}_{LPC}$	——
6	$[\eta_{m,HP}{}^{*}\mathrm{WRK}_{HPT} - (\mathrm{WRK}_{HPC} + \mathrm{WRK}_{ACC})]/(\mathrm{WRK}_{HPC} + \mathrm{WRK}_{ACC})$	——
7	$(W_{26}{}^{*}H_{26} + W_{61}{}^{*}H_{61} - W_{62}{}^{*}H_{62})/(W_{62}{}^{*}H_{62})$	——
8	$(\mathrm{TM}_{26} + \mathrm{TM}_{61} - \mathrm{TM}_{62})/\mathrm{TM}_{62}$	61: hot-stream main-mixer entry
9	$(UW_{61} - W_{61})/W_{61}^{d}$	62: main-mixer exit upon mixing

[a] W_1, W_{21}, W_{42}, and W_{52} are computed from maps, using corrected speed and pressure ratio. W_1, i.e., fan entry mass flow, defines the basis for all upstream mass flow estimations by appropriately deleting or adding bypass, bleed, and fuel flows at various stations to W_1.
[b] W_{26} is computed from $p_{26} = p_{61}$ (state variable), $T_{26}(=T_2)$, P_{26} (P_2: state variable$^{*}\sigma_{BP}$), and A_{26}.
[c] W_{62} is computed using downstream A_{nz} and nozzle pressure ratio characteristics.
[d] W_{61} is computed from upstream P_{61}, T_{61}, p_{61} (state variable), and A_{61}.

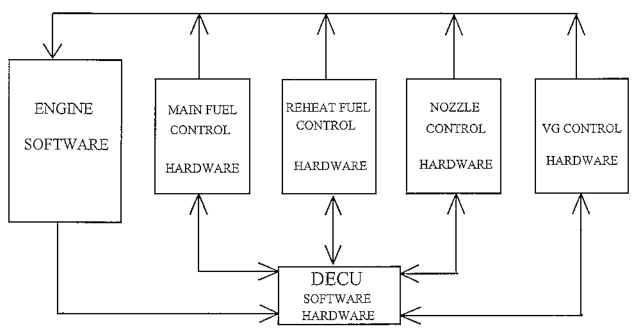

Fig. 1 Hardware-in-loop simulation.

to bridge this time lag. It enables testing of the dynamic response of control system hardware in conjunction with the engine model. This methodology is termed as the hardware-in-loop simulation (HILS).

During HILS, the plant is represented by real-time software, to which the control system is integrated in the hardware form. Thus testing and evaluation of control system hardware need not wait until full-scale development of actual engine hardware. The typical schematic of HILS is shown in Fig. 1, where DECU stands for digital electronic control unit, and VG denotes variable geometry in compressor stators.

Thermodynamic Simulation

Requirements

The engine simulation must accurately represent the engine behavior over its complete running range and over the entire flight envelope. It should be readily understandable to nonsimulation specialists, should be brought into use rapidly without lengthy setup time, should have high degree of reliability and repeatability, and should readily incorporate design modifications.

Computer Considerations

Engine simulation can be implemented on a digital, analog, or a hybrid (analog + digital) computer. The fundamental difference between an analog and a digital computer is that analog is parallel in operation, whereas digital is serial. Being a parallel computing machine, an analog computer permits simulation in realtime, despite its inability to represent nonlinear algebra and storing a program for future use.

But with the availability of very high computing speed and storage capacity at low cost, digital computers too can effectively handle the real-time simulation and have gradually replaced the analog and hybrid computers. The real-time simulation is further aided by parallel processing on a digital platform. Besides, digital computers guarantee reliability and repeatability, once the program is debugged. It is quite simple to change components' characteristics as development phase progresses by merely changing the data sets. The digital simulation is highly portable, can easily be extended to any engine configuration with suitable modifications, and an engine company can supply its aircraft customers with a copy of simulation model.

Modeling

The development of an engine mathematical model is central to a simulation study and is approached from the viewpoint of engineering thermodynamics. It uses compressor and turbine characteristics and is founded on the techniques of component matching. The thermodynamic behavior of every component is represented by a set of theoretical or empirical equations. The relationship between the components is fixed by the physical layout of engine and by the thermodynamic behavior of each component. Thus, for a given engine if all the component characteristics and the engine layout are known, then the engine is precisely defined, and its dynamics can be expressed mathematically.

The identification of various components and stations and performance presentation is very important in an engine simulation. The aerospace recommended practices and aerospace standards,[1−5] published and revised periodically by the Society of Automotive Engineers (SAE), must be followed for this purpose, to make the program confirm to international standards. Also a uniform notation makes the program easy to understand and enables the modifications easily.

The inputs to the model are flight conditions and control parameters, i.e., fuel flow in the main and reheat combustion chambers, compressor VG setting, and A_{nz}. A set of engine parameters called state variables are chosen, which define the operating point of each component, for prescribed inputs. A typical state vector for a twin-spool, mixed-flow turbofan includes P_2, P_3, P_5, P_6, p_{61}, P_{62}, T_{62}, N_L, and N_H. The station designation can be inferred from Fig. 2 and Table 1.

Figure 2 shows a typical model for a mixed-flow twin-spool turbofan engine. LPC and HPC denote low-pressure (LP) and high-pressure (HP) compressors, respectively. Similarly, LPT and HPT stand for the LP and HP turbines.

Dynamic or Transient Analysis

It determines the time history of engine state and path followed by the engine from its existing steady-state to the new steady-state condition because of a disturbance in the flight and/or control inputs. Alternatively, pseudotransients can be simulated to identify engine steady state at given flight condition and control system inputs. At the prescribed flight condition components' operation is found, using the control inputs and initial guess of engine state vector. As a general case, there will be a work imbalance (or a net torque on compressor-turbine assembly), and a flow mismatch (or mass accumulation) at various engine stations.

The torque difference between a compressor and a turbine is used to generate the time derivative of rotational speed, from which rotor acceleration or deceleration is found.

The flow imbalance may be treated on one of the two ways:

1) The iterative method works on the basic assumption that flow continuity is maintained at all times. The engine parameters are iteratively adjusted to satisfy the flow compatibility without any change in the rotor speed.

2) With the inter-component volumes method the individual components are inter-connected by control (mixing) volumes. The mass

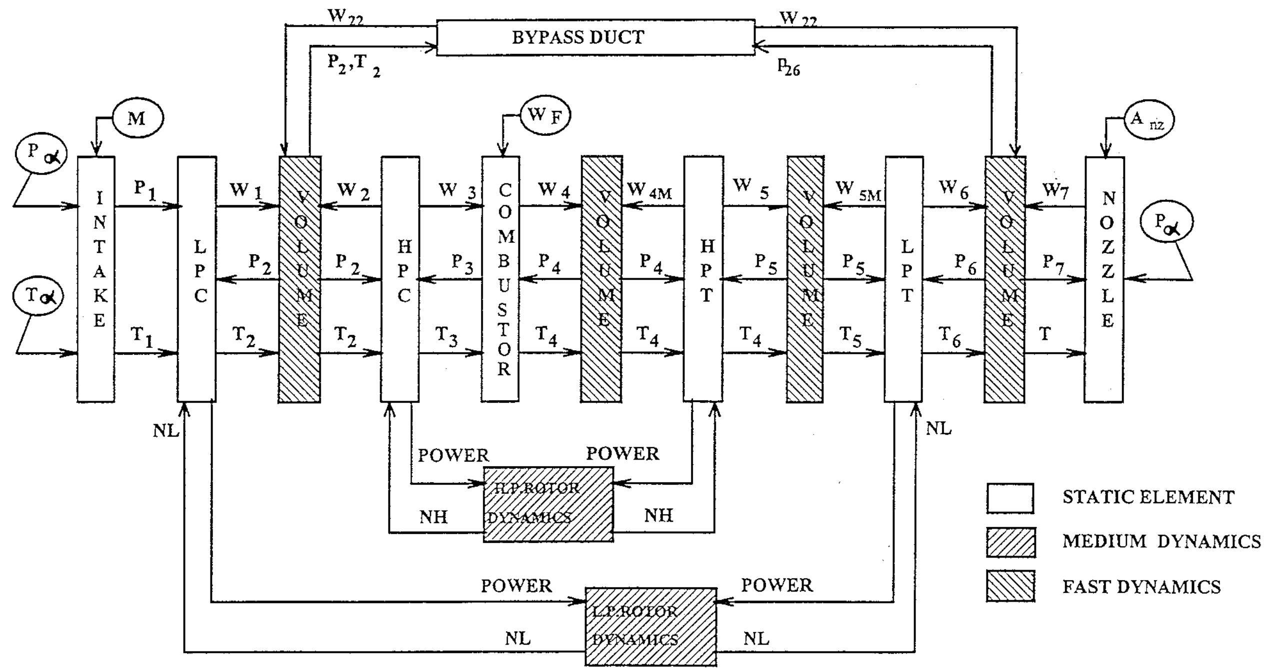

Fig. 2 Flow logic for a mixed-flow turbofan.

flow accumulation in control volumes is assumed, which is used to calculate the rate of pressures change with time ($\mathrm{d}P/\mathrm{d}t$) at various engine stations, as given by Eq. (1).

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \frac{\gamma RT}{\mathrm{Vol}} \cdot \Delta W \tag{1}$$

where Vol is control volume and ΔW is the mass flow error in control volume.

The next engine state is computed by integrating the state variables derivatives, and steady state is reached when these time derivatives diminish.

Steady-State Analysis

For determining steady-state operation of a mixed-flow turbofan engine at the prescribed flight condition and control inputs, the necessary and sufficient conditions are mass flow continuity at various engine stations and rotational speed and power balance between the compressor and turbine on the same rotor. There are added constraints of static pressures, enthalpy, and momentum balance between the cold and hot streams during mixing. Using these constraints and an initial guess of state vector, a total of nine errors contained in Table 1 are generated for a mixed-flow, twin-spool turbofan. The prefix U represents upstream, WRK is component work, TM is total momentum, and MDNR denotes multidimensional Newton Rapson.

The initial guess of state variables is continuously updated using the MDNR scheme until the errors come within a prescribed tolerance band. McKinney[6] and Koeing and Fishbach[7] give a FORTRAN source code listing to calculate the design and off-design steady-state performance of the turbojet and turbofan engines, based on the MDNR method. An alternate nested-loop approach for steady-state performance estimation is stated in Sanghi et al.[8]

Literature Review

Fundamentals

To understand gas turbine as a system before attempting its modeling and simulation is extremely important. Cohen et al.,[9] Oates,[10–12] Mattingly,[13] and Walsh and Fletcher[14] are some of the outstanding textbooks that provide a comprehensive understanding of the key concepts governing the gas turbines. They give an excellent description of engine cycle selection, components' design features, component matching, operating characteristics and performance engineering, and form the basis of modern gas-turbine theory. Flack[15] also gives a good and an easily understandable description of component models and their matching procedure.

Detailed Engine Simulation

The analytical and experimental investigation of gas-turbine dynamic behavior began around the early 1950s, when the twin-spool engine was just appearing on the scene. Otto and Taylor[16] were probably the first to show that a single-spool engine could be approximated by a first-order system to determine the rotor speed response to a step change in fuel flow.

Fawke and Saravanamuttoo[17] review the initial developments in the field of engine simulation. They briefly describe the early analog and digital simulation studies that were centered on calculating rotor-speed time constant of a single- and a twin-spool (turbojet and turbofan with mixed and unmixed exhausts) engine, by treating them as a simple linear or a nonlinear system together with the application of necessary matching conditions and a knowledge of component characteristics.

More emphasis has been placed on digital simulation in recent years, for the reasons discussed earlier. Fawke and Saravanamuttoo give further details of currently used digital methods of simulating gas-turbine transient behavior, as described earlier. It also discusses a variety of issues such as the comparison of the linear and component models, choice of computers, comparison of the iterative and intercomponent volume approaches to digital simulation, and the methods of incorporating and accessing component characteristics in a digital simulation.

The linear system assumption is the simplest representation of a gas-turbine system. The dynamics is described by simple mathematical expressions involving time constants and partial derivatives, the values of which can be obtained from the analysis or engine tests. But the assumption of linearity limits the validity of the simulation model to small perturbations about a single operating point and hence the scope of simulation. Any alteration to the engine means new values must be obtained for time constants and partial derivatives, which necessitates further engine analysis or tests. Thus, the component model approach is preferred because it is more flexible, versatile, and permits a greater insight into engine dynamics.

In comparison to the iterative method, use of intercomponent volumes enables us to track accurately the pressure dynamics and gives a better physical representation of the gas-turbine system. The computing time may not differ significantly because of the conflicting requirements. The intercomponent volume approach requires marching with small integration time step because pressure dynamics has a small time constant. In the iterative approach, though larger time steps can be taken because the approach considers only the rotor dynamics (which has a higher time constant than the pressure dynamics), each time step will involve iterations to satisfy the flow compatibility.

Except for a mixed-flow turbofan, values of intercomponent volumes were not observed to be critical. Choosing a larger volume than the actual physical volume permits the use of larger integration time steps and hence a reduction in overall computing time. However, in a mixed-flow turbofan bypass duct volume is critical because the pressure levels in the bypass duct determine the flow split at fan exit. Thus the volumes used are the actual physical volumes.

The results are presented for a variety of engines such as the single- and twin-spool turbojets, a twin-spool turbofan with mixed exhausts, and a three-spool turbofan with separate exhausts. Using the intercomponent volume approach, a good agreement was shown between the engine tests and the simulation studies.

Prior to Ref. 17, Saravanamuttoo and Fawke[18] discussed the application of both analog and digital computer methods for simulating dynamics of a twin-spool turbojet with variable nozzle, compared the relative merits of analog and digital simulation, and highlighted the simulation requirements. Fawke and Saravanamuttoo[19] verified that results from digital simulation[17,18] are in good agreement with the engine test bed running, indicating that the proposed simulation technique is an invaluable tool in the development of new engines.

Subsequent to Ref. 17, Fawke and Saravanamuttoo[20] provided a comprehensive methodology for digital simulation of the dynamics of a twin-spool turbofan engine with mixed exhausts. It utilizes the concept of state variables and makes use of intercomponent volumes. The method was validated by comparing predicted results with actual engine running. A brief discussion of heat-transfer effects on engine dynamics is also included. References 17 and 20 can be viewed as the major contributions to the field of engine simulation, as they propose a simulation model that predicts engine dynamics with high accuracy, and which has found widespread application in following years.

Extending the description of Refs. 6 and 7, Seller and Daniele[21] reported a FORTRAN source code, which included the prediction of transient performance as well, in addition to the steady-state performance. Daniele et al.[22] present a dynamic simulation approach that incorporates temperature dynamics also besides rotor and pressure dynamics.

Reference 23 contains a dynamic engine analysis FORTRAN code (DEAN), which follows a similar methodology as in Ref. 21 but illustrates an approach that is highly modular and flexible. It allows the user to simulate engine subsystems as well as the full engine with relative ease. The differential equations that define the engine dynamics may be solved by one of four integration schemes: a second-order Runge–Kutta, a fourth-order Runge–Kutta, an Adam's Predictor-Corrector, or Gear's method. DEAN has been written for two-spool, two-stream turbofan engines, and can easily be modified for application with a variety of other gas-turbine configurations. It also supports an extensive graphics capability for displaying simulation results.

Merrill[24] describes HYTESS II, which is representative of a hypothetical, low-bypass turbofan engine with an advanced control and failure detection logic. It includes a description of engine dynamics, control algorithm, and sensor failure detection logic. Details of the simulation block diagrams, variables and subroutines descriptions, common block definitions, and input requirements are given. Example simulation results are also presented.

References 25–31 are a few of numerous published works on the simulation of gas-turbine steady-state and dynamic performance.

The design document[32] uses the experience of existing works and has made available a comprehensive in-house expertise to Gas Turbine Research Establishment (G.T.R.E.) at Bangalore, India, to estimate dynamic and steady-state response of a variety of gas-turbine configurations with high accuracy.

Steenken[33] describes a method that is an extension of the capabilities of engine transient cycle deck and can be used to predict the poststability operation of a turbofan engine. Typical predictions are presented and compared with the results obtained from the testing of a modern augmented turbofan. The potential manners in which the digital simulation tool may be used are also discussed.

Khalid and Hearne[34] present a mathematical model to incorporate the additional levels of details that may be included in the engine simulation model to improve its accuracy. These include time-varying fluid properties, heat transfer between gas and metal, variations in turbine cooling air, and turbomachinery clearance variations.

The work of Zhu and Liao[35] is another publication in which the engine working processes during acceleration and deceleration are modeled to estimate heat transfer between the gas and engine components. By simulating a two-spool mixed-flow turbofan engine, the effects of a variety of heat-transfer processes on thrust response were calculated and compared for cool and hot accelerations under the same fuel schedule. The results indicate that because of heat transfer the difference between cool and hot accelerations is significant.

Tang and Cai[36] have investigated the effects of hot gas ingestion and recirculation of exhaust gas from a vertical/short takeoff and landing aircraft. It brings the engine into an unstable region and may cause trouble for flight. A pulse-monitored fueler is recommended for improving engine stability. A digital model for this purpose is presented, which consists of a first-order fuel-feed model, a component volume model, and a rotor-dynamic model. The engine dynamic and steady-state response are predicted based on this model. The results indicate that simulation effects of this model are satisfactory.

Orkisz[37] derives an implicit equation for the acceleration time of a turbojet, in which expansion into power series contains first-order partial derivatives. These derivatives represent the sensitivity of acceleration time caused by the variation of 1) design parameters of compressor (stability margin, moment of inertia, efficiency, compression ratio), 2) technical conditions (deformation of blade profiles, caused by erosion, turbine blade clearance), and 3) service conditions (flight speed and altitude).

Lambert[38] presents a simulation model that incorporates a measure to estimate the effect of deterioration in components on engine performance. The fixed engine control schedules may not be optimal for the deteriorated engine. The engine deterioration parameters cannot be measured directly, but can be estimated. A Kalman-filter technique is presented to estimate deterioration in engine performance parameters.

Zaita et al.[39] also illustrate an approach to model the performance deterioration of an aircraft gas-turbine engine caused by fouling, erosion, and wear as it accumulates operating time in the field. The performance deterioration model interfaces with the manufacturer's baseline simulation model. The effects of deterioration are determined in terms of reduced pressure ratio, flow capacity, and efficiency for the compressors, and reduced efficiency and increased flow capacity for the turbines. The initial values of the affected parameters are then modified in the engine cycle deck.

O'brien[40] discusses the dynamic simulation models with emphasis on fundamental principles and methods used to represent the components and stage flow characteristics. Results from several dynamic simulations of multistage compressors are shown as are their comparisons with the experimental data. Possibilities for advanced computational techniques for near real-time simulation of compressors and gas turbines are reviewed.

Reference 41 contains the notes of a lecture series delivered at the Von Karman Institute for Fluid Mechanics at Belgium. It includes an overview of the fundamental behavior of gas-turbine engines, transient behavior and its effects on engine operability and controllability, the nature of models used to simulate engine transient behavior, utilization of gas-turbine simulation systems, and computer programs, nonlinear solvers, and algorithms used in engine simulation.

Chappell and McLaughlin[42] have dealt with the approach to model continuous gas-turbine operation from startup to shutdown

(ATEST-V3). This approach is capable of simulating engine operation continuously from near static condition to maximum engine power, including windmill starting, spooldown, and starter-assisted starting.

Torella[43] details the main steps of a work carried out for developing expert systems for turbofan engine simulation. The first part of the paper deals with the selection of computer language. Successively, a large numerical database about the behavior and performance of the engine is obtained from the application of the simulation. The use of numerical data for developing sets of logical rules for a high flexibility knowledge base is shown. Finally examples of an expert system for different aspects of turbofan simulation are presented and discussed.

Drummond[44] presents an object-oriented approach for gas-turbine simulation. It offers a generalized framework for the steady-state and transient simulation and proposes that simulation will benefit significantly in terms of code reliability, maintainability, and manageability using the object-oriented programming language.

NASA[45] has also developed a object-oriented approach for engine simulation. The program is a prototype for a more complete, commercial grade engine performance program now being proposed as part of the Numerical Propulsion System Simulator (NPSS). NPSS was initiated at NASA/Lewis in cooperation with industry, academia, and other government agencies in the United States to develop the technologies necessary to enable numerical simulation of a complete airbreathing engine.[46] It consists of there main elements: engineering models for multidisciplinary analysis of large subsystems and systems at various levels of details, a simulation environment, and a cost-effective, high-performance computing platform.

Schobeiri et al.[47,48] describe a novel computational method for accurate simulation of the nonlinear dynamic behavior of single- and multispool core engines, turbofan engines, and power-generation gas turbines. Row-by-row calculation procedures that account for specific turbine and compressor cascades and blade geometry and characteristics are implemented. The nonlinear, dynamic behavior of the subject engine is calculated by solving a number of systems of partial differential equations, which describe the unsteady behavior of each component individually.

Ivanov[49] discusses the perspective problems in the simulation of the gas turbines, right from design stage to production, and its entire life on aircraft.

Reference 50 is an outcome of a lecture series on mathematical models of gas turbines and their components. It identifies some peculiarities of complex multicomponent and multidisciplinary models for the whole flow passage of bypass engines, core, multistage compressors and turbines, and other engine components. Solutions of the steady and unsteady problems are given using the high efficiency monotone numerical methods, and the theoretical basis of these methods are presented.

Hideaki[51] incorporates the combustor transient performance into the base simulation model. The combustion efficiency is impaired significantly during snap acceleration, and it has been quantified and modeled as the function of fuel-to-air ratio over-richness in the primary combustion zone. The verification of the resulting improved model has been carried out with engine test results.

The nonlinear simulation methods have become highly complex, and it may be extremely difficult for a nonspecialist to use them. The user's interface is an extremely useful facility for easy execution of such simulation codes.

Reed and Afjen[52–55] describe the Turbofan Engine System Simulation (TESS) software, which is an interactive graphical simulation environment for gas-turbine engine analysis. TESS combines a lumped-parameter gas-turbine simulation code and Application Visualization System (AVS) interactive programming environment to provide a graphical user interface (GUI) and an operating environment that allows the user to easily create and simulate gas-turbine systems. This integrated system provides the ability to graphically construct arbitrary gas-turbine configurations, select and control steady-state and transient operation of the system, and view results in graphical form as the simulation is executing.

Over the last several years, TESS has served as a research platform for investigating the feasibility of integrating high-fidelity (more detailed) component analysis models into low-fidelity (less detailed) engine models. This concept, which is called component zooming, provides a method for selectively investigating the physical process occurring in jet engines without having to model the complete engine at a high level of detail. The TESS has been adopted as the prototype simulation executive in NPSS project.[56,57]

Davis[58] and Hale and Davis[59] describe the modeling technique, theory, and capabilities of a dynamic turbine engine compression code (DYNTECC). DYNTECC is a stage-by-stage simulation of axial compression system to analyze a generic compression system for single- and dual-spool systems. Davis[60] further shows implementation of an interactive user interface to aid in the analysis of complex dynamic phenomena in a gas-turbine engine compression system.

Ganji and Khadem[61] present an integrated general-purpose simulation package for steady-state and transient simulation of gas-turbine propulsion systems. The standard techniques of steady-state and transient matching have been used. The program is capable of simulating an open-loop engine, as well as an engine and its control system as one dynamic unit. The program is equipped with a graphic user interface for configuring the engine as well as its control system, accepting inputs, commanding the run-time routines, and providing the outputs in graph forms.

Xie et al.[62] report an adaptive engine simulation model by means of modification factors. According to the parameter measurements of the engine on a test rig and in flight, the engine component characteristics are rectified, and as a result, outputs of the simulation model are in accordance with the measurements. The application of this method is demonstrated to rectify the parameters in the simulation model of a twin-spool reheated turbojet.

Real-Time Engine Simulation

The design, development, and implementation of a gas-turbine engine real-time model is accomplished through a complex series of tasks that draw upon a variety of engineering, mathematical, and programming skills, choice of an appropriate computing platform, and interaction of real-time model with simulation environment (i.e., its input/output connections with other systems). The implementation of real-time models must also balance the constraints of cost, execution time, consistency with the system being modeled, and capability to be scaled to match the new design information.

The common engine model types for real-time simulation are aerothermodynamic, and piecewise linear state-space, and transfer function.

Reference 63 contains a comprehensive review of modeling methodologies for real-time simulation of gas-turbine engine performance and applications of real-time models. Characteristics of the models, algorithms used, and system integration issues are also reviewed. In addition, example FORTRAN source codes of digital models are also provided. Reference 63 is intended to be a source of information on current practices and procedures for developing real-time turbine engine models and a basis for communication between the supplier and the customer.

Szuch[64] has reviewed many of the approaches that have been used to develop real-time simulations. He discusses the digital as well as the hybrid techniques with specific examples, mainly from the standpoint of their usefulness for full authority digital electronic control unit (FADEC) development. The work of Ref. 64 has been revised here briefly for the sake of continuity, and the developments that have taken place subsequently have been incorporated for completeness.

Reference 64 indicates that computation time is a major drawback while implementing a detailed thermodynamic simulation on a digital computer. This problem is further aggravated by use of a simple Euler explicit integration scheme because small time steps are required to update pressure dynamics because of its small time constant. Thus either the calculation time needs to be decreased and/or the size of time steps should be increased for real-time simulation.

One of the possible ways to develop a real-time simulation model is to linearize the nonlinear model about the selected operating points. The coefficients of the linear model can then be functionally related to the engine state and the inputs. The resulting piece-wise linear model can be implemented as transfer function model using recursion formulas, as in Hurt.[65]

Litt et al.[66] have also developed a linear real-time simulator (where cycle time is 12 ms) of a Pratt and Whitney F100 engine for real-time code verification and for actuator diagnosis during full-scale engine testing. This self-contained unit can operate in an open-loop stand-alone mode or as part of closed-loop control system. It can also be used for control system design and development. In its present form it is a small perturbation model that can evolve into a full-envelope, full-engine real-time simulation with advances in microprocessor hardware.

Mihaloew[67] describes a dynamic digital real-time model of an advanced propulsion system for use in piloted simulators, based on a piece-wise linear state variables methodology.[68]

Here, the engine model uses the state variables and matrix formulations of partial derivatives to represent the engine process at specific operating points. The engine is modeled using three types of variables, i.e., states, inputs, and outputs. States represent temperature, pressure, and speed. Inputs are variables that perturb the system, such as fuel flows and nozzle areas. Outputs are additional parameters of interest other than the state and input variables, like engine airflows, thrust, specific fuel consumption, and surge margins. Dynamically, an engine is characterized by differential equations relating the time rate of change of state variables to the state variables themselves and the input parameters. States are obtained transiently by calculating the derivatives and numerically integrating them in time.

The state variables model was derived using a comprehensive aerothermodynamic simulation of a Rolls-Royce Pegasus II engine and has a cycle time of 8.9 ms on a Xerox Sigma 9 computer.

But linear models have a limited scope, for the reasons described in an earlier section, and may not be suitable over the entire flight envelope. Increasing the time-step size offers another possibility for real-time simulation.

McLaughlin[69] has evolved an implicit formulation of engine equations and an iterative solution of these equations in order to incorporate an increased time-step size. By using backward-difference integration, a stable solution could be obtained even for time steps larger than the smallest time constant in the engine model. To prevent computing time from exceeding the prescribed time-step size, the Broyden technique[70] was used to eliminate the need to calculate new Jacobean matrices during transients. Stable, real-time simulations were obtained on a Digital Equipment Corporation PDP-11/55 with a time step of 27 ms. It does demonstrate that the implicit method can produce real-time simulations of stiff systems (i.e., the systems with widely varying time constants) on low-cost microcomputers, but this time step may be too large for some control applications.

The most desirable approach to achieve real-time simulation is perhaps to speed up the calculations. Though expensive, a faster hardware would permit the solution of detailed nonlinear models in real time, without simplifications.

The parallel processing using a hybrid computer is one such possibility. Szuch and Bruton[71] and Szuch et al.[72] have successfully used a hybrid computer for real-time simulation. But real-time hybrid simulation is difficult to program, time consuming, expensive, and nonportable. Carlin and Tjonneland[73] at Boeing airplane company have made use of special-purpose, hard-wired hybrid computers (SPHYC) to achieve a low cost, real-time simulator for a F100 engine, that is portable, but lacks reprogrammability.

The aforesaid shortcomings of hybrid simulation have led to all-digital microcomputer-based approach to parallel processing in order to achieve a more general-purpose, cost-effective, real-time simulation capability.

Blech and Arpasi[74] present the development of microcomputer-based, parallel processor systems for real-time engine simulation. The basic structure of the simulator is a transfer controller that synchronizes N (up to 10) 16-bit processing elements (PE) on a high-speed data transfer bus. All but two (N-2) of the PE perform simulation calculations. One of the remaining PE is dedicated to input and output functions. The last PE is a special purpose processor that links low-speed, operator commands to the high-speed simulator. This PE is termed as the real-time extension of the front end processor. It provides the operator's interface to the simulator and handles peripheral communications, program loading, etc.

The simulator cycle is separated into two basic periods, namely, a compute period and a transfer period. The transfer period is initiated when all of the PE have completed their computations. During the transfer period, data are exchanged between the simulation PE as dictated by the transfer controller. The real-time operation of the simulator depends on the calculations being distributed among PE by the user in such a way that the sum of the largest computing time and the transfer time does not exceed the specified step size (frame time).

The development of real-time engine simulations for the simulator will depend upon the selection and implementation of a suitable numerical integration algorithm. Miranker and Liniger[75] have proposed use of a parallel, predictor-corrector algorithms for the solution of ordinary differential equations on parallel processor systems. The most obvious advantage of these algorithms is they do not require the partitioning of a simulation model for parallel solution.

Krosel and Milner[76] have applied fourth-order Miranker and Liniger algorithms to the engine simulation problem and have concluded that in engine applications a practical limit of four processors exists because of algorithm complexity. Further increase in the number of processors requires smaller time steps to maintain accuracy, or else it leads to numerical instability.

Roth and Celiberti[77] describe an experimental multiprocessor real-time engine simulation system to verify FADEC. The high-fidelity engine model was functionally partitioned into dynamically logical blocks of codes, and real-time requirements were met by allowing these blocks to execute simultaneously in parallel on several microprocessors.

Zeng et al.[78] introduce a real-time simulator of a twin-spool turbojet, implemented on a parallel processor/microcomputer system. A PC 286 microcomputer is used as the host computer, and four TM32020 digital signal processors are chosen as processing units of the parallel system. The A/D and D/A boards serve as the interfaces for HILS of the control system. The aerothermodynamic engine model was partitioned for parallel processing. The elements of the Jacobean matrix in the Newton–Raphson iterative method are computed in parallel in the four processing units. This real-time engine simulation (with simulation frame cycle time of 29.6 ms) was used for HILS to evaluate control system performance.

The use of dedicated, high-speed computers and use of real-time programming techniques is another option to produce real-time simulations.

Mihaloew and Hart[79] and Mihaloew[80] have proposed a real-time digital simulation technique that can produce faster than real-time simulation when run on a dedicated, general-purpose mainframe (Xerox Sigma 8). In this case the computer was part of a moving-base flight simulator facility, and the engine model had to be integrated with the simulation of an airplane. The proposed technique involves multirate scheduling (updating) of various parts of the model, elimination of control volume dynamics, use of high-gain integrators to converge resulting algebraic loops, and curve fitting of component performance maps with segmented polynomial and geometric functions.

The resulting simulation was stable with time steps as large as 50 ms and exhibited satisfactory low-frequency (rotor) dynamics. Although this technique has been successfully demonstrated in a powered-lift application at low-altitude low-speed condition, more work is needed to determine if the simplifications can be generalized and applied to other engine systems over a wide range of operating conditions.

Sugiyama[81] has used a special purpose AD-10 digital computer to implement a generalized engine model, and real-time response was demonstrated with a frame time of 1.1 ms for a twin-spool turbofan engine. But the major drawback is that an AD-10 digital simulation is not a cost-effective and portable solution.

Drummond[82] explores and compares two approaches for modeling turbofan component volume dynamics with a view toward application to real-time simulation of short takeoff and vertical landing (STOVL) aircraft. The first approach considers only the heat and mass balances, whereas the second one includes a momentum balance and substitutes the heat equation with a complete energy balance. Results for a practical test case are presented and discussed.

Ouzts and Drummond[83,84] report the development of a real-time propulsion system dynamic model for a STOVL aircraft under the AD-100 simulation environment. The dynamic model was adapted from a FORTRAN-based simulation using the dynamic programming capabilities of the AD-100 ADSIM simulation language. The dynamic model includes an aerothermal representation of a turbofan jet engine, actuator and sensor models, and a multivariable control system. The AD-100 model was tested for agreement with the FORTRAN model real-time execution performance. The propulsion system model was also linked to an airframe dynamic model to provide an overall STOVL aircraft simulation for the purpose of integrated flight and propulsion control studies.

Instead of using the highly expensive state-of-the-art hardware, an alternate cost-effective solution is to use a simplified aerothermodynamic mathematical model.

French[85] presents a novel mathematical formulation to derive a Simplified Cycle Response Analysis Model (SCRAM). Though simplified, it is a fairly accurate mathematical model to estimate engine dynamics and is based on the correlations drawn from the experience of a detailed simulation techniques. Reddy et al.,[86] by utilizing the description of Ref. 85 and the experience of detailed simulation model of Ref. 32, have developed a personal computer-based real-time engine simulation, which was used for HILS studies of a military turbofan at the G.T.R.E., Bangalore, India. Reference 86 also confirms the confidence with which it can be used, by validating the real-time simulation results with respect to that obtained from Ref. 32.

Blech et al.[87] also show the development of a real-time, portable, microcomputer-based jet engine simulator, which forms the part of a piloted flight simulator. The component model approach was used, in which the component performance maps were represented as curve fits, and high frequency volume dynamics were omitted. The engine model was coded in floating-point FORTRAN. The microcomputer board was based on an Intel 8086 microprocessor and 8087 floating-point coprocessor. The availability of a FORTRAN compiler for 8086-8087 microcomputer greatly assisted the portability of the code from the program development computer to the simulator. The application was demonstrated for a small turboshaft helicopter engine, which meets the requirement of a 30-ms frame time.

Reference 88 contains another digital real-time simulation on a single microcomputer for a two-spool afterburning turbojet engine. To overcome the contradiction between the computation precision and the speed necessary for real-time simulation, the component characteristics have been simplified. A 80286 macroassembly, 80287 float arithmetic parallel processing method, and a few suitable programming techniques have been adopted. The comparison of the simulation result with measured data shows that its calculation accuracy and speed are suitable for real-time simulation.

Liu et al.[89] also establish a simplified mathematical model for real-time simulation of a twin-spool turbojet engine. It comprises a linearized compressor characteristics model, simplified turbine characteristics, and a dimension-reducing method of nonlinear equations set. Under the identical flight conditions, the simulation results from real-time model, non-real-time model and test data compare well, thereby justifying the fundamental hypothesis of the study. The model makes a good compromise between computational speed and accuracy and has good convergence.

MacInnis[90] illustrates the development of a simplified cycle-matching transient simulation (SCTS) code, derived from the more detailed computational model of AE3007 turbofan. Although it is not fast enough to be considered real-time on current computer systems, it is valuable as a fast and accurate transient cycle deck that also provides for heat storage effects, customer bleed, and horsepower demand during transient simulation.

Sieros et al.[91] present a method for analytical representation of compressor and turbine performance maps, obtained from the experimental or computational methods. It enables a reduction in the running time of a digital simulation, a desirable feature for real-time simulation. The method has been validated with engine test running.

A recent paper by Magill et al.[92] is based on the advanced precision analog computing techniques for real-time simulation of fast nonlinear dynamics, with particular attention to stall and surge. Though analog simulation is not as readily configured as a digital simulator, high execution speeds can be achieved with small circuits. The paper describes the building blocks for constructing analog simulation. Using simulation of a simple compression as the design example, results are presented to show that resulting simulation is up to 10 times faster than real time, and accuracy also matches with that of a digital simulation.

Typical Design Applications

The primary applications of detailed engine simulation have been for understanding engine behavior in early design phase and for control system development. Besides, it can also be used for gas-flowpath design, engine performance and health monitoring, cycle selection, and estimation of start, restart, and wind-milling characteristics.

Reference 93 is an excellent reference describing the advantages of dynamic simulation in control system development. Case studies pertaining to RM12 turbofan engine (used on JAS-39 Gripen) have been discussed to illustrate the importance of simulation as a development tool. It further discusses various simulation-related aspects like type of mathematical models (such as continuous and discrete, distributed and lumped parameter, and linear and nonlinear), engineering applications of simulation, model representations, simulation tools and software, numerical solution of ordinary differential equations, real and non-real-time simulations, and HILS. Reference 93 can be viewed as a comprehensive publication on the art and role of engine simulation.

Reference 94 is one of the early papers that describes dynamic simulation as a tool for component design. Khalid,[95] besides highlighting the importance of accurate dynamic simulation in engine design and development, shows the application of a representative engine model to the flowpath design and controls optimization in a fast-response, two-spool, mixed-flow afterburning turbofan.

O'brien[96] presents the control applications of detailed dynamic engine simulation. It gives a general overview of the need and necessity to have a reliable dynamic simulation for control system development.

Pierre et al.[97] highlight the contribution of dynamic simulation to military turbofan control system design. Some of the applications presented are the determination of in situ compressor surge line, engine response analysis during flight testing, effect of the dynamics of a given element on engine response, and design of control laws.

Adams et al.[98] indicate that improved definition of dynamic response provides valuable information and insight leading to reduced maintenance and overhaul costs on existing engine configurations. It also provides a considerable cost reduction in the development of new engine by eliminating some of the trial and error procedures done with the engine hardware development.

Macisaac[99] discusses the role of modeling and computer simulation in the design, development, and validation of an engine performance and health monitoring system.

Lambiris et al.[100] present a method of performance simulation of jet engines, with the possibility of adapting to engine particularities. It employs an adaptation procedure coupled to a performance model solving the component matching problem. The proposed method provides an accurate simulation for engines of same type, with differences that are caused by manufacturing or assembly tolerances. It does not require accurate component maps because they are derived using the adaptation procedure. It can also be used for health monitoring, for component fault identification, and for condition assessment. The effectiveness of this method is demonstrated by application to two commercial jet engines.

Hamed et al.[101] present the results of a numerical study of the dynamic response of a turbojet engine to planar-wave inlet distortion. The one-dimensional numerical simulation was used to evaluate the sensitivity of an eight-stage axial-flow compressor in a complete J-85-13 turbojet. Engine dynamic response accompanying planar-wave-induced compressor surge is also characterized over a maximum anticipated range of simulated compressor deterioration.

Sun and Hu[102] show the application of a dynamic model of a dual-spool turbojet engine with poststall capability. This dynamic model was adopted to simulate surge operation induced by opening nozzle, and the mechanism of surge control of fuel pulse cutoff (FPCO) is also investigated by computer simulation. The effect of the parameters of FPCO on surge control was analyzed, and some guidelines of the surge control design for a dual-spool turbojet engine were brought forward.

Disturbances in air intake flow at the engine face of a jet aircraft, in the form of ramps and transients in inlet total pressure or total temperature, can produce adverse effects on the performance and stability of an aircraft's propulsion system. Abdel-Fattah[103] has adopted DYNTECC to perform a parametric study of the effect of inlet flow distortion on the stability of a Pratt and Whitney TF30 engine. The primary purpose was to predict the onset of system instability caused by simulated full-scale rapid inlet temperature ramps during armament firing. The code was also run with sinusoidal total pressure oscillations of varying amplitudes and frequencies at the inlet. The code predictions were compared with available data whenever possible and were found to be consistent with observed experimental trends.

Huang and Sun[104] propose the development of a multivariable adaptive controller that extensively makes use of an engine simulation model. Using this multivariable controller, it was possible to reduce engine acceleration time by about 19% in comparison with the conventional controller.

Kotsiopoulos[105] uses the simulation code of a twin-spool turbofan engine to make quantitative assessment of the reduction in life caused by the requirements of a faster transient response. The phenomenon investigated here is thermal fatigue, and the main focus is in the hot sections, specifically the turbine blades. The present investigation suggests a thermal life reduction of approximately 25–35% when comparing a fast acceleration of 2–3 s with a slower one of 8–10 s.

Agrawal and Yunis[106] describe a simulation model to estimate engine starting characteristics, based on the generalized compressor and turbine characteristics and component matching technique. It can be used to define aircraft starter system specifications, or to determine the time taken from startup to light-up and to idling speed.

If the low-speed compressor and turbine characteristics are available, the method of Shou[107] can be used for simulating wind-milling characteristics of a turbojet engine. It gives a complete description of the mathematical model, component matching, component characteristics representation, and two approximate methods that can be used if component characteristics are not available. Wind-milling characteristics are necessary for combustor design to determine the reliable relighting under wind-milling.

Similarly, Morita et al.[108] describe a mathematical model to simulate the restart characteristics of a turbofan engine. It is based on the experimental data, which can be obtained from engine start tests, and gets rid of low-speed component characteristics, which are usually not available readily.

The engine simulations are also an integral part for optimum cycle(s) selection and preliminary aircraft sizing over a prescribed mission. The description of procedures and typical case studies are contained in Sanghi and Sane[109] and Sanghi et al.[110]

The current applications of real-time engine models aim at the development and testing of control systems, integrated flight/propulsion control evaluation, embedded software for control systems for failures detection and accommodation, and flight simulators. Reference 63 gives a complete overview of the requirements, role, and utility of real-time simulation for each of these applications.

Szuch,[111] Vizzini et al.,[112] and Scoles[113] highlight that FADEC is an essential complement to the hydromechanical hardware to satisfy the demanding requirements placed on the propulsion system. The development of FADEC is greatly facilitated by the use of real-time engine simulations. Szuch[114] further gives a qualitative description of the application of real-time simulation to the development of propulsion controls.

Lin and Lee[115,116] show the design of a multivariable control system for a J-85 turbojet engine. A nonlinear engine model was first developed and linearized around 50 selected operating points throughout the flight envelope of a J-85 turbojet. The Edmund's method was used to design a linear controller for each operating point. Finally, for full flight envelope operation the controller gains were assumed to be power functions of engine altitude, Mach number, and compressor rotor speed with unknown power parameters. The extended Kalman-filter technique was used to identify these unknown parameters. The objective was to design a simple controller that achieves the desired performance criteria.

Delaat and Merill[117] state that the objective of advanced detection, isolation, and accommodation is to improve the overall reliability of the digital electronic control system. The engine can continue to be controlled accurately, even during transients, with one or more sensors giving false readings. For this purpose an algorithm was developed. The performance of this algorithm was evaluated using a real-time engine simulation[66] and was demonstrated on a full-scale F100 turbofan engine.

According to Throndson,[118] the purpose of a survivability based engine control (SuBEC) is to provide realistic engine response to tactical aircraft damage. Normal control algorithms are predicted on healthy engine behavior and have limited ability to control adequately an engine whose performance has been degraded by ballistic projectiles or by warhead fragments. SuBEC adds special algorithms to the fuel control so that the system detects damage and then provides tolerant and appropriate control. Turbofan engine computer simulation and tests have been used to investigate SuBEC control for various damage conditions and have also been successfully demonstrated on a General Electric 404 engine.

The real-time models are also used as embedded objects in the engine control system for sensor in-range fault accommodation, real-time detection, estimation and control accommodation of gas-turbine gas-flowpath damage caused by normal wear, mechanical failures, foreign object ingestion, estimation of in-flight engine performance variations, and synthesizing unobservable engine parameters. References 119–121 contain such typical applications.

McGlone[122] states that during development of multifunction digital electronic control systems there exists a possibility of software/logic escapes that could cause an engine to operate inappropriately. Some logics may operate as intended when tested with the engine, but may operate differently when combined with pilot and aircraft interactions. It is therefore highly desirable to test the entire vehicle management system electronic architecture with simulations of the aircraft and the engine and to operate the total system before the first flight. Pratt and Whitney has established a facility for testing of FADEC and its logic before delivery of the logic to production or a large-scale simulation facility. Innovations in engine and aircraft simulation capability have made it possible to affordably implement a facility where the engine electronics and software are integrated with the aircraft simulation. The integrated system can be operated manually with pilot-in-loop, which permits important customer feedback early in engine program that normally proceeds an aircraft program by several years.

Conclusions

A comprehensive survey of the work pursued in the field of engine simulation has been presented, right from its initiation in the 1950s to the state-of-the-art practice. It gives a complete overview of detailed thermodynamic modeling and simulation technology, real-time simulations, and simulation applications to the design and development of gas turbines and its controls and diagnostic systems.

With the availability of low-cost, high-speed computers, an all-digital simulation has gradually replaced the analog and hybrid simulation to incorporate the ease of simulation with high reliability and repeatability. The engine simulation complexity has evolved from simple linear representation to a full-envelope, fully nonlinear models, with secondary effects like effects of gas-metal heat transfer and operating tip clearances included to improve the fidelity of simulation models. The emergence of microprocessors has made possible the development of simulation-oriented, parallel-processor systems that allow a cost-effective and portable implementation of a high-fidelity, real-time engine simulation.

The recent advancements have primarily taken place in the form of computational platforms and programming and implementation techniques to speed up the execution time and strong graphic user interfaces to enable a nonsimulation specialist also to make use of engine simulations. There has been no radical change in mathematical modeling and component representation.

References

[1]"Aircraft Propulsion System Performance Station Designation and Nomenclature," Society of Automotive Engineers, Inc., Aerospace Recommended Practice, ARP 755 B, Warrendale, PA, Oct. 1994.

[2]"Gas Turbine Engine Performance Presentation for Digital Computer Programs Using FORTRAN 77," Society of Automotive Engineers, Inc., Aerospace Recommended Practice, ARP 4191 A, Warrendale, PA, April 1995.

[3]"Gas Turbine Engine Steady State and Transient Performance Presentation for Digital Computer Programs," Society of Automotive Engineers, Inc., Aerospace Standard, AS 681 G, Warrendale, PA, Sept. 1996.

[4]"Gas Turbine Engine Real-Time Performance Model Presentation for Digital Computer Programs," Society of Automotive Engineers, Inc., Aerospace Recommended Practice, ARP 4148 A, Warrendale, PA, May 1996.

[5]"Gas Turbine Engine Interface Test Data Reduction," Society of Automotive Engineers, Inc., Aerospace Recommended Practice, ARP 1210 C, Warrendale, PA, Nov. 1996.

[6]McKinney, J. S., "Simulation of Turbofan Engine," Air Force Aero-Propulsion Lab., Wright–Patterson AFB, Ohio, AFAPL-TR-67-125, Aug. 1967.

[7]Koeing, R. W., and Fishbach, L. H., "GENENG—A Program for Calculating Design and Off-Design Performance for Turbojet and Turbofan Engines," NASA TND-6552, Feb. 1972.

[8]Sanghi, V., Lakshmanan, B. K., and Sundararajan, V., "Digital Simulator for Steady-State Performance Prediction of Military Turbofan Engine," *Journal of Propulsion and Power*, Vol. 14, No. 1, 1998, pp. 74–80.

[9]Cohen, H., Rogers, C. F. C., and Saravanamuttoo, H. I. H., *Gas Turbine Theory*, 3rd ed., Longman Scientific and Technical, England, 1987.

[10]Oates, G. C., *Aerothermodynamics of Aircraft Engine Components*, AIAA Education Series, AIAA, New York, 1985.

[11]Oates, G. C., *Aerothermodynamics of Gas Turbines and Rocket Propulsion*, AIAA Education Series, AIAA, New York, 1988.

[12]Oates, G. C., *Aircraft Propulsion System Technology and Design*, AIAA Education Series, AIAA, Washington, DC, 1989.

[13]Mattingly, J. D., *Elements of Gas Turbine Propulsion*, McGraw–Hill, New York, 1996.

[14]Walsh, P. P., and Fletcher, P., *Gas Turbine Performance*, Blackwell Science, Ltd., England, 1998.

[15]Flack, R. D., "Analysis and Matching of Gas Turbine Components," *International Journal of Turbojet and Jet Engines*, Vol. 7, Nos. 3 and 4, 1990, pp. 217–226.

[16]Otto, E. W., and Taylor, B. L., "Dynamics of a Turbo-Jet Engine as a Quasi-Static System," NACA TN-2091, 1950.

[17]Fawke, A. J., and Saravanamuttoo, H. I. H., "Digital Computer Methods for Prediction of Gas Turbine Dynamic Response," Society of Automotive Engineers, Inc., Paper 710550, June 1971.

[18]Saravanamuttoo, H. I. H., and Fawke, A. J., "Simulation of Gas Turbine Dynamic Response," American Society of Mechanical Engineers, Paper 70-GT-23, May 1970.

[19]Fawke, A. J., and Saravanamuttoo, H. I. H., "Experimental Investigation of Methods for Improving the Dynamic Response of a Twin-Spool Turbojet Engine," American Society of Mechanical Engineers, Paper 71-GT-14, March 1971.

[20]Fawke, A. J., and Saravanamuttoo, H. I. H., "Digital Computer Simulation of Dynamic Response of Twin-Spool Turbofan with Mixed Exhausts," *Aeronautical Journal*, Sept. 1973, pp. 471–478.

[21]Seller, J., and Daniele, C. J., "DYNGEN—A Program to Calculate Steady-State and Transient Performance of Turbojet and Turbofan Engines," NASA TND-7901, April 1975.

[22]Daniele, C. J., Kresel, S. M., Szuch, J. R., and Wisterkamp, E. J., "Digital Computer Program for Generating Dynamic Turbofan Engine Models (DIGTEM)," NASA TM-83446, Sept. 1983.

[23]Sadler, G. G., and Melcher, K. J., "DEAN: A Program for Dynamic Engine Analysis," NASA TM-87033, July 1985.

[24]Merrill, W. C., "HYTESS 2: A Hypothetical Turbofan Engine Simplified Simulation with Multivariable Control and Sensor Analysis Redundancy," NASA TM-87344, 1986.

[25]Muller, S. G., "A Generalized Gas Turbine Model," *International Journal of Control*, Vol. 17, No. 5, 1973, pp. 977–993.

[26]Palmer, J. R., and Cheng-Zhong, Y., "TURBOTRANS—A Programming Language for Performance Simulation of Arbitrary Gas Turbine Engines with Arbitrary Control Systems," American Society of Mechanical Engineers, Paper 82-GT-200, April 1982.

[27]Pilidis, P., and Maccallum, N. R. L., "A General Program for the Prediction of Transient Performance of Gas Turbines," American Society of Mechanical Engineers, Paper 85-GT-209, March 1985.

[28]Schobeiri, T., "A General Computation Method for Simulation and Prediction of Transient Behaviour of Gas Turbines," American Society of Mechanical Engineers, Paper 86-GT-180, June 1986.

[29]Chao, Y., and Ho, R., "Digital Simulation of the Gas Turbine Engine Performance," *Journal of the Chinese Society of Mechanical Engineers*, Vol. 7, Oct. 1986, pp. 319–328.

[30]Torella, G., "Numerical Codes for Unsteady Simulation of Turbojet, Turbofan and Turboprop Engines for Training Purposes," AIAA Paper 89-2259, July 1989.

[31]Fan, S., Xu, Y., and Shu, Z., "Mathematical Model and Digital Simulation of Turbojet Acceleration," *Chinese Journal of Aeronautics*, Vol. 3, May 1990, pp. 123–130.

[32]"Design Document on Kaveri Engine Simulation," Gas Turbine Research Establishment, ITM/ES8704, Bangalore, India, Nov. 1991.

[33]Steenken, W. G., "Turbofan Engine Post-Instability Behaviour: Computer Simulations, Test Validation, and Application of Simulations," *AGARD Engine Response to Distorted Inflow Conditions*, 1987.

[34]Khalid, S. J., and Hearne, R. C., "Enhancing the Dynamic Fidelity for Improved Prediction of Turbofan Engine Transient Performance," AIAA Paper 80-1083, July 1980.

[35]Zhu, Z., and Liao, K., "Analysis of Heat Transfer Impact on Gas Turbine Engine Transients," *Journal of Propulsion Technology*, Vol. 17, No. 3, 1996, pp. 10–15.

[36]Tang, D., and Cai, Y., "A Dynamic Digital Model for the Turbojet with Pulse-Monitored Fueler," *Journal of Aerospace Power*, Vol. 4, April 1989, pp. 137–140.

[37]Orkisz, M., "Simulation Analysis of the Influence of Variation in Some Selected Design and Control Parameters on the Acceleration Time of a Turbojet Engine," *Engineering Transactions*, Inst. of Fundamental Technological Research, Polish Academy of Sciences, Vol. 39, Nos. 3–4, 1991, pp. 351–367.

[38]Lambert, H. H., "Simulation Study of Turbofan Engine Deterioration Estimation Using Kalman Filtering Technique," NASA TM-104233, 1991.

[39]Zaita, A. V., Buley, G., and Karlsons, G., "Performance Deterioration Modeling in Aircraft Gas Turbine Engines," *Journal of Engineering for Gas Turbine and Power*, Vol. 120, No. 2, 1998, pp. 344–349.

[40]O'brien, W. F., "Dynamic Simulation of Compressor and Gas Turbine Performance," AGARD LS-183, 1992.

[41]Curnock, B., McDonald, P., and McLaughlin, P., "Gas Turbine Engine Transient Behavior," Von Karman Inst. for Fluid Mechanics, Lecture Series 1993-06, Belgium, May 1993.

[42]Chappell, M. A., and McLaughlin, P. W., "Approach to Modeling Continuous Turbine Engine Operation from Startup to Shutdown," *Journal of Propulsion and Power*, Vol. 9, No. 3, 1993, pp. 466–471.

[43]Torella, G., "Expert System for the Simulation of Turbofan Engines," *Proceedings of the Eleventh International Symposium on Air Breathing Engines*, ISABE Paper 93-7133, Sept. 1993.

[44]Drummond, C. K., "Gas Turbine System Simulation: An Object Oriented Approach," NASA TM-106044, 1993.

[45]"Object Oriented Approach for Gas Turbine Simulation," NASA TM-106970, July 1995.

[46]Lytle, J. K., "Numerical Propulsion System Simulation-Concept to Product," *Proceedings of the Thirteenth International Symposium on Air Breathing Engines*, ISABE Paper 97-7107, Sept. 1997.

[47]Schobeiri, M. T., Attia, M., and Lippke, C., "Nonlinear Dynamic Simulation of Single and Multispool Core Engines, Part I: Computational Method," *Journal of Propulsion and Power*, Vol. 10, No. 6, 1994, pp. 855–867.

[48]Schobeiri, M. T., Attia, M., and Lippke, C., "GETRAN—A Generic, Modularly Structured Computer Code for Simulation of Dynamic Behavior of Aero- and Power Generation Gas Turbine Engine," American Society of Mechanical Engineers, Paper 93-GT-388, May 1993.

[49]Ivanov, M. J., "Perspective Problems of Gas Turbine Engine Simulation," National Technical Information Service, NTIS N95-19026/0/HDM, 1994.

[50]"Mathematical Models for Gas Turbine Engines and Their Components," AGARD LS-198, 1994.

[51]Hideaki, Y., "High Fidelity Simulation of Turbofan Engine Acceleration Characteristics with Effect of Combustor Performance Variation Under Transient Conditions," AIAA Paper 94-2957, June 1994.

[52]Reed, J. A., and Afjen, A. A., "Development of an Interactive Graphical Propulsion System Simulator," AIAA Paper 94-3216, June 1994.

[53]Reed, J. A., and Afjen, A. A., "An Intelligent Visualization and Control System for Multidisciplinary Numerical Propulsion System Simulation," AIAA Paper 96-4034, Sept. 1996.

[54]Reed, J. A., and Afjen, A. A., "An Interactive Graphical Simulation Environment for the Study of Gas Turbine Engines," AIAA Paper 96-2563, July 1996.

[55]Reed, J. A., and Afjen, A. A., "An Interactive Graphical System for Engine Component Zooming in a Numerical Propulsion System Simulation," AIAA Paper 95-0118, Jan. 1995.

[56]Reed, J. A., "Development of a Prototype Simulation Executive with Zooming in the Numerical Propulsion System Simulation," NASA CR-200613, July 1995.

[57]Reed, J. A., and Afjen, A. A., "Development of an Intelligent Monitoring and Control System for a Heterogeneous Numerical Propulsion System Simulation," NASA CR-202435, 1996.

[58]Davis, M. W., Jr., "A Stage-by-Stage Dual Spool Compression System, Modeling Techniques," American Society of Mechanical Engineers, Paper 82-GT-189, March 1982.

[59]Hale, A. A., and Davis, M. W., Jr., "Dynamic Turbine Engine Compression Code DYNTECC—Theory and Capabilities," AIAA Paper 92-3190, 1992.

[60]Davis, M. W., Jr., "Interactive User's Interface for a Dynamic Compression System Simulation," AIAA Paper 95-0244, Jan. 1995.

[61]Ganji, A. R., and Khadem, M., "An Integrated Software for Gas Turbine Simulation," AIAA Paper 96-2588, July 1996.

[62]Xie, G., Zeng, Q., and Zhang, V., "Adaptive Rectification of Parameters in Aero-Engine Simulation Model," *Journal of Aerospace Power*, Vol. 13, No. 1, 1998, pp. 37–40.

[63]"Real-Time Modeling Methods for Gas Turbine Engine Performance," Society of Automotive Engineers, Inc., Aerospace Information Rept., AIR 4548, Warrendale, PA, Dec. 1995.

[64]Szuch, J. R., "Advancements in Real-Time Engine Simulation Technology," AIAA Paper 82-1075, June 1982.

[65]Hurt, J. M., "New Difference Equation Technique for Solving Non Linear Differential Equations," *Proceeding of the Spring Joint Computer Conference*, Vol. 25, 1964, pp. 169–179.

[66]Litt, J. S., Delatt, J. C., and Merill, W. C., "A Real-Time Simulator of a Turbofan Engine," NASA TM-100869, March 1989.

[67]Mihaloew, J. R., "A Piecewise Linear State Variable Technique for Real Time Propulsion System Simulation," NASA TM-82851, 1982.

[68]Roth, S. P., Sahgal, R., Thomson, D. N., and Zant, R., "Full Authority Digital Electronic Control: Real Time Dynamic Propulsion Model for Man-in-the-Loop Simulators," Pratt and Whitney Aircraft Group, PWA FR-9433, West Palm Beach, FL, Dec. 1977.

[69]McLaughlin, P., "A New Technique for the Implementation of Nonlinear Models as Real-Time Digital Simulations-with Application to Aircraft Turbine Engine Design," *Proceedings of the Summer Computer Simulation Conference*, 1980, pp. 111–115.

[70]Broyden, C. G., "Quasi-Newton Methods and Their Application to Function Minimization," *Mathematics of Computation*, Vol. 21, 1967, pp. 368–381.

[71]Szuch, J. R., and Bruton, W. M., "Real-Time Simulation of the TF30-P-3 Turbofan Engine Using a Hybrid Computer," NASA TM X-3106, 1974.

[72]Szuch, J. R., Seldner, K., and Cwynar, D. S., "Development and Verification of Real Time Hybrid Computer Simulation System of F100-PW-100(3) Turbofan Engine," NASA TP-1034, 1977.

[73]Carlin, C. M., and Tjonneland, E., "Propulsion System Controls Design and Simulation," AIAA Paper 82-0322, Jan. 1982.

[74]Blech, R. A., and Arpasi, D. J., "An Approach to Real-Time Simulation Using Parallel Processing," NASA TM-81731, July 1981.

[75]Miranker, W., and Liniger, W., "Parallel Methods for Numerical Integration of Ordinary Differential Equations," *Mathematics of Computation*, Vol. 21, 1981, pp. 303–320.

[76]Krosel, S. M., and Milner, E. J., "Application of Integration Algorithms in a Parallel Processing Environment for the Simulation of Jet Engines," NASA TM-82746, 1981.

[77]Roth, S. P., and Celiberti, L. A., "Micro-Computer/Parallel Processing for Real-Time Testing of Gas Turbine Control System," AIAA Paper 87-1926, July 1987.

[78]Zeng, Q., Zhanf, Y., and Guan, Y., "Real-Time Simulation of a Two-Spool Turbojet by Parallel Processing," *Journal of Aerospace Power*, Vol. 8, No. 4, 1993, pp. 368–370.

[79]Mihaloew, J. R., and Hart, C. E., "Real-Time Digital Propulsion System Simulation for Manned Flight Simulators," NASA TM-78598, 1978.

[80]Mihaloew, J. R., "A Nonlinear Propulsion System Simulation Technique for Piloted Simulators," NASA TM-82600, 1981.

[81]Sugiyama, N., "Real Time Digital Simulation of Jet Engines," Aerospace Engineering Dept., Univ. of Michigan, TR, Ann Arbor, MI, April 1979.

[82]Drummond, C. K., "STOVL Propulsion System Volume Dynamics Approximations," NASA TM-102397, Dec. 1989.

[83]Drummond, C. K., and Ouzts, P. J., "Real-Time Simulation of an F110/STOVL Turbofan Engine," NASA TM-102409, Nov. 1989.

[84]Ouzts, P. J., and Drummond, C. K., "An AD100 Implementation of a Real-Time STOVL Aircraft Propulsion System," NASA TM-103683, Oct. 1990.

[85]French, M. W., "Development of a Compact Real-Time Turbofan Engine Dynamic Simulation," Society of Automotive Engineers, Inc., Paper 821401, Oct. 1982.

[86]Reddy, G. B., Palsane, S., Lakshmanan, B. K., and Sundararajan, V., "Development of a Real-Time Dynamic Engine Simulation Model of a Turbofan Engine," *Proceedings of the Eleventh International Symposium on Air Breathing Engines*, ISABE Paper 93-7132, Sept. 1993.

[87]Blech, R. A., Soeder, J. F., and Mihaloew, J. R., "A Real-Time, Portable, Microcomputer-Based Jet Engine Simulator," NASA TM-83550, April 1984.

[88]Liu, S., Wang, X., and Xueyu, Z., "Digital Real-Time Simulation of a Twin-Spool Turbojet," *Journal of Aerospace Power*, Vol. 6, No. 3, 1991, pp. 254–258.

[89]Liu, Y., Liu, W., and Chen, F., "A Real-Time Simulation Model of a Twin-Spool Turbojet Engine," *Journal of Aerospace Power*, Vol. 9, No. 4, 1994, pp. 357–360.

[90]MacInnis, D. V., "A Simplified Cycle-Matching Transient Simulation of a Turbofan Engine," AIAA Paper 94-2960, June 1994.

[91]Sieros, G., Stamatis, A., and Mathioudakis, K., "Jet Engine Component Maps for Performance Modeling and Diagnosis," *Journal of Propulsion and Power*, Vol. 13, No. 5, 1997, pp. 665–674.

[92]Magill, J., Bond, J., Dorsey, J., and Brooke, M., "Application of Analog Computing to Real-Time Simulation of Stall and Surge Dynamics," AIAA Paper 93-2231, June 1993.

[93]Johansson, O., Linden, T., and Ornberg, G., "Dynamic Simulation—A Control System Development Tool," Volvo Technology Rept., 1990, pp. 54–67.

[94]Gardner, W. B., and Sampl, F., Jr., "Dynamic Simulation—A Tool for Engine Component Design," Society of Automotive Engineers, Inc., Paper 690386, April 1969.

[95]Khalid, S. J., "Role of Dynamic Simulation in Fighter Engine Design and Development," AIAA Paper 89-2467, July 1989.

[96]O'brien, W. F., "Control Applications of Detailed Dynamic Turbine Engine Simulation," National Technical Information Service, N95-36843, 1995.

[97]Pierre, L., Duponchel, J., and Gerard, P., "Contribution of Dynamic Simulation to Military Turbofan Control System Design and Development," *Advanced Aero-Engine Concepts and Controls*, National Technical Information Service, N96-36596, 1996.

[98]Adams, M. L., Padovan, J., and Fertis, D. G., "Engine Dynamic Analysis with General Non-Linear Finite Element Codes," NASA CR-187222, Oct. 1991.

[99]Macisaac, B. D., "Engine Performance and Health Monitoring Models Using Steady-State and Transient Prediction," AGARD LS-183, 1992.

[100]Lambiris, B., Mathioudakis, K., Stamatis, A., and Papailou, K., "Adaptive Modeling of Jet Engine Performance with Application to Condition Monitoring," *Journal of Propulsion and Power*, Vol. 10, No. 6, 1994, pp. 890–896.

[101]Hamed, A., Gahura, A., and Tabakoff, W., "Simulation of Propulsion System's Transient Response to Planar Wave Inlet Distortion and the Effect of Compressor Wear," AIAA Paper 93-2384, June 1993.

[102]Sun, J. G., and Hu, S. M., "A Study of Surge Control by Using Pulse Cut-Off for Dual-Spool Turbojet Engines," *Acta Aeronautica at Astronautica Sinica*, 1993.

[103]Abdel-Fattah, A. M., "Response of a Turbofan Engine Compression System to Disturbed Inlet Conditions," *Journal of Turbomachinery*, Vol. 119, No. 4, 1997, pp. 677–685.

[104]Huang, T. Q., and Sun, J. G., "Multivariable Adaptive Control Using Only Input and Output Measurements for Turbojet Engines," American Society of Mechanical Engineers, Paper 94-GT-422, June 1994.

[105]Kotsiopoulos, P., "Transient Performance Analysis of a Two Spool Turbofan for Lifing and Handling Purposes," American Society of Mechanical Engineers, Paper 97-GT-199, June 1997.

[106]Agrawal, R. K., and Yunis, M., "A Generalized Mathematical Model to Estimate Gas Turbine Starting Characteristics," *Journal of Engineering for Power*, Vol. 104, 1981, pp. 194–201.

[107]Shou, Z. Q., "Calculation of Windmilling Characteristics of Turbojet Engines," *Journal of Engineering for Power*, Vol. 103, Jan. 1981, pp. 1–11.

[108]Morita, M., Sasaki, M., and Torisaki, T., "Restart Characteristics of Turbofan Engines," *Proceedings of the Ninth International Symposium on Air Breathing Engines*, ISABE Paper 89-7127, Sept. 1989.

[109]Sanghi, V., and Sane, S. K., "Digital Simulation of Propulsion System Performance for Cycle Optimization Studies," *International Journal of Turbo and Jet Engines*, Vol. 16, No. 1, 1999, pp. 27–37.

[110]Sanghi, V., Kishore Kumar, S., Sundararajan, V., and Sane, S. K., "Engine-Airframe Integration During Conceptual Design for Military Application," *Journal of Aircraft*, Vol. 35, No. 3, 1998, pp. 380–386.

[111]Szuch, J. R., "Control Technology," NASA CP-2092, Oct. 1979.

[112]Vizzini, R. W., Lenox, T. G., and Miller, R. J., "Full Authority Digital Electronic Control Turbofan Engine Demonstration," Society of Automotive Engineers, Inc., Paper 801199, Oct. 1980.

[113]Scoles, R. J., "FADEC—Every Engine Should Have One," Society of Automotive Engineers, Inc., Paper 861802, Oct. 1986.

[114]Szuch, J. R., "Application of Real Time Engine Simulation to the Development of Propulsion System Controls," AIAA Paper 75-1176, Sept. 1975.

[115]Lin, S., and Lee, M., "Multivariable Control of J-85 Turbojet Engine for Full Flight Envelope Operation," *Journal of Guidance, Control, and Dynamics*, Vol. 19, 1996, pp. 913–920.

[116]Lin, S., and Lee, M., "Control of the J-85 Turbojet Engine Using the Edmund's Method and the Extended Kalman Filter," *International Journal of Turbo and Jet Engines*, Vol. 13, No. 2, 1996, pp. 103–112.

[117]Delaat, J. C., and Merill, W. C., "Advanced Detection, Isolation, and Accommodation of Sensor Failures in Turbofan Engines: Real-Time Microcomputer Implementation," NASA TP-2925, 1990.

[118]Throndson, L., "Survivability Based Engine Control," AIAA Paper 93-3924, Aug. 1993.

[119]Luppold, R. H., Roman, J. R., Gallops, G. W., and Kerr, L. J., "Estimating In-Flight Engine Performance Variations Using Kalman Filter Concepts," AIAA Paper 89-2584, 1989.

[120]Kerr, L. J., Nemec, T. S., and Gallops, G. W., "Real-Time Estimation of Gas Turbine Damage Using a Control Based Kalman Filter Algorithm," *Journal of Engineering for Gas Turbine and Power*, Vol. 114, No. 2, 1992, pp. 187–195.

[121]Healy, T. A., Kerr, L. J., and Larkin, L. T., "Model Based Fuzzy Logic Sensor Fault Accommodation," *Journal of Engineering for Gas Turbine and Power*, Vol. 120, No. 3, 1998, pp. 533–536.

[122]McGlone, M. E., "Transition of a Technology Base for Advanced Aircraft Gas Turbine Control Systems," *Journal of Engineering for Gas Turbine and Power*, Vol. 120, No. 3, 1998, pp. 437–441.