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APPLICATION OF TRANSIENT AND DYNAMIC SIMULATIONS TO THE U.S. ARMY T55-L-712 HELICOPTER ENGINE

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ABSTRACT

The T55-L-712 turboshaft engine, used in the U.S. Army CH-47D Chinook helicopter, has been simulated using version 3.0 of the Advanced Turbine Engine Simulation Technique (ATEST) and version 1.0 of the Aerodynamic Turbine Engine Code (ATEC). The models simulate transient and dynamic engine operation from idle to maximum power and run on an IBM-compatible personal computer. ATEST is a modular one-dimensional component-level transient turbine engine simulation. The simulation is tailored to a specific engine using engine-specific component maps and an engine-specific supervisory subroutine that defines component interrelationships. ATEC is a one-dimensional, time-dependent, dynamic turbine engine simulation. ATEC simulates the operation of a gas turbine by solving the one-dimensional, time dependent Euler equations with turbomachinery source terms. The simulation uses elemental control volumes at the sub-component level (e.g. compressor stage).

The paper discusses how limited information from a variety of sources was adapted for use in the T55 simulations and how commonality between the models allowed reuse of the same material. The first application of a new turbine engine model, ATEC, to a specific engine is also discussed. Calibration and operational verification of the simulations will be discussed, along with the status of the simulations.

NOMEMCLATURE

C_p	Specific Heat at Constant Pressure
h	Enthalpy
I	Shaft Inertia
P	Pressure
PR	Pressure Ratio
T	Temperature
t	Time
TR	Temperature Ratio
W	Gas Flow
WA	Airflow
WFE	Engine Fuel Flow
XN	Shaft Speed
α	Shaft Rotational Acceleration
γ	Ratio of Specific Heats
δ	Ratio of Pressure to Standard Pressure
θ	Ratio of Temperature to Standard Temperature
ω	Shaft Rotational Speed

Subscript

2	Compressor Inlet
3	Compressor Exit
4	Gas Generator Turbine Inlet
5	Gas Generator Turbine Exit
C	Corrected to Standard Conditions
e	Component Exit
GG	Gas Generator Shaft
i	Component Inlet
PT	Power Turbine Shaft
ref	Reference for Normalization
std	Standard Day Condition
t	Total

INTRODUCTION

At the Arnold Engineering Development Center (AEDC), as at other sea-level and altitude ground test facilities, turbine engines are routinely tested for operability characteristics throughout an engine's life cycle. Operability testing of an engine is performed during engine development and qualification to define engine stability limits, during production in response to problems in service, and during engine improvement programs as part of requalification. Test programs are performed at AEDC by turbine engine manufacturers and operators in support of all of these efforts. Increasingly high costs of engine testing and competitive pressures to reduce engineering turnaround times require that these test programs be designed to minimize time and costs while completing the program's objectives.

The work reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. Work and analysis for this research

Computer simulations of the turbine engine are used in support of operability testing for test optimization and for test analysis. Transient turbine engine models are used pretest to select required test conditions, as well as online and posttest for test data reduction and analysis. Fully dynamic turbine engine models are used as an analysis tool in the investigation of highly dynamic events such as surge and rotating stall and their effects on full engine operability. Dynamic models allow extrapolation of test data to areas of operation where testing of an actual engine is dangerous or destructive.

The description of an engine model as transient or dynamic is subject to interpretation, so the two terms will be defined within the context of this paper to avoid confusion. A transient engine model solves the equations for conservation of mass and energy, and nonsteady terms in the equation for conservation of momentum are neglected. Time-dependent compressibility effects within engine components are typically not modeled, so a transient cycle model can simulate unsteady engine behavior of approximately 20 Hz or less. The lumped-component cycle deck that simulates normal engine throttle and flight transients is typical of this type of model. A dynamic engine model includes the equation for conservation of momentum, and simulates unsteady engine behavior at frequencies up to approximately 300 Hz. This includes aerodynamic phenomena at a subcomponent level, such as inlet distortion, combustor instabilities, or compressor rotating stall or surge, as well as normal transient engine behavior.

This paper describes the development of two T55-L-712 engine simulations for use in support of engine operability testing. The simulations use transient and dynamic mathematical engine models developed at AEDC and engine information from a variety of sources. The transient engine model, the Advanced Turbine Engine Simulation Technique (ATEST), is a mature model that has been in use since 1991. The dynamic engine model, the Aerodynamic Turbine Engine Code (ATEC), has recently been developed at AEDC and the T55 simulation is the first application of this model. The simulations are being used to support an experimental investigation by the Army Vehicle Propulsion Directorate (VPD) at the NASA Lewis Research Center to investigate the starting characteristics of the T55-L-712 turboshaft engine.

T55-L-712 ENGINE

The T55 engine is a turboshaft gas turbine for a helicopter, with seven axial stages and one centrifugal stage of compression connected to a two-stage axial turbine in the gas generator. A compressor air bleed between the sixth and seventh axial stages is actuated for surge prevention during starts, accelerations and decelerations. The combustor is a reverse-flow annular design with atomizing fuel nozzles. Power is supplied to the helicopter through a concentric shaft connected to a two-stage axial free power turbine. A cutaway schematic of the T55-L-712 is shown in Fig. 1.

The engine is controlled by a Hamilton Standard JFC31-22 hydromechanical fuel control. Through the helicopter control systems, the pilot sets two engine control lever inputs. The lever inputs are arbitrary angle values with a defined relationship to one or more physical parameters. The first lever angle input, Alpha1, provides the engine control system with the desired maximum gas generator speed. The second lever angle input, Alpha2, provides the engine control system with the desired power turbine torque and speed. In addition to pilot inputs, the engine control uses four engine feedback parameters: XN1 and XN2, gas generator and power turbine speeds, respectively; T2, engine inlet temperature; and P3, compressor exit pressure. The control output from a throttling valve is the metered engine fuel flow rate, WFE.

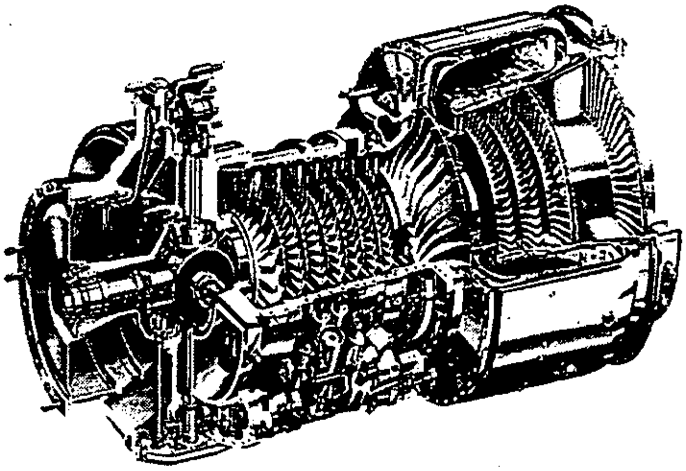

Figure 1. T55-L-712 Turboshaft Engine

The control also provides a pneumatic signal to the compressor air bleed actuator. This signal opens and closes the compressor air bleed for surge protection during rapid engine transients, including starts. Bleed actuation is a function of an internal control parameter and requires no additional pilot inputs or feedback parameters.

The T55-L-712 was qualified for production in the mid-1980's and has been in service since then. Information on the engine for use in building the simulations was obtained from a variety of sources. Because of the engine's age, the only digital computer simulation of the engine available before the current effort was a manufacturer's steady-state performance model. This computer model is calibrated to give the minimum guaranteed performance for a production engine. Other useful information included a design report for the engine, hydromechanical control development reports, and data from a compressor rig test. Information extracted from these sources and adapted for simulation use will be discussed for each model below.

MODEL DESCRIPTIONS

Two simulations of the T55 were developed, a transient simulation and a dynamic simulation. The transient T55 simulation is an application of version 3.0 of the Advanced Turbine Engine Simulation Technique (ATEST). The dynamic T55 simulation is the prototype application for a new dynamic turbine engine model developed at AEDC, version 1.0 of the Aerodynamic Turbine Engine Code (ATEC). These models and their application to the T55 are discussed below.

The simulations were both developed in FORTRAN 77 on an IBM-compatible personal computer (PC). The Microsoft® Powerstation™ Version 1.0a FORTRAN development platform was used, and the simulations use Microsoft® FORTRAN namelist files for input. Namelist input is not a FORTRAN 77 standard, but most current FORTRAN compilers have a namelist extension, so porting the simulations to other platforms is not difficult. Both simulations have been ported to one or more UNIX workstations, including Silicon Graphics, DEC and Hewlett Packard.

Execution of either simulation on a PC or workstation requires only seconds or minutes of processor time. Exact execution time required for either simulation is dependent on the computer platform being used and the simulation length and type, as well as simulation user-selected options such as simulation output frequency. A representative run-time ratio (computer execution time / engine simulation time) for an ATEST T55 simulation providing output every 25 milliseconds on a 90 mHz Pentium^{tm} PC with 32 Mbytes of memory is approximately 12:1. This means a 5 second engine acceleration would require about a minute to execute. A similar ATEC simulation would have a run-time ratio of approximately 15:1. Simulation of a dynamic event with ATEC would increase this due to smaller time steps and higher output frequency.

ATEST Model

ATEST is a modular one-dimensional component-level transient turbine engine model developed at AEDC (Chappell and Blevins, 1986). ATEST 3.0 is capable of continuously simulating the full range of turbine engine operation, including starts, windmill, and operation from idle to maximum power. The behavior of the engine components is ATEST is represented by empirical data in the form of performance maps. The component map representations used in ATEST 3.0 are selected to avoid discontinuities or indeterminate values in the start or windmill regimes. For example, the compressor maps use temperature ratio instead of efficiency, since at zero shaft speed temperature ratio is identically one, while efficiency is undefined. A detailed description of ATEST 3.0, its modeling technique, component map representations, and capabilities were reported by Chappell and McLaughlin, 1993.

The objective of the T55 ATEST model is to simulate steady-state and transient operation of the engine, including fuel control, from startup through the normal operating region to maximum power. The T55 ATEST model uses six modular ATEST components: inlet, compressor, burner, two turbines (gas generator and power), and exit diffuser (Fig. 2). Engine component maps covering operation from idle to maximum power were extracted from the engine manufacturer's steady state performance digital computer model. These maps included burner, combustor, gas generator turbine and power turbine maps, and an overall compressor map, and have been incorporated into the ATEST simulation. The compressor map has surge bleed effects imbedded in it for low speed steady-state operation.

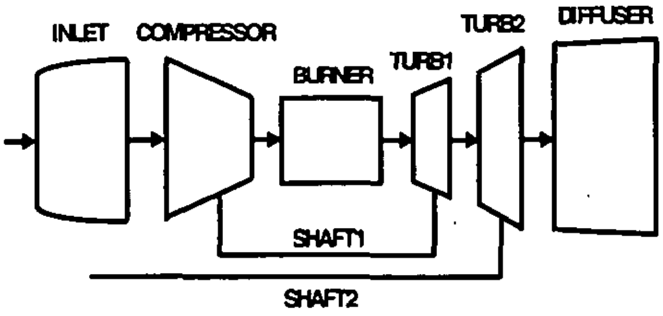

Figure 2. T55-L-712 ATEST Components

The compressor maps extracted from the steady-state model were in the classical form of two dependent parameters, compressor pressure ratio and efficiency, as a function of two dependent parameters, inlet corrected airflow and corrected rotor speed. The corrected airflow map was used directly; the efficiency map was converted to a map of compressor temperature ratio as a function of the same independent parameters (Fig. 3). This conversion was made using the assumption of constant ratio of specific heats, γ, and specific heat at constamt pressure, Cp (values for air were used); the simulation's compressor model compensates output values from the map for actual gas properties.

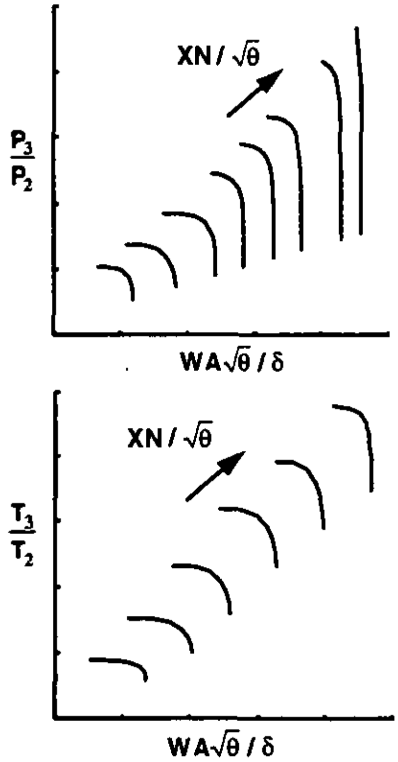

Figure 3. Typical Compressor Performance Specification Curves

As with the compressor, the turbine maps from the steady-state model required conversion for use in ATEST. The original maps had the form of turbine mass flow function and efficiency as a function of pressure ratio and corrected shaft speed. The ATEST form after conversion was turbine mass flow function as a function of turbine work factor and corrected speed, and temperature ratio as a function of pressure ratio and corrected speed (Fig. 4). The conversion was made using the assumption of constant γ and Cp (values for air were used); the simulation's turbine model compensates output values from the map for actual gas properties.

The ATEST burner model uses maps for pressure losses, burner efficiency, and combustor lightoff boundary. The pressure loss maps are in the form of a dry duct pressure loss and a heat addition pressure loss. The dry duct pressure loss is a function of corrected flow or any user-selected parameter, and heat addition pressure losses can be either calculated or tabulated. The combustion efficiency map may be as a function of either temperature rise and pressure, or fuel-air ratio and pressure. The lightoff boundary map is in the form of fuel-air ratio as a function of a user-defined loading parameter. The T55 ATEST simulation uses a calculation for combined (dry and heat addition) pressure losses, and the dry loss map is set to zero. The T55 ATEST combustion efficiency map is tabulated as a function of fuel-air ratio and pressure. The pressure loss calculation and the efficiency map are from the manufacturer's steady-state model. The T55 ATEST lightoff boundary map is in the form of fuel-air ratio as a function of a

Combined Air Loading Factor developed by Herbert, 1957. Since no information was available for the T55, Herbert's flammability data for a generic can type combustor is used, as shown if Fig. 5.

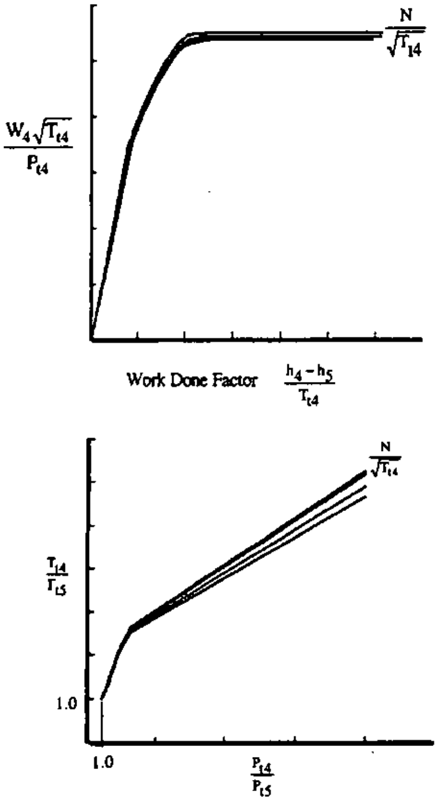

Figure 4. Typical Turbine Performance Specification Curves

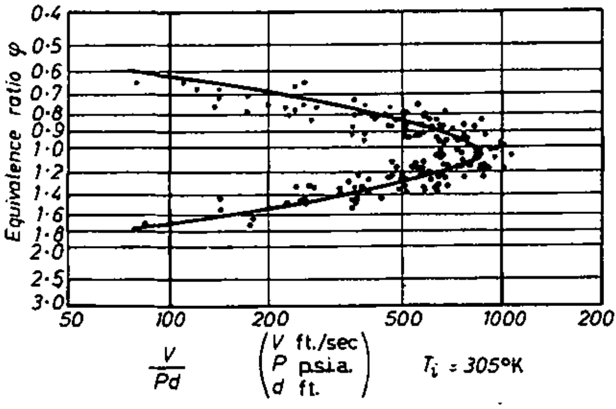

Figure 5. Flammablity Data as Given By Herbert, 1957

Rotor dynamics during engine transient operation are modeled in ATEST using shaft inertias and a shaft work balance. The model uses a summation of torques on the shaft from attached components (e.g. compressors, turbines, starter, power extraction shafts) to calculate the change in shaft rotational speed. Torque is used instead of power because acceleration based on power is indeterminate at zero shaft speed, as shown in Eq. (1).

$$\alpha = HP / (XN * I) \qquad (1)$$

where α is the shaft rotational acceleration, HP is the available horsepower, XN is the shaft speed, and I is the rotor polar moment of inertia. Instead, the change in rotational speed is given by Eq. (2):

$$\frac{d\omega}{dt} = \frac{1}{I}\left(\Gamma_t - \Gamma_c - \Gamma_p - \Gamma_o + \Gamma_s\right) \qquad (2)$$

where, ω is the shaft rotational speed, Γ_t is the torque produced by the turbine, Γc is the torque required by the compressor, Γ_p is the torque required to satisfy any customer power requirements, Γ_o is the torque required to account for user-defined viscous or parasitic losses, and Γ_s is the net torque produced by the starter and delivered to the rotor. T55 shaft inertias were obtained from an engine design report.

A T55 control simulation was coded from the logic block diagram shown in Fig. 6 and digitized values from the graphic schedules provided. This information was extracted from a nonlinear analysis report of the complete helicopter control system at limited flight conditions. The nonlinear analysis was to determine the transient response of the system at high power, so low power information on control schedules was limited. Although the hydromechanical control is analog, the digital simulation assumes a fixed control cycle time equal to the engine simulation transient time step of 10 milliseconds. The two user inputs required are Alpha1 and Alpha2 as described in the previous section, while the output is WFE, engine fuel flow rate. The control simulation includes code for control actuation of the engine surge bleed, but information on the surge bleed port flow characteristics has not been included into the engine simulation. This is because the compressor maps already have bleed effects embedded in them. Use of the control signal will require the modification of the simulation to use separate compressor maps before and after the bleed port.

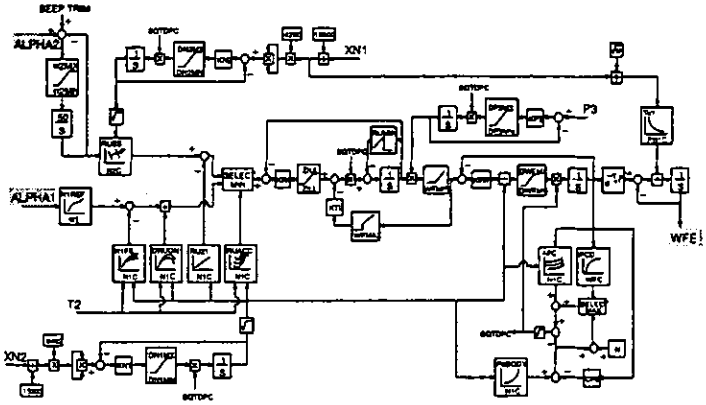

Figure 6. Hamilton Standard JFC31-22 Hydromechanical Control Logic

Basic steady-state and transient capability is available from the T55 ATEST model. The model can be run with the control, requiring inputs of Alpha1 and Alpha2, or without the control, requiring inputs of fuel flow rate, along with the desired power turbine shaft speed. The model provides formatted tabular output of selected component and engine aerodynamic and performance data.

ATEC Model

ATEC is a dynamic turbine engine simulation that solves the one-dimensional, time dependent Euler equations with turbomachinery source terms. The simulation uses elemental control volumes at the sub-component level, such as a section of inlet duct or a compressor stage.

Initial development of the ATEC model was performed at AEDC, as reported by Garrard, et al., 1995. The simulation is based upon the dynamic compressor model and simulation DYNTECC (Hale and Davis, 1992), which models dynamic compressor behavior at constant rotor speed, using an explicit solver. ATEC 1.0 has the added capability to model rotor dynamics and employs an implicit and an explicit equation solver. This means engine transient simulations can be conducted efficiently with the implicit solver and its relatively large time steps, while maintaining the capability to simulate dynamic events such as compressor stall or engine surge, using the greater efficiency of the explicit solver at small time step sizes (Garrard, 1995).

ATEC incorporates a unique variable time step algorithm to take advantage of both solvers. The algorithm uses derivative limits on selected variables to interactively choose the appropriate solver and set the solution time step. Details of the algorithm and its implementation are reported in Garrard, 1995.

The geometry for the model was obtained from a T55 Compressor rig and a T55 Design manual. The reverse flow combustor section of the engine cannot be modeled exactly in a one dimensional model, but the linear distance and volume of the section has been matched to ensure appropriate dynamic response, as presented in Fig. 7. The lack of as-built geometry and the modifications for the 1-D model introduce recognized errors that will require trimming of the simulation during validation. The model consists of 45 control volumes - 12 in the compressor, 6 in the combustor, 3 in the gas generator turbine, 4 in the power turbine, and the rest in ducting (Fig. 8).

ATEC uses a stage-by-stage model of the compressor system, as opposed to the lumped-component overall representation of ATEST. Steady-state compressor stage characteristics provide the necessary source terms to solve the governing equations. These characteristics are in the general form of a pressure coefficient and a temperature coefficient for each stage as a function of a flow coefficient and corrected shaft speed, as shown in Fig. 9. The actual form of these chararacteristics and their use in the dynamic model are reported in detail by Garrard, 1995. For the T55 simulation, the compressor stage characteristics were obtained from experimental data from a compressor rig test (Owen and Bobula, 1994).

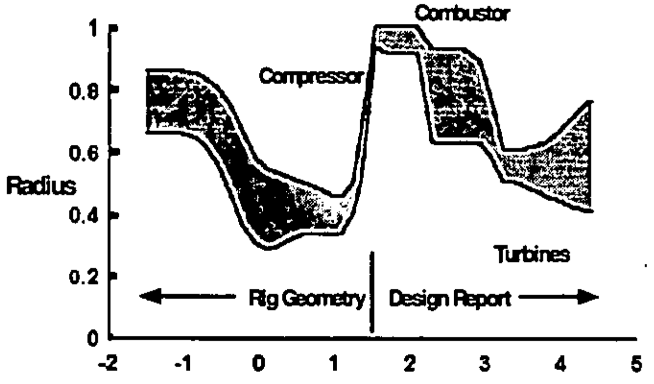

Figure 7. T55 Geometry Representation for ATEC (Garrard, 1995)

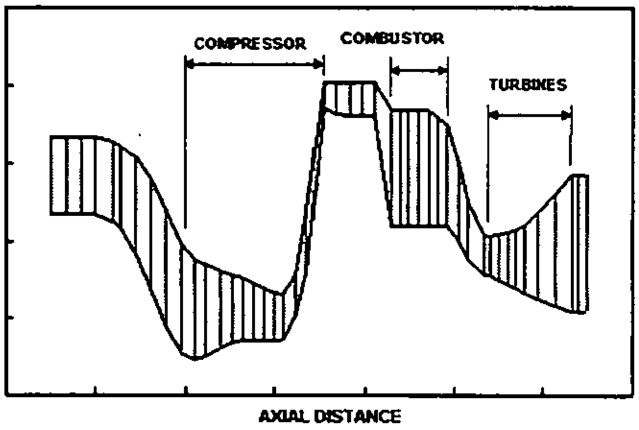

Figure 8. T55 Control Volumes for ATEC

Because of the lack of stage data for the turbine, ATEC was restricted to modeling the turbine overall performance, not stage-by-stage. This allowed the use of the turbine maps developed for the ATEST simulation to obtain source terms for ATEC. Note that although the simulations' turbine models differ, they can use the same maps without modification. Multiple control volumes were specified in the ATEC turbine geometry to more accurately model the system dynamics (Garrard, 1995). The temperature and pressure changes across the turbine are calculated from the maps and distributed linearly over the control volumes of each turbine.

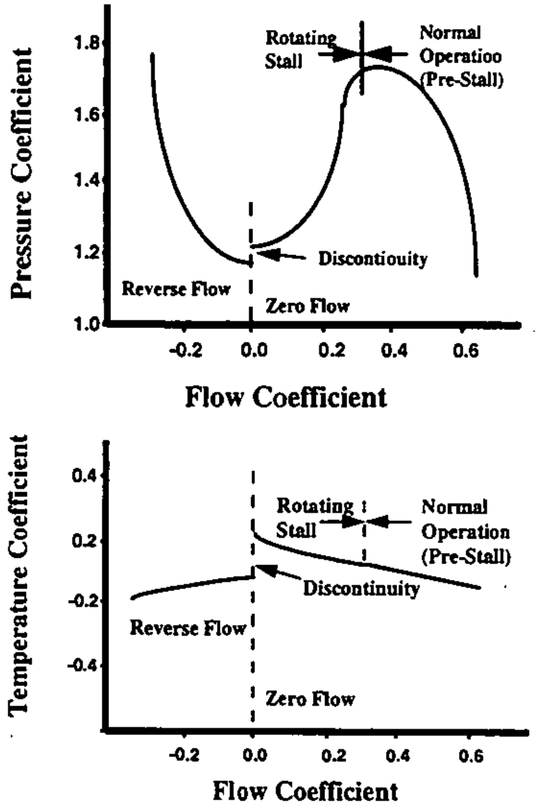

Figure 9. Typical Compressor Pressure and Temperature Stage Characteristics

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