Gas Path Analysis Applied to Turbine Engine Condition Monitoring

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An approach is presented to turbine engine gas path analysis and monitoring, which permits the isolation of single or simultaneous multiple engine faults, with a quantitative assessment of their relative severity. The software approach is described, showing features of its mathematical development and thermodynamic justification. Measureable engine parameters are treated as dependent variables, changes in which are mathematically interrelated to changes in component performance brought about by physical engine faults. Typical results are presented from real programs, wherein engine data were analyzed to provide meaningful and verified diagnoses of single and multiple engine faults.

Nomenclature

Twin Spool Engines

T_{5c3} = H.P. turbine inlet temperature corrected to hp compressor inlet
N_{2c3} = H.P. spool speed corrected to hp compressor inlet
A_{JN} = exhaust nozzle area (turbojet); core engine exhaust nozzle area (turbofan)
N_{1c2} = L.P. spool speed corrected to L.P. compressor inlet
N_{2c2} = corrected H.P. spool speed
T_{3c2} = corrected L.P. compressor discharge temperature
P_3/P_2 = low-pressure compressor pressure ratio
T_{4c2} = corrected H.P. compressor discharge temperature
P_4/P_2 or
P_B/P_2 = over-all compressor pressure ratio
W_{fc2} = corrected fuel flow
T_{7c2} = corrected L.P. turbine exhaust temperature
P_6/P_2 = inter turbine to engine inlet pressure ratio
P_7/P_2 = E.P.R.—engine pressure ratio
T_{5c2} = corrected H.P. turbine inlet temperature
A_5 = H.P. turbine inlet nozzle area
A_6 = L.P. turbine inlet nozzle area
A_{JD} = fan duct exhaust nozzle area
F_{nc2} = corrected net engine thrust
Γ_{T2} = corrected fan airflow
Γ_{CL} = LPC airflow corrected to LPC inlet (turbofan)
Γ_2 = corrected L.P. compressor airflow (turbojet)
Γ_3 = HPC airflow corrected to HPC inlet
η_F = fan adiabatic compression efficiency
η_{CL} = LPC adiabatic compression efficiency
η_{CH} = HPC adiabatic compression efficiency
η_{tH} = H.P. turbine adiabatic expansion efficiency
η_{tL} = L.P. turbine adiabatic expansion efficiency
SFC_{c2} = corrected specific fuel consumption.

Introduction

THE purpose of any gas turbine engine condition monitoring system is to permit meaningful conclusions on engine status to be drawn from measurable data in a cost effective fashion. In a general sense, any engine may be viewed as consisting of accessory equipment, rotational mechanical equipment, and the thermodynamic gas path elements. The accessory equipment includes such elements as the fuel control, fuel pump, lubrication system, ignition system, and engine air bleed system. The rotational mechanical equipment includes the various main engine bearings, rotors, and gear trains. The gas path elements include the gas containment path, the compressors, the burner, and the turbines. In view of the fact that physical problems may exist in any of these general areas, a totally integrated diagnostic system must have a proper balance of emphasis on all of them, with the measured data from the three areas often serving in a mutually complementary fashion to lead to proper diagnoses. For example, rear end vibration coupled with gas path performance changes might be indicative of lost or damaged turbine rotor blades, whereas rear end vibration coupled with high lubricating oil temperature might be indicative of a damaged main rear bearing.

Diagnostic treatment of the accessory and rotational equipment is reasonably straightforward and has been expertly dealt with by others in prior public presentations and published government and industry reports. Without in any way detracting from their relative importance—rather, emphasizing their absolute necessity for a completely viable engine diagnostic system—this discussion considers in greater detail an approach to gas path analysis less well explored in the literature.

Gas Path Analysis

In the course of its useful life the gas containment path of any engine is susceptible to encountering a wide variety of physical problems. These include such things as erosion, corrosion, fouling, built up dirt, foreign object damage (F.O.D.), worn seals, excessive tip clearances, burned or warped turbine stator or rotor blades, partially or wholly missing blades, plugged fuel nozzles, rotor disk or blade cracks induced by fatigue or operation outside normal intended limits, etc. The object of gas path analysis is to implicitly detect as many of these problems as is economically feasible through the observation of judiciously chosen parameters. To be implicitly detectable (i.e., implied from their effects on the measurable parameters) the problems or faults clearly must be of a nature and magnitude that will produce an observable change. Thus certain problems, such as fatigue cracks in rotor disks or blades, or corrosive attacks on the metallurgical structure but not the geometry of turbine blades, are undetectable by any analytical technique and must either be designed out of the engine, or sought by radiography, zyglo, boroscope, or other visual inspection means. A large portion of the potential faults however are amendable to detection by gas path analysis.

Each of the detectable faults, whether caused by normal wear, degradation, F.O.D., or abnormal abuse, may be viewed as affecting one or more components in one or

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35000 FT. CRUISE P_6/P_2 CONSTANT

	Γ_{T2}	Γ_{CL}	Γ_3	η_F	η_{CL}	η_{CH}	η_{tH}	η_{tL}	A5	A6	A_{JN}	A_{JD}
	1% DECREASE								1% INCREASE			
$\%\Delta N_1C_2$	.41	.21	0	–.15	–.03	–.01	–.02	–.23	0	.29	.13	.20
$\%\Delta N_2C_2$	–.09	.12	.27	.17	.07	–.26	–.41	.13	–.19	.56	–.08	0
$\%\Delta WfC_2$	–.28	.37	0	.41	.09	.56	.78	.41	.15	1.15	–.24	.01
$\%\Delta T_6C_2$	–.21	.27	0	.37	.14	.72	1.05	.29	.22	0	–.17	.01

NOTE THAT EFFECTS ON MEASURED $\%\Delta$'s ARE VERY NEARLY THE SAME

	FOR FAULT OF	AS FOR
1	$\eta_F = -1\%$	$\eta_{TL} = -1\%$
2	$\Gamma_3 = -1\%$	$A_5 = -2.9\%$ PLUS $\eta_{TH} = -0.6\%$
3	$A_{JN} = -1\%$ PLUS $\eta_F = -1\%$	$A_5 = -3.1\%$ $\eta_{TH} = -0.9\%$, $A_6 = -0.17\%$ PLUS $\eta_{TL} = -0.9\%$

ETC. FOR MANY OTHER COMBINATIONS

Fig. 1 Turbofan fault coefficients.

more of their basic performance parameters. For example, compressor or fan faults will manifest themselves as changes in either the air pumping capacity or the adiabatic compression efficiency, or both; turbine faults will manifest themselves as changes in either the turbine effective nozzle area size (affecting flow and hence power absorption capability) or the adiabatic expansion efficiency, or both; exhaust system faults, as changes in the engine match point brought about by exhaust nozzle effective area variation; etc. These primary independent parameters, although fundamental in nature and leading directly to the detection of engine faults are not readily or practically measurable. The parameters which can be measured are typically the various corrected temperatures, pressures, fuel flow, and rotor speeds throughout the engine. These parameters are dependent variables whose absolute values depend on the absolute levels of all the primary independent engine variables. Therefore, since changes in these dependent variables are brought about by changes in the primary independent variables, differences in these parameters from their baseline expected values can be used to implicitly determine which elements of the gas path have undergone distress or departed from their initial or expected condition. It should be stressed that any parameter in itself is not necessarily indicative of faults in any particular element. For example, at any given rotor speed, a change in compressor discharge pressure does not necessarily mean that there is a compressor fault. The change may also be due to a combined compressor and turbine fault, or due to a turbine fault alone.

An obvious requirement for successful diagnostics is a means to interrelate changes in the measurable variables to basic engine faults. Among the more widely known prior techniques is the so called Fault Coefficient Matrix (FCM) method, which relies on measuring changes in the dependent variables and comparing them with tables of precalculated expected deviations in these parameters for various possible engine faults to determine the statistically most probable single fault. Among the shortcomings of this technique are the following: 1) a limited set of measurements coupled with an extensive set of possible faults can often lead to ambiguities in interpretation, i.e., two dissimilar physical faults may produce virtually identical changes in the observed parameters; 2) a single fault may have an indistinguishably similar effect on the observed parameters as a totally unrelated set of multiple faults; 3) one set of multiple faults may have virtually the same effect on the observed parameters as another unrelated set of multiple faults. Figure 1, based on a high-performance turbofan engine, illustrates these points. Although FCM analysis has demonstrated value when properly applied in single fault situations, perhaps the more serious ambiguities are those associated with multiple faults, since engine problems (gradual service degradation or fouling, for example) most frequently tend to be combinations of multiple faults.

A preferred approach has been developed and applied to a broad range of engine types and programs, which permits the simultaneous evaluation of combinations of primary faults within the gas path. A fundamental premise of the concept is that, as stated earlier, the measurable engine parameters are dependent variables, changes in which, at any given power and environmental condition, are brought about by deviations in the fundamentally independent component performance parameters, which in turn are caused by physical problems. Using the techniques found in "Gas Turbine Engine Parameter Interrelationships," a book by the author of this paper, it can be shown that a general influence coefficient matrix may be derived for any particular thermodynamic cycle, defining the set of differential equations which interrelate the various dependent and independent engine performance parameters. Complimentary copies of the book are available

	ΔT_{5C3}	ΔN_{2C3}	ΔA_{JN}	AIR BLEED INTER STAGE ΔW_{BL}	AIR BLEED COMP EXIT ΔW_{BL}	PUMPING CAPACITY LOW SPOOL $\Delta \Gamma_2$	PUMPING CAPACITY HIGH SPOOL $\Delta \Gamma_3$	COMPRESSION EFFICIENCY LOW SPOOL $\Delta \eta_{CL}$	COMPRESSION EFFICIENCY HIGH SPOOL $\Delta \eta_{CH}$	ΔA_5	EXPANSION EFFICIENCY HIGH SPOOL $\Delta \eta_{tH}$	EXPANSION EFFICIENCY LOW SPOOL $\Delta \eta_{tL}$
$\Delta T_{5C3} =$	1	0	0	0	0	0	0	0	0	0	0	0
$\Delta N_{2C3} =$	0	1	0	0	0	0	0	0	0	0	0	0
$\Delta A_{JN} =$	0	0	1	0	0	0	0	0	0	0	0	0
$\Delta N_{1C2} =$	a1	a11	a21	a101	a111	a31	a41	a51	a61	a71	a81	a91
$\Delta T_{3C2} =$	a2	a12	a22	a102	a112	a32	a42	a52	a62	a72	a82	a92
$\Delta P_3/P_2 =$	a3	a13	a23	a103	a113	a33	a43	a53	a63	a73	a83	a93
$\Delta T_{4C2} =$	a4	a14	a24	a104	a114	a34	a44	a54	a64	a74	a84	a94
$\Delta P_4/P_2 =$	a5	a15	a25	a105	a115	a35	a45	a55	a65	a75	a85	a95
$\Delta W_{FC2} =$	a6	a16	a26	a106	a116	a36	a46	a56	a66	a76	a86	a96
$\Delta P_6/P_2 =$	a7	a17	a27	a107	a117	a37	a47	a57	a67	a77	a87	a97
$\Delta T_{7C2} =$	a8	a18	a28	a108	a118	a38	a48	a58	a68	a78	a88	a98
$\Delta P_7/P_2 =$	a9	a19	a29	a109	a119	a39	a49	a59	a69	a79	a89	a99
$\Delta N_{2C2} =$	a10	a20	a30	a110	a120	a40	a50	a60	a70	a80	a90	a100
$\Delta T_{5C2} =$	a121	a122	a123	a124	a125	a126	a127	a128	a129	a130	a131	a132
$\Delta A_6 =$	a133	a134	a135	a136	a137	a138	a139	a140	a141	a142	a143	a144
$\Delta F_{NC2} =$	a145	a146	a147	a148	a149	a150	a151	a152	a153	a154	a155	a156

NOTE: ALL Δ'S ARE IN % OF POINT VALUES

Fig. 2 Twin spool turbojet general matrix for major parameters of interest.

upon written request to the author. A typical matrix, specifically derived for a turbojet engine with twin spool gas generator, showing the major parameters of interest would be of the form in Fig. 2. Each row of the matrix is a differential equation wherein the net change in the dependent variable specified at the left of the row is the arithmetic sum of the coefficients times the change in the variable specified at the head of each column. Each of the coefficients in any row is derived from the basic laws of thermodynamics applicable to the particular thermodynamic cycle of the specific engine, taking into account such factors as conservation of mass and energy, power balance between driving and driven members, pressure rise and fall continuity, specific shapes of component performance maps, variable specific heat effects, nozzle flow coefficient and unchoking effects, etc. The thermomathematical form and derivation of each of the many coefficients could consume a textbook and is well beyond the intended scope of this discussion; however, those skilled in the art of gas turbine performance analysis should be able to produce them, with more or less difficulty, for any particular type of engine.

As shown in the referenced book, the general matrix is useful in solving an endless variety of engine performance problems; engine diagnostics is simply one more specific useful application.

Since the matrix represents a set of simultaneous equations interrelating dependent and independent variables, the first step in its application is to decide which of the possible independent parameters will truly be subject to variation in the application of interest and from that determine how many dependent variables must be monitored. For example, assume for the engine of Fig. 2 that the pumping capacity and efficiency of the two compressors, the area and efficiency of the two gas generator turbines, and the exhaust nozzle effective area were all

	ΔT_{5C3}	ΔA_{JN}	$\Delta \Gamma_2$	$\Delta \Gamma_3$	$\Delta \eta_{CL}$	$\Delta \eta_{CH}$	ΔA_5	$\Delta \eta_{tH}$	$\Delta \eta_{tL}$
$x_a - a_{11}(x_b - 1/2\, x_c) =$	a_1	a_{21}	a_{31}	a_{41}	a_{51}	a_{61}	a_{71}	a_{81}	a_{91}
$x_c - a_{12}(x_b - 1/2\, x_c) =$	a_2	a_{22}	a_{32}	a_{42}	a_{52}	a_{62}	a_{72}	a_{82}	a_{92}
$x_d - a_{13}(x_b - 1/2\, x_c) =$	a_3	a_{23}	a_{33}	a_{43}	a_{53}	a_{63}	a_{73}	a_{83}	a_{93}
$x_e - a_{14}(x_b - 1/2\, x_c) =$	a_4	a_{24}	a_{34}	a_{44}	a_{54}	a_{64}	a_{74}	a_{84}	a_{94}
$x_f - a_{15}(x_b - 1/2\, x_c) =$	a_5	a_{25}	a_{35}	a_{45}	a_{55}	a_{65}	a_{75}	a_{85}	a_{95}
$x_g - a_{16}(x_b - 1/2\, x_c) =$	a_6	a_{26}	a_{36}	a_{46}	a_{56}	a_{66}	a_{76}	a_{86}	a_{96}
$x_h - a_{17}(x_b - 1/2\, x_c) =$	a_7	a_{27}	a_{37}	a_{47}	a_{57}	a_{67}	a_{77}	a_{87}	a_{97}
$x_i - a_{18}(x_b - 1/2\, x_c) =$	a_8	a_{28}	a_{38}	a_{48}	a_{58}	a_{68}	a_{78}	a_{88}	a_{98}
$- a_{19}(x_b - 1/2\, x_c) =$	a_9	a_{29}	a_{39}	a_{49}	a_{59}	a_{69}	a_{79}	a_{89}	a_{99}

WHEREIN:

$x_a = \Delta N_{1C2}$ $\quad x_f = \Delta P_4/P_2$

$x_b = \Delta N_{2C2}$ $\quad x_g = \Delta W_{fC2}$

$x_c = \Delta T_{3C2}$ $\quad x_h = \Delta P_6/P_2$

$x_d = \Delta P_3/P_2$ $\quad x_i = \Delta T_{7C2}$

$x_e = \Delta T_{4C2}$

Fig. 3 Twin spool turbojet component degradation measurement matrix.

	ΔN_{1c2}	ΔN_{2c2}	ΔT_{3c2}	$\Delta P_3/P_2$	ΔT_{4c2}	$\Delta P_4/P_2$	ΔW_{fc2}	$\Delta P_6/P_2$	ΔT_{7c2}
$\Delta \Gamma_2 =$	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
$\Delta \Gamma_3 =$	b_{11}	b_{12}	b_{13}	b_{14}	b_{15}	b_{16}	b_{17}	b_{18}	b_{19}
$\Delta \eta_{CL} =$	b_{21}	b_{22}	b_{23}	b_{24}	b_{25}	b_{26}	b_{27}	b_{28}	b_{29}
$\Delta \eta_{CH} =$	b_{31}	b_{32}	b_{33}	b_{34}	b_{35}	b_{36}	b_{37}	b_{38}	b_{39}
$\Delta \eta_{tH} =$	b_{41}	b_{42}	b_{43}	b_{44}	b_{45}	b_{46}	b_{47}	b_{48}	b_{49}
$\Delta \eta_{tL} =$	b_{51}	b_{52}	b_{53}	b_{54}	b_{55}	b_{56}	b_{57}	b_{58}	b_{59}
$\Delta A_5 =$	b_{61}	b_{62}	b_{63}	b_{64}	b_{65}	b_{66}	b_{67}	b_{68}	b_{69}
$\Delta A_6 =$	b_{71}	b_{72}	b_{73}	b_{74}	b_{75}	b_{76}	b_{77}	b_{78}	b_{79}
$\Delta A_{JN} =$	b_{81}	b_{82}	b_{83}	b_{84}	b_{85}	b_{86}	b_{87}	b_{88}	b_{89}
$\Delta T_{5C2} =$	b_{91}	b_{92}	b_{93}	b_{94}	b_{95}	b_{96}	b_{97}	b_{98}	b_{99}
$\Delta F_{nc2} =$	b_{101}	b_{102}	b_{103}	b_{104}	b_{105}	b_{106}	b_{107}	b_{108}	b_{109}
$\Delta SFC_{c2} =$	b_{111}	b_{112}	b_{113}	b_{114}	b_{115}	b_{116}	b_{117}	b_{118}	b_{119}

Fig. 4 Twin spool turbojet equation set relating implicit parameter changes to measured dependent parameter changes at constant P_7/P_2.

subject to degradation in any random combination, and that there was no service or overboard bleed.

There would then be nine independent variables (A_{JN}, Γ_2, Γ_3, η_{CL}, η_{CH}, A_5, η_{tH}, A_6, η_{tL}), requiring the monitoring of the changes in nine appropriate dependent variables (N_{1c2}, N_{2c2}, T_{3c2}, P_3/P_2, T_{4c2}, P_4/P_2, W_{fc2}, P_6/P_2, T_{7c2}, all at constant P_7/P_2). Letting the percentage measured dependent variable changes be called

$$\Delta N_{1c2} = x_a \quad \Delta P_3/P_2 = x_d \quad \Delta W_{fc2} = x_g$$

$$\Delta N_{2c2} = x_b \quad \Delta T_{4c2} = x_e \quad \Delta P_6/P_2 = x_h$$

$$\Delta T_{3c2} = x_c \quad \Delta P_4/P_2 = x_f \quad \Delta T_{7c2} = x_i$$

the pertinent elements of the general matrix may be extracted and rearranged to yield Fig. 3. This may now be solved as a set of simultaneous equations to yield the changes in T_{5c3}, A_{JN}, Γ_2, Γ_3, η_{CL}, η_{CH}, A_5, η_{tH},and η_{tL}. Since the headings of all columns are now known, the general matrix may be now used to solve for the changes in T_{5c2}, A_6, F_{nc2}, and SFC_{c2}.

As a practical matter it would require excessive computer memory to perform the simultaneous solution of a multivariable set of equations such as that illustrated. In practice this is easily overcome by recognizing that, since the coefficients may be treated as constants for any operating regime or window, the equations may be transformed by matrix inversion to a set of linear equations of the independent variables in terms of the measured dependent variables as shown in Fig. 4. The change in any independent variable is thus the simple arithmetic sum of the appropriate "b" coefficients times the change in the dependent variables.

Also, in fulfillment of the original premise, since the affected components have been identified by their changes in performance, the locations of the engine's physical problems, in whatever combination, have been isolated. Note that in this illustrative case, all major implicit parameters were assumed variable. If in a particular application this is not necessary, because of the engine's development maturity or benign environment, the appropriate equation set corresponding to Fig. 4 for a reduced number of variables may be readily derived from the complete original matrix of Fig. 2. It should also be obvious that the choice of constant P_7/P_2 to determine measured parameter deltas is arbitrary, and that it is mathematically valid to choose any other parameter. The measured deltas would differ in magnitude, but so would the "b" coefficients, with the net result being identical implicit parameter deltas, and hence the same diagnostic message.

The precise values of the matrix coefficients vary somewhat with operating conditions. Therefore, for ground based analysis multiple implicit parameter equation sets covering contiguous operating ranges are stored and the proper one chosen during analysis to correspond with the EPR and Mn of the operating point. In this way analysis can be made of data from Take-off, Climb, or Cruise operation. Useful in-flight analysis may be conducted by storing only the set applicable to cruise conditions in the airborne equipment, and analyzing all cruise data. The computer memory requirement would be minimal, with a maximized usefulness of output, since most gas path problems such as dirty, worn or missing parts will manifest themselves to an equal extent on engine performance in either Takeoff, Climb, or Cruise operation. The remaining possible gas path problems such as pressure level or stress level dependent leaks, etc., will be caught by the ground based analysis of Take off and Climb data.

Since the approach is based on interrelating differential changes, an important task is to gather baseline data in the useful power range on the parameters to be measured. If there was no engine to engine variation among new production line engines, the stored baselines for all engines could be a single set of nominal baselines. In point of fact, new engine variability is of the same order of magnitude as the deterioration changes being sought and therefore individual custom base lines of the particular engine being observed in its as received state must be stored. This is most readily accomplished by letting the first dozen or so data gathering events be used to establish the engine custom baselines. At any point in time after the engine has been used or abused measurements are repeated on the dependent variables, and the differences calculated between their baseline values and present state values at the measured value of the baseline abscissa parameter. These differences may then be used in the interrelationship matrix to determine what changes and in whatever combination have occurred in the basic independent parameters, and hence the probable cause of the fault or faults, and the action to be taken. Limits may also be set on the changes in the independent variables, and changes in them plotted out with time to permit their trending for limit exceedance and prognostication purposes.

The adequacy of the input data of course, is a direct determinant in precision of the diagnostic errors. In this regard it is well to emphasize that the approach is a dif-

$$\Delta\Gamma = -2.15\Delta N_{1c2} - 0.14\Delta N_{2c2} - 0.16\Delta P_B/P_2 - 0.65\Delta T_{7c2}$$
$$\Delta\eta_c = 0.80\Delta N_{1c2} - 2.39\Delta N_{2c2} + 0.92\Delta P_B/P_2 - 0.65\Delta T_{7c2}$$
$$\Delta B.F.S = -0.19\Delta N_{1c2} + 0.56\Delta N_{2c2} - 1.17\Delta P_B/P_2 - 0.17\Delta T_{7c2}$$
$$\Delta F.T. = -0.071\Delta N_{1c2} + 2.16\Delta N_{2c2} - 1.27\Delta P_B/P_2 - 0.65\Delta T_{7c2}$$
$$\Delta TIT = -0.16\Delta N_{1c2} + 0.47\Delta N_{2c2} - 0.01\Delta P_B/P_2 + 0.85\Delta T_{7c2}$$
$$\Delta SFC = -0.08\Delta N_{1c2} + 0.23\Delta N_{2c2} - 0.06\Delta P_B/P_2 + 0.75\Delta T_{7c2}$$

Fig. 5 FT4 turboshaft engine diagnostic equations.

ferential technique determining changes in state and not absolute levels. Therefore input data accuracy is a minor concern; what is important is data repeatability. Sensor inaccuracy is largely eliminated as an error source by using custom baselines (i.e., by comparing all engine data to their initial values) and determining answers only on the basis of changes that have taken place from an initially known state. Sensor nonrepeatability does remain as an error source, but this is always many times better than absolute accuracy for any particular instrument.

Program Applications and Results

The gas path analysis technique outlined in the preceding discussion has been used in a variety of engine condition monitoring programs. Engine types have included turboshaft engines with single spool and twin spool gas generators, large bypass ratio unmixed flow turbofans, and medium bypass ratio mixed flow turbofans. Engine installations have included military helicopters, stationary electric power generators, commercial transports, and military fighter planes. This section briefly examines some results from two of these programs.

Large Twin Spool Turboshaft

The TRENDS program is an active current application concerned with engine condition monitoring of the FT4, a 25-Mw output turboshaft engine with twin spool gas generator used as a stationary power plant by electric utility companies for peaking power generation. The complete

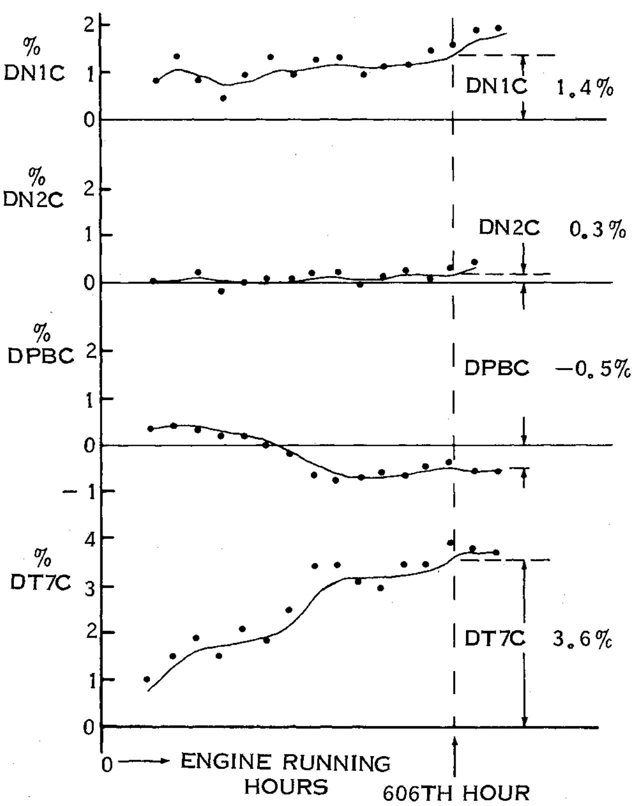

Fig. 6 FT4 engine 1 measured parameter trends.

ENGINE DATA

TIME	106 16	52 07
MW	49.83	50.44
TEH	606.	20.
NS	43.	5.
ART	0.3	4.0
EPR	2.307	2.410
N1	5792.	0.
N1C	5752.	0.
N2	8255.	0.
N2C	8197.	0.
PB	173.18	122.57
PBC	12.011	8.503
TT7	967.2	481.3
T7C	1406.6	927.6
T7S	1.2	2.0
PT2	29.353	29.343
PT7	38.23	41.23
SF	5.	7.
TAM	66.76	66.76
PAM	29.497	29.497
OTG	0.0	85.0
OTT	0.0	0.0
OPG	9.52	37.74
OPT	11.01	42.17
DPG	8.63	23.78
DPT	7.53	24.41
OLG	16.09	7.66
OLT	16.05	3.73
VG	0.000	1.447
VT1	0.008	1.415
VT2	0.000	1.406
DMWC	0.00	0.00
DN1C	1.4	- 3.3
DN2C	0.3	-49.1
DPBC	- 0.5	4.4
DT7C	3.6	-34.3
DT7S	-111.7	-88.0
DOTG	14.3	-58.2
DOTT	-148.0	22.9
DOPG	-19.97	8.53
DOPT	-16.48	5.27
DDPG	- 1.38	16.88
DLPT	- 1.16	17.10
DOLG	6.34	- 1.75
DOLT	3.05	8.68
DVG	0.499	- 0.941
DVT1	0.673	- 0.781
DVT2	0.974	- 0.484
DSFC	2.62	-37.09
DTIT	2.93	-51.84
DCEL	- 2.49	141.15
DFT	- 2.03	-87.24
DBFS	- 0.18	-26.34
DAFL	- 5.59	35.53

MAINTENANCE MESSAGE

```
A GO  CLEAN            -43
    COMPRESSOR
ACK CODE    1 3
TIME 106   16   52   07

A GO  INSPECT          -57
    FOULED   TURBINE
    OR   WORN   SEALS
ACK CODE    1  2
TIME 106   16   52   06

A TIT                  -21
ACK CODE    2
TIME 106   16   52   06

A SFC                  -38
ACK CODE    1
TIME 106   16   52   06
```

Fig. 7 Actual TRENDS® diagnostic output.

system continuously monitors engine accessories, rotational elements, and the engine gas path through the measurement of oil temperatures and pressures, oil quantity, spool speeds, vibration levels, air and gas temperatures and pressures, and other parameters with the objective of providing early detection of impending malfunction or loss of performance. On the basis of the measured data it automatically performs a diagnosis to pinpoint the fault location, provides a prognosis of time remaining before limit exceedance by extrapolation of the data trend, and indicates the corrective action required. The pertinent data and messages, issued as English language instructions are printed out on a "tear-off" strip printer. No data reduction or evaluation is required of the operator. The messages are repeated at regular intervals until corrective action is taken or until the operator, through a pushbutton, acknowledges that he has implemented his instructions.

The gas-path analysis portion of the system is concerned with detecting compressor fouling, high-pressure turbine first-stage nozzle bowing, fouled turbines or worn turbine seals, missing blades, and burner nozzle plugging, and in assessing the attendant changes in turbine inlet temperature and SFC. Compressor fouling is detected by loss in either engine airflow or compressor efficiency; bowed first stage by an increase in first turbine area cou-

$$\Delta T_{5C} = 0.476\Delta T_{3C} - 0.125\,\Delta W_{fC} + 0.125\,\Delta HP_C + 0.99\,\Delta T_{9C}$$
$$\Delta W_{aC} = -3.85\Delta N_1C - 0.03\Delta T_{3C} + 1.29\Delta W_{fC} - 0.29\,\Delta HP_C - 2.32\Delta T_{9C}$$
$$\Delta \eta_C = -2.47\,\Delta T_{3C}$$
$$\Delta A_5 = 0.23\,\Delta T_{3C} + 1.23\,\Delta W_{fC} - 0.19\,\Delta HP_C - 1.83\,\Delta T_{9C}$$
$$\Delta\eta_T = 2.09\,\Delta T_{3C} + 0.13\,\Delta W_{fC} + 0.18\,\Delta HP_C - 1.01\,\Delta T_{9C}$$
$$\Delta\eta_{PT} = 0.10\,\Delta T_{3C} - 1.22\,\Delta W_{fC} + 0.65\,\Delta HP_C + 1.71\,\Delta T_{9C}$$
$$\Delta A_N = -0.10\,\Delta T_{3C} + 1.22\,\Delta W_{fC} - 0.65\,\Delta HP_C - 1.71\,\Delta T_{9C}$$

Fig. 8 T53 diagnostic equations.

pled with a related high-pressure turbine efficiency loss; fouled turbines or worn turbine seals by a combined loss in high- and low-pressure turbine efficiency; missing blades by excessive vibration coupled with a performance shift; and burner nozzle plugging by a change in the downstream turbine temperature profile. These changes are detected whether they occur singly or in random combination. Note that these changes do not include all of the possible gas-path problems which could theoretically occur in a twin-spool turboshaft engine. This is a reflection of the relative developmental maturity of the FT4 engine and of the environment in which it is run. The problems sought are only those which have a high probability of being in any given problem set. For example, by virtue of its position in the gas stream coupled with its physical design, the free-power turbine is much less likely to suffer gas-path damage than the gas generator turbines, and then most probably only after damage has progressed to an appreciable degree in the first two turbines. Also, since the engine is installed in a concrete block house with the airflow coming through the roof of a well protected plenum, it is very unlikely to suffer foreign object damage by ingestion; based on experience, the most likely effect of compressor fouling or dirt build up is to degrade first and second compressor airflows, and/or efficiencies, in known proportional combinations.

The diagnostic equations for this specific application thus reduce to the simple set shown in Fig. 5, and only require knowledge of the changes in N_{1c2}, N_{2c2}, P_B/P_2 and T_{7c2} at constant P_7/P_2.

A manual plot of some actual data on Engine 1 of a dual engine installation is shown on Fig. 6. A facsimile "tear off" strip printout of the data, diagnostics, and prognostics from the 606th hour is shown on Fig. 7. The trended, curve fitted, gas-path deltas for the 606th hour are printed out as

DN1C = 1.4%	DPBC = −0.5%
DN2C = 0.3%	DT7C = 3.6%

The calculated gas path deviations are

DCEL = −2.49% compressor efficiency loss
DFT = −2.03% turbine efficiency loss
DBFS = −0.18% bowed first-stage measure
DAFL = −5.59% compressor airflow loss
DTIT = 2.93% true turbine inlet temp increase
DSFC = 2.62% SFC increase

The diagnostic and prognostic messages for Engine 1 are:

Clean the compressor, at the present rate you are within 43 hr of an unacceptable degree of fouling.

Inspect the gas generator turbines for fouling or worn seals. At the present rate you are within 57 hr of exceeding an acceptable limit for the turbines.

At the present rate the combined effect of the existing problems will raise TIT above an acceptable limit within 21 hr.

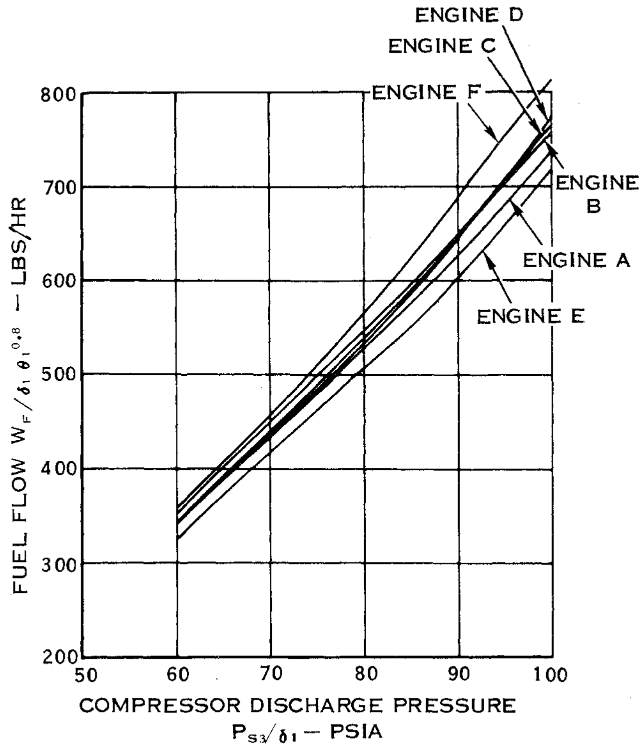

Fig. 9 Fuel flow baselines for six different engines.

At the present rate the combined effect of the existing problems will raise SFC above an acceptable limit within 38 hr.

A hot section inspection and cleaning of the compressor confirmed the presence of the enumerated problems.

Note that Engine 2 was not fully instrumented (N_1 and $N_2 = 0$) and hence the system attempted no diagnostics on it.

Military Helicopter Turboshaft

The AIDAPS program, run in close cooperation with the U.S. Army Aviation Systems Command, was an experimental demonstration of the feasibility of a comprehensive engine/aircraft power train monitoring system. The vehicle chosen was the UH-1 helicopter, powered by a single $T_{53}L_{13}$ turboshaft engine. The entire system monitored the engine accessories, rotational equipment and gas path, as well as the main overhead rotor gearbox and the two gearboxes in the tail rotor transmission system. Measurements were made of various system oil and gas tem-

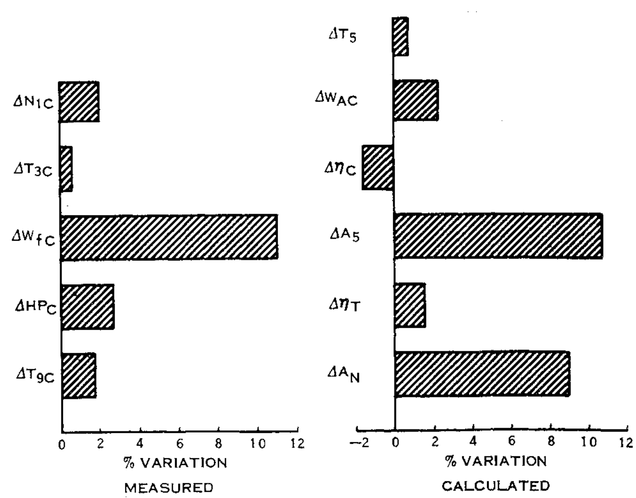

Fig. 10 Parameters for Engine A.

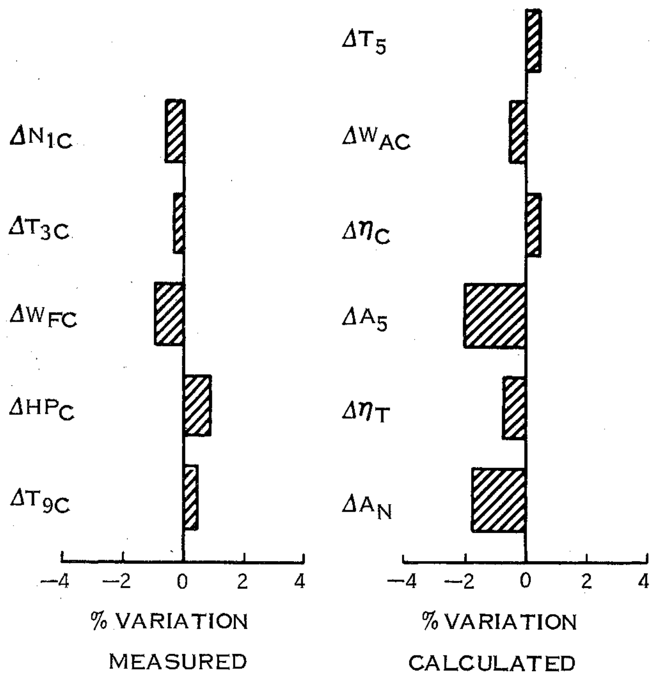

Fig. 11 Parameters for Engine B.

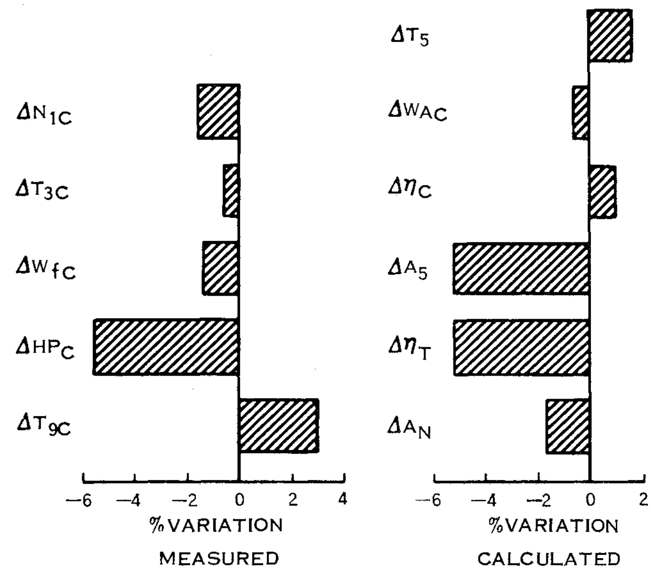

Fig. 12 Parameters for Engine C.

peratures and pressures, vibration levels at several engine locations and on the enumerated power system gear boxes, gas generator and power turbine speeds, engine fuel flow, power turbine torque, aircraft power system voltages, and various other pertinent parameters.

The T_{53} engine gas path consists of combined axial-centrifugal flow compressors bolted to a single shaft, a reverse flow annular combustion chamber, a two-stage high-pressure turbine to drive the compressor, and a two-stage low-pressure free-type power turbine. Reduction gearing within the air inlet housing reduces power turbine speed to output shaft speed. The gas path analysis portion of the system was concerned with detecting compressor damage or degradation through changes in air pumping capacity (W_{oc}) and compressor efficiency (η_c), gas generator turbine problems through changes in high-pressure turbine inlet area (A_5) and efficiency (η_t), free power turbine problems through changes in low-pressure turbine inlet area (A_N) and efficiency (η_{PT}), and combustion hot spots or plugged nozzles by changes in exhaust gas temperature (T_{9C}) profile. Measurements were taken of compressor discharge temperature (T_{3C}), gas generator spool speed (N_{1C}), engine fuel flow (W_{fc}), free turbine horsepower from torque and speed (HP_c), free turbine exhaust gas temperature (T_{9C}), and compressor discharge pressure (P_{3C}). Changes in the parameters were determined by comparing their "present state" values to their "baseline" values at the measured values of P_{3C}, and the resultant deltas inserted into the diagnostic equations of Fig. 8 to compute the basic implicit parameter changes, and the change in true turbine inlet temperature.

Because the nature of the program precluded extended endurance running to develop component faults, and then attempt their diagnoses, the method chosen was to conduct calibration runs to establish the baseline signatures of the new engines, and then to insert bad parts, singly or in combinations unknown to the diagnoser, and request isolation of the part or parts through data gathered in actual flight. In regard to baseline signature, Fig. 9 lends visual emphasis to previous comments on the need to establish custom baselines for reach particular engine. Although the fuel flow baselines shown are all for known good engines, the spread among them is as great or greater than the parameter shift experienced because of faulty components within a given engine.

Figures 10–12 are bar charts showing the averaged values for a complete flight of the measured and implicit parameter deltas for three of the implanted bad parts runs conducted during the program. From the implicit parameter deltas, Engine A was correctly diagnosed as having burned open gas generator and power turbine inlet nozzles. Engine B was correctly diagnosed as having no gas path fault; vibration analysis traced the fault to an implanted mechanical problem. Engine C was correctly diagnosed as having gas generator turbine damage. Although many other tests were run during the program, it is beyond the intended scope of this paper to discuss them all. Suffice to say that a high degree of success (88% overall) was demonstrated in detecting implanted malfunctions and degraded parts by vibration and gas path analysis.

Conclusions

Gas path analysis for multiple fault isolation provides a powerful tool which, when used in conjunction with the better known techniques for accessory and mechanical component diagnosis, can lead to significant benefits to engine users in terms of reduced maintenance, overhaul and operating costs brought about by timely, exact knowledge of engine status. The technique is applicable to all engine types and in practice is customized to the particular engine installation, instrumentation, and operational history. It is based on relative shifts rather than absolute measurements and hence is primarily influenced by instrumentation repeatability, which is always better than absolute accuracy. It is valid for all multiple combinations of sought for faults, with isolation to specific modules. Execution requires minimal computer memory, involving only multiplication and addition to solve a simple set of linear equations. In any installation, the informational yield from any given set of measurements is greater using gas path analysis than any known competitive technique.