Table 4 Fault matrix

DETERIORATED CONDITIONS	SPEED	OPR	TIT	M_a	M_f	sfc	WORK OUTPUT	HP SPEED	LP WORK	HP WORK
$0.95\eta_{lpc}$	HIGH	↑	↑	∪	↑	↑	↑	↑	↑	↑
	MID	↑	↑	∩	↑	↑	↑	↑	↑	↑
	LOW	↑	↑	∩	↑	↑	↑	↑	↑	↑
0.03 Bleed	HIGH	↓	↑	—	↑	↑	↓	↑	↓	↓
	MID	↓	↑	↑	↑	↑	↓	↑	↑	↓
	LOW	↓	↑	↑	↑	↑	↓	↑	↑	↑
$0.95\eta_{hpt}$	HIGH	↑	↑	↓	↑	↑	↑	↓	↑	↓
	MID	↑	↑	↓	↑	↑	↑	↓	↑	↓
	LOW	↑	↑	↓	↑	↑	↑	↓	↑	↓
$1.024\ A_{hpt}$	HIGH	↓	↓	∪	∪	—	↓	↓	∪	↓
	MID	↓	↓	∪	∩	∩	↑	↓	↑	↓
	LOW	↓	↓	∪	↑	↑	∩	↓	↑	↓
$1.02\ A_{lpt}$	HIGH	↑	↑	↑	↑	↑	↑	↑	↓	↑
	MID	↑	↑	↑	↑	∩	↑	↑	↓	↑
	LOW	↑	↑	↑	↑	∪	↑	↑	↓	↑

LP – SPEED = INDEPENDENT VARIABLE.

caused by the increase of fuel flow and hence TIT. If, however, the maximum allowable TIT is taken as the control parameter, this will result in reduced rotor speed and decreased work output.

Here the HP turbine erosion may appear to improve performance. If erosion causes the HP turbine flow area to increase, the work load of the HP-spool decreases and the load of the LP-spool increases. For fixed TIT or work output, the LP rotor has to run at a higher speed, which may not be permissible for mechanical reasons. For actual erosion, it would also be expected there would be some drop of the efficiency; so the erosion may be the combination of deteriorations (3) and (4) that more likely will depress the performance rather than improve it.

As examples of graphic output, Fig. 5 shows the LP compressor map and the comparison of running lines; Fig. 6 shows the relationship between the two rotor speeds. As HP turbine mechanical damage is specified in these maps, it appears that the deterioration will raise the LP compressor running line toward surge and lower the HP-speed for a specified LP-speed.

3 Development of Fault Matrix. A fault matrix is a common tool used for field diagnostic analysis. By evaluating the trends of parameter variation, the operator can roughly locate the engine problem for further investigation.

Since only a few faults might be found in service, the complete fault matrix cannot be developed by real engine operation. It has to be produced by a diagnostic model with simulated faults implanted. A fault matrix produced by the LM-1600 model is shown in Table 4. The LP-spool speed is taken as the independent variable in the matrix, where the LP-speed varies from 100 percent design speed to 95 percent and 90 percent. The sign of "↑" or "↓" indicates parameter increase or decrease compared with the nominal engine; "∩" or "∪" indicates slight increase or decrease; and "—" means almost no change. It can be seen that the magnitude of the independent parameters has some effect on the various trends; for this reason, a restricted operating range should be specified for use with the fault matrices.

The model has been verified against field results from a pipeline. Because of the short time the engine has been in service, no extensive information on faults is available; thus, the fault matrix presented is developed from the mathematical model and has still to be proven. If either the VSVs or IGVs are out of tolerance, considerable shift in the parameters will result if LP speed is used as the independent variable; the fault matrix may, therefore, be a useful tool for checking errors in the variable geometry settings. Alternatively, HP speed could be used as the independent variable, and another fault matrix developed.

The fault matrix is a useful tool, because the effect of specific deteriorations can be implanted; not all of these may occur in service, and some may only be experienced at very high running hours, so the mathematical model offers a significant predictive capability.

Conclusions

A mathematical model representing the performance of the LM-1600 has been generated, showing excellent agreement with field results. The model is flexible in use and can generate fault matrices, which can be used for diagnostic purposes, a feature that is particularly useful when little operating experience has been built up. The model has modest computing requirements and can be run on a PC compatible with those installed at pipeline compressor stations.

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DISCUSSION

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This paper presents an interesting piece of work in the area of gas turbine performance simulation. We would like to pose

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some questions to the authors, because we think that some points are not sufficiently clear in the paper.

Our first question is related to the way that component maps have to be modified in order to match overall engine performance. Since the authors state that their model is useful for inexperienced operators, we wonder how such operators will be able to produce the required changes on map parameters, without risking being involved in a lengthy trial and error procedure. The authors do not seem to be aware of the existence of methods of automatically adapting the component maps to engine performances (Stamatis et al., 1990a).

A second question is related to the calculation method itself. It is not clear to us how the iterations are done. Since constants A, B, C, D contain the compressor efficiencies, their estimation will have to be effected at each iteration. It seems, therefore, that at each step it will be necessary to "go back to the beginning of the calculation," contrary to what the authors state. With respect to the comments of the authors about other iteration procedures, we would like to know what the authors mean by "difficult numerically." Do they imply long computer time, or problems of nonconvergence and instability? Although the authors discard solution procedures involving matrix methods, they do not state how their iteration procedure is effected, implying that it is a direct substitution one. For such a method, however, it is known that convergence problems may exist. In this respect we would like to mention the work of Wang Yonghong (1991), which has actually introduced the same idea as the one the authors employ in engine modeling, while it discusses comprehensively the numerical aspects of the problem.

We would also like to have information about the reduction in computer memory and running time achieved by the proposed method. Could the authors provide figures about memory requirements and speed of their model, as well as of models over which they claim improvement? Here we would like to comment that in our opinion the necessary speed of calculations is being provided by present-day computer capabilities. In this respect we think that sacrificing model accuracy by simplifying assumptions (as for example by assuming a single turbine characteristic at low pressure ratios or not correcting for compressor efficiency variation) should be avoided. Our experience is that very low running times (fractions of a minute) can be achieved when using full models in today's standard portable PCs.

A final point we would like to have the authors' comments on, is the usefulness of fault matrices. Although they were of great value when first introduced, in the early 1970's, we think their current usefulness is being overemphasized in the present paper. Such matrices give only qualitative information about faults and anyway cannot at all resolve situations with simultaneous presence of different component faults. On the other hand, quantitative methods capable of directly identifying component problems as to their kind and location have been introduced (Stamatis et al., 1990b). In any case the present-day needs (as identified, for example, by Doel, 1990) require information interpretable by expert systems, rather than relying on observations by the engine operator. The method of the present paper does not seem to reply to such needs.

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Authors' Closure

The authors are grateful for the interest in their paper.

It was made clear in the paper that there was absolutely no information available to the authors on either compressor or turbine characteristics. The objective of the work was to produce a full-range thermodynamic model of the engine, which had recently entered service. Compressor characteristics were generated from generalized maps previously published, while single line characteristics based on nozzle data were used for turbines; there would certainly not have been any point in using variable speed turbine characteristics. It should also be noted that the gas generator turbines operate over restricted running ranges, and only the power turbine is subjected to operation over a wide range of speed and pressure ratio. When field test data became available the authors made adjustments to the characteristics to achieve good agreement; it was never intended that field operators would be involved in this process.

The Hot End Method introduced in the paper (HEM) permits all turbine working points to be established initially, and by using pressure equilibrium the work compatibilities can be reduced to a second-order equation with only one unknown. As this equation is solved, the compressor working points can be fixed on the maps; any errors in compressor efficiency can be corrected through iteration and update of the constants A, B, C, and D. This is a half-loop iteration and it is not necessary to go back to the beginning of the calculation. The computer program was computed in the winter of 1989 and the work of Wang Yonghong did not become known to the authors until after the publication of this paper. Both Wang's method and the HEM start from the turbine matching process, fixing the turbine operating points. Wang makes use of this to avoid the numerical instability of the full matrix and then solves a reduced matrix for work compatibility and the cold end; HEM solves the second-order equation directly and finds the rest of the unknowns from flow compatibilities of the cold end. HEM uses a simple one-dimensional search method based on the basic thermodynamic cycle. The authors feel that the simple mathematical model using basic concepts is preferable to a more complex numerical model.

The authors agree that the power of modern PCs makes computing speed a secondary issue; this particular model required about 1.5–2 min running time. They do not agree that using multiline turbine characteristics would improve accuracy, especially where no data are available.

There is no doubt that in the future expert systems will play a role. The key point, however, is where can the data be found to produce the required rules? It will certainly not be easy to generate these from actual field data; failures may arise where no previous information was available, so no rules would exist. Different engine types will exhibit different deterioration modes, but a large amount of operational data will eventually determine the more common causes of failure. The fault matrix is still valuable as a means of systematically predicting the effect of various faults that can be introduced; what is needed, however, is experimental work to define better the magnitudes of efficiency/flow deterioration in components and studies of this type are being initiated at Carleton University by Sjolander. Another potential source of information is test bed evaluation of engines returned for overhaul in "as-received" condition. A great deal of work still must be done to develop soundly based rules for use in expert systems.