Gas-path Component Fault Diagnosis for Gas Turbine Engine: A Review

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***Abstract*—Gas turbine engines have been the key power machine for energy conversion & utilization in the 21st century efficiently and cleanly. To improve equipment reliability and availability, prolong service life and reduce O&M costs, gas path component diagnosis is an effective technique for detecting evolving deterioration. Although many diagnostic methods based on steady state or quasi-steady state have been obtained, but no complete scientific system of gas-path diagnosis has been formed yet. Aiming at the above problems, a research route of gas-path component fault diagnosis for gas turbine engine is proposed. The proposed research route provides a new solution for diagnosis for complex nonlinear thermodynamic systems.**

Keywords-Gas turbine; Diagnosis; Health parameter; Fault evolution; Model-data hybrid drive

I. INTRODUCTION

The gas turbine engine is a power machine with internal combustion, which converts the energy of the fuel into useful power output by using continuous working medium. According to the application, gas turbines are divided into marine, small, aero, heavy duty, micro & industrial gas turbine engines [1-3]. Gas turbine failures (seen in fig.1) can be classified into two types. One type is only related to mechanical property, for example, rotor dynamic imbalance, shaft misalignment, oil film instability, bearing defects [4-7], and other failures. And many approaches, for example, thermal imaging, acoustic analysis, metal temperature, load analysis, oil chip analysis, stress analysis, vibration analysis [8-11] and so on, can be used to diagnose such fault conditions. The other type is only related to aerodynamics/thermodynamics, for example, external/inner damage, fouling, thermal distortion, corrosion and so on. And gas path analysis (GPA) is an effective approach for detecting evolving deterioration [12].

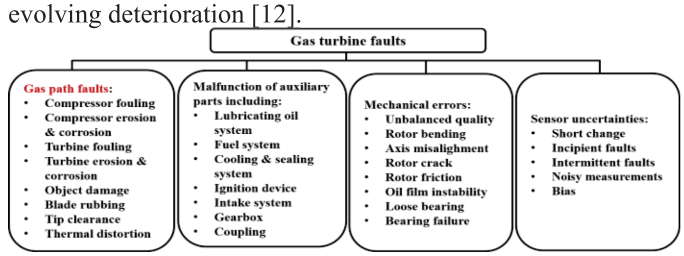

Fig.1 Gas turbine common faults

So as to improve equipment reliability and availability, prolong service life, and reduce the operation and maintenance costs, gas turbine engine users need to take related maintenance strategies according to health status through diagnostic means, which is so-called condition-based maintenance (CBM). Generally, the reliability and effectiveness of condition-based maintenance (CBM) depends on the following two main processes: (1) Diagnostics: *i*. fault detection, monitoring evolving or impending deterioration; *ii*. fault isolation, locating degraded components; *iii*. fault identification. (2) Prognostics: *i*. predicting evolving deterioration; *ii*. assessing remaining useful life of the gas turbine engine. After years of development, many theoretical achievements of gas path diagnostic algorithms have been obtained based on gas turbine steady-state/quasi-steady state operating condition, and however, a complete scientific system has not been formed yet. It involves many complicated factors, such as the wide application of variable geometry compressor, the advancement of bleeding cooling technology, the optimization identification of component health parameters under transient conditions, etc.. Moreover, today's gas turbines increasingly need to operate more flexibly in grid support mode (including frequent variable operating conditions and transient loading or unloading modes).

II. RESEARCH STATUS OF GAS PATH FAULT DIAGNOSIS

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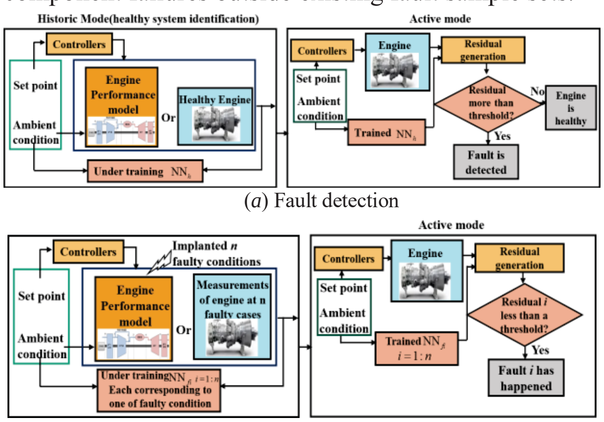
Gas turbine health status information can be derived from gas path component health parameters, for example, flow characteristic index, and efficiency characteristic index of the compressors and turbines [13], which cannot be measured directly and therefore difficult to monitor and diagnose.

A. *Data-driven based gas-path diagnosis*

A gas turbine engine is a thermodynamic system with input-state-output strong nonlinear coupling. Change in ambient conditions & control parameters will cause significant change in the internal state of this thermodynamic system (such as the performance parameters of each component). It is a daunting task to diagnose component failures in such a highly nonlinear thermodynamic system. Data-driven based gas-path diagnosis methods, for example, neural networks, Bayesian networks, fuzzy logic, support vector machines and rough set theory and so on, as shown in fig.2, are dependent on existing fault sample sets. And it is difficult for these data-driven based gas-path diagnosis methods to obtain accurate diagnostic results for component failures outside existing fault sample sets.



(*a*) Fault detection

(*b*) Fault isolation

Fig.2 Artificial neural network for (*a*) fault detection and (*b*) fault isolation [14]

For a new commissioned gas turbine, due to lack of calibrated failure data, it is hardly to accumulate the relationship between the failure mode and the fault symptom. And it is difficult for these data-driven based gas-path diagnosis methods to quantitatively diagnose fault severity.

B. *Model-based gas-path diagnosis*

During engine operation, when some components are degraded or damaged, their component performance parameters will change, and gas path measurable parameters will also change, seen in fig.3.

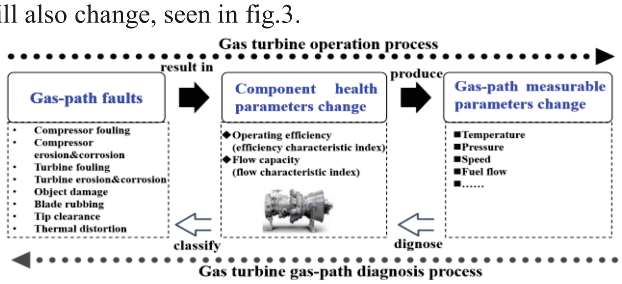


Fig.3 Thermodynamic coupling relationship between component performance and gas-path measurable parameters

In response to the above problems, thermodynamic model-based methods have emerged. The principle is to use the measurable gas path parameters to obtain component health parameters through thermodynamic coupling relationship, by comparing the operating point of the component in the case of performance degradation/damage and the operating point in the health condition on the same component characteristic map diagram to observe the degree of characteristic map offset, seen in fig.4. This is used to detect, isolate, and quantify the components that are degraded/damaged.

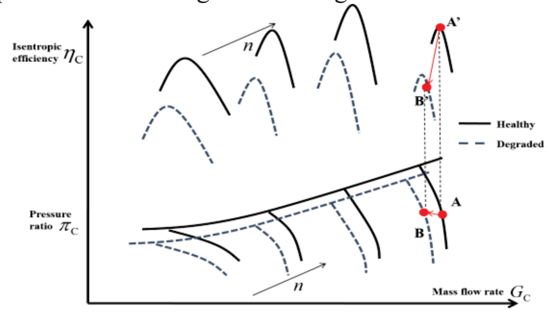


Fig.4 A shift of the characteristic curves on compressor map due to degradation or damage

The inverse mathematical process of thermodynamic model-based diagnostic methods for evaluating the performance health of the equipment is as shown in fig.5.

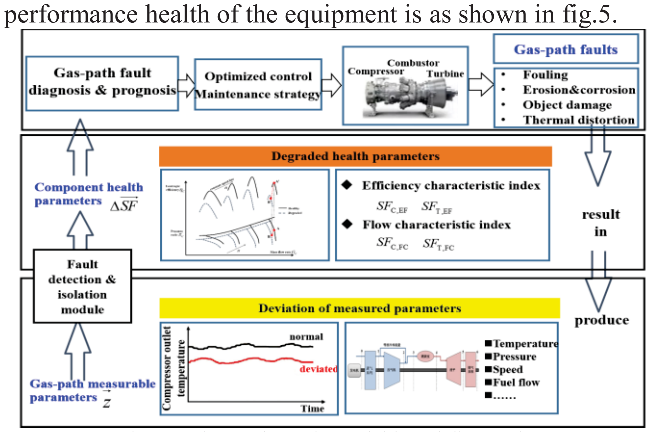


Fig.5 Thermodynamic model-based diagnostic process

It is no need for thermodynamic model-based diagnostic methods to accumulate component fault sample sets. And these methods can be divided into linear & nonlinear methods. [15].

Under current gas turbine thermodynamic modeling technology, the modeling accuracy depends on the accuracy of compressor characteristic maps [16]. For users, it is usually impossible to obtain the gas turbine engine characteristic maps due to manufacturer's confidentiality. Users may only adopt a set of generic gas turbine engine characteristic maps by scaling for thermodynamic modeling. So as to let the component maps of thermodynamic model match the real ones well, many adaptive modeling methods have been proposed based on gas-path measurements. However, for each constant corrected speed curve on the flow characteristic map and the efficiency characteristic map of the component in the thermodynamic model, the intrinsic nonlinear shape correction other than the overall offset and rotation cannot be realized.

And therefore the effectiveness of these adaptation methods highly depend on shape similarity of characteristic maps. The stage-stacking technique has become a reliable method to generate compressor characteristic maps, which is based on mean-line one-dimensional flow continuity equations together with the generalized stage characteristic curves, seen fig.6.

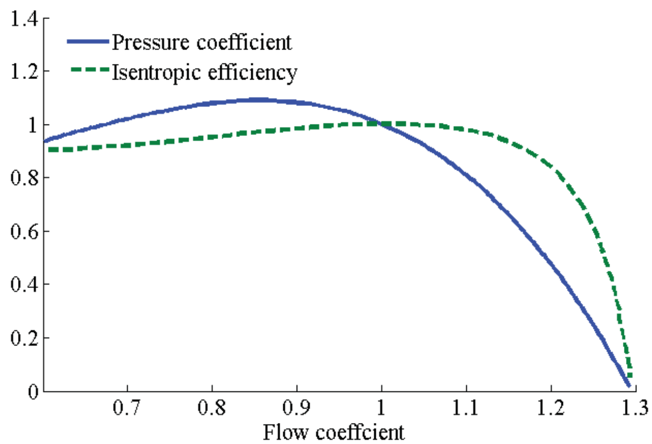
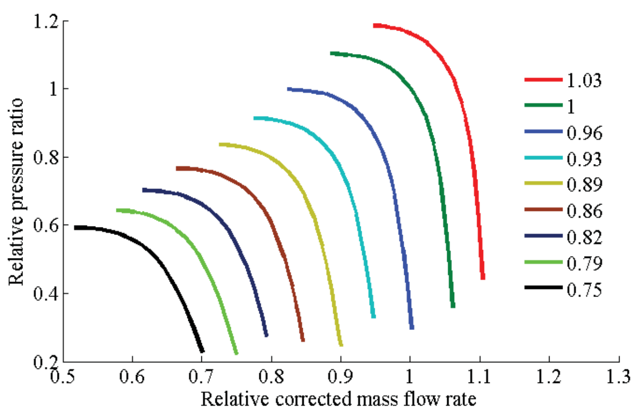
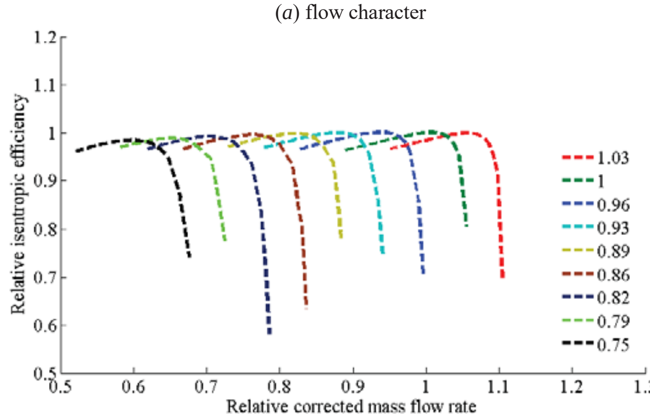


Fig.6 Compressor generalized stage map

And the compressor characteristic maps generated by the stage-stacking calculation is as shown in fig.7.



(*a*) flow character



(*b*) efficiency character

Fig.7 The compressor characteristic maps generated by the stage-stacking calculation

Since the geometric parameters of the blade stages of the real compressor are usually unknown to the user, and the different stage character of different types of stages (such as subsonic, transonic and supersonic stages) are neglected, this method has a certain degree of unavoidable error in thermodynamic modeling.

The inherent problems and diagnostic accuracy of solving the low reliability of the diagnosis caused by the linearization of the thermodynamic system have been greatly developed for the sensitivity of the sensor measurement noise and deviation, measurement parameter selection, control parameters and environmental conditions. However, the diagnostic process is always dependent on the assumption that when the degree of degradation or damage is small, due to its geometric structure of the component (such as compressor, combustion chamber, turbine, etc.) has not changed significantly, the characteristic map usually maintains the same shape as the original one. However, when the degree of degradation or damage become large, the actual component characteristic map may undergo an inherent nonlinear shape change. At this time, the error of the conventional gas path diagnosis result will inevitably expand with the actual degree of degradation or damage.

III. Urgent Problem of Gas Path Diagnosis

The above-mentioned gas path fault diagnosis method essentially uses known input and output parameters to obtain unknown internal state parameters by decoupling of the input-state-output strong nonlinear coupling relationship from the thermodynamic mechanism, and introduces reasonable component health evaluation parameters to achieve the purpose of gas path fault diagnosis and prognosis. The essence of its mathematics is to study the mathematical means of optimizing identification and time series regression of fuzzy data. After years of development, the gas path fault diagnosis method has obtained many theoretical achievements based on the engine steady-state/quasi-steady state operating condition. Nowadays, due to the wide application of variable geometry components and the advancement of bleeding-cooling technology, and that gas turbines are increasingly required to operate more flexibly in grid support modes (including frequent off-design changing conditions and transient loading or unloading operating modes), therefore, it is urgent to consider new theories and new methods of gas-path diagnosis and prognosis under transient off-design conditions.

From the analysis of research status of gas path fault diagnosis and prognosis based on thermodynamic model, it is known that there are still some urgent problem to be solved for such a highly nonlinear coupled thermodynamic system of gas turbines such as strong nonlinear coupled thermal systems, as follows.

i. At present, the gas path diagnosis method seldom consider the influence of frequent variable operating conditions, and is only applicable to the diagnosis of gas turbine at quasi-steady state conditions with fixed geometric components. Therefore, it is important to study an adaptive transient thermodynamic modeling method suitable for variable geometry components and transient operating conditions to improve the applicability and reliability of the gas path diagnosis method.

ii. The reliability of existing gas path diagnostic methods have certain requirements on the degree of component degradation or damage.

iii. The current gas path fault prognosis is mainly for the performance degradation trend prediction of the whole system, and the lack of detailed and quantitative performance health indicators of each major component brings inconvenience to the development of appropriate and reasonable optimization control and maintenance strategies. Therefore, it is urgent to study a multi-dimensional time series regression prediction method that integrates the diagnostic information of the main components.

iv. The mathematical essence of gas path diagnosis and prognosis is to solve the mathematical problem of optimizing identification and time series regression of fuzzy data. Some basic theories and methods of mechanism modeling, optimization identification and time series regression still need to be improved continuously, which determines many other research work of gas path fault diagnosis and prognosis needs to be carried out.

IV. DEVELOPMENT DIRECTION OF GAS PATH FAULT DIAGNOSIS TECHNOLOGY

Aiming at the urgent problems to be solved in the above-mentioned diagnosis method, a research route is proposed, including adaptive thermodynamic modeling method, optimization identification of component health parameters and gas path diagnosis based on model-data hybrid drive. The concrete methods involved include the stage-stacking calculation method for generating variable geometry component characteristic map, the regression method of the nonlinear shape of the component characteristic maps, the equivalent cooling flow thermodynamic modeling method based on the ISO2314 criterion, diagnostic method based on intrinsic nonlinear adaptation of the component characteristic map shape, and diagnostic method based on quadratic feature extraction.

A. Technical Route of Adaptive Transient Thermodynamic Modeling Method

1) Stage-stacking Method for Variable Geometry Component Characteristic Map

In terms of gas turbine thermodynamic modeling, the model accuracy depends mainly on the accuracy of its compressor characteristic maps. Due to the manufacturer's confidentiality, the user usually cannot obtain the component characteristic maps of the relevant gas turbine engine. Therefore, the stage-stacking method becomes a reliable and effective means for initially generating the characteristic maps of the compressor. The calculation process is based on a continuous flow equation at a one-dimensional average radius and a set of generalized stage map. This set of generalized stage map obtained from a large number of existing compressor stage (subsonic, transonic and supersonic stages) test data, and can be used to represent the stage characteristics of the target compressor [17].

Since gas turbines are typically regulated to operate in a transient partial load mode, the angle of the first or first few stages of the compressor's vanes are typically adjusted as the operating condition changes. For example, the inlet guide vane of the first stage of the compressor of AE94.2 gas turbine is adjustable, and the inlet guide vanes of the first two stages of the compressor of AE94.3A gas turbine are adjustable.

For a well-designed axial-flow compressor, under different operating conditions, through regulation (such as adjustment of the angle of the first or the first few adjustable vanes or inter-stage bleed-off), the attack angle of the airflow entering each blade is approximately equal. And then the flow coefficient of each stage and the absolute exit airflow angle of the vane theoretically satisfy the following equation.

$$d\left(\frac{1}{\phi}\right) = d(\tan \alpha_1) \tag{1}$$

where ϕ is the flow coefficient of stage; α_1 is the absolute exit airflow angle of the vane.

Generally, the relative exit airflow angle of the compressor blade and the stage efficiency are only a function of the attack angle of the airflow entering blades. And then the flow coefficient and the pressure coefficient satisfy the following relationship:

$$\frac{\psi}{\phi} = cons \tag{2}$$

The above two Equations (1) and (2) can be derived from the velocity triangle of the stage shown in fig.8.

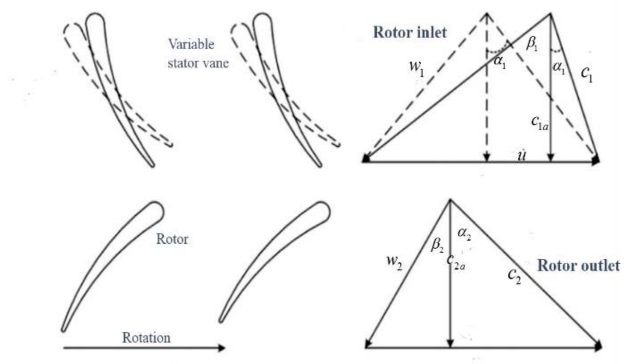


Fig.8 Compressor stage velocity triangle

The generalized stage map based on fixed geometry combined with the above two Equations (1) and (2) can be used for generating the characteristic maps of the variable geometry compressor. Moreover, the thermodynamic modeling of the inter-stage air extraction for turbine cooling and inter-stage bleed-off for compressor anti-surge can be easily considered by the stage-stacking calculation method.

2) Regression Method for Nonlinear Shape of Compressor and Turbine Characteristic Maps

The aim of constructing effective nonlinear shape regression function of compressor and turbine component characteristic maps (including flow character and efficiency character) is to accurately describe the nonlinear shape for their flow and efficiency characteristics. The closer the form of the regression function (such as the rotating elliptical fitting function, partial least squares fitting function (seen in fig.9) [16], etc.) is to the nonlinear shape of the characteristic maps of the component itself, and the lower the complexity of the regression function, the better the real-time performance and the more accurate the thermodynamic model can be guaranteed. It should also be emphasized that the constructed regression function needs to ensure excellent generalization performance (i.e., interpolation and extrapolation performance) in addition to the fitting accuracy of the component characteristic map itself.

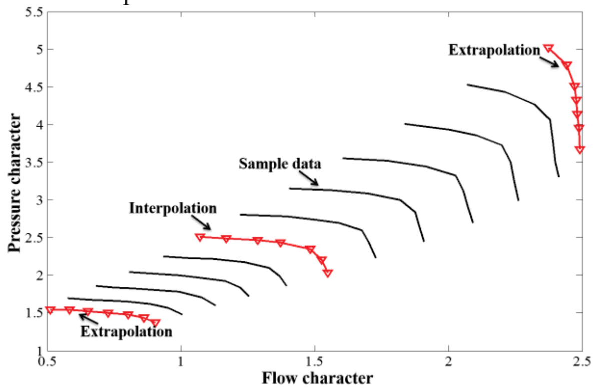


Fig.9 nonlinear shape regression for compressor characteristic map

3) Equivalent Cooling Flow Processing Method Based on ISO2314 Criterion

For heavy duty gas turbines, such as the AE94.3A heavy-duty gas turbine, the compressor has five inter-stage air extraction points for cooling turbine hot gas path, three of them are external flow paths from the outer cylinder, and two are internal flow paths extracted from the inner roulette. In addition, two airflow paths are taken from the compressor outlet to provide cooling air for the first stage of turbine vanes and blades.

Considering the actual air extraction cooling condition of the engine and taking into account the complexity of the thermodynamic model, the one-dimensional thermodynamic modeling method based on detailed flow design cannot meet the requirements of real-time calculation. Based on the ISO2314 criterion (the international standard for gas turbine acceptance testing), thermodynamic modeling is performed using the equivalent cooling flow processing method, as shown in fig.10 and fig.11, which not only simplifies the thermodynamic model, but also ensures real-time calculation performance. Moreover, the inter-stage air extraction and turbine inter-stage cooling conditions do not destroy the integrity of the compressor and turbine characteristics maps, facilitating subsequent gas path diagnostics.

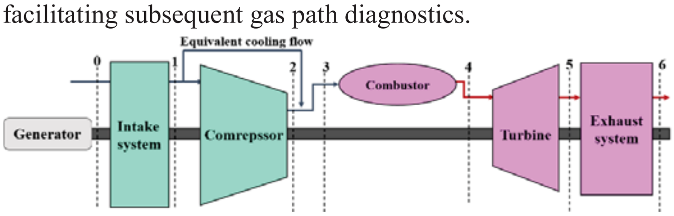


Fig.10 Equivalent cooling flow processing method based on ISO2314 criterion

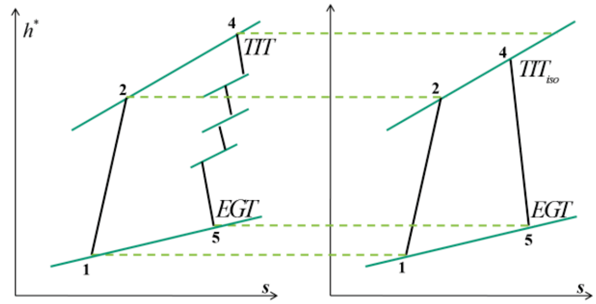


Fig.11 Equivalent cooling flow processing method based on ISO2314 criterion

However, the equivalent cooling flow processing method will lead to the "equivalent" meaning of the inlet and outlet gas path parameters of some components in the thermodynamic model, and no longer correspond to the measured parameters at the location of the sensor measuring point. This makes it difficult to adaptively correct the transient thermodynamic model and achieve component gas path diagnosis based on the measured gas path parameters of the target engine. Taking the equivalent cooling flow processing method shown in Figure 1 as an example, in order to make the inlet and outlet gas path parameters and the character of components themselves in the thermodynamic model correspond to the measured gas path parameters and the real component characteristics as much as possible, the simplified process of equivalent cooling flow can follow the following principles: *a*. The pressure, temperature, mass flow rate and working fluid composition of the cross section 1 and 2 at the inlet and outlet of the compressor are the same as the real situation; *b*. Compressor power consumption is the same as the real situation; *c*. The working fluid composition at the cross section 4 of the turbine inlet is the same as the exhaust gas at the cross section 5 of the turbine outlet; *d*. The pressure, temperature, mass flow rate and working fluid composition at the cross section 5 of the turbine outlet are the same as the real situation; *e*. The turbine power output is the same as the real situation.

According to the above equivalent cooling flow processing principle, the enthalpy entropy diagram shown in Figure 15 can be obtained (the process of 1-2 is the process of compressor power consumption; the process of 2-4 is the combustion process of the combustion chamber; the process of 4-5 is the process of turbine power output). At this time, the pressure, temperature, mass flow rate, and working fluid composition at the cross sections 0, 1, 2, 5, and 6 of the thermodynamic model are the same as the real situation. In addition, unlike the steady-state thermodynamic model, the transient thermodynamic model increases the first-order differential equations dominated by volume inertia, thermal inertia, and rotational inertia. And therefore the gas turbine transient thermodynamic model is represented by first-order differential equations and algebraic equations.

B. Technical Route of Gas Path Diagnosis Method Based on Intrinsic Nonlinear Adaptation of The Component Characteristic Map Shape

The gas path diagnosis involved in the paper is based on the inherent nonlinear variation of the shape of the component characteristic maps, seen in fig.12.

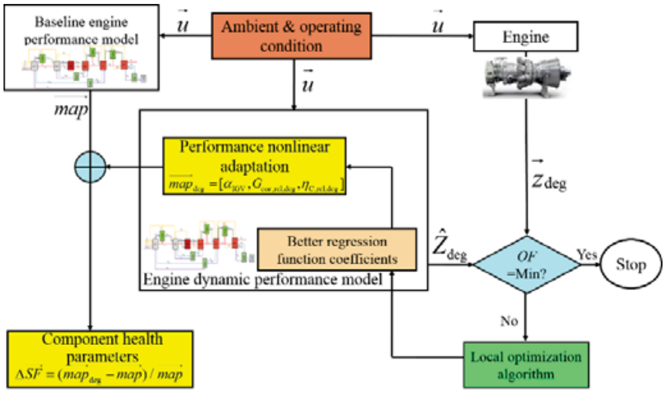


Fig.12 the gas-path diagnosis method based on the intrinsic nonlinear adaptation of the shape of the component characteristic maps

On the one hand, diagnostic algorithm is required to ensure reliability and accuracy over a wide range of component degradation or damage. The coefficients of the fitting functions of each component characteristic map is adaptively corrected by the appropriate local optimization algorithm by using the measured gas path parameters of the engine, matching the component characteristics of the thermodynamic model to the component characteristics of the actual target engine, to diagnose the health parameters of the main components of the target engine.

On the other hand, the diagnostic algorithm is required to dynamically output the component health parameters in real time as the engine operates in frequent off-design changing conditions and transient loading or unloading operating modes. It requires that the optimal identification of component health parameters requires the selection of a reasonable local optimization algorithm to ensure real-time diagnostics. The reasonable selection of the local optimization algorithm is especially important for the real-time performance and accuracy of diagnosis. It is necessary to comprehensively consider the number of coefficients of component characteristic map regression functions, the number of operating points of the engine required for each iteration, and the complexity of the diagnostic driving algorithm itself. Therefore, to propose a high-efficiency and reliable gas path diagnosis method is the research difficulty in this part, and it is also one of the key problems to be solved in the future [18,19].

V. CONCLUSIONS

This paper expounds the connotation of gas turbine engine gas path fault diagnosis, analyzes the research status, and summarizes the urgent problems of to be solved for such a highly nonlinear coupled thermodynamic system of gas turbine. Aiming at the basic problems of gas path fault diagnosis, the research route is proposed. Firstly, the adaptive thermodynamic modeling method with variable geometry component is proposed; secondly, the gas-path diagnosis method based on the intrinsic nonlinear adaptation of the shape of the component characteristic maps is proposed using the measurable gas-path parameters, to obtain the health parameters of each main component in real time. From the aerodynamic and thermodynamic mechanisms, the effective coupling of the gas turbine performance analysis and diagnosis based on the intrinsic nonlinear adaptation of the component characteristic map shape is achieved, which provides new theories and methods in the field of fault diagnosis for complex and strong nonlinear thermodynamic systems; In terms of function, it realizes detailed, quantitative and accurate gas path fault diagnosis purposes for each major component, and provides theoretical guidance for formulating appropriate and reasonable optimization control and maintenance strategies. It plays an important theoretical and practical value for the reform of the maintenance concept that promotes the transition from preventive maintenance to predictive maintenance.

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