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Fast Response Wall Pressure Measurement as a Means of Gas Turbine Blade Fault Identification

The distortions of the pressure field around rotating blades of turbomachinery components due to alterations of their shape can be utilized for the identification of faults related to the blading. Measurement of the unsteady pressure field near the wall provides information on such flow and pressure distortions and can thus be used for diagnostic purposes. An experimental investigation of the compressor rotating blade pressure field of an industrial gas turbine has been undertaken, in order to demonstrate the feasibility of the abovementioned principle. Various realistic gas turbine blade faults have been examined. Application of the appropriate processing techniques demonstrates that unsteady pressure measurements can be used to identify the occurrence of minor blade faults (not traceable by standard techniques) as well as the kind of fault. The proposed methodology has the potential for being incorporated in a computerized engine health monitoring system.

1 Introduction

Methods for detecting the presence of faults in gas turbine components have received considerable attention recently. The diagnosis is achieved by measuring various physical quantities, appropriately processing the collected data and finally interpreting the reduced information. According to the kinds of measurements employed, different components and various categories of faults can be monitored. For example, aerothermodynamic measurements can be used to deduce the condition of the gas path components, while mechanical damages can be detected by vibration analysis (e.g., Mathioudakis et al., 1989a).

Most of the existing diagnostic techniques have the capability of identifying the component where a major fault is located. The reason for such fault identification is that the measured quantities, whether they are mean thermodynamic values or structural vibrations may not undergo a significant variation, unless the fault is of sufficient magnitude to produce visible changes in them, as for example discussed by Baines (1987). Such measurements will indicate the presence of severely damaged blades, while a minor shape modification of a few blades will not be felt. It is desirable, however, for a demanding engine monitoring system to be capable of identifying faults of small extent, in order to predict a later significant degradation or to locate failures that can grow very rapidly to catastrophic extent. A situation of one slightly bent or twisted blade, for example, which in itself might not significantly influence engine operation, can have catastrophic consequences if it results in a blade loss.

A method of diagnosing such minor faults on rotating turbomachinery blades is proposed in the present paper. The features of unsteady pressure signals related to rotating blades are utilized in order to extract diagnostic information about the blade condition. Such faults occupy the majority of steam turbine damages, as reported by Kaspar (1982) and Simmons and Smalley (1990). Methods applying the same principle have been discussed in the past by Barschdorf and Korthauer (1987), Barschdorf (1986), and Valero and Esquiza, (1988). Although several cases of turbomachines have been examined in the above references, they were mainly related to test models and no application to field gas turbines was reported. On the other hand, the main emphasis was concentrated on pattern recognition methods, but aspects related to operating conditions have not been mentioned.

The work presented here is based on experiments performed on a commercial gas turbine, functioning in conditions usually encountered in field operation. The feasibility of the employed procedure is demonstrated and the dependence on operating conditions is discussed. A feature of the proposed methodology is that it provides information that can be easily interpreted by expert systems used for condition monitoring.

2 Background

The time variation of pressure at a fixed location facing a blade row at the interior of a turbomachine casing is caused by the rotation of the blade-to-blade pressure field. The pressure field between blades of a turbomachinery cascade is determined by the geometry of the cascade and the operating conditions, namely, the flow conditions at cascade inlet and outlet.

Blade faults result in the distortion of the cascade geometry

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and consequently will generate nonuniformities in the blade-to-blade pressure fields. For example, bending or twisting a blade results in destroying the periodicity of the pressure field between the blades. Blade erosion, corrosion, or fouling result in the alteration of the airfoil shape and consequently of the blade-to-blade pressure field. For all these blade fault categories, the resulting pressure field is directly related to geometric distortions. It is implied that knowledge of the initial intact, and the later distorted, pressure fields can lead to the identification of geometry alterations and finally to the blade faults. Also, the variation of the operating conditions of a compressor blade row corresponds to a change of the incidence angle of the blade airfoil, which affects the pressure distribution along the blade. These changes of the blade pressure field reflect upon the fluctuating pressure. The change of operating point might therefore influence the fluctuating pressure and, in such a case, this effect should be separated from the effect of blade faults.

In order to verify the abovementioned principles and demonstrates their practical implication, an experimental investigation of situations with different blade faults was undertaken. The tests that were performed and the corresponding experimental conditions are now described.

3 Experimental Investigation of Engine Faults

The Ruston Tornado Gas Turbine, described by Wood (1981) and Charchedi and Wood (1982), was the engine used as the test vehicle. Fast-response pressure transducers were flush mounted at the compressor inner casing wall. They were Kulite XST-190-25 SG type. The positioning and coding of the sensors on the compressor casing is schematically shown in Fig. 1. Data were acquired through a data acquisition system manufactured by LMS, with a total capacity of 32 channels and maximum total sampling frequency of 960 kHz. A key phasor signal and bearing proximity probe signals from the engine bearings were acquired simultaneously with unsteady pressure inside the compressor. All the data discussed in this paper have been acquired with a sampling frequency of 32 kHz and were low pass filtered at 16 kHz. Aerothermodynamic performance data were acquired by means of a data logging system described by Timperley and Smith (1983). Performance data provide information about operating conditions and cycle parameters for each operating point. In all the tests, data were collected at four operating points, hereafter designated as points A, B, C, and D, corresponding to nominal speed and full, 3/4, 1/2, and 1/4 load, respectively.

A number of blades of the compressor of the test engine were modified, in order to produce faults. Tests were conducted at four different configurations, which are now described:

Test 1: Datum test; this test provided the baseline data for all the subsequent tests with implanted faults. The compressor blading was in intact condition.

Test 2: Rotor fouling test; in order to examine the possibility of identifying fouling of an individual rotor, the stage 2 rotor of the compressor was coated with a textured paint. The paint layer roughens the blade surfaces and causes a slight alteration of their contour, thus simulating fouling of this rotor.

Test 3: Individual rotor blade fouling; the purpose of this test was to examine the possibility of identifying alteration in individual blades. Two blades of stage 1 rotor were painted with textured paint. The two painted blades are separated by five intact blades, as shown in Fig. 2(*a*). The painting of blades is expected to alter the aerodynamic pressure field around them due to two reasons: (*i*) alteration of the blade surface roughness: The surfaces of the painted blades are rougher than the intact ones; (*ii*) the layer of paint on the blade surface gives a slight modification of blade thickness. This results in a corresponding modification of blade shape, which in turn results in distorting the pressure field around the blade.

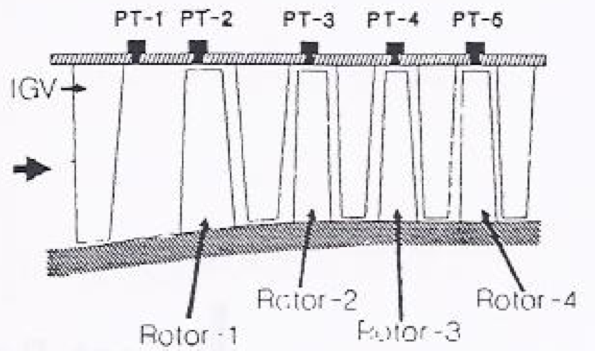

Fig. 1 Compressor layout and positioning of fast-response pressure transducers

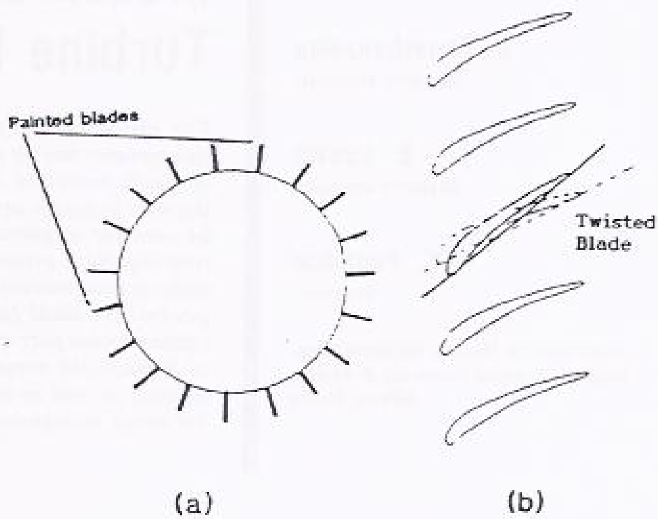

Fig. 2 Position of painted blades and schematic of twisted blade of stage 1 rotor

Test 4: Individual twisted blade; the purpose of this test was also to examine the possibility of locating alterations in individual rotor blades. This second kind of rotating blade alteration (the first being TEST-3) is also useful in determining whether the type of blade alteration can be identified, namely whether different rotating individual blade faults can be distinguished from each other. In our case it was desired to investigate whether painted blades (fouled) can be distinguished from twisted ones. A single blade of rotor 1 was twisted, as shown schematically in Fig. 2(*b*). The twisting of the blade tip was achieved by using a tool especially manufactured for this purpose. The magnitude of the twist angle was estimated to be approximately 8 degs. The change of blade stagger will result in a corresponding variation of incidence angle. Changes in incidence will result in changes of the blade pressure field, which are expected to be detectable by appropriate data capture.

The results obtained from the experimental study are now presented.

4 Measurement Results for Healthy and Faulty Operation

A series of tests were conducted with the engine operating at point A as described in section 3. Signals from pressure transducers installed in the inner surface of the compressor casing are shown in Fig. 3 and 4. The signals represent approximately one and a half periods of rotation and the sig-

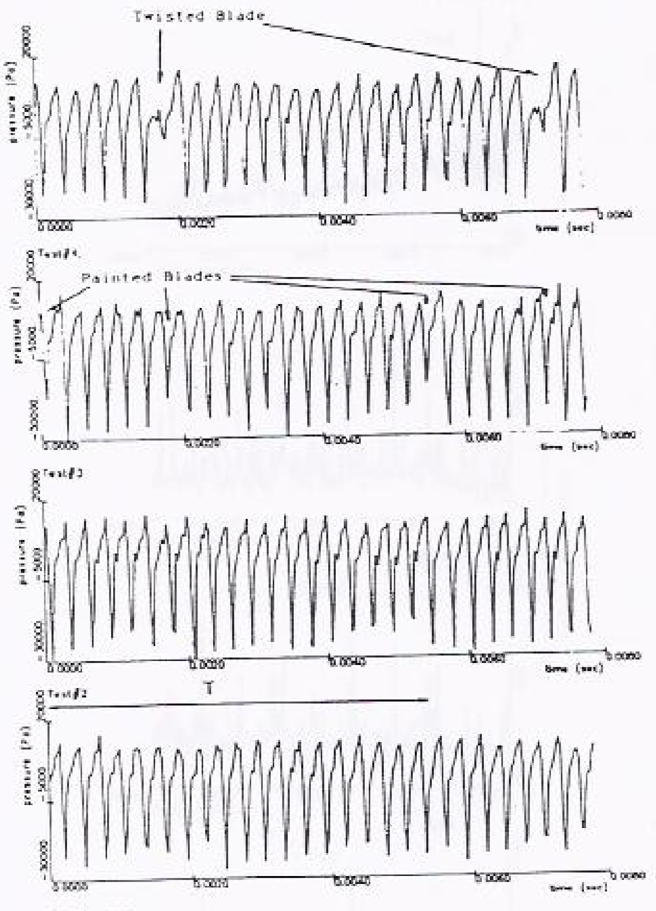

Fig. 3 Pressure traces from pressure transducer 2 for the different tests

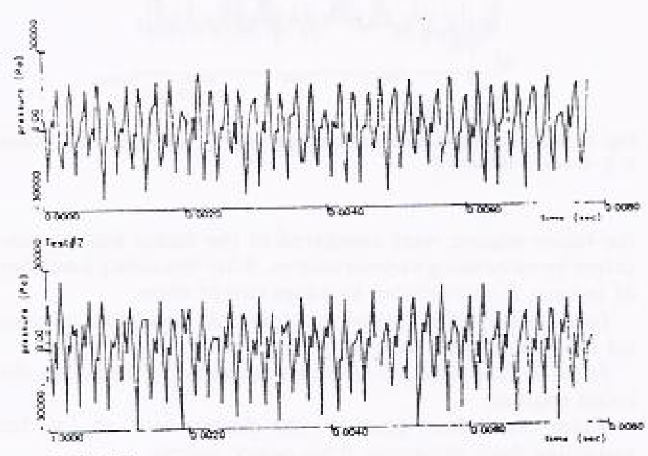

Fig. 4 Pressure traces from pressure transducer 3 for tests 1 and 2

natures of the individual blade passages are repeated. The existence of noise is evident and can be attributed to flow nonuniformities and rotational unsteadiness. In Fig. 3, the time traces from the pressure transducer PT-2 facing stage 1 rotor are displayed. For the fault of test 2, which is located on rotor stage 2, it can be seen that no obvious variation of the peaks can be deduced, with respect to the baseline. For the fault of test 3, where two blades on rotor stage 1 are fouled, a clear difference from baseline is observed, as shown by the arrows. Finally for the fault of test 4 the trace of the twisted blade is clearly distinguishable from the intact blades.

Time traces of the pressure transducer PT-3 facing stage 2 rotor for the cases of test 2 and the "healthy" engine are shown in Fig. 4. The introduction of fouling produces a reduction of the trace amplitude for the case of the fouled stage 2 rotor and distinct variation of the peak form per period. The time traces for test 3 and test 4 have also been examined and found by visual inspection almost identical to the intact engine ones. Information about the faults of stage 1 rotor is not obvious from such traces, because the flow recovers after passing through the stator cascade before entering the second rotor.

The raw signals contain the influence of the periodic components as well as of the random noise, which results in ambiguities in the interpretation, especially for the case of the painted blades. In order to remove this influence we apply phase averaging on the signals. The technique of phase averaging takes into account the variation of the period of rotation, and also gives the possibility to determine the location of the faulty blades, by using the key phasor signal as a reference. When the same key phasor is used for all cases, healthy and faulty, the circumferential position of a faulty blade is immediately determined. The phase-averaged signal from pressure transducer 2, facing rotor 1, for one twisted blade, is shown in Fig. 5(*a*). Comparison to the corresponding raw signal (Fig. 3) shows a more uniform distribution of peaks and valleys corresponding to blade passages, while the passage corresponding to the twisted blade is clearly identified. The same picture for the case of the two painted blades is shown in Fig. 5(*b*). For this case we see that the existence and location of the two painted blades is defined without ambiguity, which is not always true for the raw signal. On the raw signal (Fig. 3), the random influence might result in the ambiguity of the location of the painted blades, since some valleys corresponding to healthy blades look similar to the ones corresponding to the painted blades.

In order to reveal the harmonic content of the time signals, the power spectra have been calculated. Although the spectra extend to a frequency range of up to 16 kHz, the limitations in the frequency response of about 12 kHz of the transducers should be taken into account. A general feature of these spectra is that they consist of a broad-band component upon which pure tones are imposed at various multiples of the shaft rotational speed and predominant harmonics corresponding to the blade passing frequency of each stage.

The power spectra of the pressure transducer signals of the sensors facing stage 1 and stage 2 rotors are depicted in Figs. 6(*a*) and 6(*b*), respectively. When the pressure transducer PT-2 is examined, one notices a visible variation in the spectrum form, which makes evident the fault existence, for the cases of faults in tests 3 and 4. This variation appears mainly as an increase of the shaft rotational harmonics in the regions between the blade passing frequency of the first rotor. Almost no variation is observed for the fault at test 2. Also, an increase level of power can be observed in the entire broadband, which is caused by the implanted deficiencies. This variation makes the spectra from faulty engines clearly distinct from the datum baseline. The spectrum from PT-3 facing rotor stage 2 shows also a differentiation when the fouled staged 2 rotor is examined, but no visual differentiation can be revealed when the faults of tests 3 and 4 are present.

The power spectrum of pressure transducers PT1, PT3, PT4, and PT5 for test 4 are shown in Fig. 7, in order to indicate how the spectrum of measurements at different stages is influenced by the presence of a fault on rotor 1. The harmonic envelope in the spectrum of PT1 has developed when the fault was implanted. On the other hand, the spectra of PT3, PT4, and PT5 exhibit no visual change by the implantation of the fault on rotor 1. This indicates that the nonuniformity produced by the fault decays as it travels downstream through the compressor stages.

Further analysis has been applied upon the spectra by com-

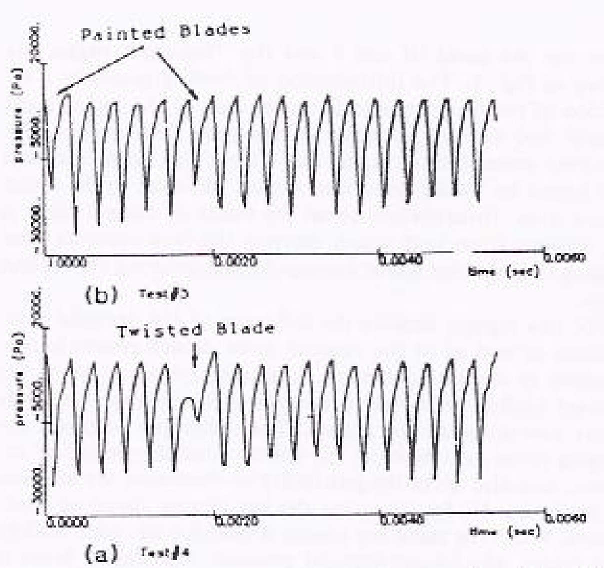

Fig. 5 Phase-averaged pressure traces from pressure transducer 2, for tests 3 and 4

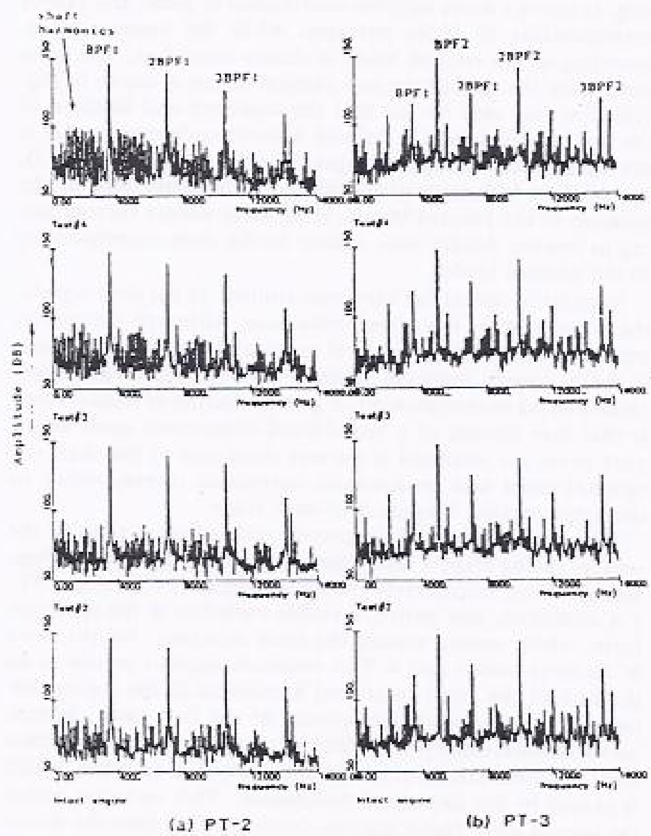

Fig. 6 Power spectra of pressure measured by pressure transducer 2 and 3 for the different tests

paring the amplitude at each frequency, and it is discussed in a later section.

5 Fault Indices

The power spectra from the pressure transducers were further processed in order to provide more information about differences arising from implanted faults. The algebraic manipulations to compare spectra from the "faulty" machines with the "healthy" one are now described.

The amplitudes of the power spectra at each frequency for

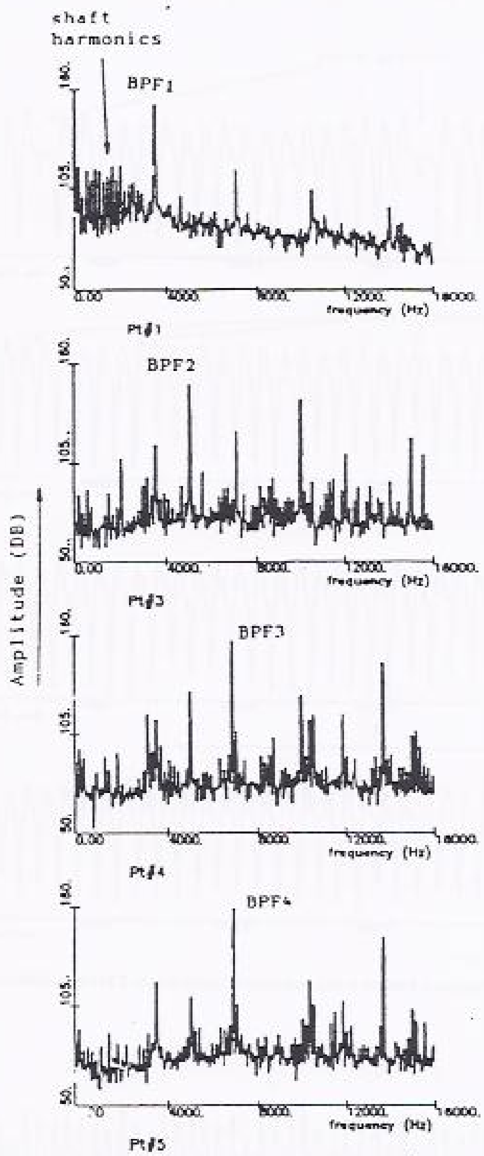

Fig. 7 Power spectra of pressure measured by pressure transducers 1, 3, 4, and 5 for test 4

the faulty engines were compared to the datum healthy machines by calculating various indices. After inspecting a number of indices, it was decided to adopt two of them:

Index 1: The difference of the amplitude logarithms of spectra from intact and faulty engines.

Index 2: The ratio of spectra amplitudes of faulty to the intact engines.

These two indices provided the clearest way, so far, for extracting fault signatures from power spectra.

Index 1 was applied to the output spectra from transducer PT-2 for engine tests 2, 3, and 4 at operating point A, and an example of results is shown in Fig. 8(*a*). Test 1 provided the results for the intact engine. When the fault of test 2 is examined, a variation on the entire broadband level can be seen, while an increase for tones without a specific pattern exists. Examining the fault of test 3, an increase in the overall power level can be noticed with an increase at the harmonic peaks at multiples of the shaft rotational harmonics. The signature of fault of test 4 becomes clear when the corresponding Index 1 is examined. A considerable increase in the shaft passing harmonics over the entire frequency range can be seen. Index 2 was also applied for all fault cases on signals from transducer PT-2 and the results are shown in Fig. 8(*b*). An increase in the

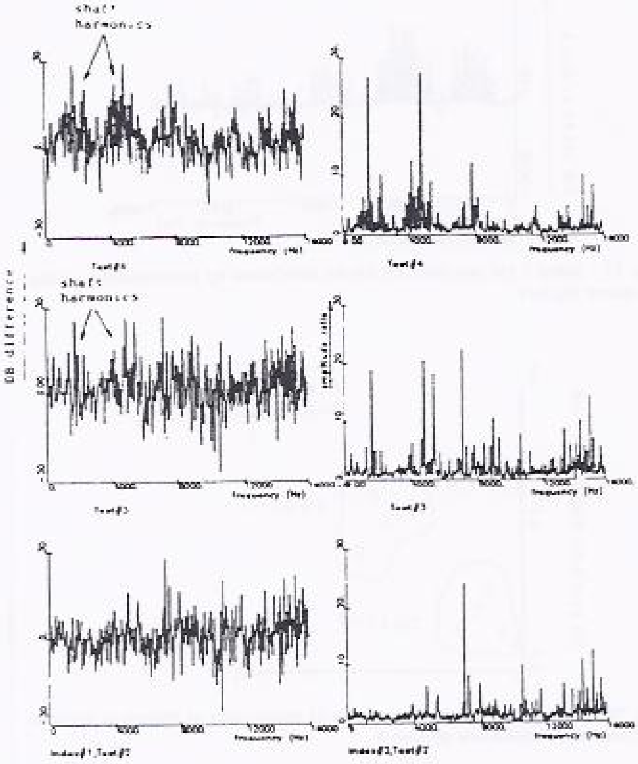

Fig. 8 Spectral comparison indices for pressure transducer 2 data: (*a*) Index 1; (*b*) Index 2

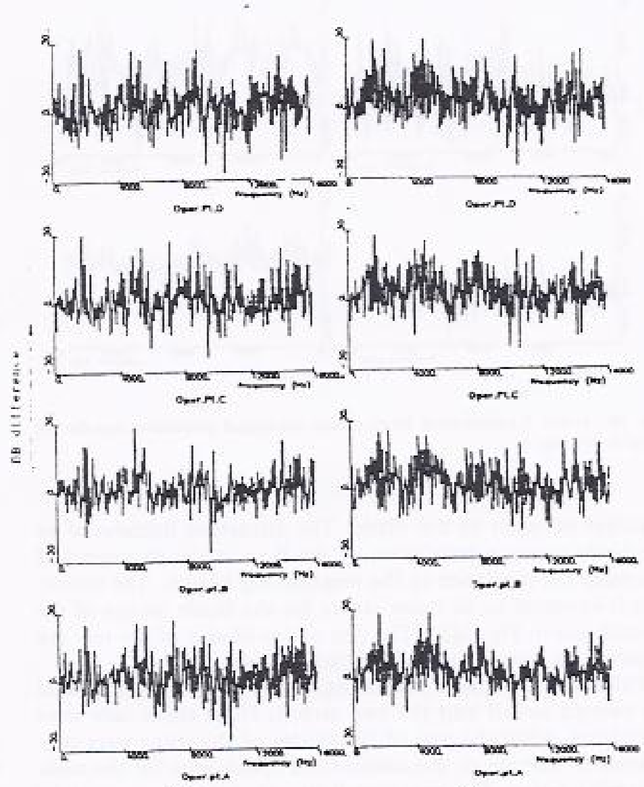

Fig. 9 Index 1 for different operating conditions: (*a*) tests 3; (*b*) test 4

broadband level for all the faults is seen. Inspection of either one of the indices shows that the signature of every fault is distinguished from the other two.

Similar analysis was performed upon the spectra from transducer PT-3 for all the cases of implanted faults, but the results are not presented here due to space limitations. When the indices were applied, there was a slight variation in the overall broadband level, and the defective stages corresponding blade passing frequency peaks. Most differentiation was observed for the fault of rotor stage 2, which faces PT-3. As a partial conclusion it can be stated that the comparison indices are very useful to identify a fault signature, but this signature becomes less traceable when the sensor is located downstream of the faulty stage.

In order to examine the dependence on operating conditions, for the faults of tests 3 and 4, Index 1 was applied to the power spectra of pressure transducer PT-2, when the machine is operating at points A, B, C, and D. This kind of variation of operating conditions is typical in power generation applications, where rotational speed remains unchanged and the output load varies. Figure 9 displays the application of Index 1 at the power spectra for faults of tests 3 and 4, respectively. It is seen that the influence of load upon the form of Index 1 is insignificant. The general qualitative form of the fault signatures is preserved regardless of load variations for both fault cases. The form is therefore preserved, even though the overall spectral energy varies with operating point, which was demonstrated by Mathioudakis et al. (1990). These observations indicate that the examined indices combined with selected spectra from sensors adjacent to faulty stages can provide a useful diagnostic tool.

Since phase averaging preserves the signal features, which are repeatable at the averaging period, it was thought that its application prior to power spectra calculation might enhance spectra and signatures, as long as periodic components are concerned. Employing such spectra for the calculation of Index 1 gives the result of Fig. 10, where a comparison to the corresponding index from raw data is presented. The indices from pressure transducer 2 for tests 3 and 4 are examined. It is noticed here that in the low-frequency range (up to two times the blade passing frequency of rotor stage 1) the index is significantly enhanced by predominance of information on harmonics, giving thus a picture of the envelope of the harmonics. On the other hand, at higher frequencies new information is added. This information should be examined very carefully, however, since the introduction of pseudo-periodic components is possible by the phase averaging, when the Nyquist frequency is approached.

6 Simulation of Blade Fault Signatures

The modification of the pressure field caused by the presence of a distorted blade in a rotating blade row can be calculated by means of flow analysis programs. Calculation of the pressure field for both the intact and the faulty blade row provides the possibility of reproducing pressure signals, which can then be processed in the same manner as the measured pressure signals discussed so far. The advantage of applying such a procedure is that signatures can be derived by analytical means and therefore the identification of faults can be done by comparison to these signatures, thus eliminating the need for performing tests and producing reference signatures for various blade faults. On the other hand, since the signatures are produced by calculation, such signatures can be derived for any other engine of known geometry, without the need for performing tests every time a different engine is considered.

The possibility of producing signatures by analytical means has been examined for one test case examined in this paper. The case of one twisted compressor rotor blade has been considered. The pressure field produced by the presence of one twisted blade in the stage 1 rotor was calculated by considering the following reasoning: Twisting of one blade, as shown in Fig. 2, causes a modification of the flow at the two blade

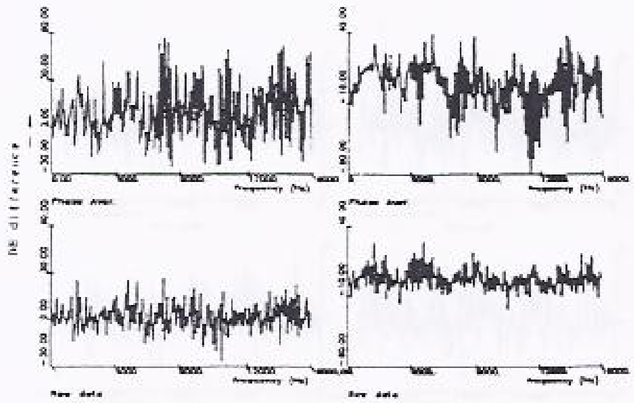

Fig. 10 Index 1 calculated from phase-averaged pressure signals: (*a*) tests 3; (*b*) test 4

passages adjacent to the blade. The distortion introduced by the blade causes a restriction of the flow in the passages and increases the incidence to the neighboring blades. The restriction is expected to be more severe for the blade on top of the twisted one in Fig. 2(*b*). The rest of the blades of the row are expected to operate at undistorted condition.

Following the above reasoning, the pressure fields around the twisted airfoil and the two airfoils from either side were calculated, while the rest of the blades of the rotor were considered to operate at the undistorted conditions for the same operating point. The pressure field calculation was done by very simple means, namely a singularity method (Wilkinson, 1967). By concatenating the calculated pressure fields, a pressure signal was produced, corresponding to the pressure signal of pressure transducer 2 in test 4. Similarly, a pressure signal was produced for the healthy rotor. The power spectrum calculation and application of Index 1 gave the signature of Fig. 11. The similarity to the corresponding measured signature, Fig. 8, is very good.

The accuracy of reproducing signature in this way depends on the sophistication of the flow analysis methods employed. It is remarkable that in the present case, a very simple flow analysis method was employed.

7 Signature Similarity Discriminants

It has been shown in the previous sections that the signatures of each fault are distinguishable and do not vary with engine load. This statement was based upon visual inspection of the corresponding figures. The similarity features observed on these figures can be mathematically formulated, in order to give objective criteria for comparison of the signatures. An example of application of such a procedure is described in this section.

A quantitative estimation of the similarity of two waveforms is known to be their cross-correlation coefficient (for definition, see for example Bendat and Piersol, 1971). If the indices are considered to constitute waveforms, their relative similarity can be expressed by such a coefficient. If certain signatures of a fault are considered as a reference, calculation of this coefficient for any signature derived from measurement data should give a value that would be indicative of their similarity to the particular fault signature.

This idea was applied to the fault indices calculated from the data of the present experiment. A reference signature was produced for the twisted blade fault. This signature was derived by averaging the values of Index 1 for each frequency over the four operating points of the engine. Index 1 was then calculated for every individual experiment and the correlation coefficient to that signature was calculated. The frequency range up to the second harmonic of the first rotor blade passing was considered. The results of the calculation are shown in Fig. 12, where each letter represents the corresponding operating point. It is observed from this figure that data from test 4, namely one twisted blade, all give values very close to unity, indicating thus that the signatures are similar to the reference one. The values are much smaller for data from test 3, showing that these signatures are not similar to the reference and therefore, a different fault is present. Data from test 2 give even smaller values, indicating that the fault is not related to the reference one and yet different from fault 3. Similar conclusions have been reached by using as a reference the other two fault indices.

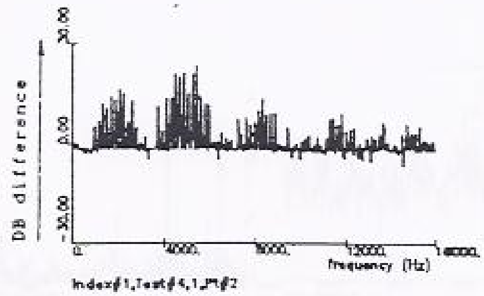

Fig. 11 Index 1 for one twisted blade, produced by computation of the pressure signals

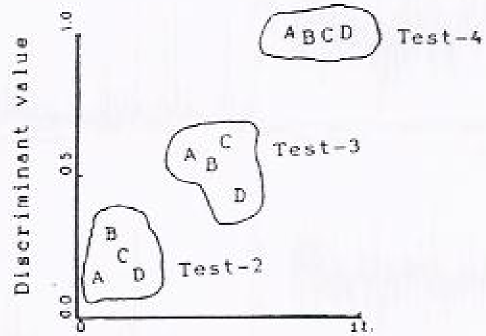

Fig. 12 Discriminant for comparison of signatures of different tests to the reference signature of test 4

The above analysis shows that it is possible to decide whether a set of data can be classified as belonging to a particular class of faults, by simply observing the value of a single quantity, which can thus be used as a discriminant for fault classification. This choice of appropriate data organization and the derivation of several such discriminants is the subject of an investigation currently in progress by the authors.

8 Discussion

The analysis presented in the above sections has demonstrated the feasibility of detecting faults on rotating blades of gas turbine components. The particular feature of our investigation is that the experiments were performed on a commercial gas turbine operating under conditions that are the same as operating conditions in the field.

The faults that are detectable by the described procedure are of very small magnitude and cannot be detected by condition monitoring methods employing thermodynamic measurements. The deviations in performance caused by such faults are not of a magnitude sufficient to produce deviations in measured thermodynamic quantities. In this respect, the present method is complementary to performance condition monitoring, providing the capability of detecting the exact location and the kind of blade faults (in contrast to grossly detecting the component suffering from faults or deterioration). On the other hand, the variation in mechanical characteristics of the engine shaft is also minor, and conventional monitoring systems (see for example Baines et al., 1987) cannot reveal the existence of those faults. This has also been experimentally verified during the present experiments. Shaft displacement signals acquired simultaneously with the pressure transducer signals gave no distinguishable signatures when the examined faults were implanted, as discussed by Mathioudakis et al. (1989b).

It was also demonstrated that discriminants can be derived from spectra and spectral indices. These discriminants are single numbers whose value can be used for identifying the kind of existing blade fault. The decision on the kind of fault is thus straightforward and can easily be performed by a computer program. This feature makes the procedure particularly suitable for incorporation into an expert system. From this point of view it meets current requirements of monitoring techniques, which aim to automate the procedure and eliminate the need of specialized personnel for interpreting the results of the measurements.

Finally, it should be mentioned that fast-response pressure transducer measurements, as the one reported here, can also be used for identification of another kind of operational malfunction, namely rotating stall in a compressor, which can lead to mechanical damage, as reported by Simmons and Smalley (1990). This possibility can be deduced from measurement results reported by Mathioudakis and Breugelmans (1988), as well as results from other investigations of this phenomenon. The occurrence of rotating stall is accompanied by the appearance of distinct waveforms in the measured pressure, corresponding to a rotational speed that is a fraction of the shaft rotational speed (namely the speed of rotation of stall cells).

9 Conclusions

A method for identification of rotating turbomachinery blade faults by measuring unsteady pressure at the inner casing surface has been presented. A commercial gas turbine was used as a test vehicle, and tests with different implanted blade faults were performed.

It was demonstrated that by calculating power spectra and subsequently producing spectral comparison indices, the kind of blade fault can be identified. The behavior of these indices was investigated and it was concluded that:

- The signatures are different for different blade faults.
- The signatures do not depend on the operating point, at least as long as the rotational speed remains the same.

Signatures for one of the experimentally tested faults were also produced by a simple computational procedure and they were found in very good agreement with the measured ones.

Finally, it was demonstrated that single-valued discriminants can be produced from the spectral indices, thus giving the possibility of introducing simple criteria for fault identification. This feature of the described procedure makes it suitable for inclusion in an expert system for fault diagnosis.

Acknowledgments

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