BLADE FAULT RECOGNITION BASED ON SIGNAL PROCESSING AND ADAPTIVE FLUID DYNAMIC MODELLING

A. Stamatis, Research Associate
N. Aretakis, Research Assistant
K. Mathioudakis, Assistant Professor

Laboratory of Thermal Turbomachines
National Technical University of Athens

Techniques for the Identification of Faults of Blades in Gas Turbines

Interest in Blade Faults: They account for a substantial percentage of gas turbine failures.

The usual procedure by existing techniques:

-Signatures are derived by processing measurement data and reducing them to a form appropriate for fault identification.

-Personal judgement or artificial intelligence techniques are used in order to take a decision about the presence of a fault, once a signature is available.

THE PRESENT WORK

An approach for identification of faults in blades of a gas turbine, based on physical modelling is presented.

A measured quantity is used as an input and the deformed blading configuration is produced as an output.

-This is achieved without explicitly using a "signature".

A fluid dynamic model is used in a manner similar to what is known as "inverse design methods":

- A signal of the pressure variation on the blade-to-blade plane, is measured. Blade cascade geometry that has produced this signal is then determined by the method.

Several test cases are presented including theoretically produced faults and experimental cases.

BLADE FAULT RECOGNITION BASED ON SIGNAL PROCESSING AND ADAPTIVE FLUID DYNAMIC MODELLING

Interrelation of Cause and Effect: Fault Identification.

Adaptive Fluid Dynamic Modeling and Geometry Alteration Identification.

Establishing Signatures for One-To-One Correspondence.

- **-Disadvantages of Spectral Fault Signatures.**
- **-Introduction of new Fault Parameters.**

Application test cases, experimental data.

Discussion, Conclusions.

INTERRELATION OF CAUSE AND EFFECT:
Fault Identification

For diagnosing a machine condition a correspondence to the values of the measured quantities should be known.

This correspondence is established through the physical laws governing the operation of the machine.

In the case of turbomachines, the variation of the flow quantities is determined, via the laws of fluid mechanics, from the geometry of the solid boundaries and the physical properties of the fluid.

-A change in geometry will then reflect on the values of the flow quantities.

-Suitable measured quantities can be used to indicate the presence of a fault.

-If the possibility to calculate the flow field for the different geometries exists, then the change in the measurement quantities can be evaluated. Then, its signature is obtained by calculation. In this way, a library of signatures can be build.

-When an experimental signature becomes available, the corresponding fault can be recognized by comparison to the signatures of this library (‘Direct’ Approach).

The method we introduce here achieves a solution to the ‘inverse’ problem of the previous one: geometry changes are calculated from the changes in fluid dynamic quantities.

Adaptive Fluid Dynamic Modelling and Geometry Alteration Identification

Fault Symptom (Signature) Modelling.

1. Geometry Vector Definition:

$$g = [g_1 , \ldots , g_L]$$

2. Pressure Signal Calculation. (F_f : Simulator)

$$S_c = F_f (g)$$

3. Fault Parameter Vector Calculation (D: Processing Operator)

$$d_c = D(S_c) = D(F_f(g))$$

INVERSE APPROACH

The Problem is to obtain the geometry g which has produced a measured fault parameter d_m.

Step 1: Condition identity vector f definition with elements.

$$f_i = \frac{g_i}{g_{i,o}}$$

where:

$g_{i,0}$: geometry parameter of Blade i in its initial healthy condition.

g_i: geometry parameter of Blade i in unknown condition.

Step 2: Application of direct simulation approach to g.

$$d_c = D(F_f(g))$$

Step 3: Error Estimation

$$e = d_c - d_m = D(F_f(g)) - d_m$$

Step 4: Solution of the non-linear equations:

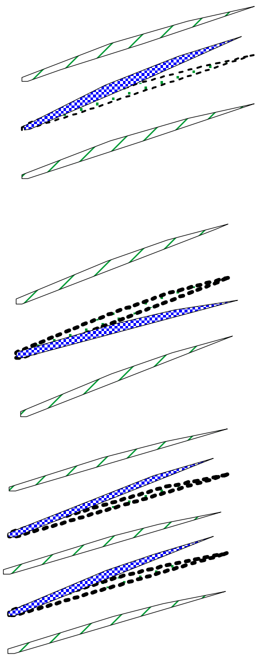
$$e(f)=0 \textbf{ or } \|e(f)\| = \min$$

Newton-Rampson procedure is applied, based in the following updating scheme:

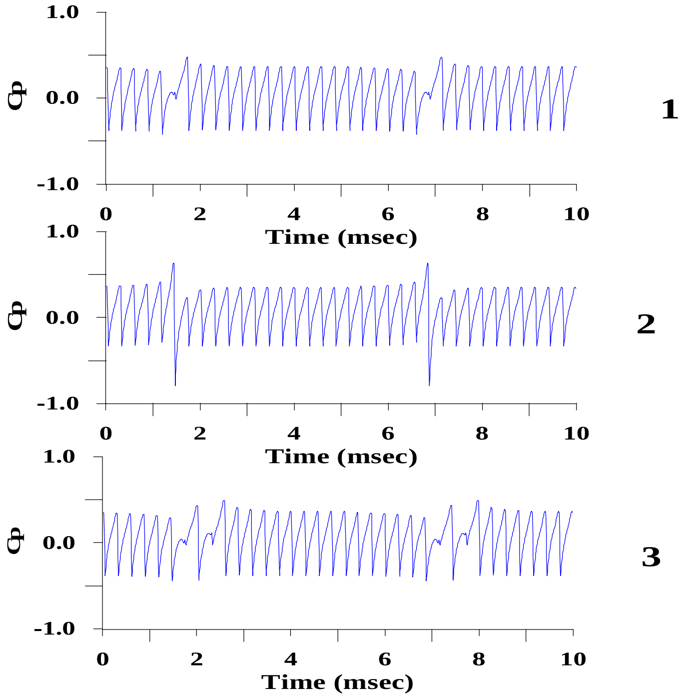
$$f^{n+1} = f^n + J^{-1} e^n$$

Establishing Signatures for One-To-One Correspondence

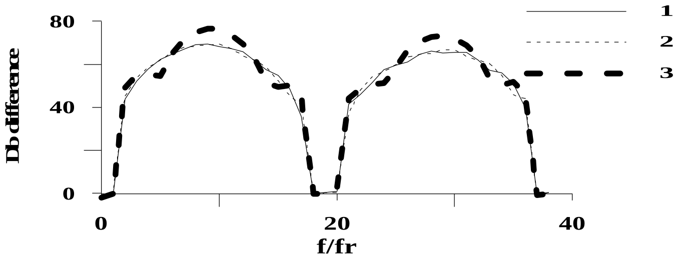
Spectral Fault Signatures: Inadequacies.



Blade Faults



Time Signals



Spectral Fault Signatures

- Spectral differences are good for identifying the existence and kind of blade faults.
- Do not provide information as to the location of a faulty blade.
- They may confuse some cases of different faults.

INTRODUCTION OF NEW FAULT PARAMETERS
(Overcoming the Disadvantages of the Spectral Ones)

Requirements:

One-to-one correspondence between fault and fault signature.

> - *For identification of a fault, it must have a unique fault signature.*

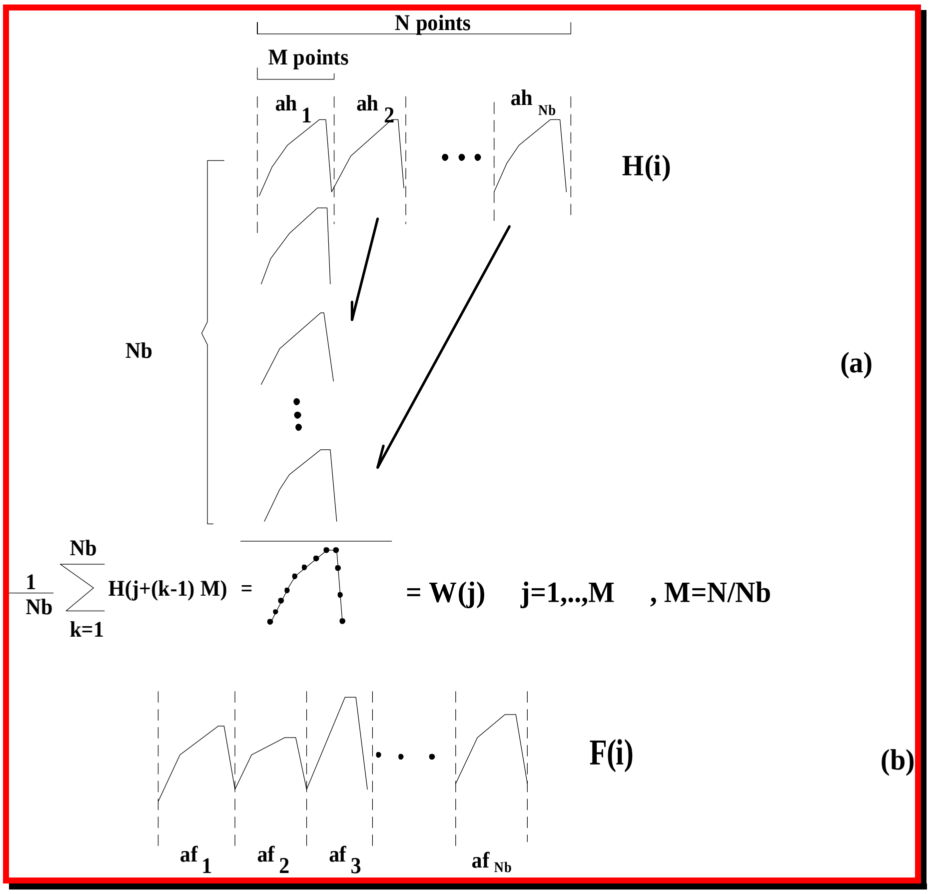
The more detailed the diagnosis, the more geometrical properties should be reflected in the fault parameters.

> *-For example, when dealing with blade faults it is desirable to know not only that a blade is faulty but also what is the location of this blade and what is the kind and severity of the fault.*

They should contain information sufficient for defining the geometry of every individual blade of a blade row.

A fault parameter reflecting the condition of a blade should be sensitive to small changes in this blade geometry, but relatively insensitive to changes in neighbouring blades.

A. Correlation Coefficients for Blade-to-blade Pressure distribution



Derivation of Average Passage Pressure Signal

$$a\,h_k = \frac{\overline{h(t)\cdot W(t)}}{\overline{W(t)^2}}$$

Fault Signature Vector

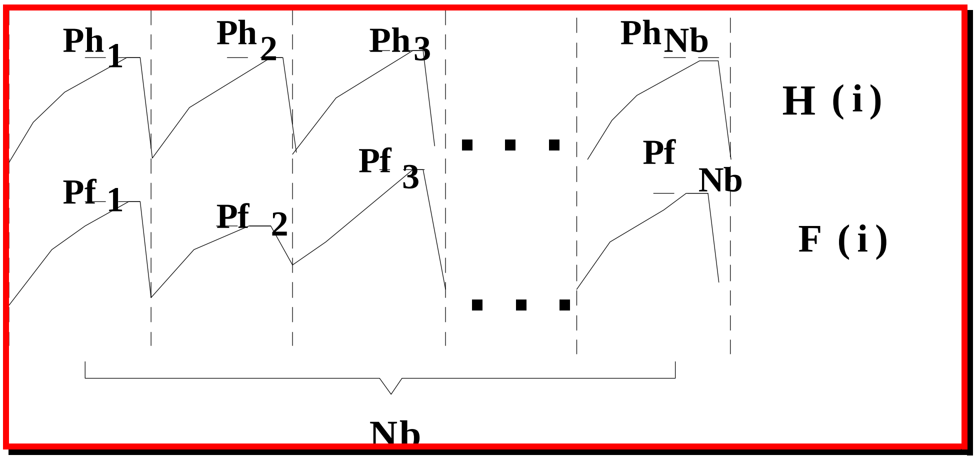
$$Da_k = \frac{af_k - ah_k}{ah_k}\cdot 100 \qquad k=1,\ldots,Nb$$

$$a\,f_k = \frac{\overline{f(t)\cdot W(t)}}{\overline{W(t)^2}}$$

Discretized Form of af_k

$$af_k = \frac{\sum\limits_{j=(k-1)\cdot M+1}^{k\cdot M} F(j)\,W(j-(k-1)\cdot M)}{\sum\limits_{j=1}^{M} W(j)^2} \qquad k=1,\ldots,Nb$$

B. Passage Maximum Pressure coefficients.



Blade-to-blade maximum pressure coefficients

Fault Signature Vector

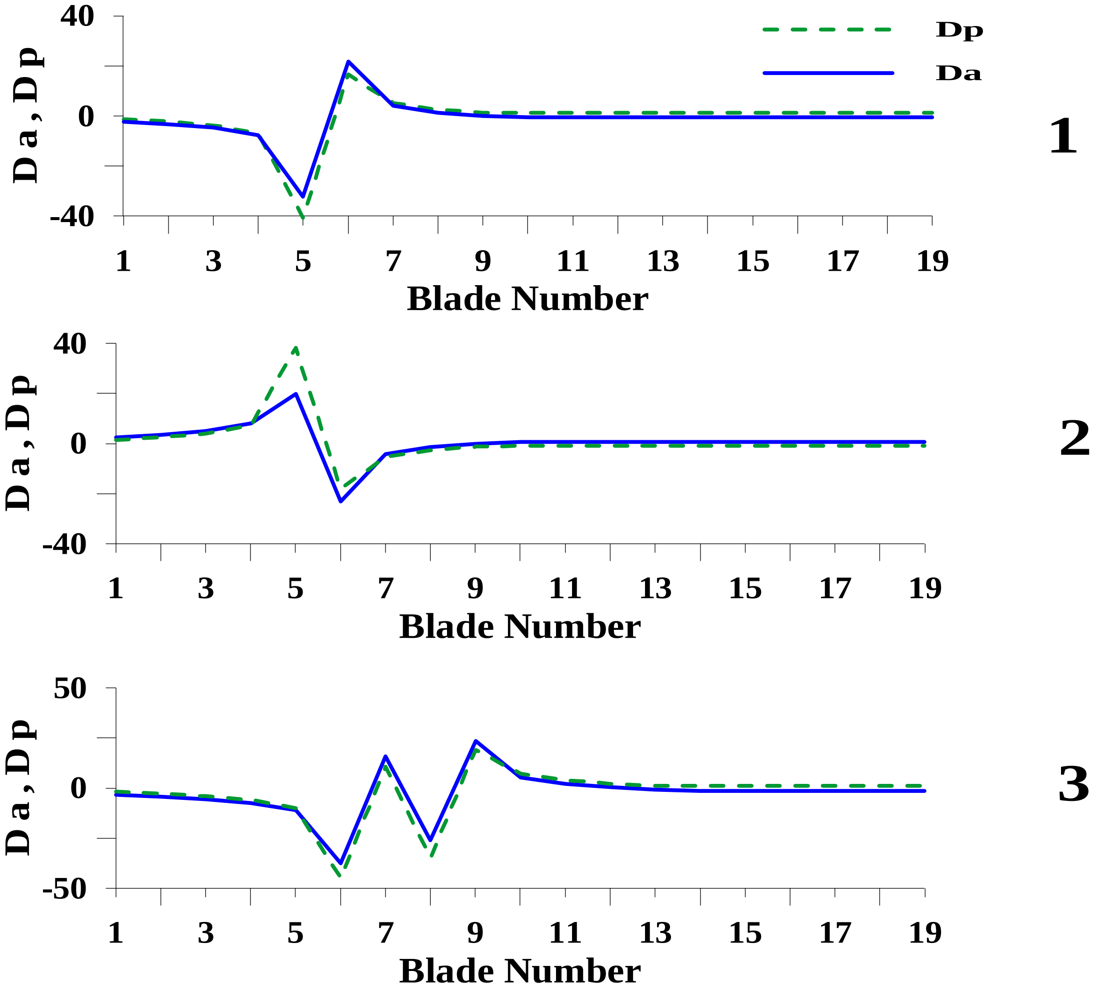
$$\left.\begin{aligned} Ph_k &= \max_{t_{k-1}\le t\le t_k}[h(t)] \\ Pf_k &= \max_{t_{k-1}\le t\le t_k}[f(t)] \end{aligned}\right\} \quad Dp_k = \frac{pf_k - ph_k}{ph_k}\cdot 100 \quad , \quad k=1,\ldots,Nb$$

Discretized Form

$$Ph_k = \max_{i=1}^{M}\left[H(i+(k-1)\cdot M\right]$$

$$Pf_k = \max_{i=1}^{M}\left[F(i+(k-1)\cdot M\right] \qquad k=1,.., Nb$$

APPLICATION CASES



Fault signatures in terms of Da and Dp. (1). One Blade Twisted by -7 deg. (2). One Blade Twisted by 7 deg. (3). Two blades twisted by -7 deg. and separated by one healthy blade.

- Each fault produces a distinctly different signature.
- New parameters overcome the disadvantages of spectral differences.

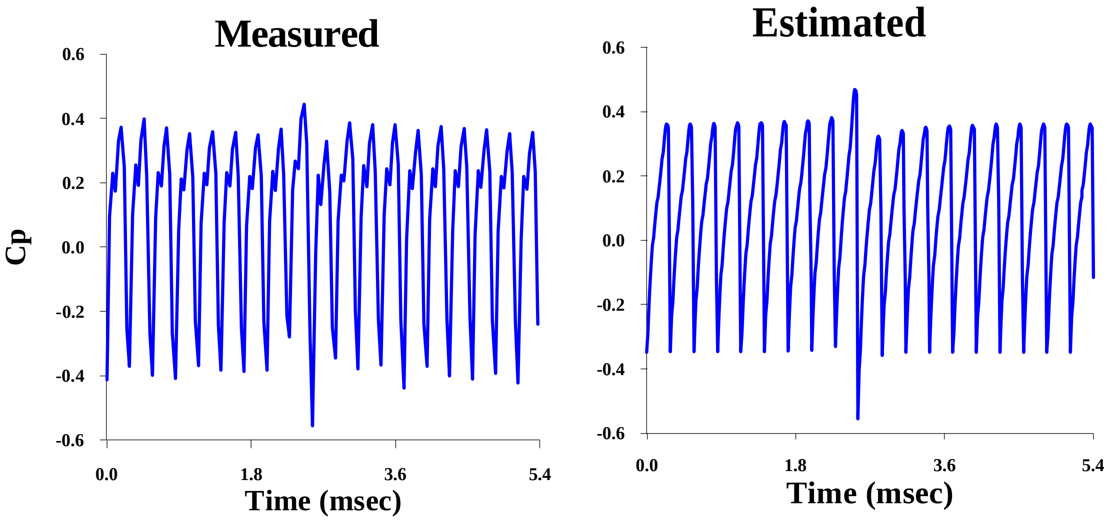
APPLICATION CASES

Reconstitution of Actual Faults from Measurement Data

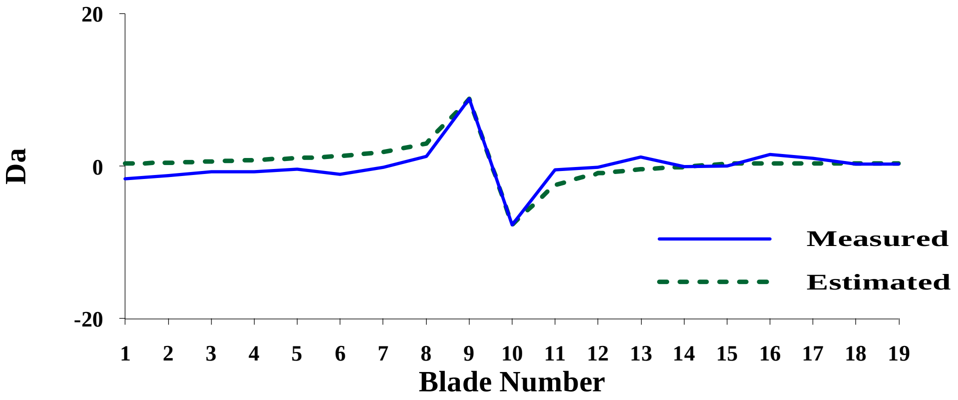

Real

Estimated

Cascade Geometry



Time signals



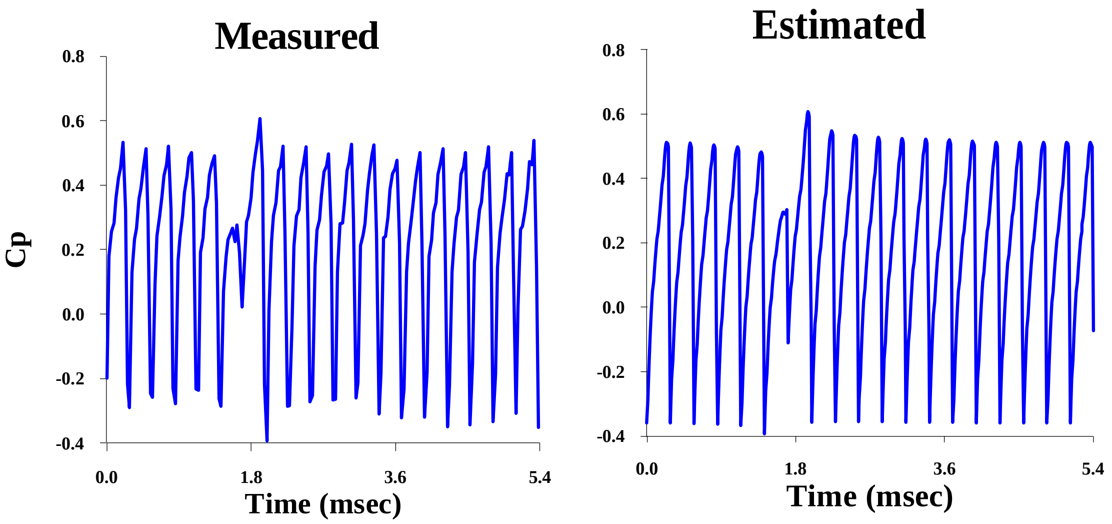
Fault Signatures

one blade twisted (small positive twist).

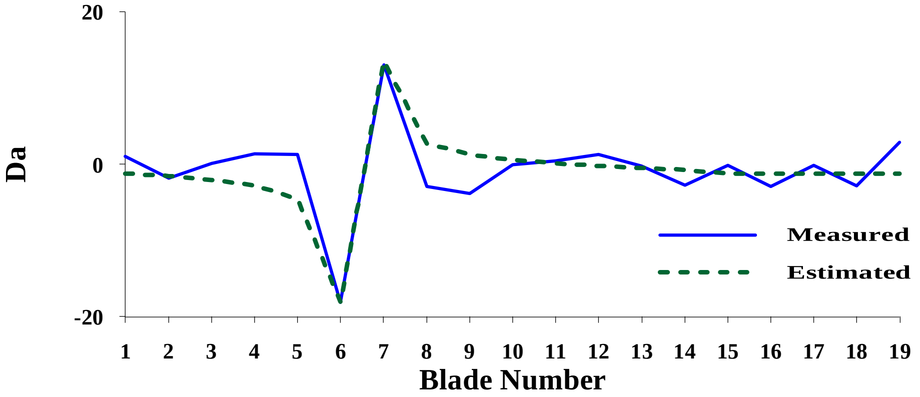
APPLICATION CASES

Reconstitution of Actual Faults from Measurement Data

Cascade Geometry



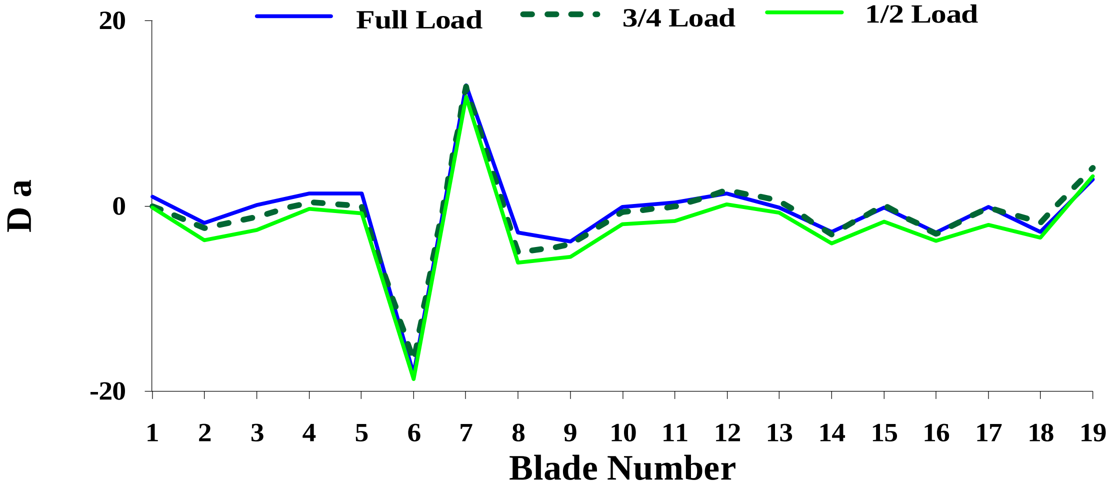
Time signals



Fault Signatures

one blade twisted (large negative twist).

Dependence on Operating Point



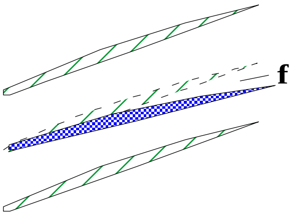
One blade twisted (large negative twist)

Comments on Application to experimental Data

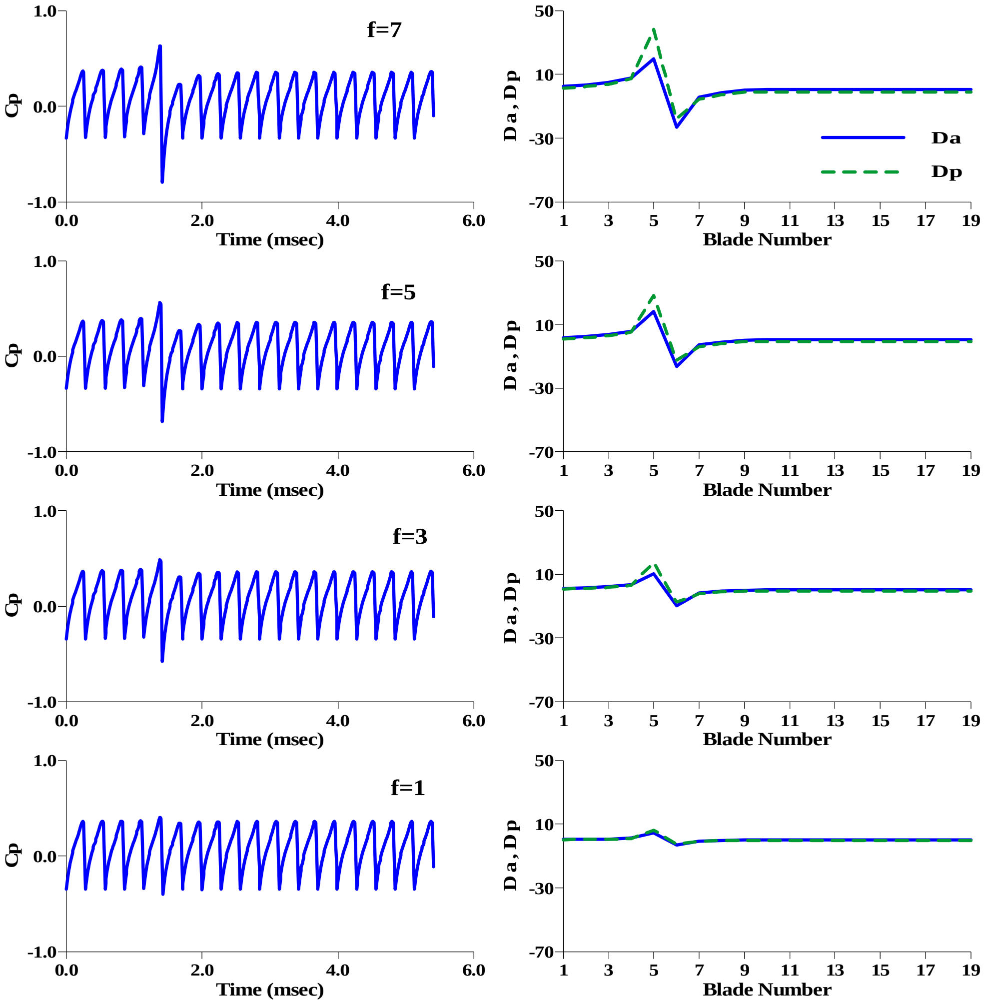
- The reproduced fault is identical to the actual one.
- The measured signals show remarkable similarity to the corresponding estimated ones .
- The method has correctly identified the twist of the blades, which was in opposite directions and of different magnitudes in the two cases.
- Identification was possible from data at different operating points of the gas turbine.

OTHER APPLICATION EXAMPLES

Time signals and corresponding fault signatures, Case 1.



Cascade geometry



Time signals

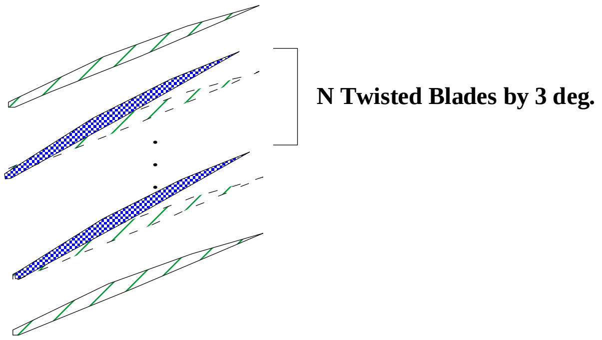
Fault signatures

one blade twisted by different angles (positive twist).

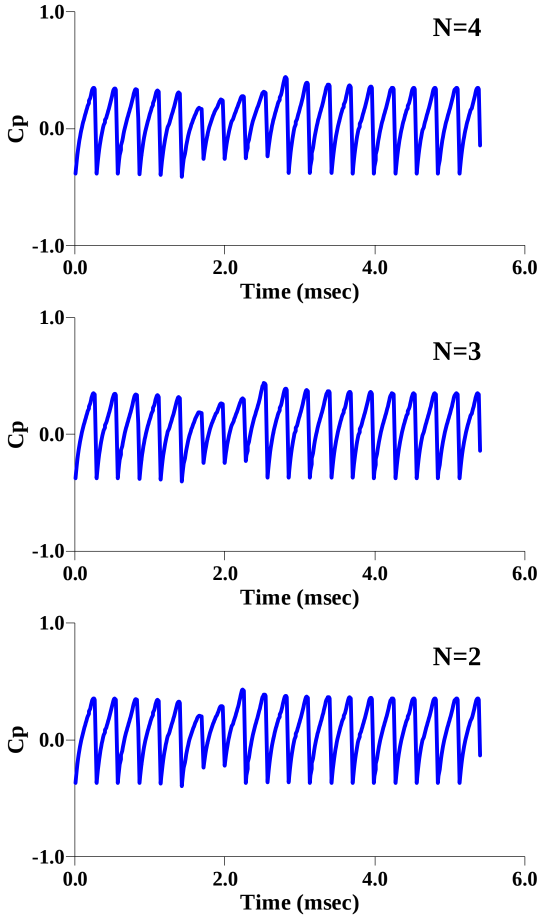
The twisted blade is identifiable even if different twist angles exist.

OTHER APPLICATION EXAMPLES

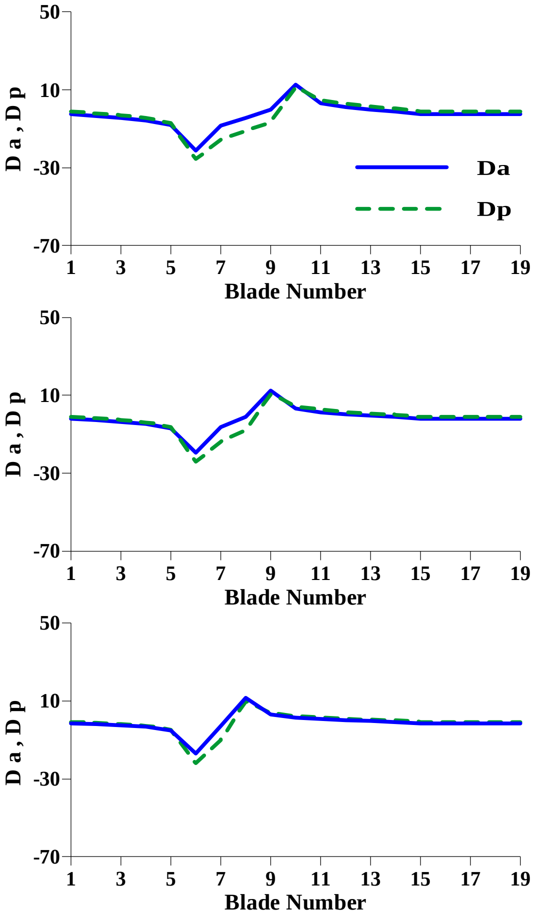
Time signals and corresponding fault signatures, Case 2.



Cascade geometry



Time signals

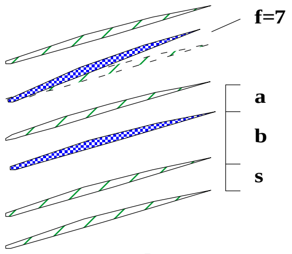


Fault signatures

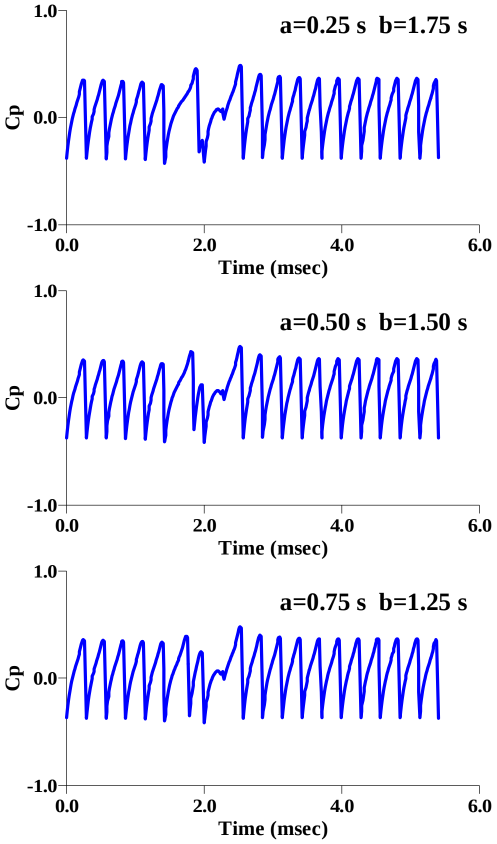
two, three and four adjacent blades twisted by -3 deg.

OTHER APPLICATION EXAMPLES

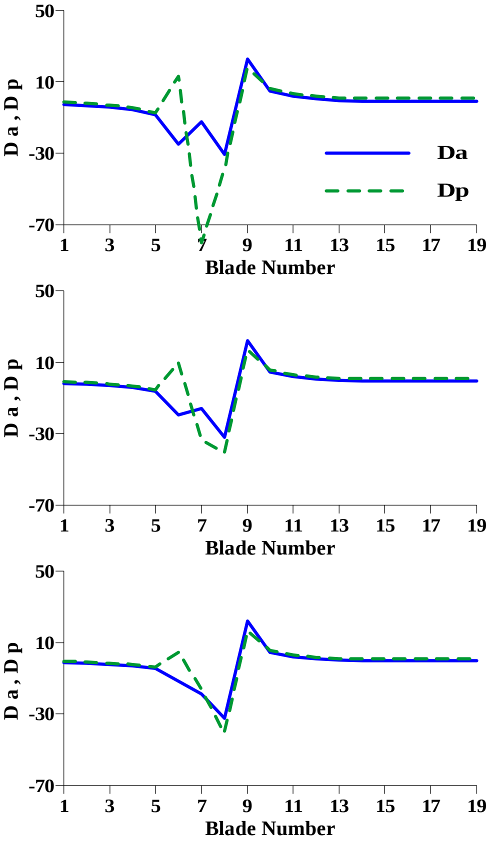
Time signals and corresponding fault signatures, Case 3.



Cascade geometry



Time signals



Fault signatures

one twisted and one misplaced blade separated by one healthy blade (different percentages of misplacement)

DISCUSSION

The possibilities of the method rely on the reliability of the signature simulation model.

-The present model is based on a rather simple fluid dynamic solver but has been proven to be sufficiently reliable for fault signature prediction.

-Advantages expected by a more sophisticated model are marginal in view of a high penalty in computation time.

Implementation of the method presented has become realistic only through the advances in development of digital computers.

-Performing direct simulations is achieved in a few minutes for a rotor with a realistic number of blades, on a PC.

-Solution of the inverse problem is much lengthier on a PC, since it involves a number of "direct" passes.

Solution: *Parallelization of the algorithm.*
Result: *Diagnosis in "quasi real time".*

Presentation is given in a generalised form, so that it does not rely on a particular type of simulator or fault signature.

-Other kinds of fault signatures can be employed.

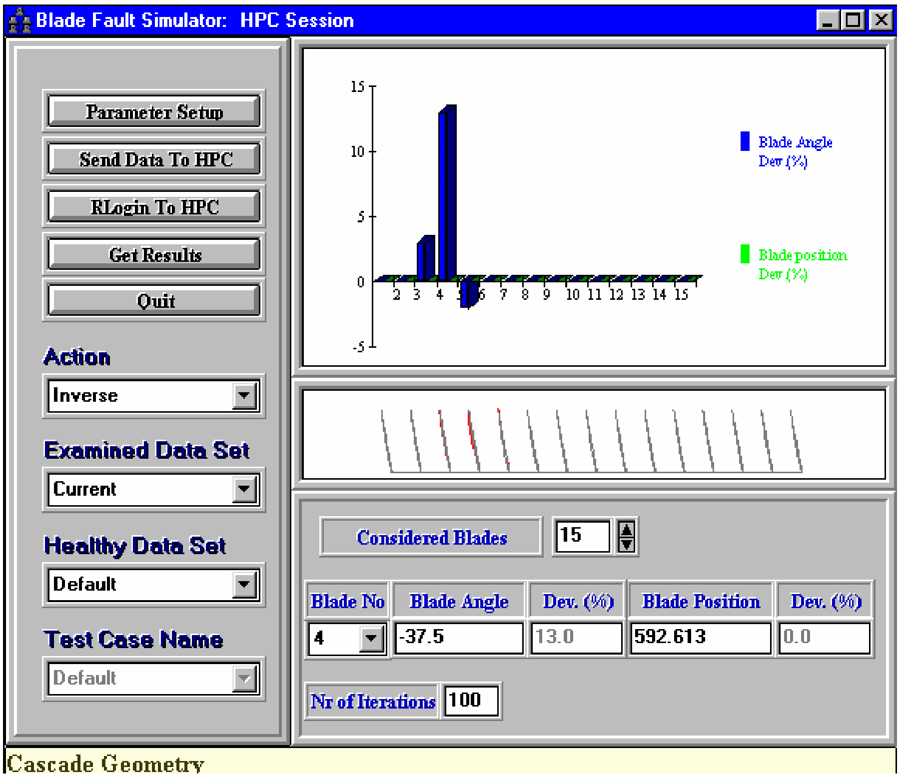
-The fault parameters must change smoothly with the parameters characterising the faults, because non-smooth changes may induce problems to the iteration scheme.

FURTHER COMMENTS

Advantages of the method

- The first obvious advantage is the form in which the result is offered, which needs no interpretation.
- Elimination of the need for a fault signature data base.
- The methods provides information which would have needed very extensive data bases, if the signature approach were followed.
- Faults covered here are essentially limited to those for which a good simulation capability exists. The steps of the procedure apply to any case for which the modelling possibility exists.

Implementation of the method on a PC in a user friendly environment.



Blade Fault Simulator: HPC Session

Action: Inverse

Examined Data Set: Current

Healthy Data Set: Default

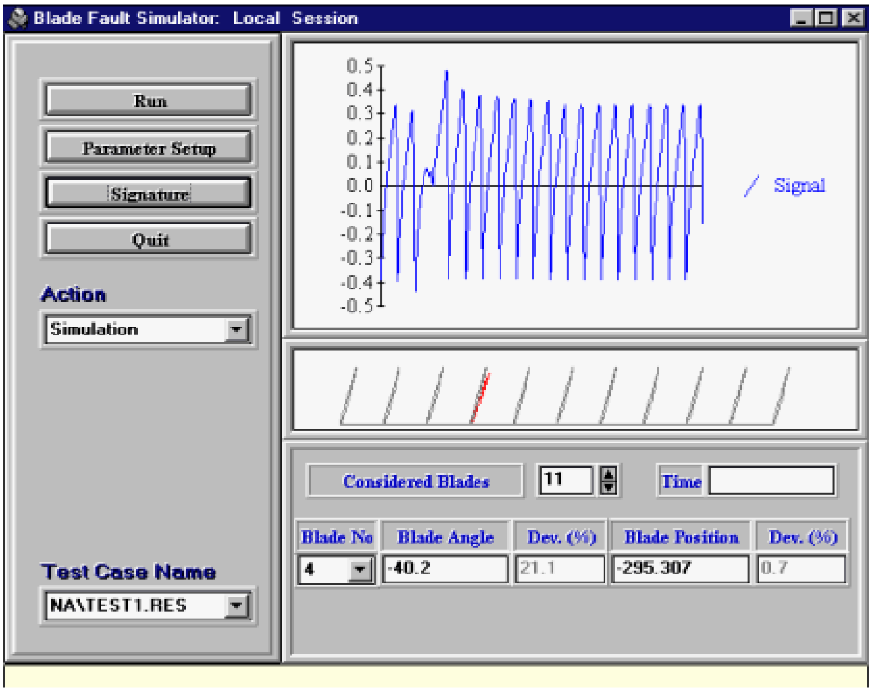
Test Case Name: Default

Considered Blades: 15

Blade No	Blade Angle	Dev. (%)	Blade Position	Dev. (%)
4	-37.5	13.0	592.613	0.0

Nr of Iterations: 100

Cascade Geometry



Blade Fault Simulator: Local Session

Action: Simulation

Test Case Name: NA\TEST1.RES

Considered Blades: 11

Time:

Blade No	Blade Angle	Dev. (%)	Blade Position	Dev. (%)
4	-40.2	21.1	-295.307	0.7

CONCLUSIONS

- **A new method for direct identification of faults in blades of gas turbine components has been presented.**

- **It provides a direct geometrical picture of blade faults and does not rely on fault signatures and related procedures.**

- **Its capability to successfully identify faults was demonstrated by application to experimentally available data.**

- **The method as presented here offers the basis for an extension to other diagnostic applications, covering data or faults of a nature different from the ones examined here.**