The Rise and Fall of the Rotor Blade Strain Gauge

Peter Russhard

Abstract In any gas turbine the understanding of the way in which the rotor blades vibrate is essential for both the development and production phases. For many years the standard method of obtaining such data has been with the use of strain gauges in conjunction with radio telemetry units or slip rings. With the complexity of the machine increasing and as the operating environment becomes more and more hostile for such systems, new methods are being investigated that will ultimately lead to a non-intrusive technology being developed. Here we review the progress and pioneers of strain gauge measurement dating back to the 1930s and look at a number of technologies that have tried to displace them from their positions as the mainstay of rotor blade vibration measurement.

Keywords Strain gauge · Radio telemetry · Rotor blade vibration

1 Introduction

The measurement of rotor blade vibration in turbine engine development is made to ensure a physical understanding of how blades behave. Advancement in acquisition and analysis tools has the potential to reduce the amount of development time required to validate new designs. Blades fail due to the stresses in them being too high and there are a number of ways of generating stress. All of the many mechanisms for blade failure during engine operation are the result of excessive blade vibration. By quantifying blade vibration through measurement it is possible to define a set of criteria to protect components from these problems. There are a number of reasons for requiring a new technology and most hinges on both the lead-time and cost of application. Today's gas turbine development programs are up to 50 % shorter than those of a decade ago and the machines operate at increasingly higher speeds and temperatures. Instrumentation failure is high, as is the mortality

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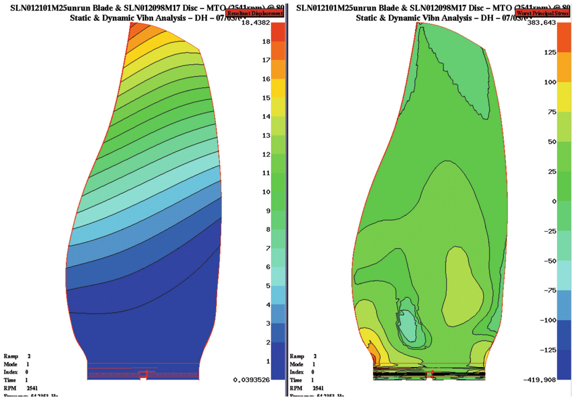


Fig. 1 Rotor blade modelling

of a strain gauge in such an environment. Similarly, in a production environment, it is desirable to have an indication of blade health for the most vulnerable rotors of a gas turbine. This leads to lower maintenance costs and fewer removals and routine inspections. With significant profit now coming from the Total Care™ packages offered by OEM's (Original Equipment Manufacturers) the desire to have a reliable Blade Health Monitoring system (BHM) is high. Unfortunately strain gauges are not suitable for long-term health monitoring of rotor blades [1].

During the design stage of a compressor/turbine rotor blade, a number of blade simulations provide predictions of blade deflection and stress distribution for all of the blade natural frequencies. These levels are often the maximum allowable, but not necessarily that which will be encountered in operation. Factors affecting the prediction of rotor blade stresses include the uncertainty in calculating both the structural and the aerodynamic damping associated with each mode of vibration. Current design simulation software is unable to accurately calculate these values and direct measurement is often required to obtain them. A measurement system requires the ability to confirm expected blade behaviour and to provide additional data to allow the system to be accurately modelled (Fig. 1).

2 Measurement of Rotor Blade Strain

Between the years 1931 and 1938, aircraft propeller failures in flight ran anywhere from 8 to 41 times a year. By 1938 OEM's had begun to study all of the installations in the field and restricting them so that they did not operate under conditions of severe vibrations. In 1939 there were 6 failures and in 1940 there were none. The result of this was that aircraft and pilot losses went from 40 to zero. The necessity for measuring and understanding rotor blade strains had become imperative and was the main driver for the development of rotor blade strain measurement technology [2].

A number of alternate technologies have challenged the dominant position of strain gauges with one in particular starting to displace it.

3 Strain Gauges

Strain gauges have been described as the preferred transducer for blade vibration measurement [3], strain gauges are a field proven technology for extracting accurate real-time information [4] relating to the alternating strains arising in critical areas of a blade. In addition, strain gauges have proven to be well established and reliable when applied to non-rotating components for most applications.

One of a number of strain gauges pioneers was Charles M. Kearns, Jr. who invented the bonded carbon strain gauge whilst working at Hamilton Standard Propeller Co [5]. Within 4 years, in-flight propeller failures went from dozens per year to zero. The carbon gauge is sold, copied, and spreads like wild fire worldwide. Prior to this Kearns experimented with a mixture of sulphur and graphite (Aquadag) that changed its resistance with stress but also with just about everything else. The first carbon based gauge was simply a ground down carbon resistor cemented to a beam which appeared to have a linear relationship between strain and resistance. Kearns achievements included;

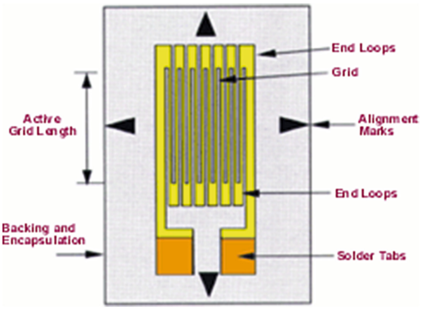
- Developing and characterising carbon resistor strain gauges
- Attached carbon resistor strain gauges to HS propellers
- Designed and fabricated a turntable silver graphite slip ring
- Determined necessary signal conditioning
- Collected data for the strain gauges
- Solved a propeller vibration problem
- Implemented changes in propeller design and manufacture

This is a process that is still repeated today in the development of measurement technology.

The carbon gauge was replaced around 1945 with the application of SR-4 resistance wire strain gauge and finally Peter Scott Jackson [6] (UK RAF) invented the foil strain gauge in 1952 (Fig. 2).

Developments in the size, sensitivity and adhesive technologies have kept the application of rotor blade strain gauges current since then. This combined with their ease of conditioning and processing makes it a simple but reliable method of measuring rotor blade strain.

Fig. 2 Foil strain gauge



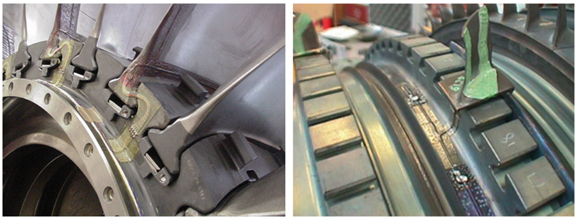


Fig. 3 Typical rotor strain gauge installation

However for rotating components, strain gauge measurement systems suffer from a low operating life. This limited life expectancy is often due to the use of the slip ring or telemetry systems to transmit the strain gauge signals from the rotating structure to the stationary analysis hardware and the ever increasing temperatures and flows that the gauges have to operate in.

In addition, the strain gauges attached to the component under observation, Fig. 3, and the wire paths can alter the blade structural characteristics as well as interfering with the local fluid flow field, hence restricting the number of strain gauges to a few blades per rotor stage. Associated with this test method, the strain gauge measurements can provide valuable information on certain parts of the blades but are statistically inaccurate due to blade-to-blade differences in response caused by mistuning. The introduction of blisks in compressor designs and the mistuning characteristics associated with them compounds the problem of relying on a small number of strain gauges for design validation.

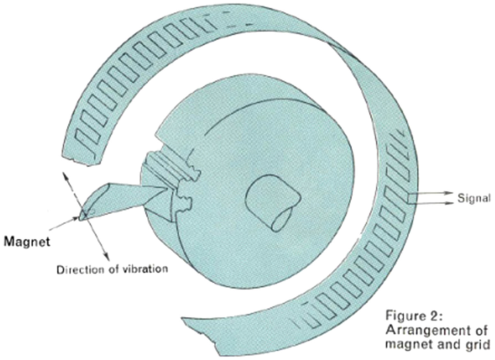
4 FM Grids

In April 1962 Bristol Siddeley Engines Ltd published a paper [7] describing a new method of quantifying the stress in a rotor blade by an indirect method that measured blade displacement. It was shown that the maximum bending stress in a blade is proportional to the amplitude (a) of vibration and its frequency (f). This was an approximation that held for blades regardless of their form and applies to torsional and flexural modes of vibration. The principle, which is still in use today in some industries, is that the product af to cause a blade failure is constant for any given material.

The measurement of blade displacement is achieved by attaching a magnet into a blade tip and having a conductive wire grid arrangement embedded in the rotor liner (Fig. 4). A combination of the grid shape, magnet and rotor speed causes a signal to be induced into the grid. The frequency of this signal is affected by blade vibrations which cause frequency modulation that is directly proportional to the blade af. This arrangement is known as the Frequency Modulated (FM) Grid System.

Today FM demodulation is an easy technique to apply and the resulting demodulated signal can be used directly in analysis. A comparison made in 1962

Fig. 4 FM Grid arrangement



shows that both strain gauge and FM grid measurement techniques give similar results. The calibration of the FM grid system was often completed by comparison with a strain gauge allowing further and future engine testing to be completed without referring back to the strain gauge. Blade modelling methods were not mature enough to do this otherwise (Fig. 5).

Today we can repeat the comparison for the FM grid system with a more recent technique, Blade Tip Timing (BTT), and demonstrate that again we have similar results. In this case both techniques measure *af* directly. The use of strain gauge data in this type comparison requires the use of a validated model to convert stress at the measurement point into displacement at the tip (Fig. 6).

By fitting more than one grid in the rotor path it is possible to obtain data from multiple points on the blade. This data can be used to confirm the mode shapes at operating conditions. Figure 7 shows the attachment of a magnet in the blade tip.

5 Blade Tip Timing

In July 1984, Ray Chi from the United Technologies Research Centre, Connecticut USA published one of the first papers [8] that dealt with the practical application of a non-contact strain measurement system (NSMS). It provided the mathematical background to explain how data collected from casing mounted sensors could be used to infer rotor blade stresses. This was followed in 1988 by a paper

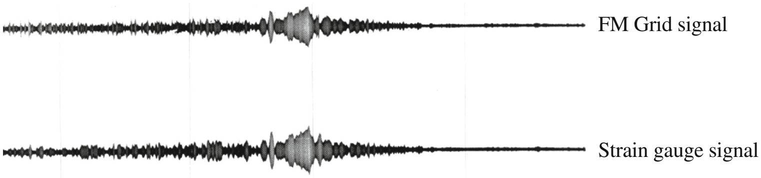


Fig. 5 Visual comparisons of strain gauge and FM grid output

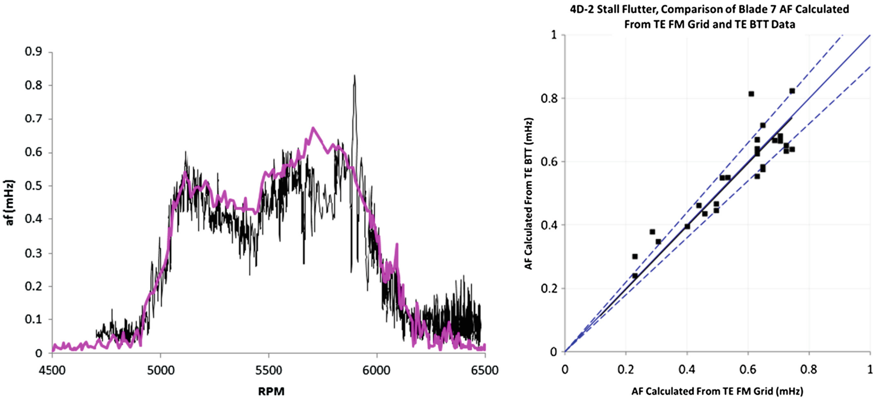


Fig. 6 Quantitative comparison of tip deflection measurements

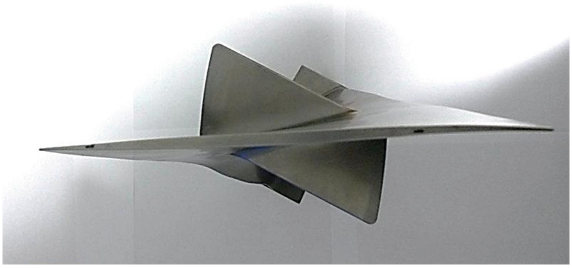


Fig. 7 Blade magnet arrangement

demonstrating and reporting results from a practical application during a rig test of a first stage turbine [9]. At this time the other Gas Turbine OEM's were also developing the same technology and it was not until 2002 when the US government funded an engine demonstration test at Rolls-Royce Indianapolis that three separately developed systems were finally brought together for comparison.

5.1 Overview of the XTL17 Technology Demonstrator

An experiment, designated XTL17, was designed to quantify the amplitude of the mode 8 response, distinguish it from the mode 7 response and detect a possible flutter event (Fig. 8). This was part of a High Cycle Fatigue (HCF) experiment using blade coatings to dampen responses and to understand the processing capabilities of several tip timing systems fitted to the vehicle.

The data collected from a variety of instrumentation was compared against strain gauge data obtained via a radio telemetry system. The result being that BTT and strain gauge correlation had a ±25 % uncertainty value associated with it. This is not consistent with BTT being a potential replacement for strain gauges (Fig. 9).

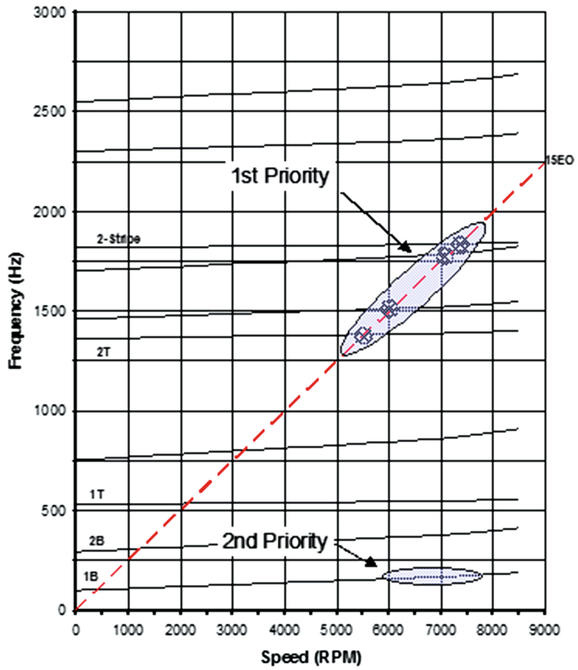


Fig. 8 XTL17 analysis requirements

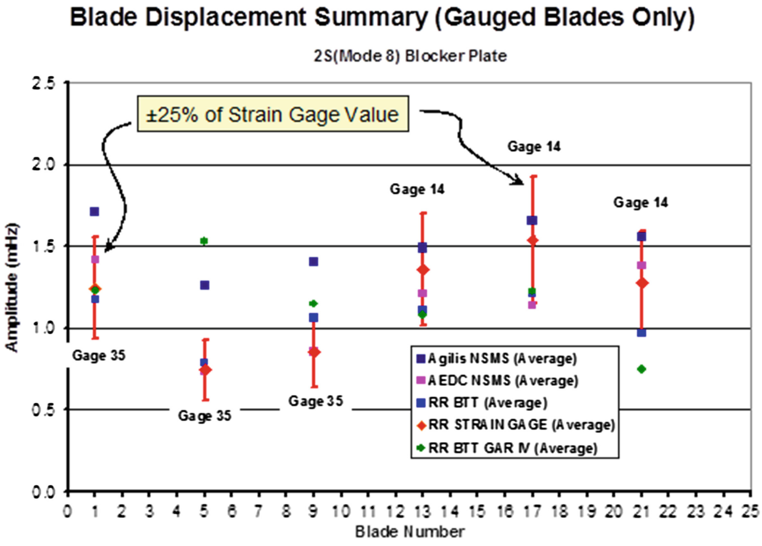


Fig. 9 BTT comparisons circa 2002

The secrecy under which BTT technology had been developed contributed to the significant uncertainty between systems. Over the next few years gas turbine OEM's formed partnerships in a number of military programs and this led to a desire to standardize the techniques which has been driven by the US and the UK defence departments.

Improvements in computing power and investment is academic research has moved the technology to a point where much of the validation is complete, the process of application to analysis is understood, and some of the OEM's have achieved the long promised cost savings associated with BTT. A standards committee has been formed and BTT is now well on the way to becoming a technique that all turbine manufacturers can begin to adopt. Currently the detailed knowledge is held by a small group of individuals working across the gas turbine industry but the release of detailed algorithms and best practice aim to spread the knowledge and drive down the cost of application.

5.2 *How Does It Work: In Brief*

Typically, tip deflections are obtained by measuring the blade arrival time at a number of probes situated around the casing with reference to a stable non-vibrating Once per Revolution (OPR) signal obtained from a shaft or a disc. A typical system for doing this was described by Heath [5]. The portion of blade illuminated by the laser light is the position where the deflection is measured and is the positions where calibration data must be relevant in any later analysis. The laser spot size may be different for different size of blade but is typically between 100 µm and 1 mm in diameter. A number of probe technologies can be employed but each has an effect on the measurement capability of BTT. Figure 10 shows typical outputs for a blade passing under probes using different sense technologies.

At constant speed, non-vibrating blade tips pass the probes at equal intervals of time on each revolution. However, vibrating blades will reach the probes slightly

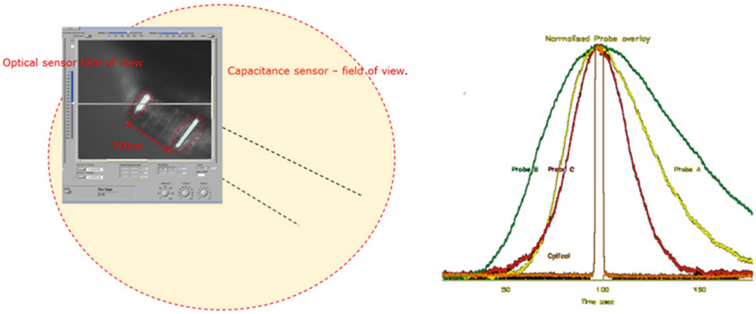
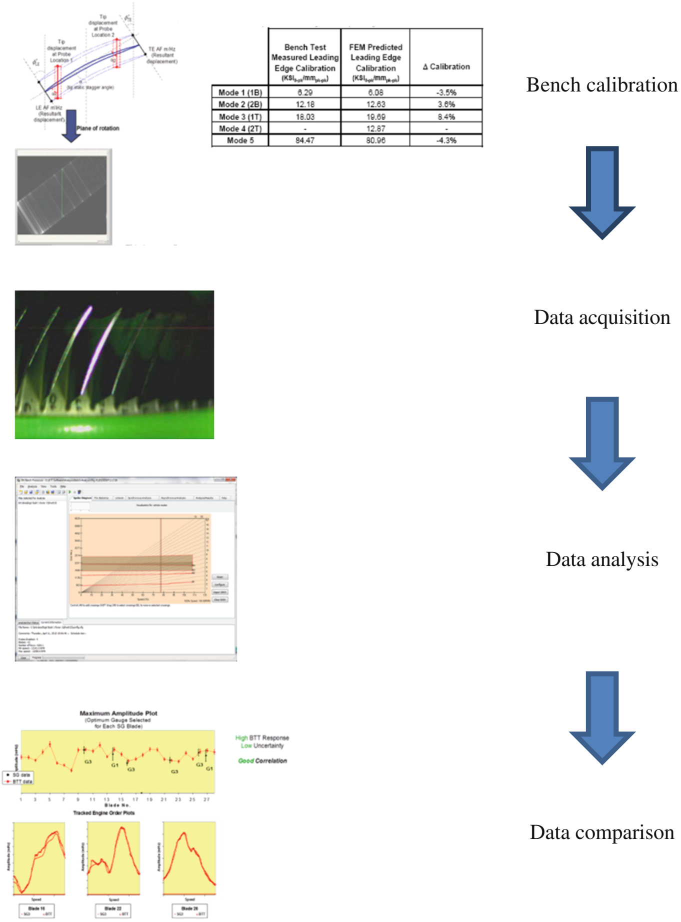


Fig. 10 Probe waveforms



	Bench Test Measured Leading Edge Calibration (KSI_{0-pk}/mm_{pk-pk})	FEM Predicted Leading Edge Calibration (KSI_{0-pk}/mm_{pk-pk})	Δ Calibration
Mode 1 (1B)	6.29	6.08	-3.5%
Mode 2 (2B)	12.18	12.63	3.6%
Mode 3 (1T)	18.03	19.69	8.4%
Mode 4 (2T)	-	12.87	-
Mode 5	84.47	80.96	-4.3%

Fig. 11 Simplified BTT—strain gauge correlation process

later or earlier. Taking the difference between the expected and actual arrival times allows the calculation of individual blade tip displacements at the probe. Combine the test data with calibration information and proprietary data analysis methods to resolve blade stress. Figure 11 shows a simplified BTT process for performing strain gauge correlation.

5.3 *Current BTT Capabilities*

The large Gas Turbine OEM’s have the resources to complete hundreds of strain gauge and FEM correlations with BTT data, the gradual release of this data allows the technique to be adopted outside of the aerospace sector. The ability to

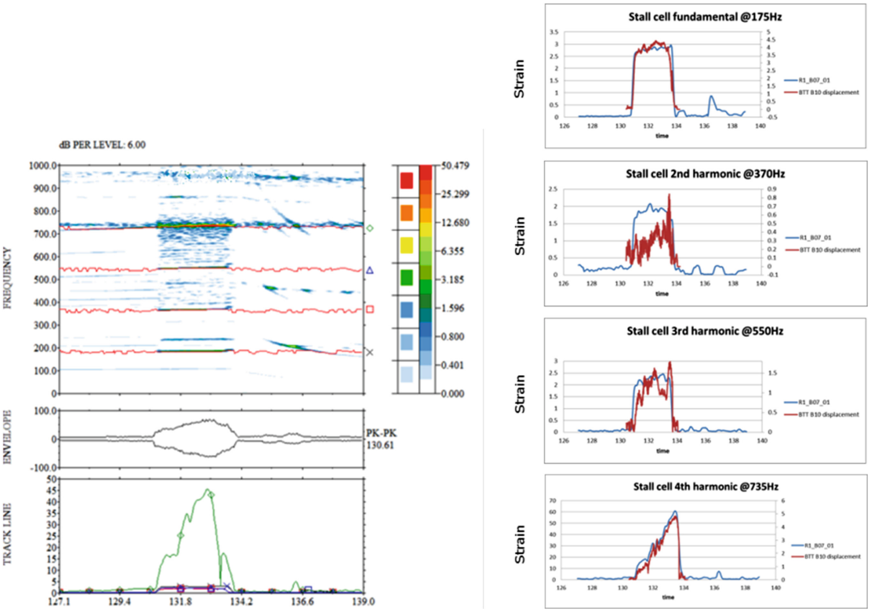


Fig. 12 Stall analysis and comparison

characterise both integral and non-integral vibrations is common, as is the analysis of stall events. The differences now seen in the correlation between strain gauge and BTT are mostly associated with the proprietary analysis and comparison techniques used by different companies. These differences are usually built into any safety margins when the data is used for component certification. Standardisation of the technique will help to narrow these differences.

A complex stall event (Fig. 12) shows the correlation between a strain gauge and BTT analysis [10]. Detection capability is limited by the acquisition process and typical end to end figures of 20 μm are common.

6 Conclusions

The use of strain gauges for rotor blade vibration measurement has declined due to the restrictions imposed by the latest standard of machinery. The requirement for more statistical data to support both the design and in-service phase's favours a technology that can be applied from the casing captures data from all blades, has line replaceable units and can build on data collected during the development cycle.

Blade tip timing alone will not replace rotor strain-gauges but combined with FE models and fatigue test data it has displaced numerous expensive telemetry tests in the past few years and has provided superior statistical data on blade behaviour.

Data gathered during the development phase is directly applicable to long term health monitoring and sub sets of data can be used to develop detection and trending techniques prior to entry into service.

More robust probe technologies are available and the standardisation of techniques is beginning to make this available to all.

In the development of rotor machinery BTT has met the goal of replacing telemetry tests and shortening development cycles. In particular modifications to existing equipment have benefitted most. The next phase is to understand the potential of in-service data and to exploit it.

References

1. Russhard P (2010) Development of a blade tip timing based engine health monitoring system—thesis, Faculty of Engineering and Physical Sciences, School of Mechanical Aerospace and Civil Engineering, Manchester University, Sept 2010
2. Niska H (2012) Strain Gage Pioneers and Propulsion Engine History Joint EVI-GTI and PIWG conference, Oct 2012
3. Kadambi JR, Quinn RD, Adams ML (1989) Turbomachinery blade vibration and dynamic stress measurements utilizing nonintrusive techniques. J Turbomach 111(4):468–474
4. Heath S (1996) A study of tip-timing techniques for the determination of bladed disk vibration characteristics, Imperial College of Science and Technology, University of London, PhD Thesis, 1996
5. Kearns CM Jr (1936) Stress measuring means—US patent application
6. Jackson PS (1953) Foil strain gauge England—patent application
7. ThomasJC (1962) A new technique for investigating blade vibrations. Bristol Siddeley J
8. Chi RM et al (1984) Conceptual design of a non-interference stress measurement system for gas turbine engines. Arnold Engineering Development Centre 1984
9. Chi RM et al (1988) Demonstration of testing of a non-interference technique for measuring rotor blade stress, AIAA/ASME/SAE/ASEE 24th joint propulsion conference 1988
10. Russhard P (2012) Analysis of rotating stall in a contra-rotating system using blade tip timing, IIS conference June 2012

http://www.springer.com/978-3-319-09917-0

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