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Turbine Blade Vibration Measurement Methods for Turbocharges

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Abstract This paper presents and compares the most important and often used methods to measure turbine blade vibrations: use of strain gauges and telemetry system which is an intrusive method or, on the other site. The Blade Tip Timing (BTT) method known as Non-Intrusive Stress Measurement (System) NSMS. Both methods have advantages and disadvantages which are described below. This paper focused on synchronous vibrations, which are more important in terms of turbine blades fatigue prediction and design optimization.

Keywords: *blade, vibration, measurement, turbochargers, tip timing*

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1. Introduction

Turbocharger turbine can rotate at a rotational speed of 300,000 rpm up above. At such high speed there are various factors which may cause blade vibrations. The three main factors are: the rotor-stator interaction, the wake flow of vanes and fluctuating suction-sided vortex [1]. These vibrations, occurring for a long period of time lead to material fatigue and damage to the blades. Especially dangerous are flutter and the synchronous vibrations which are vibrations around resonance frequencies and their multiples. When, for a long time, the turbine remains at the speed generating such vibrations, their amplitude rapidly increases and forces accompanying this raise can cause irreversible damage to the blades. Additionally a number of other factors such as: the type of material, the shape of the blades and the turbine or mistuning have a major impact on the size of the amplitude of the vibration.

In order to avoid this type of damage, turbines using FEA / FEM are designed to counteract the growing of such vibrations in the turbocharger operating range. Unfortunately, all the computer simulations, especially for such a high speed and strength, low tolerance and the impact of a number of additional, often random factors cannot fully predict the actual behaviour of the turbine and blades vibration [1,2]. To verify that the turbine designed in such a way works properly, the series of vibration measurement tests is essential. However, such a process is quite complex due to high turbine rotational speed, high temperature of exhaust gases driving the turbine and often small dimensions preventing the installation of the complicated measuring system in such a way as to not interfere with the conditions inside the turbocharger as well as measurement results [3]. Information about blades natural frequencies, in the simplest way can be obtained by means of laser vibrometry. Two methods are used for blade vibration measurement. The first method is using strain gauges and telemetry devices.

The second method, is blade tip timing, and is considered as an indirect and non-contact method and is based on the measurement of the time, when the blades pass the sensors mounted on the turbine housing. This method has been successfully used since the 70's for Turbo-machinery, since a few years back it has been used for turbochargers. The structure of this paper is as follows: firstly the intrusive method is described and in section 3 Blade Tip Timing is explained. The experimental procedure describes the procedure for desirable wheel excitation. Section 5 shows what commonly used data presentation methods are and at the end both systems are compared.

2. Strain Gauge Based Systems

The first systems for turbocharger blade vibration measurement based on strain gauge, appeared in the 1960s [4]. Strain gauges were attached to one or more blades to measure deflection in a most effective way. Strain gauges were connected with opposite end through drilled turbine shafts. The major difficulty in this type of application is the data transfer from highly rotating turbine to an external data acquisition system. First applications used copper or mercury slip rings as the solution. Although this approach has its limitations. With increasing rotational speed, the signal has an increasing level of noise [5] which makes slip rings very difficult to use in a turbocharger, mainly due to the large turbine rotational speed and small diameter of the shaft. As early as 1956 Campbell showed

that even for large turbomachines the quality of data transmitted through radio telemetry is at least as good or even better [6].

Today, a typical strain gauge based system consists of two main parts: rotating and a stationary one. The rotating one is powered by an inductive power supply. Apart from the coil supply, it consists of strain gauges attached to the blades of the turbine and a transducer with a transmitting antenna integrated with a coil power supply and typically attached to the compressor end of the shaft (Figure 1). The antenna is mounted on the compressor side rather than the turbine because the temperature on the compressor side is much lower and electronic components are not exposed to excessive heat.

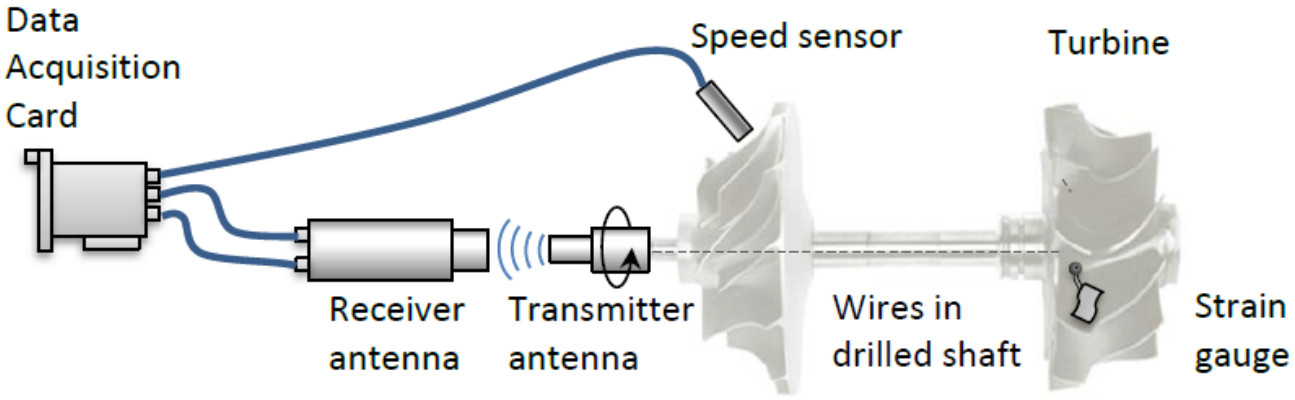

Figure 1. Diagram of the Strain Gauge system

The place for fitting the strain gauge is selected based on the FEA and it is not the place of the biggest vibration to occur but the place having known factor of the vibration amplitude to the other places where the amplitude of the vibration is greatest or where the number of modes have similar levels of vibration and this level is significantly larger than electrical noise [7]. If a strain gauge was attached to a high vibration region, it would be easily to damaged due to high amplitude and frequency of the vibration.

The use of compensation strain gauge or thermocouple is imperative to remove the temperature effect occurring in static strain gauges when exposed to large changes in temperature, otherwise, these changes can be confused with a blades' load. Dynamic stain gauges are in use where blades' load is not important.

The second major part of the system is the stationary part which consists of a receiving antenna, a proximity speed sensor operating on the 1/rev signal or counting all the blades of the compressor (this approach gives a more accurate speed reading and indicates the change during one revolution), data acquisition device and a PC that process, display and store data. Figure 2 shows a diagram of a typical arrangement of a telemetry system. In some cases there is only one antenna to transmit both: Strain Gauge signal and power [8]. Speed measurement is required to determine the order of vibration which is a number of cycles per revolution, beyond the frequency of the vibration.

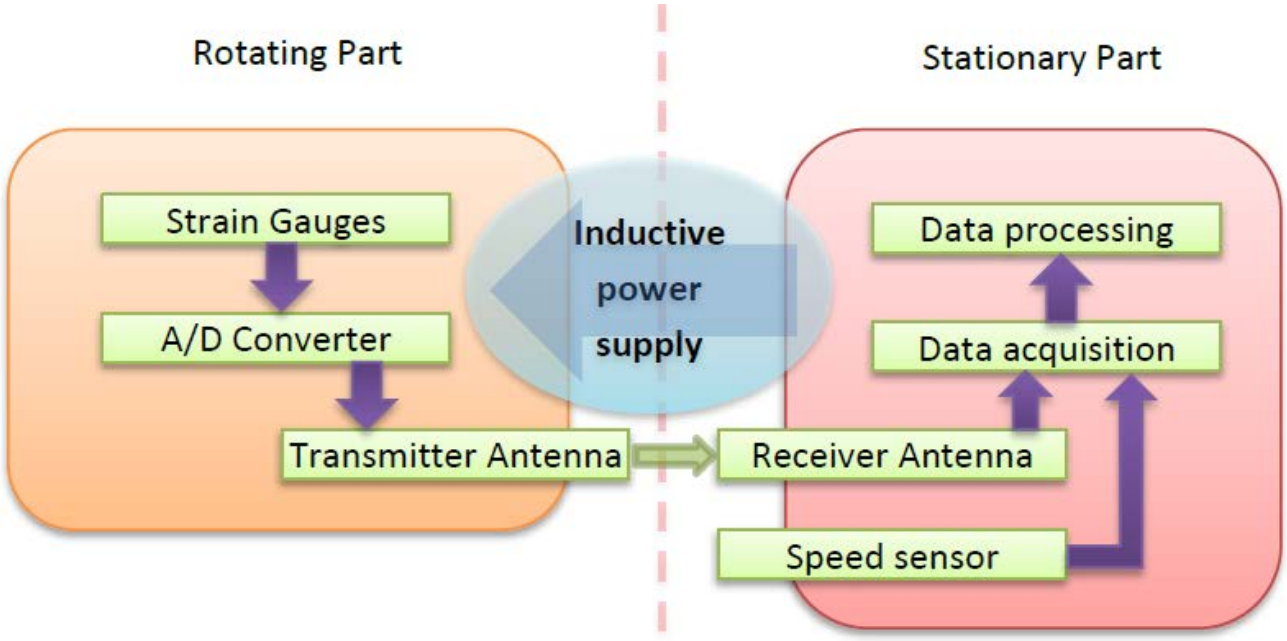

Figure 2. Strain gauge telemetry system diagram

The most popular and commonly used method of data processing is FFT, which gives an overview for all kinds of vibrations, synchronous and asynchronous. The advantages of strain gauges and telemetry systems

are, high quality and accuracy of reading data, possibility of use high sampling rate independent from rotational speed, enabling to create strain maps, possibility of real time data processing using FFT even for the highest speed and a large database of historical results.

3. Blade Tip Timing (BTT)

The beginnings of non-contacting measurement date back to the late 40's when this type of system was first patented [9]. But it was not completely a non-intrusive system because small magnets were installed in the tips of the turbine blades. The signal was read by a circumferentially distributed grid-coil. The first truly non-invasive systems based on proximity sensors were presented in 1967 by Hohenberg [10] however this method could only roughly measure the amplitude of vibration, without any frequency information. In 1970's Zablotsky and Korostelev introduce their own device to vibration measurement which was called ELURA [11] [12]. Since that time a lot of different methods and improvements to BTT system have been developed, but due to the lack of small enough sensors and sufficiently fast computers to process and store data, Blade Tip Timing method had to wait until 2008 to be successfully used in turbochargers [13].

The BTT method is based on an accurate measurement of the time when the blades pass the sensors installed in the housing – blade passing events. In the turbocharger, due to the huge rotational speeds and small blades, this measurement must be very accurate, made by DAQ a very high sampling rate - usually 1-5 mega samples per channel.

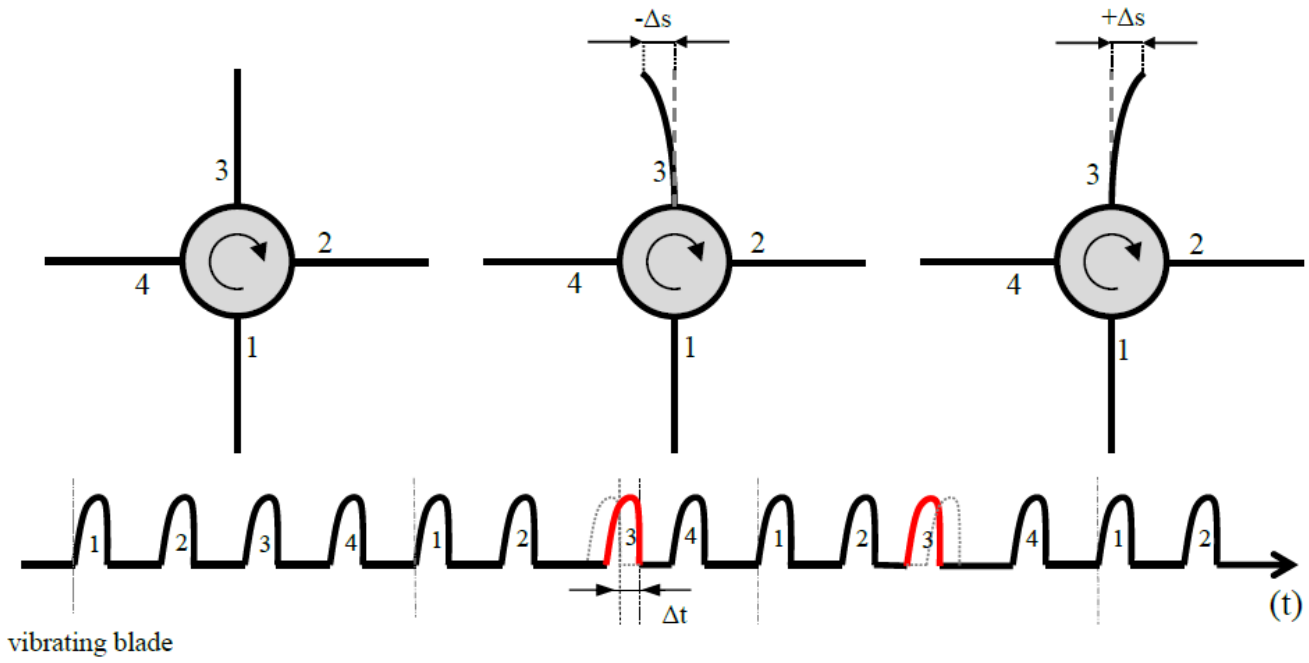

Figure 3. Difference between non-vibrating and vibrating blade seen by a sensor

When the blade starts to vibrate, the tip of this blade changes its position in relation to the tip of the non-vibrating blade – datum. Because of that movement, the rotating blade tip passes a sensor a bit earlier or a bit later than datum (Figure 3) – depending on which direction it is deflected at a given moment. The time difference between the measured time of arrival and the rotating datum, together with a rotational speed allows for calculation of blade deflection at the measurement point.

The rotating datum can be calculated from the rotational speed and angular sensor position. For the general BTT method there are a few variants of calculating the rotational speed, such as: using Once Per Revolution Probe or Blade Root Probe or Reference Rotor, but because of the structure and size, for the turbocharger the best variant is Blade Tip Time Averaging. This method takes all blade passing events for all blades for all sensors during one or more revolutions and use averaging algorithms to calculate rotational speed or directly rotating datum. The biggest advantage of that method is that it does not need any additional sensors or hardware modifications, also, because based on many measurements, it is not sensitive to noise and can detect speed changes during one revolution. The weak point of this approach is that it is sensitive to resonance vibration [14].

A crucial factor in the BTT method is the correct placement of the sensors. Axial position, which is common for all probes, depends on mode shape. Probes are arranged on the circumference in such a way that measured the deflection at the point where they are largest for a given mode. In turbochargers, for the first mode, this is an Exducer tip. If one set of the probes will be measured more than one mode, using FEM must be found a place on the edge where the deflection for two modes is significant, and as large as possible [13]. The number of sensors is equal to 2m + 2 where m is the number of all possible simultaneous excitation of multiple modes. Usually it is 8 probes. Figure 4 shows an example of 4^{th} order sensors distribution. Probes should be distributed in a way to cover one full cycle of the lowest order of interest [17] but in a manner which allows picking up higher orders. It is not always physically possible to distribute probes in that way, but the closer to this arrangement, the smaller is the influence of noise on the measurement result.

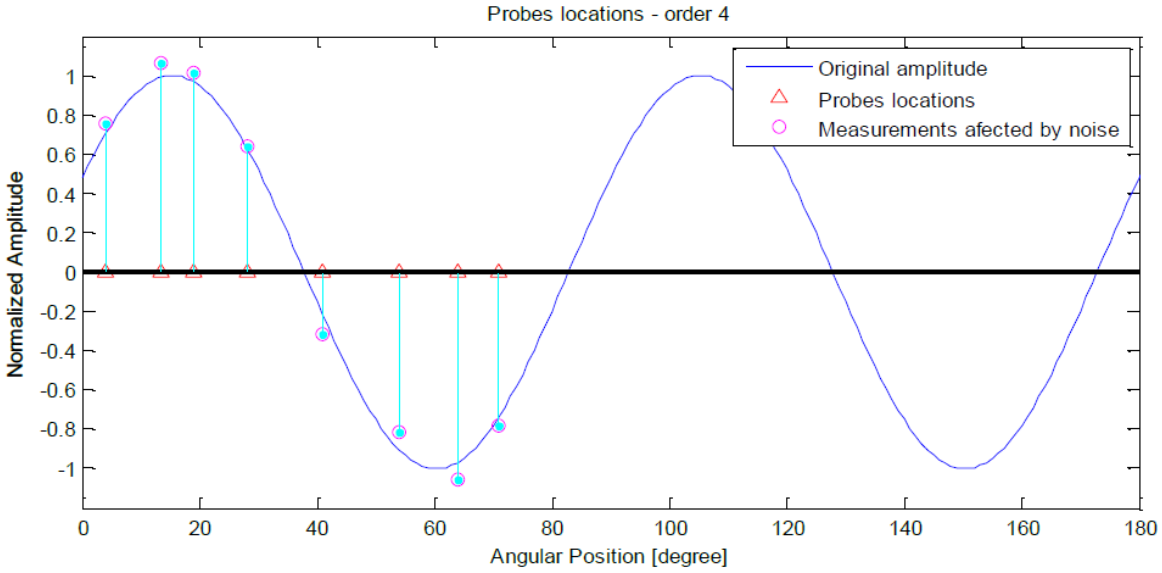

Figure 4. Sensors distribution example

The main assumption for data processing of the synchronous vibration is that vibration frequency is integer multiple of rotational speed. Basing on that assumption, and sine fitting method (usually Least Square Model Fitting – LSMF), amplitude and phase of vibration can be calculated [18].

For measuring asynchronous vibration different methods are used. For some of them even one probe is enough, but for frequencies similar or higher than 1/rev, signal is heavily under sampled. Because of aliasing there is not a full overview of existing vibration. However, asynchronous vibrations are not the subject of interest of this paper.

4. Experimental Procedure

Vibrations of the turbocharger rotor blade are measured either on a combustion engine or on a gas stand. It is very difficult to produce a sustained and repeatable excitation of the blade in either test environments. To carry out the test it is required to steadily increase (or decrease) the rotational speed of the rotor blade in a controlled manner. The typical cycle is referred to as a ramp test where the rotor wheel speed is increased (or decreased) by controlling the throttle position (for engine) or turbine inlet gas flow/pressure (gas stand). Figure 6 shows a typical engine test cell arrangement. The advantage of testing on the "gas stand" is the ease of control. All input parameters like gas flow and temperature and through that turbo speed. Additionally on the gas stand the compressor is not in the loop with the turbine, so the load applied from the compressor to the turbine could be controlled as well. Most importantly the advantage of the on engine testing is that the engine represents much better original working conditions of the turbocharger like cylinder combustion pressure pulses or engine cycle pulses. These pulses make rotational speed fluctuating which is shown in Figure 5 for six cylinder engine, and it is clearly visible that one engine cycle contains six pulses of the cylinders. Engine cycles (separated by a dotted line in the Figure 6) can be detected because the cylinders are at different distances from the turbocharger. A dangerous situation arises when the wheel stays on a speed related to natural frequency as the resonance vibrations keep growing. Speed fluctuation strongly reduces that effect because wheel doesn't dwell on the resonant frequency to let vibrations grow.

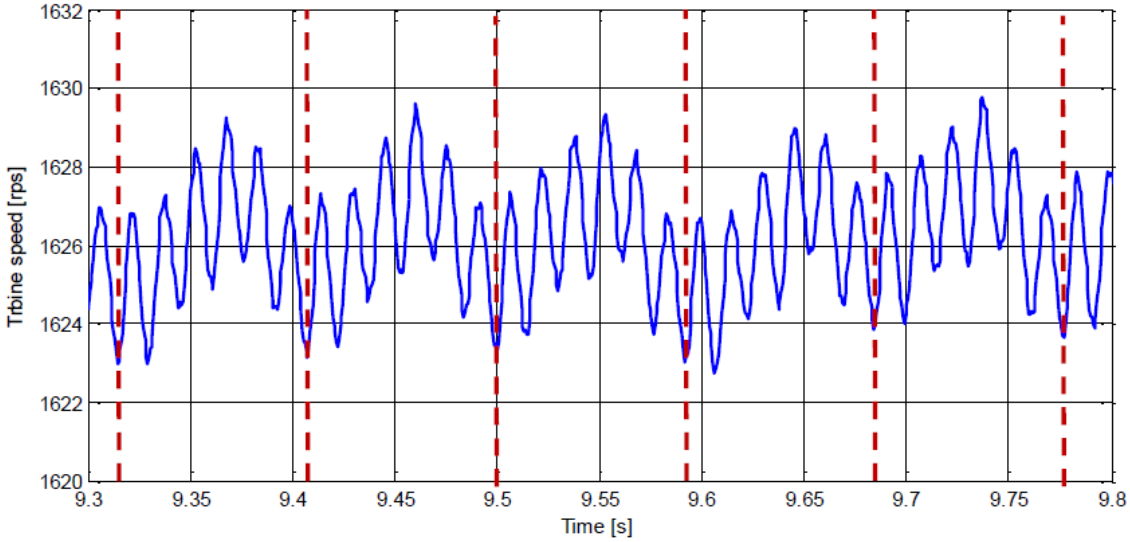

Figure 5. Speed fluctuation

The main advantage of the test is relatively high repeatability of measurements and the ability to scan a frequency range that will include at least one full order of vibration for all the blades. Another type of test, used mainly with strain gauge telemetry, was a dwell test where the operator tried to achieve speed with resonance vibration and stays on it to get the highest possible level of vibrations.

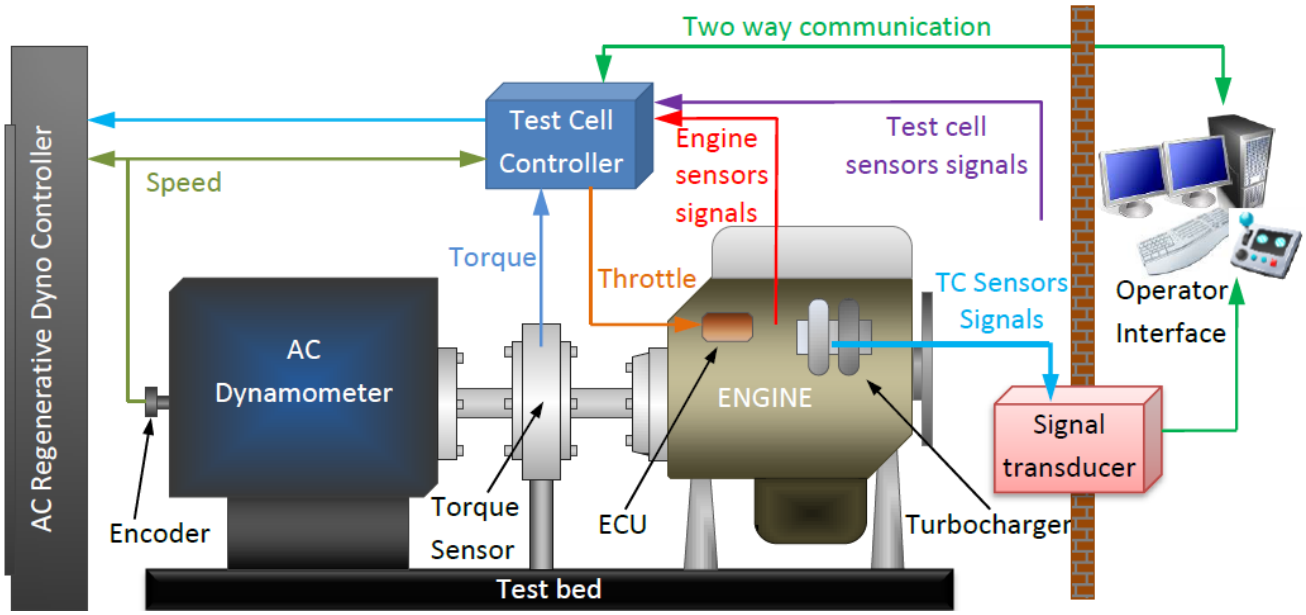

Figure 6. Typical Test Cell arrangement

5. Results of the Measurement

Both blade measuring systems acquire data in different way and therefore the results are presented in different ways. Strain gauge telemetry is base on FFT analysis, therefore, the overall strain, strain for specific order, strain for specific frequency range can be easily processed and displayed in realtime. Offline analysis except time domain, can present strain data in frequency or turbine speed domain. Great overview gives frequency spectrum of a speed-domain strain gauge signal called also strain map as shown in Figure 7, where x-axis is frequency, on y-axis turbine speed and strain is marked as range of colours, depends of its amount.

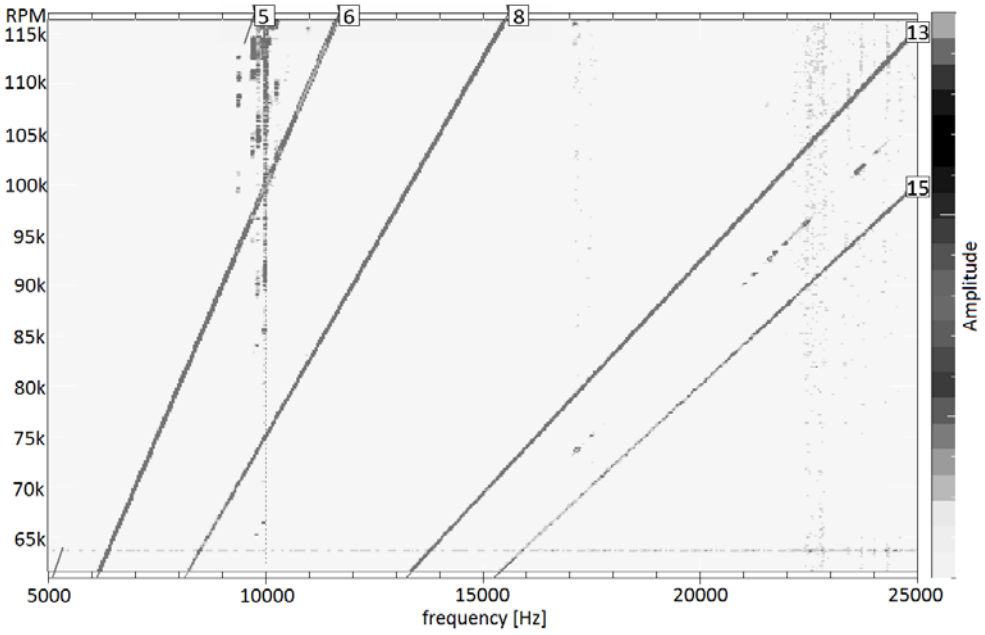

Figure 7. Frequency spectrum of a speed-domain strain gauge signal

One of the most often used ways to present blade vibration data for both techniques is Interference Diagram [19] or introduced in 1924 by Wilfred Campbell and known as Campbell Diagram [20]. This diagram presents turbine speed on abscissa (horizontal) axis and frequency on ordinate (horizontal) as shown in Figure 8. The steep lines represent successive orders, while the horizontal modes (resonant frequencies). It is quite probable for the synchronous vibrations to occur around the area where intersection points appear. Amplitude of this vibration is shown as area, curve or different size circles plotted on order lines. The main difference between Strain Map and

Campbell diagram is that the first on covers whole area and second usually only order or mode lines. But Campbell Diagram is not perfect it can only show one blade data or average of all blades. Another type of diagram complements this gap. All blades data can be seen on diagram like on Figure 9. The x-axis can have several variants like turbine speed, time or revolution number. Each y-axis corresponds to one blade, and shows vibration amplitude. Finally the others form of results presentation is bar diagrams which shows highest deflection for each blade, and second shows frequency at which that amplitude appears.

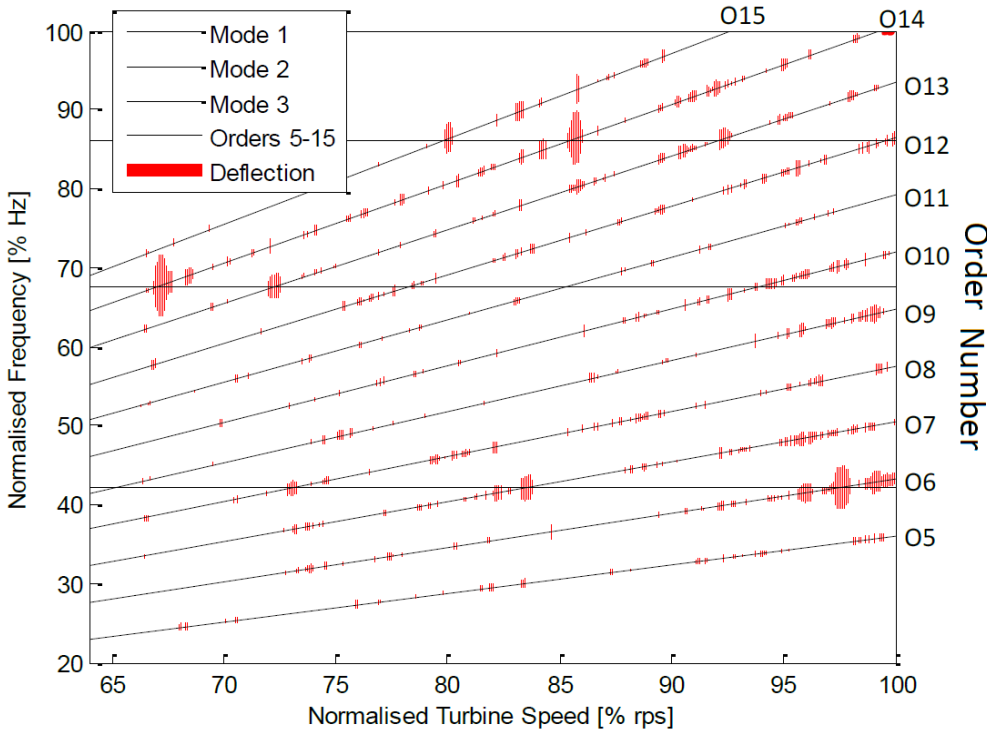

Figure 8. Example of Campbell diagram [3]

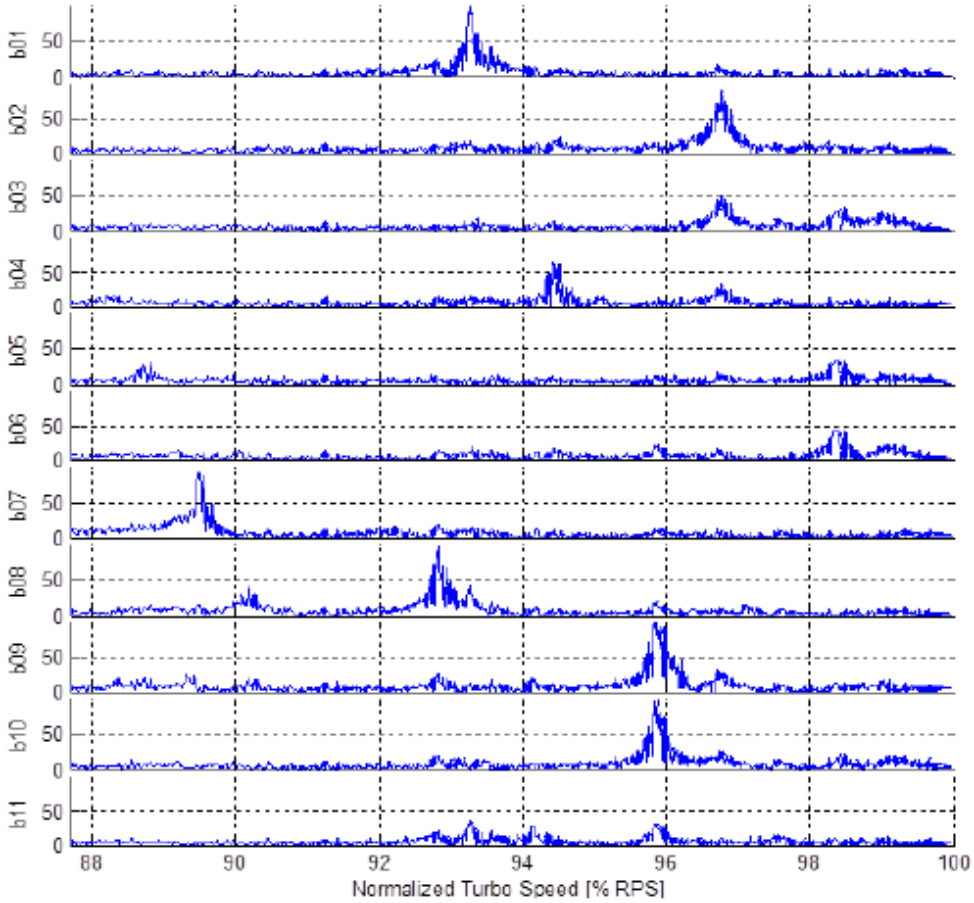

Figure 9. Example of all blades diagram [3]

In most cases, because of huge amount of data to process, Tip Timing Technique data are achieved in post process.

6. Discussion & Conclusion

Strain gauge based method as well as Blade Tip Timing has its advantages and disadvantages, but in order to get a full picture, both methods must be used simultaneously, as they well complement each other. Acceptable and good correlation can be achieved between both measurement systems using Finite Element Analysis but due to measurement uncertainty not always identical results are obtained. Cheaper in use, easier and faster to apply, and measuring all blades simultaneously Blade Tip Timing method is now increasingly used in the turbocharger industry. However intrusive and more expensive but giving higher quality data strain gauge still has a strong position if only because of the historical data from many years of use.

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