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Turbocharger blade vibration: measurement and validation through laser tip-timing

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ABSTRACT

High Cycle Fatigue (HCF) of turbine blades is a major cause of failure in turbochargers. In order to validate changes to blades intended to reduce fatigue failure, accurate measurement of blade dynamics is necessary. Strain gauging has limitations, so an alternative method is investigated.

A description of the tip-timing method is given, applied to turbocharger testing. The advantages and disadvantages of laser probes are assessed. Examples of output data and interpretation are presented and compared with computer simulation.

It is shown that laser tip-timing technology gives a more complete view of turbine vibration than the alternative measurement systems.

Acronyms

ATTEP Advanced Turbocharger Technology Engineering Project

CAE Computer Aided Engineering

CAD Computer Aided Design

CTT Cummins Turbo Technologies

FEA Finite Element Analysis

FEM Finite Element Method

HCF High Cycle Fatigue

1. INTRODUCTION

As a general rule, the phenomenon of vibration is a common effect for all bodies that posses a mass and elasticity. In the turbocharger industry, vibration not only has a direct impact on durability and warranty costs, but also plays an important role in the end user's perception of vehicle quality [1]. Additionally, it can lead to an increase of a risk of subsequent component damage. Therefore the design of each sub-component of a system requires a consideration of its oscillatory behaviour and the structural parameters that drive any problematic response. That is why an accurate measurement of blade dynamics is necessary when designing a turbine wheel. Although strain gauging has been used for this purpose for many years, it has limitations, and so an alternative method has been investigated.

Cummins Turbo Technologies (CTT) and the University of Bradford have collaborated on the Advanced Turbocharger Technology Engineering Project (ATTEP). In this project, a tip-timing method which has been proven in the aero industry, but not on small turbines as used in turbochargers, was combined with recently developed finite element simulation techniques to provide a means of assessing the susceptibility of turbine blades to High Cycle Fatigue damage. The tip-timing method uses a set of optical probes that measure the blades arrival times and uses the time differences to calculate blade deflections within a time domain. In comparison to the existing strain gauge based testing procedures, the tip-timing represents a non-invasive approach, which is more likely to record real-life turbocharger operation parameters. What is more, tip-timing can provide complete information about the total rotary system, returning a great amount of data for further system analysis, rather than the limited data related to a single blade obtained through the more conventional strain gauging approach.

The resulting findings can then be used to optimise the design of turbine wheels, making them more resistant to mechanical loads and their corresponding vibrations. Ultimately, more robust, durable and reliable turbochargers could be produced as a result of this work.

This paper will give an overview of the tip timing method, along with an assessment of laser probes relative to different types of probe. Some test results and their correlation with simulation will also be discussed.

2. TIP-TIMING METHOD

The tip timing method used involves a very accurate measurement of the times at which the blades pass by a series of unequally spaced sensors. In this case, the sensor set consists of a series of laser probes mounted in the turbine housing which reflect a beam of light off the blade as it passes. If the blade is rotating at a constant rate, a particular blade should pass each sensor at a predictable time. Deflection due to vibration causes the blade to pass the sensor either earlier or later than predicted, hence the difference of these times can be used to calculate the deflection from the initial position for each individual blade. By using a powerful laser with a small point of focus and a very fast data acquisition card, the system is able to detect vibrations of less than 0.2um at the working speed of the turbocharger.

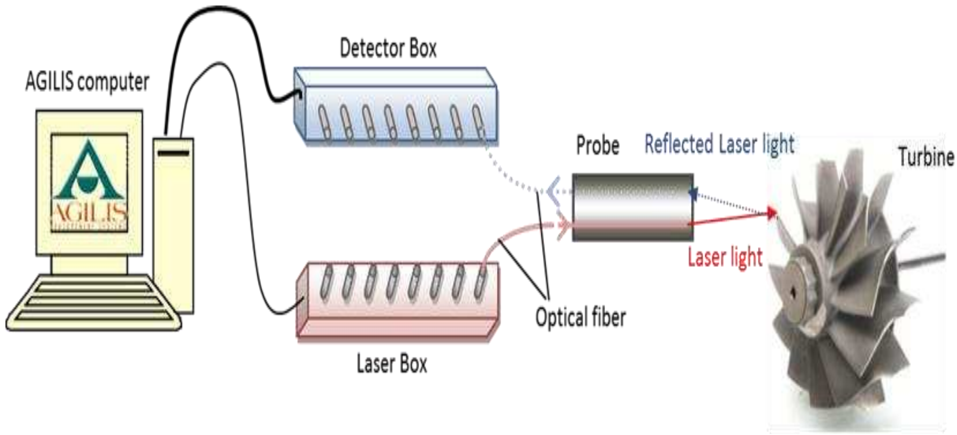

Figure 1 – System Setup

For synchronous vibration, the order of interest is defined and the software tries to match the vibration measured to that order and gives the amplitude and level related to the matched order. When there is simultaneous vibration at different frequencies (different modes), the system is still able to recognise and separate modes, provided the appropriate number of sensors are used. By increasing the number of sensors, several modes of vibration can be detected simultaneously, with 2N+2 sensors required to analyse N modes. In this case, 8 sensors were used to analyse 3 modes.

Processing the data from all 8 sensors gives the amplitude and frequency of the vibrations occurring during the measurement. Specific orders of vibration can be tracked, allowing examination of the influence of perturbations in flow caused by probes or guide vanes.

2.1 Tip-timing software with output data examples

One of the biggest advantages of the tip timing system is that it collects data from all the blades simultaneously, so this gives the opportunity to compare their vibration, which was not possible until now. Specific orders and frequencies can be tracked, and data can be plotted in a variety of different ways, allowing a more detailed understanding of the underlying physics to be gained.

Synchronous vibration analysis is based on Least Squares Model Fitting (LSMF) which curve fits sine waves to the data [2], so the first thing to determine is the order of vibration which is of interest for a given sample. The software checks which order best fits the sample and displays the data in the form of a bar chart (Figure 2). The highest bar is the most probable order of vibration measured in the given data sample.

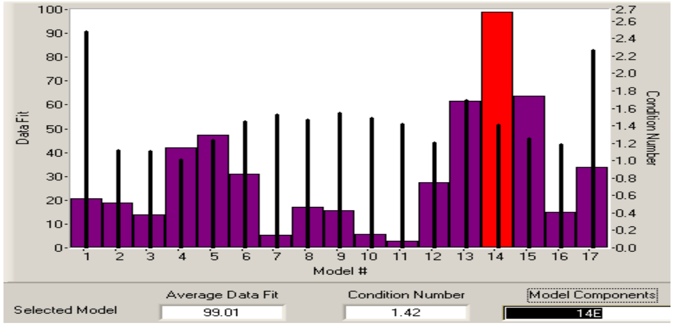

Figure 2 – Chart of Model to Test Data fit

Another way to determine the order is analysis of the Campbell diagram. A good example of this can be seen in the following figure. The example clearly shows vibrations occurring in the place where the order line crosses the mode line. The test turbine had 14 nozzles, causing this order of vibration to be strongly excited. The test was conducted in the speed range where this order crosses the 2nd and 3rd modes. In those places, the highest vibrations seen during the entire test occurred. Another major source of vibration is order 7 at the point where it crosses the first resonant frequency. The other significant vibrations in this example are order 6 mode 1, order 10 mode 2 and order 13 mode 2 and 3.

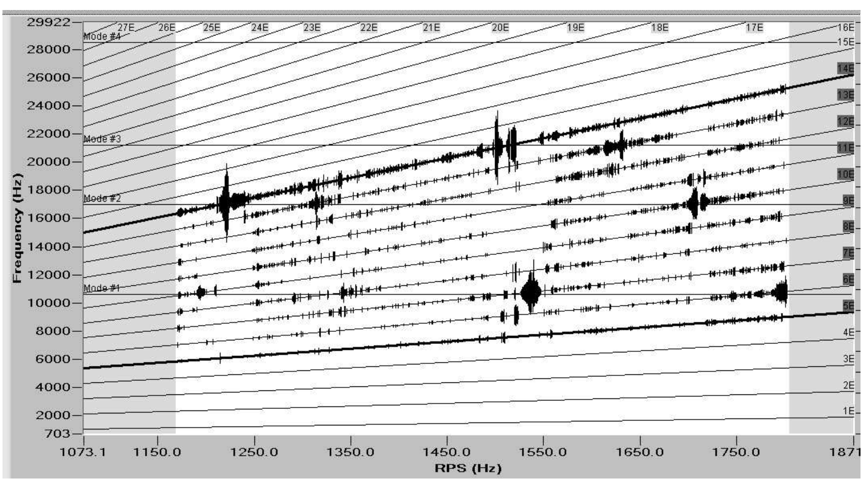

Figure 3 - Campbell Diagram showing occurrance of vibration at order / mode intersections

The next step is to analyse the data for the previously selected order. This yields a plot of frequency distribution across the blades of the wheel which shows the distribution of speeds at which a peak appeared for the selected order of vibration and the corresponding resonance frequencies for all blades (Figure 4).

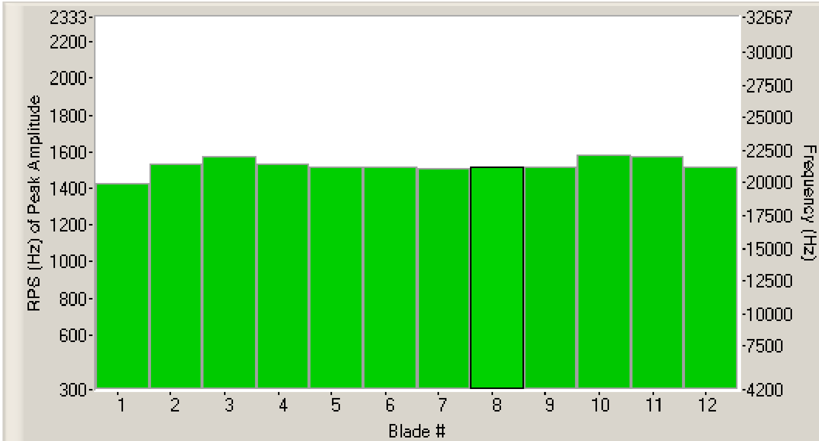

Figure 4 –Frequency Distribution Chart for order 14

Further analysis gives the relative amplitudes of vibration for each blade at that frequency (Figure 5)

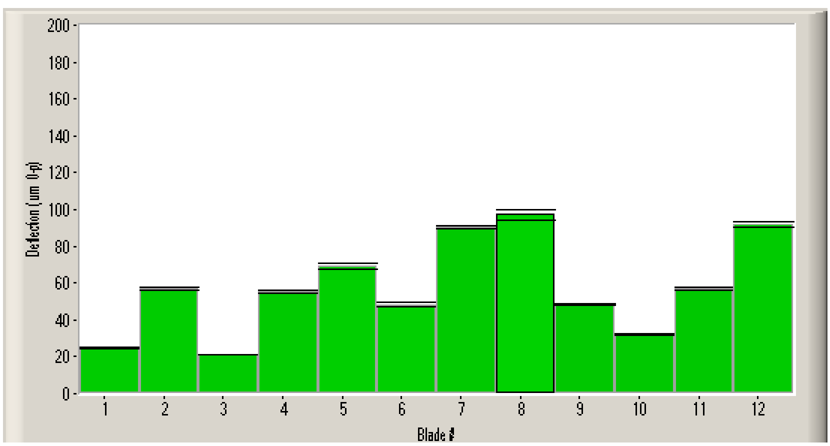

Figure 5 – Relative Amplitude Chart

Cross coupling of vibration between blades has a significant effect on the durability of the blades, this phenomenon can now be studied closely to better understand its effect and to design more resistant blades.

Figure 6 shows the output from a test of an 11-bladed turbine. The x-axis shows the rotational speed of the turbine and the y-axis shows the blade number. For each of the eleven horizontal lines, the vibration amplitudes of individual blades at a given speed is shown. The spectrum at the bottom of the graph indicates the quality of fit of the data to the order of interest. Black vertical lines show the points where individual blades reached the highest amplitude of vibration.

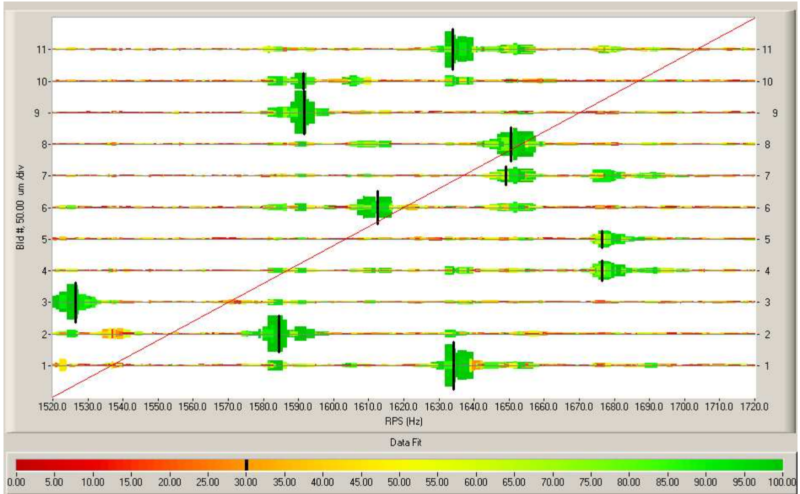

Figure 6 Typical vibration results

This example clearly shows the phenomenon of cross coupling, when two or more neighbouring blades resonate at the same or very similar frequencies. This is evident for pairs 1 and 11, 4 and 5, 7 and 8, 9 and 10. It can also be observed that there are large differences in amplitudes of vibration between blades. This data is essential in determining the actual variation in behaviour of blades relative to the nominal design.

3 COMPARISON OF LASER PROBES WITH OTHER SENSORS

There are a number of advantages of the optical sensors which are used in the tip timing method relative to the old method using strain gauges. There is always some question about measurements where the sensor needs to be attached to the component being measured – is the measurement affected by the act of measuring? The fact that the sensors are mounted in the housing means that there is no need to transmit the signal via a wireless data transmission system, which is not easy to install and creates the possibility of distortion of results. This also means that numerous wheels can be tested in the same housing, giving a direct comparison between wheels without the expense and difficulty of applying a large number of strain gauges.

The use of strain gauges requires the rotor speed to be held at the point of resonance so that a reliable measurement can be taken. It is therefore characterised by poor repeatability as it is difficult to maintain all parameters constant simultaneously. For example, maintaining the same turbine speed for some time can change the engine exhaust temperature, and hence the amplitude and frequency of vibration. It is only possible to measure total strain at the point of application of the gauge. If there is more than one modal vibration occurring at a given time it is easy to confuse them, as the sum of amplitudes of the overlapping signals could be mistaken for a strain peak.

The high rotational speed of the turbocharger and very high temperatures in the turbine stage provide a real challenge to sensors. Although tip timing will work with any kind of sensor which provides a clean trigger signal, the response time required for the high frequency vibrations under investigation means that many are not suitable. The best type of proximity sensor currently available for this application is a reflective laser sensor. These are characterised by very high working speed, a small focus point which further improves their accuracy and resistance to extremely high temperatures. They are also immune to any kind of electromagnetic interference such as produced by the dynamometer (as may be a problem with a capacitive sensor) and the ability to detect all types of materials (magnetic sensors detect only ferromagnetic). Moreover, these sensors require very little space for installation in the housing since they are smaller than most other sensors.

4. MATHEMATICAL MODELLING AND SIMULATION

For complete analysis of the system, it is crucial to accurately identify the locations and mode shapes of vibrations and to quantify probable mechanical loads [3]. Mathematical modelling and simulation very often supports (and sometimes even eliminates the need for) complete system testing, both for linear and non-linear systems, which is a great benefit of the current methodologies under development.

Simulations can be performed using various scientific tools, but Finite Element Analysis (FEA) provides the capability of computing the response of a structure to applied loadings, even when a simplified analytical solution is not possible to achieve (e.g. where nonlinearities are involved), or when the full analysis needs to include multiple interacting aspects of physics (e.g. fluid flow, heat conduction)[4].

In the ATTEP project there were many reasons to perform Finite Element Analysis. First of all, it is much quicker than testing, and therefore a more cost-effective solution, allowing many options to be explored without the need to create expensive hardware. Additionally, it may increase confidence in the expected behaviour of a mechanical structure, as well as confirm and support obtained test results

For modelling and simulation purposes, a combination of the Pro/ENGINEER software and ANSYS Workbench platform was used. A 3-dimensional solid model, described in terms of parameters, dimensions and features, was used in the downstream process via export into the ANSYS Workbench software. This allowed numerous load cases (including static-structural simulation and modal simulation) to be assessed in a variety of combinations. As a result, the understanding of a turbine as a system and the methodology of its design processes could be explored.

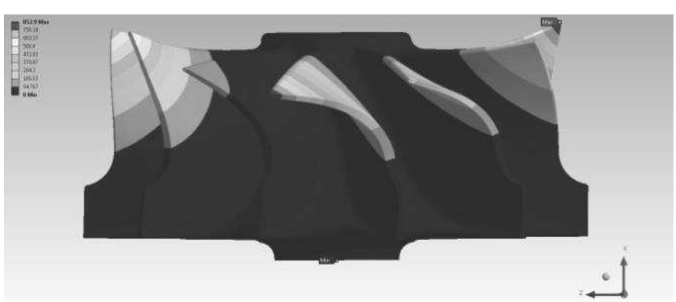

Figure 7 Example of an output from modal simulation

5 SIMULATION AND TEST RESULTS CORRELATION

In order to minimise possible variation caused by model simplifying assumptions such as cyclic symmetry, the CAD turbine models represented a complete wheel, rather than an individual blade [5]. This approach was believed to produce more complete results, providing information about the inter-coupling effects of the blades (e.g. nodal diameters, wheel bending or torsional modes) and giving a more realistic frequency distribution than is obtained using single blade models. The simulations and their inter-connectivity incorporated the effects of turbine geometry and major environmental conditions (e.g. temperature of exhaust gases, rotational speed, and prestress conditions).

The output of the static-structural analyses was a specific stress (equivalent stress, maximum principal stress, and normal stress) distribution for the turbine in areas of interest as can be seen in Figure 8.

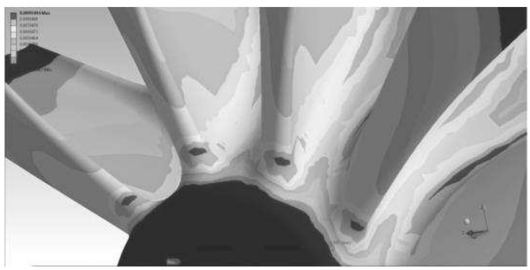

Figure 8 Example of an output from static-structural analysis

At the same time, modal analysis returned calculated natural frequencies of the wheel, together with their complex mode shape visualisations. It may be verified that the maximum number of natural frequencies for an object is the number of FE nodes. Nevertheless, due to the characteristics of the turbine forcing function, the effective vibrations diminish with the increasing frequency, or may even be impossible to achieve (e.g. for low running speeds a higher order forcing function that would match the higher frequencies of vibration may not be obtained). That is why the number of natural frequencies that were investigated has been limited to the fifth mode of vibration. The analysis of the simulation results involved a classification of the frequencies, based on their value, nodal diameters and mode shapes. This allowed plotting of the frequencies on a Campbell Diagram, which represents a vibratory response spectrum of a rotary system. (Figure 9).

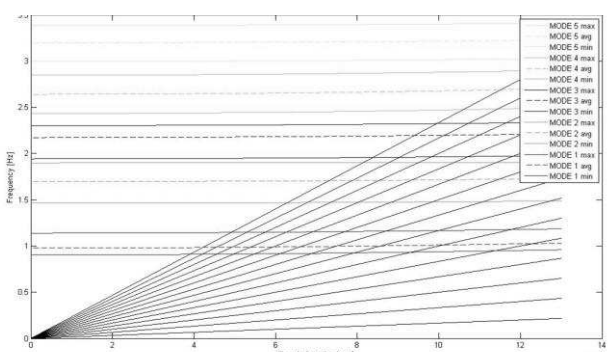

Figure 9 Example of Campbell Diagram

The Campbell Diagram shows the expected synchronous forcing functions (corresponding to harmonic orders of the rotational speed). Intersections with the modal frequency ranges (solid and dashed grey lines) are of concern, as they are points where resonance may occur

During the validation process, processed data from simulation, tip-timing, telemetry and frequency survey tests were merged together. The post-processing of results, involved the use of Agilis, Microsoft Excel and MATLAB software, along with some CTT proprietary code, which enabled an effective processing of data and allowed plotting various graphical representations that were considered to be essential for results analysis. Some of the results from a tip timing test are plotted below on a Campbell Diagram, clearly showing that the test results fall within the frequency range predicted by the FE analysis.(Figure 10)

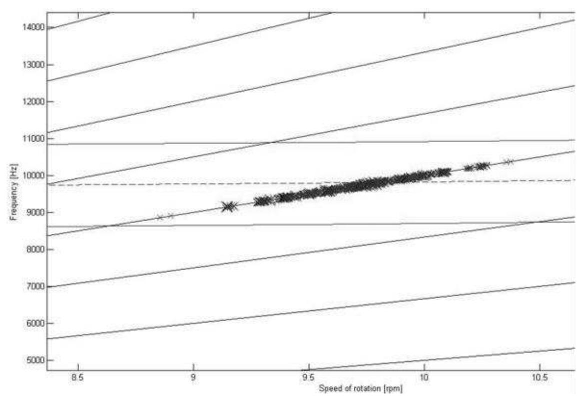

Figure 10 Example of Campbell Diagram validation with 1056 test points plotted

Validation of the results proved that the new method is capable of a successful prediction of modes 1, 2 and 3 resonant frequencies. The demonstrated accuracy for the new methodology was found to be beyond 99.9%.

6. SUMMARY

After one year of research some significant improvements have been made. They include the application of tip-timing method and advanced simulation techniques for the prediction of vibration of turbine blades.

Knowledge about turbine vibrations has been extended, enabling the fulfilment of the project's objectives. The effects of various turbocharger operation parameters have been investigated, by both simulation and tests.

The tip timing method has been validated as a reliable method of measuring vibration in turbocharger turbine blades. New techniques have had to be developed in order to achieve comparable results to other measurement methods. The techniques allow simultaneous measurement of multiple modes of vibration under complex forcing conditions

Modelling and simulation techniques have been successfully applied to model various turbine wheels, and accurately predicted their natural frequencies and corresponding mode shapes (for up to blade mode 3), which could be visualised using the ANSYS Workbench software.

Results from the experiments were used for validation of the new design procedure. The validation was performed by comparing both experimental and modelled data, and has been shown to be positive by good cross-correlation of results.

In conclusion, a new method for turbine design has been formulated and validated. The analysis of validation results showed a good match between modelled and experimental data. The aims and objectives for the project have therefore been achieved.

Acknowledgement

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