SIMULTANEOUS MEASUREMENT OF AIR FLOW AND BLADE LOADING CONDITIONS IN AN AIR-COOLED STEAM CONDENSER FAN

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SUMMARY

Large axial flow fans in air-cooled steam condenser fan arrays often experience distorted inflow due to the presence of other fans or windy conditions. The purpose of the project was to design a system which could simultaneously measure the air flow entering the fan as well as the loading conditions on a single composite fan blade as a function of its rotational position. The system was installed at a power station in South Africa and tested for a variety of weather conditions.

INTRODUCTION

Air-cooled steam condenser fan units

In a steam turbine cycle, water is boiled to produce steam which is then used to drive a turbine to generate electricity. Once the steam has passed through the turbine, it has to be condensed in order to complete the closed-loop cycle. In a direct cooled cycle the low pressure turbine exhaust steam is condensed by using either water or air as the coolant. Kröger [1] states that in arid regions where there is little or no cooling water available, air-cooling is the only viable method of heat rejection; this is known as dry cooling. In direct cooled thermoelectric power plants where air is used as the cooling medium, mechanical draft air-cooled steam condensers (ACSCs) are often used to condense the low pressure steam. In this way no water is consumed in the cooling process and the plant's total fresh water consumption is much less than that of a plant employing wet-cooling.

In a direct cooled steam turbine cycle with an ACSC, the turbine exhaust steam is ducted to steam headers which run along the top of a number of ACSC fan units. A fan unit of the facility at which measurements were taken, situated on the periphery of the ACSC, can be seen in Figure 1.

The ACSC fan unit consists of an axial flow fan that is located beneath and blows air through inclined finned tube heat exchanger bundles. The inclination of the heat exchanger bundles maximizes the available heat transfer surface area and is known as an A-frame configuration. Here steam condenses inside the finned tubes as a result of the heat transfer brought about by the ambient air being forced through the heat exchangers by the fan.

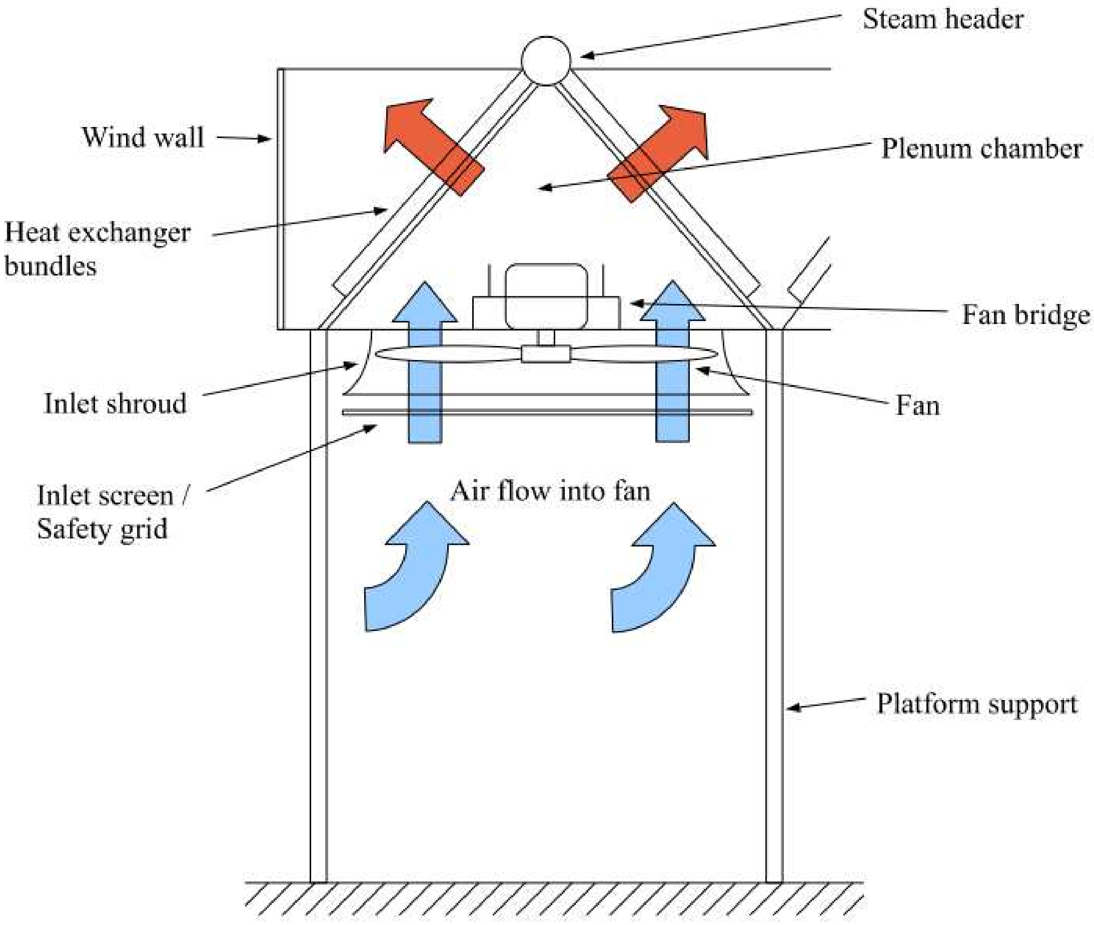

Figure 1: Peripheral ACSC fan unit

Problem definition

ACSC fan units are placed in an array of hundreds of individual units. According to Thiart and Von Backström [2] fans located in such an array are subject to distorted inflows (seen in Figure 2) due the presence of buildings, other fans and wind. One of the primary concerns is that the inner fans induce cross-flow in front of the fans situated on the outer edges of the platform. This cross-flow, which is increased by unfavourable wind conditions, causes distorted flow into the fans, which then causes a varying pressure distribution across the fan blade and induces fluctuating mechanical loads on the blades as they rotate.

When a fan or any other form of rotating machine is being designed, the designer needs to account for any variable loading which might occur during the operation of the machine. The actual loads experienced by an axial flow fan are not always available during the design phase. However, once the fan is in operation, the loading on a rotating fan blade can be measured for a variety of adverse inlet conditions. The data obtained from these measurements can be used to improve the blade design by taking into account the fatigue life of the blade due to oscillating loads.

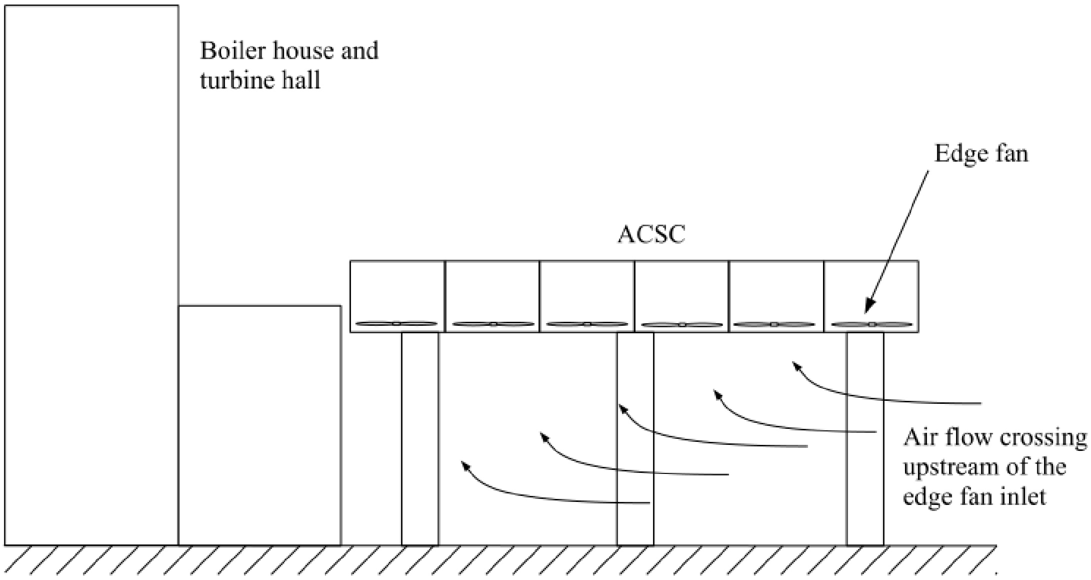

Figure 2: Causes of distorted inflow

Project objectives

The primary objective of the investigation was to develop a measurement system that would be able to measure the stresses within the neck of a fan blade during operation. The system must be able to measure, in real time, the ambient conditions and the effect thereof on the fan blades and gearbox. To achieve this goal, various measurements regarding the air flow into the fan and the blade loading conditions are required. These measurements are:

1. Ambient weather conditions
2. Loading at the blade neck as a function of the blade's position
3. Stresses and torque exerted on the fan shaft
4. Inlet air flow velocity and temperature
5. Air flow at the heat exchanger outlet

FULL-SCALE MEASUREMENTS

Fan blade and shaft loading

As a result of the aerodynamic loading, stresses exist within the fan blade. These stresses are expected to vary as the fan rotates due to the change in static pressure and air flow patterns on different sides of the fan. Blade loading can easily and reliably be determined with strain gauge measurements at the neck of the blade. A single fan blade was fitted with strain gauges in order to measure the bending strain on the blade during the rotation of the fan. Strain was measured in the flap- and lag-wise directions. The strain gauge setup on the blade can be seen in Figure 3.

Similar experiments have been conducted by Xu *et al.* [3]. They placed strain gauges at various locations on the blade to compare experimental stress values to results obtained in their finite element analysis of a 1.829 m diameter fan. Simms *et al.* [4] also used strain gauges to measure the bending of the blades on a 10 m diameter wind turbine.

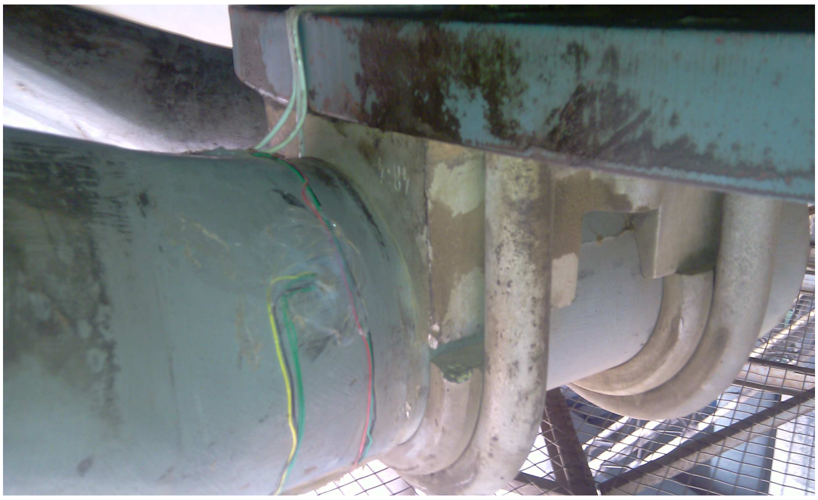

Figure 3: Strain gauge placement on fan blade

The measured strain was converted to a bending load at the blade neck by performing a calibration with a load cell and ratchet strap. The strap was placed over the blade and fastened to the safety grid with a load cell between the strap and grid at one of the ends. The strap was tightened and strain measurements recorded for a variety of loads.

The loading exerted on the fan gearbox was measured with strain gauges installed on the low speed shaft. These strain gauges were configured to measure the bending and torsion, and can be seen in Figure 4. Bending was measured by two sets of strain gauges placed 90° apart. An imbalance will produce a constant bending strain while cyclical loads will only be produced as the shaft turns through a specific angle.

Figure 4: Strain gauge placement on shaft

Full-bridge strain gauge configurations were used for all the bending and torsion measurements in order to compensate for temperature effects and axial strains. On the fan blade, axial strains are caused by centrifugal loading while the mass of the fan rotor and aerodynamic forces result in axial loading of the fan shaft.

Fan blade position

In order to analyse the strain gauge data and correlate it with air flow measurements, it was necessary to know the location of the blade at all times during its rotation. A Hall-Effect proximity sensor was used which produces a voltage output relative to the proximity of a metal object due to changes in the magnetic field.

To determine the exact location of the blade during the rotation of the fan, the proximity sensor was attached to a threaded rod extending out below the bridge where the motor and gearbox is situated. The proximity sensor was positioned above the 30 mm diameter bolts attaching the coupling flange to the hub of the fan. In order to produce the desired once-per-revolution signal a hexagonal nut was attached to the top of one of these bolt heads to act as a protrusion for the proximity sensor to detect. Figure 5 shows how the proximity sensor was installed.

Figure 5: Blade position sensor

Fan inlet air flow conditions

A measurement of the flow profile entering the fan provides a good indication of the distorted incoming air as a result of windy conditions. This incoming flow field, measured at the safety grid below the fan, can then be used to further analyse the loading that the blade experiences as it rotates.

The measurements taken for this project had to be time-dependant and not steady-state. For this reason the use of ultrasonic anemometers was an attractive solution. Ultrasonic anemometers work by transmitting ultrasonic pulses between probes and then, by using the time of flight of the pulses, the wind speed and direction can be calculated.

The final setup for measuring the inlet flow field consisted of six 2-axis ultrasonic anemometers which were mounted on six frames which were placed on the safety grid below the fan. Propeller anemometers were used in conjunction with the ultrasonic anemometers to measure the out-of-plane flow velocity. As such, each frame formed the basis of a measurement station that had sensors to measure the 3-dimensional air flow velocity vector and temperature. The frames were constructed from steel square tubing and each had a plastic cover within which all the wires were connected and kept protected from the elements. These stations could then be placed at different locations at the fan inlet depending on the purpose of the test being conducted and can be seen in Figure 6.

Figure 6: Frame with anemometers and thermocouple

Measurement of the air inlet temperature enables the calculation of the air density, which in turn allows the calculation of mass flow rates. Having measurements for the inlet air temperature also makes it possible to detect when hot air recirculation is taking place. Hot air recirculation is a phenomenon where the air that is heated up by the steam in the heat exchangers gets drawn back into the fans due to windy conditions. To measure the temperature of the inlet air, one thermocouple was placed on each of the six measurement stations.

Figure 7: Frames placed at fan inlet

Once the frames had been assembled and all the sensor connections were tested, the frames were placed along the centerline of the safety grid below the fan. The ultrasonic anemometers were oriented in such a way that they could measure the air flow in the primary plane while the propeller anemometers measured the flow in the out-of-plane direction. A photo showing how the frames were placed on the safety grid can be seen in Figure 7. Shielded cables from each of the measurement stations were fastened to the safety grid with cable ties and taken up along the side of the fan casing to the data capturing system.

DATA CAPTURING SYSTEM

Figure 8 shows an overview of the data capturing system configuration. The diagram describes how the measurement devices on the rotating fan and the devices placed at the fan inlet and bundle outlet were connected to the data capturing system. The data capturing system has been divided into three parts: wireless data capturing, wired data capturing and data synchronization and recording. Wireless data capturing refers to the measurements taken from the rotating fan assembly while wired data capturing includes all of the measurements taken from stationary devices at the fan inlet and bundle outlet. Each of the components shown in the diagram is discussed in the following sections.

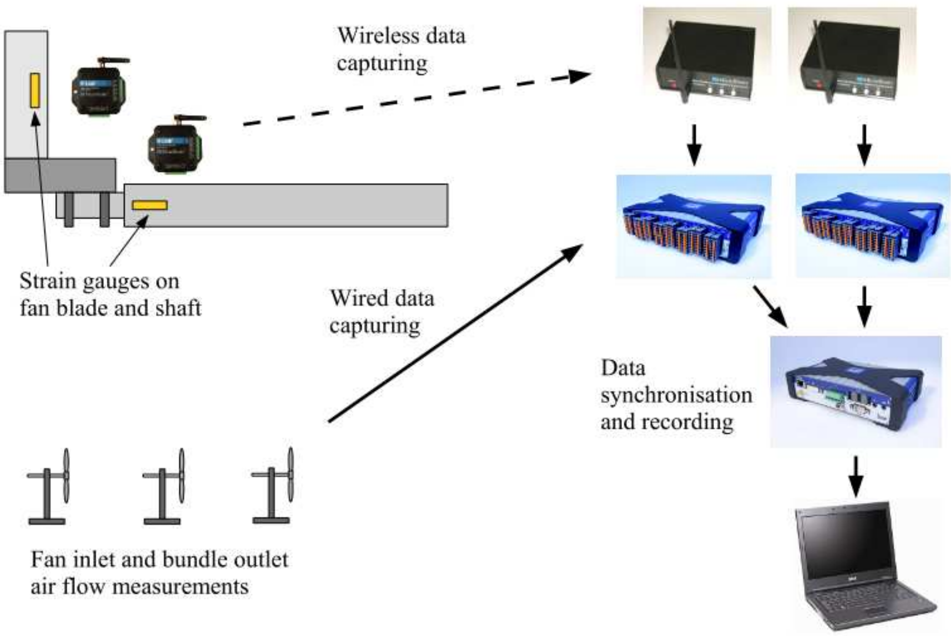

Figure 8: Data capturing system overview

Wireless data capturing from fan rotor

In order to reduce the amount of equipment attached to the fan, MicroStrain V-link wireless bridge amplifiers were used to transmit data from the strain gauges to a base station. Each V-link has four fully differential channels with on-board sensor excitation and shunt calibration. Two V-link units had to be used to capture the measurements from the 6 strain gauge channels. The bridge amplifiers were attached to the fan hub with two 4 mm screws each and can be seen in Figure 9.

As stated, these units transmit to a base station which can either be connected to a PC via a USB connection or convert the digital signal transmitted from the node to an analogue voltage output. For the purpose of this project the analogue base stations for the V-link units were used so that the V-link units can be combined with other wired sensors and used in conjunction with a simple data capturing system.

Wired data capturing

In addition to the measurements recorded with the wireless system attached to the fan hub, there was an array of sensors placed at the fan inlet on top of the safety grid as well as at the heat exchanger bundles. All of these sensors were connected to the data capturing system with shielded cabling. Once it was decided which sensors were to be used, it was found that the data capturing system required a total of 31 measurement channels. As such, the data capturing system required hardware with a large number of channels from which data could be recorded simultaneously. Six of these channels were from the two V-Link units while the rest were allocated to the array of stationary sensors. Fortunately, most of the channels would simply need to record analogue voltages or currents and as such there was no need for a complicated data capturing system with the capacity to record data from a large variety of signal sources. This simplicity allowed the specification of a data recording system with a very low cost per channel, which in turn granted the capacity to measure simultaneously from most of the sensors. Due to previous experience and adherence to the requirements of the planned data capturing system, the decision was made to use two HBM QuantumX MX1601 units. Each of these units has 16, individually configurable, channels for normalised voltage and current signals and also has the capacity to provide power to the various sensors attached to it.

Figure 9: MicroStrain V-Link units attached to fan hub

Data synchronization and recording

Even though each MX1601 is capable of recording its own data, a problem arises when there is a requirement for the data from both units to be accurately synchronised. The data could be manually synchronised using the time stamp from each reading, but at a recording rate as high as 150 Hz and no way to correlate the starting time of each unit, this was not a valid option. As a result of this difficulty it was decided to use the HBM QuantumX CX22W to not only synchronise the data, but to also record it and power the two MX1601 units.

The CX22W was connected to the two MX1601 units via FireWire which was used for data transfer as well as power supply. The CX22W has an embedded Windows operating system and bundled HBM Catman AP software which is used for real-time graphing and data recording. A laptop was connected via wireless to the CX22W from the walkway outside the plenum chamber or from a vehicle parked below the ACSC.

MEASUREMENT RESULTS

Figure 10 shows the fan unit as seen from the top. The solid black line represents the edge of the ACSC while the grey fill indicates the presence of the surrounding fan units. The fan blades rotate in a clockwise direction through the indicated azimuth angles.

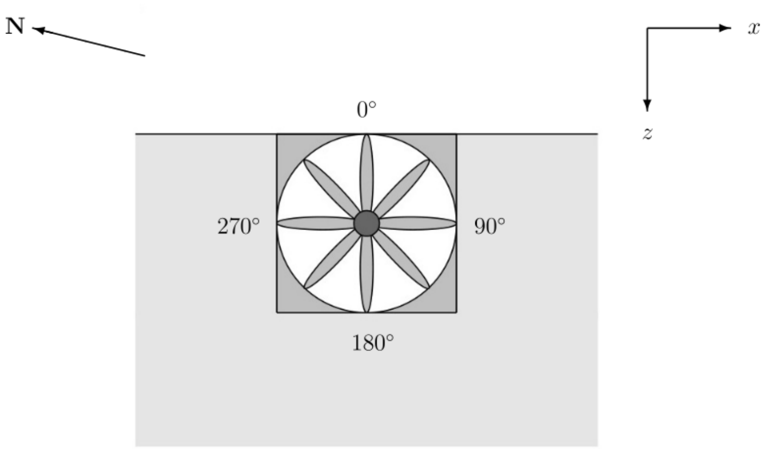

Figure 10: Directional conventions and fan blade positions

Inlet air flow and its effect on average blade loading

Figure 11 presents the air flow measured in the fan axial direction on a specific day. During this day the wind was blowing from a Westerly direction until 17:00 where it suddenly changed to an Easterly direction. At this time the wind speed also increased. The sudden change in wind conditions caused an increase in air flow into the fan.

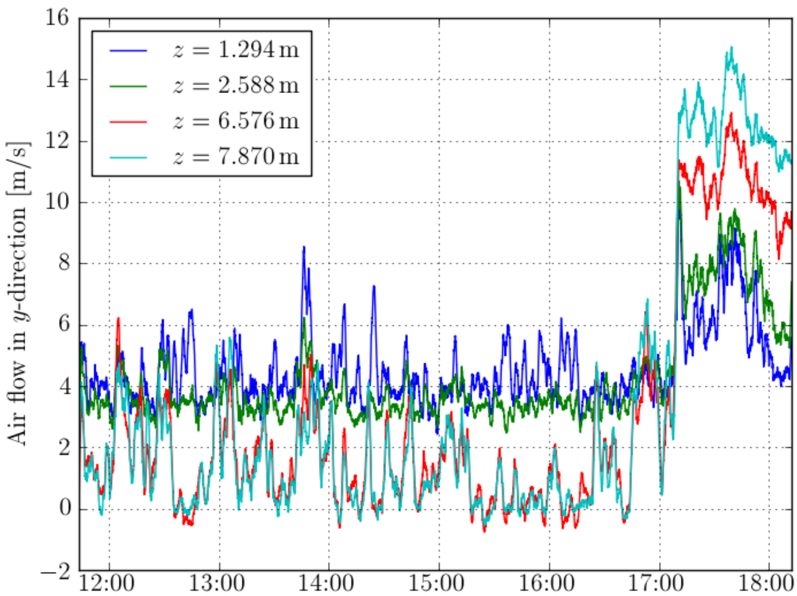

Figure 11: Inlet air flow measurements

Figure 12 shows the averaged dimensionless resultant blade loading measured on the same day as the air flow data presented in Figure 11. The resultant load is the vector sum of the flap- and lag-wise bending loads. The blade loading undergoes a sudden decrease at the same time as the increase in air flow at the fan inlet. The reason for this is that according to the fan performance curves obtained by Kröger [5], the static pressure rise over a fan decreases with increasing air flow. It can be assumed that blade loading is proportional to static pressure rise and as such it is expected that the blade loading will decrease with increased air flow. The decrease in blade loading as a result of increased air flow was approximately 20%.

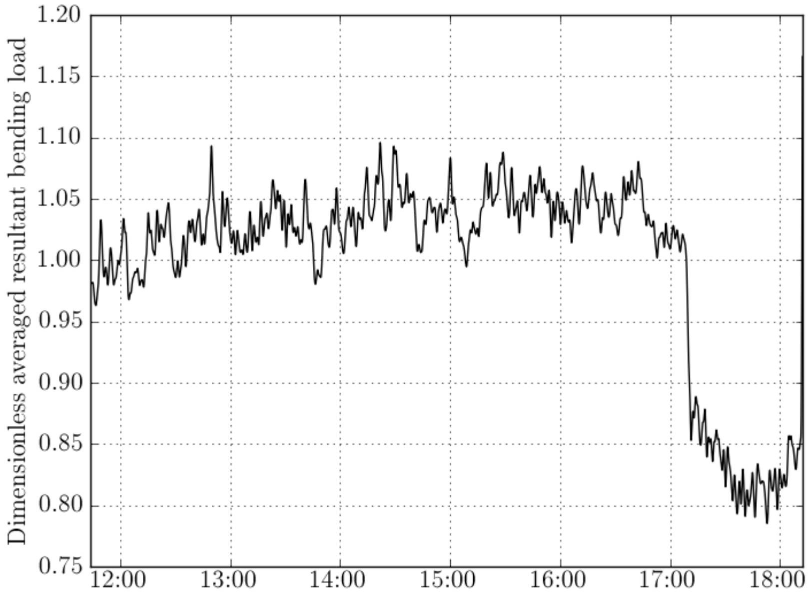

Figure 12: Averaged blade loading

Blade loading as a function of rotational position

Figure 13 presents the resultant blade loading over a short period of time as a function of the blade's azimuth position. It is clear that the blade loading is cyclical and that the loading pattern is repeated for each revolution of the fan rotor. The largest loading peaks occur at the 0° position, which is the windward side of the fan. This finding coincides with the research performed by Bredell *et al.* [6]. Through numerical simulation they also found that blade loading increases by approximately 50% for distorted inflow conditions. However, they only considered the once-per-revolution aerodynamic blade loading and not the blade's vibration.

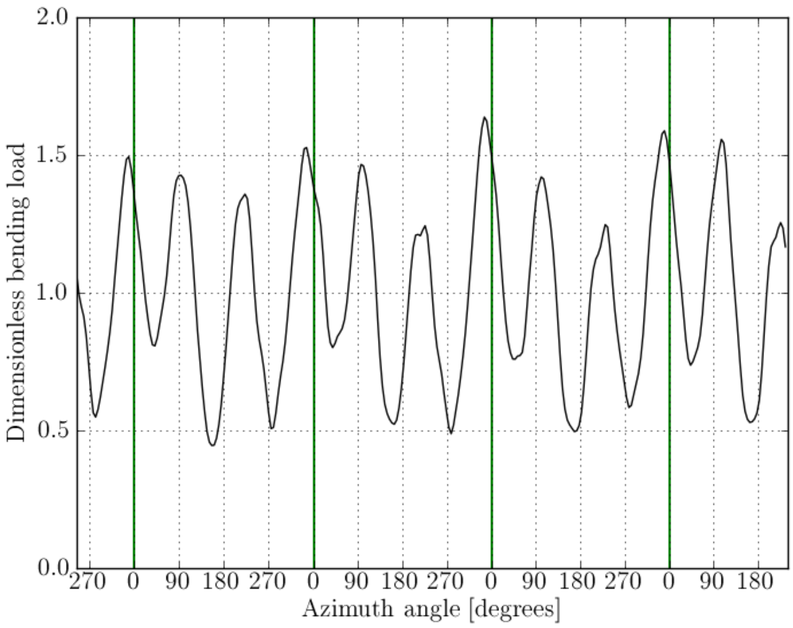

Figure 13: Dimensionless blade loading as a function of its position

In Figure 13, it is clear that the fan blade vibrates at a certain frequency and does not only displace as a result of the cyclically varying aerodynamic loading. Figure 14 shows a Fast Fourier Transform (FFT) of the blade loading data. The first dominant frequency is at 2 Hz, which is approximately equal to the rotational frequency of the fan. Another prominent frequency is at 6 Hz which is the approximate blade natural frequency as measured by Swiegers [7]. Taking into account that the fan completes two revolutions every second, it is clear from Figure 13 that the blade primarily vibrates at its own natural frequency.

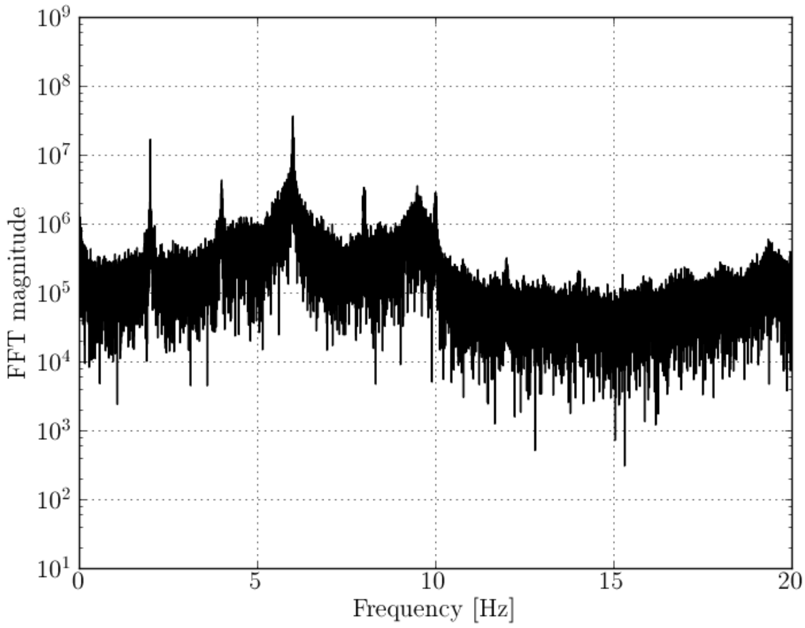

Figure 14: FFT of flap-wise blade loading

Shaft bending stress

Figure 15 shows stress measurements taken on the low-speed shaft. The cyclical bending stresses from the two orthogonally positioned strain gauge bridges are shown. It is clear that the shaft undergoes a once-per-revolution load due to the peaks from the two bridges being approximately 90° apart. There is also a constant offset in the bending stress which is due to a constant unbalanced load.

CONCLUSION

The goal to design and implement a system to simultaneously measure the air flow and blade loading conditions was achieved by using a combination of anemometers to measure air flow and strain gauges to measure loads. A versatile data recording system was implemented and functioned well enough to capture data for a variety of weather conditions.

Air flow data collected showed that blade loading decreases with increasing air flow into the fan. It was difficult to compare the work done in this project to the measurements recorded by Van Aarde [8] because his measurements were not taken at the exact same position in the ACSC. In addition to this, the weather conditions measured during his two experiments at the edge of the ACSC were not the same as those recorded for this project.

Data collected shows definite cyclical loading patterns as a result of the blade's position during its rotation. In addition to this, it was found that the blade primarily vibrates at its own natural frequency with an increase in blade loading of approximate 50% over the average bending load.

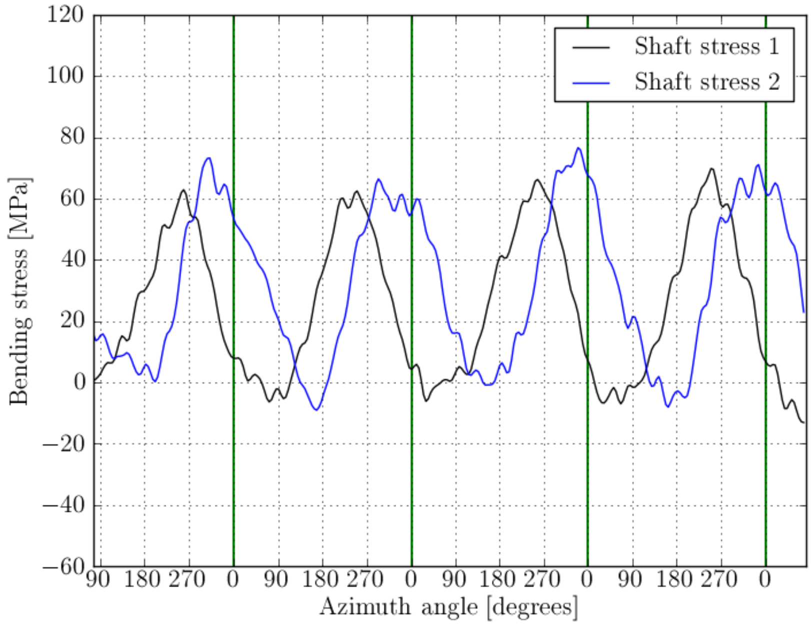

Figure 15: Shaft bending stress measurement as a function of blade position

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