Chapter 1 Introduction and Literature Study

1.1. Introduction

The on-line condition monitoring of industrial equipment is of great importance. As industry focuses more and more on productivity, conventional condition monitoring methods are not always viable options when the shutdown of equipment and possibly the subsequent shutdown of the whole production cycle is required. A practical example is the Forced Draught (FD) and Induced Draught (ID) fans found at coal powered power station boilers such as Majuba Power Station in South Africa. These fans facilitate airflow through the boilers in order to sustain combustion. This means that a whole power production unit needs to be shut down when stationary condition monitoring of these fans is required.

A big problem currently experienced with the fans is the failing of blade attachment shafts resulting in the separation of the involved blades which in turn cause secondary damage as well as production loss, both of which involve large financial implications. The blade attachment shafts experience a lot of fatigue loading during start-up and shutdown and as a result, fatigue cracks initiate and grow. For an application such as this, the need arises for blade damage qualification and quantification. This basically means that a system or methodology is needed to determine which blade shaft attachments are damaged and to which extent they are damaged.

For this type of application, a number of issues need to be addressed. In the first place, rotating equipment present a unique problem namely that of transducer signal or data transmission from the rotating parts. Also, the number of transducers used needs to be addressed. For example, if only one transducer is to be installed on each blade of a FD or ID fan, this will result in a huge amount of data to be processed as these fans typically have twenty blades each. Another issue is that of the effect of electrical noise on measurements.

For this dissertation, use is made of a test structure to develop such a methodology.

1.2. Majuba Fan Operating Conditions

To obtain better understanding and insight into the operational conditions of the FD and ID fans at Majuba Power Station, the station's Draught Plant Systems Engineer was consulted [19].

The fans at Majuba Power Station have been in operation for 12000 hours, which very roughly translates to 1.5 years of operation for 18.5 hours of operation per day. The problems experienced are not with the blades themselves, but the cracking of the blade attachment shafts. These shafts crack and these cracks then propagate until catastrophic failures occur. A typical blade attachment shaft failure is shown in Figure 1-1.

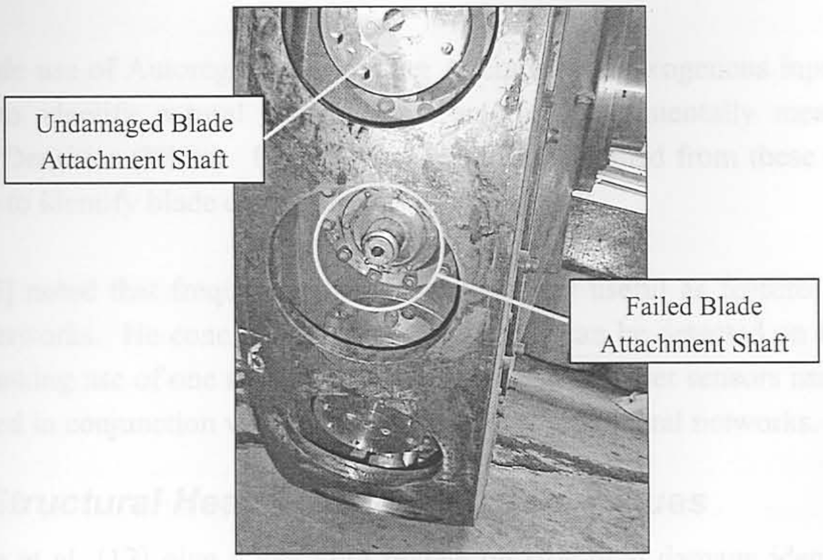

Figure 1-1: Blade Attachment Shaft Failure

The ID fans operate in the gas outlet environment. No debris deposit onto the blades is evident except for ash clinging to the oily surface caused by mild oil or grease leakage or "sweat". The maximum debris mass is estimated to be about 20 g, covering the lower third blade surface area. The fans rotate at a constant speed of 740 rpm and operate at a temperature of about 110 °C. Change in the blade characteristics is more wear-related specifically around the blade tip leading edges.

The FD fans operate in the clean air intake environment. Again, no debris deposit is evident on the blades except for dust clinging to the oily surface caused by "more than mild" oil or grease leakage. The maximum debris mass is approximated to be about 40 g, distributed over the lower third surface area of the blade. Rotational velocity is fixed at 930 rpm and operating temperatures vary from 20 °C to 60 °C.

1.3. Previous Work

This dissertation is a continuation of the work done by Smit [45]. Smit developed a methodology for detecting damage on a single blade of a fan assembly with sensors installed on the damaged blade. Smit made use of a simple finite element model to determine the sensitivity of blade natural frequencies to damage as well as to determine optimal sensor placement. He concluded that blade fatigue damage will nearly always be situated in the blade root region due to the blade loading stress distribution during operation.

Smit [45] designed the Experimental Fan Blade Damage Simulator (EFBDS) to conduct tests using piezoelectric accelerometers and piezoelectric strain sensors as transducers and a slip ring assembly for signal transmission. The EFBDS was renamed to the FaBCoM TeSt for this dissertation.

Smit made use of Autoregressive Moving Average with Exogenous input (ARMAX) models to identify natural frequencies from the experimentally measured Power Spectral Densities (PSDs). Using frequency shifts obtained from these models, Smit was able to identify blade damage levels as low as 10%.

Smit [45] noted that frequency shifts could be very useful as features for use with neural networks. He concluded that damage levels can be detected on individual fan blades making use of one sensor per blade. The use of fewer sensors may be possible when used in conjunction with global mode shapes and neural networks.

1.4. Structural Health Monitoring Techniques

Doebling et al. [12] give a literature review on structural damage identification and health monitoring using vibration characteristics changes. They note that lower modal frequencies generally cannot provide spatial information with regards to structural changes.

Higher modal frequencies however overcome this limitation where the modes are associated with local responses. These modes can be difficult to identify due to high modal density. Multiple frequency shifts can provide structural damage spatial information. Of the papers reviewed in Doebling and his co-workers, several point out that there are often not a sufficient number of damage sensitive frequencies of a structure available for unique damage location.

Hu et al. [24] developed two identification algorithms for assessing structural damage using modal test data. Unlike most approaches, the developed algorithms are not strongly dependant on analytical models. For the identification of damage location, the researchers define a normalized damage index to judge the existence of damage in a set of members in a structure. The damaged index is a function of the modal parameters of the undamaged structure as well as of the damaged structure. The damaged index is calculated for each specified structural member, where when the index is large for a specific member, it can be thought that the possibility of damage in that specific member is very high.

For practical implementation, Hu and his co-workers [24] note that the problem of not being able to measure all of the structural Degrees Of Freedom (DOFs) in the vibration modes can be overcome by employing condensation techniques or modal expansion techniques. They also developed an algorithm to estimate the extent of

damage in the possible damaged members, obtained from the damage location identification algorithm.
Hu et al. [24] validated their algorithms experimentally and numerically on a fixed-fixed aluminium beam, damaged by means of a saw-cut approximating a crack. For the detection of damage location, good results were obtained. However, accurate estimation of the damage extent was not possible.

Quek et al. [40] performed a sensitivity analysis of crack detection in beams making use of the wavelet technique. They found the method to yield very good results for simple-supported and fixed-end beams. Only numerical problems, where the static deflection profiles were obtained using FEM, were evaluated. The method is very good in locating beam cracks and perturbations. However, the deflection profile of the beam needs to be measured, which yields the technique unsuitable for this dissertation.

1.5. Measurement Techniques for Fans and Rotating Structures

Maynard and Trethewey [34] summarize field demonstrations of the feasibility of blade and shaft natural frequency changes associated with blade and shaft cracks using torsional vibration measurements. This is done using non-contact, non-intrusive measurements on operating machinery including a large wind tunnel fan, a jet engine high-pressure disk, a hydro station turbine and a large ID fan motor at a coal-fired power plant. The transducer consists of a tape shaft encoder, infrared fibre optic probe, an analogue incremental demodulator and an Analogue to Digital (AD) converter.

Williams et al. [54] describe a methodology for using rotational data acquisition techniques and rotational noise path analysis for rear wheel drive vehicle transmission and driveline development for noise vibration harshness performance. Three rotational vibration data acquisition methods are compared namely the use of a laser rotational vibrometer, paired tangential accelerometers and torsional strain gauges. For the laser rotational vibrometer, data is obtained from a reflective tape circumventing the propeller shaft. For the accelerometers and strain gauges, data transmission occurs by means of slip rings. These researchers found the accelerometer and strain gauge methods to obtain better measurements for low-level rotational vibrations levels than the laser method.

1.6. Modal Analysis of Rotating Structures

A number of researchers ([26], [31], [51]) note that modal parameter changes, whether it is mode shape, modal frequency or mass, stiffness and damping matrices, are sensitive indicators of structural damage. For this reason, it was decided to look into the modal analyses of operational structures. Authors such as Ewins [13] and Bucher [6] give in-depth theoretical discussions of in-operation modal analysis of rotating structures.

Carne and Nord [8] developed a technique to measure the vibration modes of a rotating vertical axis wind turbine. Use was made of a snap-release device installed on the rotating shaft of the turbine to excite one blade during rotation at a specific rotational speed. The device provides the ability to induce repeatable pulse inputs to a blade which allows the input force to be measured as needed for a modal analysis.

A detailed modal test of the parked turbine (or a normal static modal analysis) was performed prior to the rotating modal test in order to understand the modal characteristics well. These results were then used to update a FEM of the parked turbine. A rotating modal test was then performed and the results compared to the predictions of the FEM taking rotational effects into account. Excellent agreement was obtained.

Carne and Nord [8] also raise a very important point: As use is made of a rotating coordinate system, Coriolis effects influence the results obtained. Together with centrifugal effects, they cause the modes of the rotating system to be complex. These researchers did a thorough study on other methods of excitation during rotation such as piezoelectric crystals and gas jets. Evacuated chambers were used for testing, thus eliminating unwanted excitation forces by winds.

Wilkie et al. [53] experimentally determined rotating blade frequencies for a model generic helicopter blade for different rotational velocities. The blades were excited during rotation by means of rotor collective pitch oscillation, the frequency of which was varied over a maximum of 20 Hz frequency band in the vicinity of each modal frequency of interest. Strain gauges mounted onto the blades were used for output signals, while the strain gauge measurement of the pitch-link was used as input signal in order to generate FRFs.

No attempt was made to measure blade mode shapes during operation. The experimental results were compared to the results obtained from FEM modal analyses. Only centrifugal forces were considered during the numerical analyses that were performed in two steps namely static analysis with the centrifugal forces and a modified normal mode analysis performed as a "restart" analysis. The authors ignored the effect of damping and Coriolis terms. Good correlation between the FEM results and experimental results were obtained although discrepancies were observed for blade torsional frequencies.

Marscher [32] presents a method involving cumulative time averaging of an exponentially windowed output prior to Fourier transformation in order to determine modal characteristics of industrial and aerospace rotating machinery. The structure is artificially excited at a stationary point during machine operation and vibration measurements are taken on the machine casing. Response due to artificial excitation is separate from response due to operational excitation by means of cumulative time averaging.

Shu and Cutts [44] present two analysis methods for modal parameter extraction from strain responses of rotating bladed assemblies. The two methods are frequency spectrum interpolation and time domain modal curve fitting. Shu and Cutts found both techniques to be very reliable, efficient and easy.

1.7. Fan Blade Condition Monitoring Techniques

Ghoshal et al. [21] tested four different algorithms for damage detection in wind turbine blades namely transmissibility function, resonant comparison, operational deflection shape and wave propagation methods. The transmissibility functions were calculated as the ratios of the velocity responses at different points on the structure. Velocities were used, as this is the direct output of the scanning Laser Doppler Vibrometer (LDV) used.

These researchers identify certain advantages of using transmissibility functions:

- The excitation force is cancelled and therefore does not need to be measured if it is equal in amplitude at all points where applied.
- The ratio of responses partially cancels changes in the transmissibility functions due to environmental effects such as temperature changes.
- Transmissibility functions are ratios of two continuous functions with peaks and valleys and are therefore quite sensitive to shifts in frequencies or damping caused by damage.

It should be noted that Ghoshal et al. [21] conducted the tests for a stationary blade.

Ghosh and Rajamani [20] describe a transfer matrix approach for the vibration analysis of a rotating fan. They also developed an analytical procedure for computation of the free vibration behaviour of a rotating fan assembly. The number of blades is assumed to be large enough in order to consider the resultant blade loadings as continuously distributed.

Südmersen et al. [50] present global monitoring techniques for industrial fans and pumps including time domain analysis, spectrum analysis, correlation analysis and cepstrum analysis. The authors note that a common method to identify speed related information is time averaging of signals using external signal triggering. They also note that operating conditions with exceeded vibration levels such as during start up and shut down procedures, reduce total machine life time.

Corbelli et al. [10] investigate the applicability of damage detection using FRF data to rotating helicopter rotors. Modal parameters were extracted from FRF data obtained from a finite element model of helicopter rotor blades for the hovering condition. This was done for both an undamaged and damaged configuration. The FRF-based identification procedure was used to evaluate structural stiffness variation.

Corbelli and his co-workers found that damage detection presented in terms of stiffness variation show a good capability for damaged detection, location and quantification. As these results were obtained from numerical calculations, the authors note that future work must be done to study the influence of noise in measured FRF data on damage identification capability. They also suggest studies into the influence of torsional FRF measurements on damage identification.

1.8. Telemetry Identification

1.8.1. Data Transmission

A lot of effort was put into identifying a suitable telemetry system for data or signal transmission from a rotating machine. Two options presented themselves, namely slip ring assembly and wireless data transmission. Slip rings are most commonly used but have disadvantages such as limited operating life due to sliding contact wear, which in turn produces electrical noise ([42]). Also slip rings are usually practical only when the slip ring can be installed onto the shaft end. Due to these limitations, it was decided to look into the suitability of wireless telemetry.

The following considerations should be taken into account when selecting wireless telemetry for vibration analysis ([46]):

- Type of signal transmitted (analogue or digital)
- Digital resolution required when a digital signal is used
- Required transmission signal gain
- Signal domain type to be measured (e.g. time domain or frequency domain)
- Transducers used
- Number of channels required
- Size and weight of transmitter
- Power supply to transmitter

- Transmission range
- Type of signal transmission. Preference should be given to frequency modulated transmission of a digitised signal
- On-line transmitter configuration by base station
- Installation of the transmitter on the rotating component

The biggest limitations of currently available wireless telemetry was found to be

- Size
- Power supply to the transmitter side of the system
- Speed, as most telemetry systems are digital. Thus pre-processing is required.
- Cost

1.8.2. Advances in Wireless Telemetry

Bult et al. [7] present new methods providing diverse sensor capability with new low power solutions for wireless sensor networks. The technology reported in this paper differs from prior work in wireless sensor technology in that the sensor, control and communication system are integrated into a single unit.

The applications of Micro-electromechanical Systems (MEMS) are being expanded by a new technology called Low Power Wireless Integrated Microsensors (LWIM). Bult et al. [7] note that LWIM nodes may be in particular applied to rotating machinery without complex slip ring systems normally required for sensor electrical interface.

The requirements for individual low cost sensors nodes are that the nodes must be

- Reconfigurable by their base station
- Autonomous to permit local control of operation and power management
- Self-monitoring for reliability
- Power efficient for long term operation
- Able to incorporate diverse sensors capability with highly capable microelectronics

Bult et al. [7] note that for typical low duty cycle of a LWIM, a conventional lithium coin cell is able to provide more than three years of unattended operating life. Unfortunately, typical frequency ranges of LWIMs are not reported.

Miettinen et al. [36] developed a wireless data transfer system for measuring on-line acoustic emission, temperature distribution and angular position of polymer covered cylindrical rolls. The measured signal is transferred from the rotating rolls via Wireless Local Area Network (WLAN) to the measurement computer. An interesting advantage of using on-line monitoring mentioned by the authors, is that it can be used to determine optimum operating conditions of machinery.

The measurement system consists of amplifiers for the different sensor types, anti-aliasing filters, AD-converters and a radio transmitter. The sampling rate used was 1 MHz. Miettinen et al. [36] also describe the principles of acoustic emission.

Li et al. [28] designed a polysilicon cantilever rotation sensor able to measure angular speeds from 100 rpm to 6000 rpm. The authors used a transmission scheme in which the voltage signal from the sensor is mapped into frequency prior to transmission resulting in a very compact package (smaller than 3 cm^3). Unfortunately, Li et al. [28] tested the frequency response range of the system from about 30 Hz to only about 110 Hz. Li and his co-workers found the sensor to be temperature dependent.

Olofsson and Östling [39] investigate the implementation of Bluetooth technology in accelerometer data transmission. The concept is proven in a point-to-point sensor demonstration. Bluetooth transceivers operate in the Industrial, Scientific and Medical band at 2.4 GHz. The transceivers make use of frequency hop and spread spectrum communication in order to combat signal interference. Data transmission of up to 720 kbps over a range of up to 100 m is possible with line of sight not necessary. Bluetooth technology is already implemented in equipment such as cellular phones and wireless modems. Although Bluetooth systems are very cheap to purchase, they are expensive to develop.

1.8.3. Transducers

Brooks [5] gives an overview of different sensor generations. Currently, third-generation devices are available containing internal digital datasheets of information such as manufacturer and calibration data. The devices use mixed-mode analogue and digital transmission through on-board electronics.

Fourth-generation devices are being developed. These sensors are processor-based and will be characterised by bi-directional command and data communication, all digital transmission, local digital processing, pre-programmed decision algorithms, user-defined algorithms, internal self-verification/diagnosis, compensation algorithms, on-board storage and extensible sensor object models.

Staszewski [47] presents an overview of the suitability of emerging sensor technologies for operational load monitoring and damage detection in airframe structures. Sensor technologies viable for on-line damage monitoring include acoustic emission, optical fibre sensors, Lamb wave techniques and acousto-ultrasonic sensors.

LDVs are very suitable for in-operation fan blade vibration measurements as they are non-contact devices. Farrar et al. [15] note that the LDV is very useful in field modal tests of the mounting time associated with traditional transducers such as accelerometers is eliminated. The authors also report on a project involving the field-testing of a wind turbine blade using a LDV and a Natural Excitation Technique (NExT) procedure. At the printing time of the paper, the analysis of the project was not yet completed.

Lomenzo et al. [30] introduce a self-tracking laser vibrometry system for rotating fans. This would be an ideal solution for use in this dissertation as this system is non-contact. However, the costs involved make this system not viable.

1.8.4. Available Systems

There are quite a number of telemetry systems available for signal transmission from a rotating structure. A few of these are presented below.

Microstrain features the wireless Micro Datalogging Transceiver that is configured for conventional strain gauges. The system has a transmission range of up to 30 m with up to 1000 Hz bandwidths and has up to 8 input channels with 10 bits digital resolution. The transceiver has a storage capacity of up to 1 million data points and can operate with a 3.6 V lithium battery for up to 95 hours. The system can be upgraded in terms of measuring bandwidth (up to 10 kHz per channel) and storage capacity (up to 4 million data points) and can be modified for use with piezoelectric accelerometers. The costs of these upgrades unfortunately render the system unsuitable for this dissertation.

Krauss Messtechnik has a number of available wireless systems. One of these is the MT32 system with a measurement bandwidth of up to 3000 Hz for four channels with a 12-bit resolution. Power supply to the system can occur by means of inductive power supply, thus eliminating the need of batteries. Transmission distance is limited to a maximum of 0.5 m. The system is configurable for strain gauges, piezoelectric transducers, thermocouples and voltage inputs. Unfortunately, costs again render this system unsuitable.

Haase and Drumm [22] report on the HiBand Vibration Measurement System from ExSell that was developed for blade vibration sensing in gas turbine engines with a measurement bandwidth of up to 20 MHz. This is not a wireless system and uses a capacitive measuring system that can measure individual blade vibrations, Time-of-Arrival, radial vibration, blade tip clearance and change in rotor centre of mass. The system provides advance warning of a blade crack, foreign object damage and other engine anomalies. This system unfortunately falls outside the budgetary boundaries of this dissertation.

M-Tek has a 20-way capsule slip ring assembly namely the C-20 Slip Ring Assembly. It has a minimum life span of 12 million revolutions and a recommended maximum rotational speed of 600 rpm. As this system was used by Smit [45] and was subsequently freely available, it was decided to use it for signal transmission for this dissertation.

1.9. Neural Networks

Boek et al. [4] describe their approach to the application of intelligent information processing in large engineering systems for machine condition monitoring, making use of in-operation vibration signals. According to them this technique involves machine specification, signature recording, data acquisition, feature analysis, condition analysis and recommendations.

These researchers performed on-line condition monitoring of an oscillating desktop fan for different damage modes such as load imbalance, shaft imbalance and a cracked blade. The transducers used were two accelerometers attached to the fan motor cover. They were positioned in the radial and axial planes of the shaft.

According to Boek et al. [4] spectra of vibration data are to a large extent contaminated by noise for rotating machines. It is also known that important information is carried in the amplitudes of the rotational frequency and its associated harmonics. In some of the experiments, the authors made use only of the peak values of the rotational frequency harmonics as a representation of the fan condition, drastically reducing the dimensionality of the neural network input space. As it is virtually impossible to determine precise feature values characterising a specific machine condition beforehand, trying different combinations of harmonics, and observing which appeared to vary the most for different fan conditions determined the features selected for the experiments.

Training of the network was conducted using a back-propagation algorithm. The network consisted of a single hidden layer containing between 5 and 20 processing units. The learning rate was fixed at 0.02 and the momentum control parameter at 0.9. Best results were obtained in the detection of imbalance, but the classification thereof was in general poor. Good results were obtained for distinguishing between physically different faults such as imbalance versus blade crack. The network could however not classify the state where both an imbalance and a blade crack were present. A network making use of overall values as inputs performed a bit better.

Boek et al. [4] recommend that further work in extracting better features could lead to improved performance.

Farrar and Sohn [16] view vibration based structural health monitoring fundamentally as a process of statistical pattern recognition composed of four portions namely operational evaluation, data acquisition and cleansing, feature selection and data compression, and statistical model development for feature discrimination. The basic premise of vibration-based damage detection is that damage will significantly alter certain properties of a system, such as the structural stiffness. This system property change will in turn alter the dynamic response of the system.

Inherent in the feature selection portion of the process, is the condensation of the data. Farrar and Sohn [16] note that robust data reduction techniques must retain sensitivity of the chosen features to the structural changes of interest in the presence of environmental noise. Features used for damage detection are application specific.

Farrar and Sohn [16] note that many reported studies for rotating machinery damage detection applications exist where statistical models have been used to enhance the damage detection process. There are different classes of algorithms used in statistical model development namely supervised learning and unsupervised learning. Supervised learning refers to the case where data from both the undamaged and damaged structures are available. Unsupervised learning refers to the case where data of only the undamaged structure is available.

The damage state of a structure is described as a five-step process: Damage existence, location, type, extent and prediction. Damage existence and location can be obtained from experimental structural dynamics techniques. Damage type identification can only be done when data from structures with the specific damage cases are available. According to Farrar and Sohn [16], analytical models are usually needed to determine damage extent and remaining life predictions. For the specific case of damage in the form of a crack, remaining life predictions can be calculated using fatigue crack growth principles when the crack growth rates and structural nominal stresses are known.

Farrar and Sohn [16] note that it is important for the statistical model to be tested on actual data. False identifications of damage fall into two categories namely false-positive and false-negative damage indications. False-positive damage indication refers to the case where damage is indicated when none is present. False-negative damage indication refers to the case where no indication of damage is given when damage is actually present.

Marwala [33] presents a committee of neural networks technique, which in essence is the use of a number of independent neural networks in parallel. In this case, three independent back-propagation or multi-layer perceptron neural networks were trained using frequency response functions, modal properties and wavelet transforms. This method was tested for a three degree of freedom mass-spring-damper system and was also implemented for damage identification in a population of ten seam-welded cylindrical shells.

Marwala [33] found the committee of neural networks to identify damage cases better than the three approaches, i.e. frequency response functions, modal properties and wavelet transforms, used individually.

Lew [27] presents a neural network approach to structural damage detection based on transfer function correlation. This approach requires only a few sensors as opposed to general finite element model updating techniques. This gives the approach certain benefits such as reduced experimental hardware costs and increased effectiveness for on-line health monitoring and data processing.

Waszczyszyn and Ziemianski [52] made use of a back-propagation neural network for notch location detection in an experimental steel cantilever beam. Natural frequencies, extracted from FRFs, were used as inputs to the neural network. The results from the experimental setup are compared to that obtained from a FEM. Both yielded good results.

Castellini and Revel [9] used a scanning LDV in conjunction with neural networks to detect, localize and characterize defects in structures. The authors made use of features extracted from numerically calculated FRFs of FEMs to train the networks. The technique was successfully applied to an aluminium plate, a composite fibreglass panel and a Byzantine icon of the 17th century. Castellini and Revel [9] note that laser vibrometry seems to be the only suitable measurement technique to be used with the processing algorithms they developed due to its ability to quickly supply vibration data in a wide frequency bandwidth with high spatial resolution.

1.10. Scope of Work

The main aim of this research is to develop a methodology for on-line fan blade damage detection and identification using neural networks and a minimum number of sensors.

Use will be made of a laboratory test structure namely the FaBCoM TeSt to develop such a methodology. A FEM of the FaBCoM TeSt will be developed to determine the feasibility of using GMSF shifts for damage quantification and qualification for single and multiple damaged blades. The results of this analysis will be used to help identify GMSFs that are sensitive blade damage indicators. The FEM will be verified by means of an EMA of the FaBCoM TeSt.

Measurements will be taken for several blade damage levels for single and multiple damaged blades for several sensor locations. Neural networks will then be trained for the task of damage identification. Two different approaches will be used with regards to network training. For the first approach, features from the measured data will be identified and extracted for neural network training. The neural networks will be used to determine whether it is feasible for a sensor installed on one blade, to quantify and qualify damage on other blades.

Secondly, the feasibility of using numerically calculated FRFs of the FEM for training a neural network to be used on the experimentally measured data will be determined. This is a crucial part of the dissertation in terms of the practical significance of the dissertation. It is much more desirable to train networks from computer generated features than to artificially damage the actual structure in terms of costs.

In detail, the scope of work for this dissertation can be laid out as follows:

- The development of an extensive FEM. Smit [45] made use of a FEM of a single blade to determine the sensitivity of local blade natural frequencies to local blade damage. In this dissertation, the concern lies with the sensitivity of GMSFs to local blade damage. For this reason, a more extensive FEM consisting of the FaBCoM TeSt shaft, hubs and four blades will be developed.

- A feasibility study of the use of GMSF shifts for damage quantification and qualification. This will be done by performing modal analyses on the FEM for different conditions such as rotational velocity, operating temperature, blade damage scenario and blade damage level. The reason for the inclusion of some operational variables namely rotational velocity and operating temperature is to study their effect on GMSFs in order to determine whether monitoring of the frequencies is practically feasible.

- The identification of suitable GMSFs from the above-mentioned study for damage quantification and qualification. Typically, a GMSF of interest here will be one that is relatively insensitive to operational variables, but at the same time is a good indicator of damage level and location.

- The validation of the FEM by means of an EMA. As this FEM is intended to be used to predict GMSF shifts as a result of blade damage as well as to provide features for neural network training, it has to be validated with the actual structure. The MAC matrix will typically serve as a measurement of FEM and FaBCoM TeSt correlation.

- The identification of a suitable data or signal transmission system. This will be a system that has as little as possible influence on behaviour of the structure. It must also be able to facilitate measurements with the identified measurement bandwidth.

- Measuring data on the FaBCoM TeSt for different blade damage scenarios and sensor location scenarios. Transducers used will be three piezoelectric strain sensors installed on three of the four blades for strain measurements and a single piezoelectric accelerometer for rotational acceleration measurements. Taking measurements at different sensor locations, it will be possible to determine whether it is feasible using a sensor installed on one blade, to measure changes due to damage in another blade.

- A feasibility study of the use of neural networks for blade damage level detection using previously measured data. This will be done on the measurements taken by Smit [45] for a single damaged blade.

- The development of an experimentally supervised neural network damage detection methodology. This will include the following:
    - Identification of features suitable for neural network training with experimental supervision. These features will mostly include the identified frequencies, but can also include other features such as those obtainable from time domain analysis.
    - Identification of suitable neural network architecture. Use will be made of the architecture used by Boek et al. [4] as a guideline although the quality of results from the networks will be the final determining factor.
    - The neural networks will be trained and tested for the different sensor locations at certain damage levels. The abilities of the networks to do damage level interpolation as well as extrapolation will also be determined. The networks will be tested for damage levels between the levels trained for in order to determine their damage level interpolation abilities. The damage level extrapolation abilities will

also be tested using data recorded for additional blade damage. These abilities will serve as a guideline of the number of damage levels and scenarios the networks need to be trained for in order to yield accurate results.

- The development of a numerically supervised neural network damage detection methodology. This will include the following:
    - FEM FRF generation for the same damage cases as will be simulated in testing of the FaBCoM TeSt. FRFs will be calculated for a single force input similar to that used on the FaBCoM TeSt in the EMA. The outputs used will be similar to those measured in the experimental testing of the FaBCoM TeSt in terms of measurement location and orientation as well measurement type (e.g. strain or acceleration).
    - Feature identification from the FEM FRFs. Features will be selected on the basis of correlation with experimental features. If a sufficient number of features are identified, a neural network will be trained on the numerical features and then tested using the experimental features.