CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

The monitoring of critical equipment in industry has become more and more important in recent years. This has become necessary since it is not always economically viable to conduct maintenance checks on these equipment at regular intervals before it is required. When critical equipment such as Forced Draft (FD) and Induced Draft (ID) fans at power plants are shut down for maintenance, the whole thermodynamic cycle has to be stopped since these fans provide air to the boilers. It is therefore of cardinal importance to monitor the condition of these high value equipment, not only because of high cost, but also due to the critical nature of the equipment in the process path. A whole power plant, representing a huge capital investment, cannot be allowed to stand idle while a fan, which has failed without warning, is repaired.

The aim of this dissertation was to develop a vibration monitoring technique that will be able to detect damage in fan blades at an early stage, so that maintenance can be properly planned and scheduled. Such damage could be caused by any or all of the following:

- Fatigue.
- Corrosion.
- Imbalance due to the accumulation of residue.

It was not unreasonable to expect that vibration-monitoring techniques developed for the detection of damage in structures such as bridges and trusses may be tailored for this application by making some modifications. Typically, the output from a damage detection technique could have a series of status indicators for maintenance planning. For example:

- Green indicator: No maintenance necessary.
- Yellow indicator: Plan for a maintenance shutdown.
- Red indicator: Blade may fail at any time, immediate shutdown.

It became clear at an early stage that a general-purpose damage detection technique would probably not work for a specific application such as this. Another aspect that was very important is practical implementation. A method requiring expensive equipment such as a laser vibrometer would not at all be suited to industry based applications. The rest of this chapter is devoted to a literature study and defining the scope of this research.

1.1 Introduction to literature study

Before starting on the details of the development of this method, a comprehensive literature study was undertaken. The main focus of the literature study was on structural damage detection techniques that have been used on various structures. It was found that little work has been done in the area of rotating structures (such as fan blades). A brief look was taken at general non-destructive damage detection techniques. A wide range of vibration based damage detection methods developed over the years were investigated next. Optimal location of sensors, telemetry, system identification methods and finite element usage was also studied.

1.2 Non-destructive damage detection

The high cost of maintenance and the need to know when machinery will require maintenance in order to cut down on production loss due to unscheduled stops, has led to the development of various non-destructive damage detection methods. Only a handful of these procedures can be applied when on-line condition monitoring is required.

While techniques such as ultrasonic scanning, x-rays, conductivity and penetrating dies work very well, none of these can easily be implemented on a spinning fan blade. The high cost of the scanning methods also makes it impossible to instrument individual blades and fans. It would for example not be financially viable to install x-ray equipment on every fan for the detection of damage during brief periods when the fan is stationary.

A further disadvantage of methods such as x-rays, ultrasonic scanning etc. is the fact that defects may be overlooked due to shielding by the structure itself. Most of these methods also require highly skilled and trained operators with years of experience.

In the end it became clear that a more promising method of damage detection for an application such as a spinning fan blade was vibration monitoring. The main reasons for this decision are presented in the next section.

1.3 Damage detection using vibration monitoring

Vibration monitoring of structures and machines has received considerable interest in the last few decades. Doebling *et al.* (1996) have presented an extensive survey of this field. The main reasons for the interest in these methods are:

- The ability of such methods to do global monitoring of a structure with a few sensors, as opposed to scanning the whole structure with complex equipment.
- The equipment required for vibration monitoring are generally orders of magnitude cheaper than the equipment required for contemporary scanning methods.
- Online monitoring of equipment and structures is possible in most cases.

There are off course, difficulties when using vibration monitoring methods to detect damage. The most important are:

- It is difficult to find a characteristic to measure, that change sufficiently with increasing levels of damage.
- There are always some errors in the measured data due to sensor inaccuracies, filtering of data and random noise.
- Errors in system identification and modelling.

It became clear quite early in the literature study that different researchers have encountered various difficulties. The most promising results were, not surprisingly, usually obtained when simplistic methods were applied on basic structures. A paper by Friswell and Penny, (1997) considered the state of the art in damage detection and location using vibration data. They noted that algorithms should be tailored to a specific application, as it is unlikely that a single best method will ever emerge. The authors also noted that health assessment of structures by making use of ambient excitation was even more difficult.

The rest of this section gives an overview of the most relevant literature found on vibration based damage detection and modelling techniques and includes four case studies that focused on damage detection in rotating bladed structures.

1.3.1 Frequency changes

Exhaustive research has been done regarding the use of natural frequency shifts to detect damage. The observation that changes in structural properties caused changes in natural frequencies was the stimulus for using modal methods for damage identification and health monitoring. As mentioned earlier it was not possible to include all the work done on damage identification. Only the most relevant and recent work on natural frequency shifts is therefore reviewed here.

It soon became apparent that frequency shifts have significant practical limitations for certain types of structures. These include bridges, offshore oil platforms and other large civil structures. The low sensitivity of frequency shifts to damage requires either very precise measurements, or high levels of damage. For example, in offshore platforms, damage-induced frequency shifts are difficult to distinguish from shifts resulting from an increase of mass due to marine growth. Most of these structures are also designed with a high degree of redundant load paths and safety factors. This sometimes mean that excitation of the system become very difficult and cracks or other damage need to reach relatively high levels, before a damage identification can be done. A further complication is that frequency shifts usually only point to the existence of damage and not the specific location. If different frequencies are used, particularly those frequencies associated with higher mode shapes, it is possible to locate local damage specific to the mode shape.

The accumulation of residue on fan blades can cause a substantial imbalance if part of this residue fly of the blades under centrifugal acceleration. In most cases, it can be expected that this accumulation will not reach the levels found on offshore platforms, largely because of the centrifugal acceleration imposed on the residue. Due to the fact that a fan blade is a relatively simple cantilever system and the crack location is almost always at the position of maximum stress (the root), frequency shift could very well turn out to be a viable method.

Silva and Gomes (1994) covered the use of the inverse problem to determine the location and degree of damage in a simple cantilever system. The inverse problem consists of calculating the damage parameters such as crack length and/or location, from the frequency shifts. This was done by making use of a simple cantilever system with a crack of known depth and location. The theoretical models were developed by assuming that a cracked beam could be modelled by two shorter beams connected through a torsion spring that simulates the stiffness of the original beam at the section where the cracks exists. Silva and Gomes did a whole range of experiments and investigated modelling techniques along this vein. They found that it was possible to determine the depth of the crack very accurately and the location with a fair degree of accuracy if more than one frequency were used. They developed a computer program that used discrete intervals along the beam and tested various combinations of crack depth and locations until a match closest to the measured frequencies was found. They noted that this was a very time consuming process but obtained fairly good results.

Springer and Reznicek (1994) examined the effect of damage on the dynamics of a vibrating structure. To do this, a beam element that had an L-section and contained a crack was developed. By modelling the crack as a set of four linear springs, stress intensity values were computed. Strain gauge measurements were taken to determine the stiffness values for these springs. The resulting finite element could then be used in Finite Element Analysis (FEA) or structural dynamic modification routines. Examples of crack elements can be found in commercial packages such as MSC Marc. If the necessary physical tests to determine stress concentration values were done at some stage, these elements can be very useful.

1.3.2 Damping

Although damping is usually the most problematic modal parameter to determine accurately, some work using only this parameter as damage indicator has been done. Williams and Salawu (1997) decided to use this indicator because situations do exist in which damping may be the only indicator of distress. Damping properties are very difficult to model analytically and vibration tests are usually necessary to obtain realistic values. Generally speaking the damping of a system will increase with increasing damage. These authors concluded that Auto Regressive Moving Average (ARMA) models provided the most accurate results. For damping to be used as a damage indicator the accuracy of data acquisitioning needed to be high and the testing very well controlled.

1.3.3 Energy Transfer methods

Liang *et al.* (1997) proposed the use of the energy transfer ratio for the classification of damage. They developed the Energy Transfer Ratio (ETR) as a new modal parameter for studying the dynamics of the test structure. The main reason for using this newly defined parameter was the lack of accurate and repeatable measurements for other parameters. This made the detection of small amounts of damage very difficult. Since the mass, damping and stiffness matrices were usually unknown for a real structure, these modal parameters had to be estimated. This was done by analysing vibrational responses of the structure in the time domain. Interestingly enough, this method did not require the authors to select specific modes sensitive to damage. They found that the ETR was significantly more sensitive to damage than natural frequency and damping ratio changes. Furthermore ETR could also be used to determine the location of the damage by using different modes.

1.3.4 Model-updating techniques

Many researchers have tried to use model-updating techniques to detect damage and the location thereof. Most of the literature found on this method failed to produce good results with even relatively simple structures. The biggest problem with all model-updating algorithms was the small amount of data available, compared to the large number of possible damage locations.

Fritzen *et al.* (1996) developed a model based damage detection method that compared vibration data to a mathematical model of the undamaged structure with local description for the damage. The authors note that it was very important to compile an accurate mathematical model of the structure that was analysed and proposed the updating of the model with vibration data from the undamaged structure. The reason for this was that the residuals generated from the model for the undamaged case and the measurements from the damaged case contain not only information about the damage itself, but were also polluted by modelling errors. They studied the detection of multiple cracks in a T-frame and a three dimensional beam structure. These authors also noted that the model was inclined to spread damage around the location of the actual crack.

Friswell and Penny, (1996) considered the use of Finite Element Model (FEM) updating to detect and locate damage in structures. The authors discussed problems associated with detecting and locating damage using model updating algorithms in some detail. They note that the incompleteness of data, coupled with measurement noise made the location of damage very difficult. The biggest problem, according to the authors, was the large number of possible damage sites, compared to the amount of data available.

Other work that used FEM and model updating in conjunction to detect damage in a space frame structure, also noted the effect of insensitive modes that makes locating the damage very difficult (Pereira *et al.* 1994). The authors used updating techniques based on Frequency Response Functions (FRFs) to monitor measured data and identify the damaged area of the structure. When the updating procedure reached a good correlation between the analytical and experimental data, the model parameters of the damaged structure were compared with those of the undamaged one to find the deteriorated area. This work confirmed that the model updating methods usually struggled to locate damage, largely because of the modes that were insensitive to damage.

One of the major problems with modal analysis has always been the number of sensors required to accurately identify the modal parameters. For a fan with 20 blades, using even one sensor per blade already constitutes a large investment in sensors and a huge amount of data to be processed. Cobb and Liebst (1996) investigated the use of minimal sensors to locate structural damage. The method used, employed mathematical optimisation to minimise the deviations between measured and analytical modal frequencies and partial mode shapes. Damage was identified by determining the change that needed to be made to a FEM, to match the measured data on the damaged structure. Because the method required the decomposition of a large matrix it was computationally very expensive if sparse matrix techniques was not used. The method was demonstrated on an experimental structure and correctly determined the location and extent of structural damage. Eight accelerometers were used on a structure consisting of 64 truss-like connections.

1.3.5 Modal shape changes

Another parameter used for the detection of changes in the characteristics of a system is mode shape changes. The Modal Assurance Criterion (MAC) has been used for some time in various forms as a damage detection criterion. Joon-Ho *et al.* (*S.a.*) used Partial MAC (PMAC) and Coordinate MAC (COMAC) to detect single and multiple faults in a FEM plate model. Ko *et al.* (1994) also presented a method that combined MAC and COMAC to detect damage in steel frames. The sensitivities of the analytically derived mode shapes to particular damage conditions were computed to determine which Degrees of Freedom (DOFs) were most relevant. To determine which mode pairs were to be used, the authors analysed the MAC between measured modes from the undamaged structures and the measured modes from the damaged structure. The results they obtained indicated that particular mode pairs could indicate damage, when all mode shape pairs were used, the damage was masked by modes that were not sensitive to the damage.

Williams *et al.* (1997) introduced a new assurance criterion using the frequency changes in a number of modes to identify the location of the damage. They used a number of numerical and experimental case studies to illustrate the tolerance of the method to error levels in measurements. They established that standard error values when determining natural frequencies from FRFs were typically less than 0.1% and were all below 0.15%. Williams *et al.* also suggested that the percentage change in frequency shifts should be used rather than the absolute change. The Damage Location Assurance Criterion (DLAC) they used can be defined at a location *j* using a correlation approach similar to the MAC (Allemang *et al.* 1982) value used for comparing modal vectors. Similar to the MAC, DLAC values fell in the range 0 to 1, with 0 indicating no correlation and 1 indicating an exact match between the patterns of frequency changes. The location *j* giving the highest DLAC value determines the predicted damage site. They conclude by suggesting that problems still remain for low damage levels.

Cawley and Adams (1979) were some of the first authors to match measured changes in the natural frequencies with those from a theoretical model of the system. Penny *et al.* (1993) and Williams *et al.* (1995) produced improvements to the technique used by Cawley and Adams. These authors noted that the predicted faults in the structures were usually spread over a much wider area of the structure than was actually the case.

Several criteria for the detection of cracks were compared to each other by Yoo *et al.* (1992). The Inverse Modal Assurance Criteria (IMAC) using inverse strain mode shapes was found to be more sensitive to local changes than the MAC. The COMAC and Enhanced Modal Assurance Criteria (ECOMAC) were studied in order to identify crack location. ECOMAC was found to be less effective than COMAC. Furthermore the Absolute Difference of Strain Mode Shapes (ADSM), a method that identify crack location by strain mode shapes was developed further. It was found that COMAC, ECOMAC and ADSM based strain mode shapes were not applicable for all modes. The modified ADSM method using absolute values only, was found to be the most promising for the accurate identification of crack location.

Another comparison of different modal shape change methods was done by Salawu and Williams (1994). The curvature mode shape method, mode shape relative difference method, MAC and COMAC methods were studied. According to the authors only the curvature mode shape method was able to give an indication of multiple damage locations. The MAC and COMAC methods were however found to be more tolerant to the use of different mode shapes. The curvature mode shape methods and mode shape relative difference method depended heavily on the choice of damage sensitive modes.

A method using only the mode shape data of a structure was developed by Ratcliffe (1997). A very simple structure was tested and classified by means of a one- dimensional finite element. The author found that applying a finite difference operator to the mode shape could identify damage of 10%. Furthermore it was found that lower mode shape provided better results (detection of 0.5% damage). The higher frequencies were only of use to determine the location of the damage. A slot cut into a steel beam was also successfully located. Since the Laplacian function used, represents the curvature of the mode shape, the author suggests that modal data obtained using strain gauges may be used directly in place of the Laplacian. This was not verified experimentally.

1.3.6 Modal parameter changes

In an attempt to create more robust and reliable damage detection techniques, more and more authors look at more than one modal parameter to classify damage and improve the accuracy of damage detection.

Most of these papers deal with damage detection on large civil structures or simple laboratory based experiments. Peeters *et al.* (1996) developed an experimental program to establish the relationship between damage and changes of the dynamic system characteristics. They used a laboratory based model to simulate a bridge structure. To identify the dynamic system characteristics, they made use of system identification techniques such as polynomial models and state space models. An accurate mathematical model of the system could be compiled because they made use of an electromagnetic shaker to excite the system (input forces therefore known) and a large number of measurement points were used. They found that the modal curvature was the best indicator of location and amount of damage. Natural frequencies also classified the damage accurately, but not the location. Damping also increased with increasing amounts of damage but was found to be difficult to classify.

Mastroddi (2000) recently studied the use of a general procedure based directly on the measurement of FRFs of a structure to identify a numerical model or directly localise and quantify possible damage and failure in terms of mass, stiffness, and damping variations. The author used both a continuum analytical system and two experimental structures to test the procedure. The structures consisted of a cantilever aluminium plate and a cantilever half-wing constructed from composites. The author found that the procedure had the capability to give significant results in the presence of errors or uncertainties in the measurements.

Klein *et al.* (1994) monitored the change in modal parameters with fatigue of a structure. The authors monitored both the changes in vibration and acoustic variables that occurred with the presence of a fatigue crack. Shifts in natural frequencies, damping and other parameters were documented. The experimental test structure consisted of a simple cantilever beam. Again it was found that some modes were influenced more by damage than others. The authors found that the normalised acoustic intensity spectra also showed large changes for increasing damage for certain modes but noted that that additional tests will have to be performed to confirm these findings.

Sohn and Farrar (2000) made use of the Auto-Regressive (AR) and Auto-Regressive with eXogenous inputs (ARX) techniques to pinpoint the sources of non-linear damage by solely analysing the vibration signatures from a structure. They used the residual error, which is the difference between the actual measurement and the prediction from the previously estimated AR-ARX combined model, as the damage-sensitive feature. The premise that if there were damage in the structure, the prediction model previously defined using the undamaged time history data would not be able to reproduce the newly obtained time series data measured under a damaged state of the structure, was used. They obtained good results on a very simple test structure and noted that further work would be necessary to validate this method. The model used consisted of masses connected with springs in a series system. Damage was induced by introducing bumpers between the masses.

Local frequency changes and modal frequencies were used in a two-stage damage detection method developed by Shi *et al.* (1997). The measured mode shapes were used to obtain the location of the damage, while the modal frequencies was used to determine the magnitude of the damage. The location of the damage was found by making use of the local frequency change ratio, based on the mode shapes. The structure consisted of a two dimensional truss. The authors also noted that the effect of noise and incomplete mode shapes needed to be addressed further.

Santos and Zimmerman (1996) explored the use of the residual modal force vector and component mode synthesis as a structural damage diagnostics tool. Measured modal test data was used along with a correlated analytical substructured finite element model. Depending on the number of modes that was used in each substructure, the method was able to detect the exact location of the damage, or the substructure that contains the damage.

1.3.7 High frequency methods

Friswell and Penny (1997) recommended that high frequency techniques for damage detection should be investigated further. They reviewed a number of case studies and came to the conclusion that some problems do not seem to be suited to conventional vibration based damage detection. The higher resolution provided by higher frequencies may provide more accurate location and classification of damage. The disadvantage of these higher frequencies in global structural damage localisation is the large number of reflections and transmissions from components that are difficult to model at the higher frequencies and the high number of fixed actuators and sensors required.

Most high frequency damage detection techniques use frequencies so high that microphones usually provide better information. Sound is the result of physical objects vibrating in a medium such as air and somewhere between conventional low frequency vibration detection methods (accelerometers etc.) and ultrasonic methods it should be possible to get better resolution and greater global detection. Colonnello and Morassi, (1998) investigated the use of spectral data to solve the inverse problem. The authors found that the uniqueness results come from the fact that the highest part of the spectrum of a cracked rod separates into branches which correspond to the asymptotic spectrum of the pieces of the bar adjacent to the damaged cross section.

1.3.8 Case studies

Four case studies that applied vibration based damage detection techniques to bladed structures, were investigated.

Case study 1 : Crack in scrubber fan.

One of the most interesting papers found in the literature study, investigated the detection of cracks in a scrubber fan (Wolff *et al.* 1989). The authors used both FEM and experimental measurements to test the effects of induced cracks on a scrubber fan blade. A modal analysis was performed on the scrubber. In order to do a modal analysis it was necessary to measure the force input and a "stinger" was used in conjunction with a piezo electric force transducer. They used a zero to 3200Hz "pink" noise signal from a dynamic signal analyser.

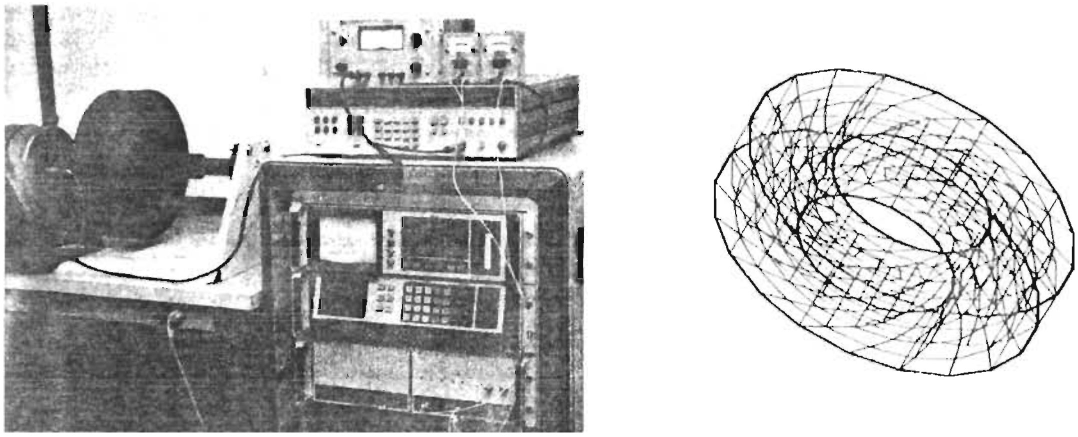

Figure 1.2: The FEM and experimental test rig used by Wolff et al. (1989)

By measuring the output from the force transducer and an accelerometer, a frequency response function can be computed. This allows modal parameters such as frequencies, damping values and mode shapes to be identified. They compared these results with results obtained after inducing cracks (using a fine hack saw) of 1.5 inches and 3 inches. Cawley and Ray (1988), found that this gave a good approximation to an actual crack.

A finite element model of the scrubber fan was constructed. The finite element model was calibrated to give similar results to the experimental model. The cracks introduced on the model consisted of untying various nodes and were therefore dependent on the mesh size. Cracks of 1.84 inches and 2.76 inches were modelled. From the results obtained, it was quite clear that some modes were a lot more sensitive to the damage than others. Furthermore the frequency shifts were very small. The experimental results failed to give an exact indication of damage for 1.5 inches and fared only slightly better with the 3 inch crack.

It was quite clear that although most of the mode shapes were found in the experimental modal analysis and frequency shifts did occur, as a damage indicator, this technique still requires some work. The authors note that the most apparent difference was found in frequency response functions due to separation and splitting of resonant peaks.

Case study 2 : Damage detection in wind turbine blade section

Another paper dealing with damage detection in blades used exotic, state of the art sensors and actuators and showed the possible future of online monitoring. Sundaresan *et al.* (1999) used a scanning vibrometer and piezoceramic actuators for detecting damage on a section of a wind turbine blade. As discussed in paragraph 1.5.1, the laser vibrometer is the ultimate diagnostics tool for vibration measurement. It is a non-contacting sensor that can measure vibration at a large number of points over a wide frequency range. Sundaresan *et al.* used three different methods for detecting damage. These methods used changes in transmissibility, frequency response functions and operational deflection shapes. Damage was simulated by a steel plate clamped to the blade and was detected by all three techniques.

The authors assumed that the wind turbine could be stopped for this application. Since the blade is easily accessible in this case, one vibrometer could be used to test various wind turbines. The Frequency Response Functions (FRF) could be constructed by making use of the periodic excitation equation and the piezoelectric ceramic patches to excite the blade. They found that reasonably good results could be obtained with all the techniques. The authors also noted that operational deflection shapes gave the most repeatable and accurate results.

Case study 3 : Damage detection in helicopter rotor blades.

Corbelli *et al.* (2000) focussed on the development of a method to detect damage in composite helicopter rotor blades in operative conditions. The authors used a FEM to obtain FRF data. The behaviour of the blades in hovering condition could then be described and numerical results were presented to validate the capability of the formulation presented to detect, localise and possibly quantify local variations of system parameters. Previous work of Mastroddi *et al.* (1996), Balis *et al.* (1997), Balis and Mastroddi (1997), Mastroddi and Balis (1998), Agneni *et al.* (2000) and Mastroddi (2000) described the numerical and experimental tests on truss, beam and fixed wing models. As typically happens in all inverse problems, results were strongly effected by noise or uncertainty in the measured FRF data.

Very complex structural and aerodynamic models were compiled by the authors to describe the behaviour of the rotor blade under hovering conditions. In particular, the velocity field induced by the wake vorticity on each blade had a great impact on aerodynamic loading distribution. The aeroelastic system was identified in terms of spatial matrices. FRF data obtained from the helicopter itself was in agreement with the FRF data obtained from the FEM. Unfortunately the authors were not clear on how the FRF data was obtained from the helicopter. The results obtained on damage detection presented in terms of stiffness variation matrices showed a good capability of damage detection, location and quantification. It was also apparent that the identified damage levels became lower and moved from the root of the blade to the tip for a fixed level of damage if global damage only was evaluated.

Case study 4: Health monitoring of Helicopter Rotor Systems

A project by McDonald Douglas (now Boeing), one of the largest aircraft manufacturing companies in the world, is currently under way to detect damage in composite helicopter rotors. The method make use one piezoceramic actuator and four piezoceramic sensors to determine FRFs and Transfer Functions (TFs) of the blade. The comparison of the measured TFs with TFs taken prior to damage was found to provide excellent results.

It was found that the size of damage that can be detected was heavily depended on the repeatability of the algorithm and the spacing of sensors. The biggest advantage of the method proposed by Schulz *et al.* (1997), was the fact that it was not necessary to compile a model of the structure.

The TFs approach was found to have three main advantages

- For a single force input the force was cancelled by the ratio of responses and thus did not need to be measured.
- The ratio of the peaks and valleys of a transmittance function was very sensitive to structural changes and could identify small amount of damage.
- Changes in the structural response due to global environmental effects were partially cancelled because transmittance functions are the ratio of two response quantities.

1.4 Output only extraction of modal parameters

From the various vibration-based monitoring techniques studied in the previous section of this chapter it became clear that most methods required input and output data for an accurate model. While it was not impossible to obtain input data for a structure such as an operating fan, it would be far more practical to make use of output only data (such as data obtained from accelerometers). This section gives a brief description of the literature found on output only extraction of modal parameters.

1.4.1 Time domain methods

Comparatively little attention has been given to practical damage identification of structures in industry. The single biggest problem with these structures was usually the lack of information on the excitation of the structure. Kriel and Heyns (1998) investigated the feasibility of detecting damage to piping structures in the chemical and petrochemical industries by making use of on-line monitoring of dynamic properties. The authors used both frequency domain (Basic Frequency Domain (BFD)) and time domain (AutoRegressive Moving Average Vector (ARMAV)) methods to estimate modal parameters. The BFD approach by Felber and Ventura (1996) was followed using software developed by Felber and Ventura. The ARMAV approach was implemented by making use of the MATLAB Structural Time Domain Identification Toolbox as implemented by Andersen *et al.* (1997). The authors found that the flow in the piping system provided enough bandwidth to excite the interesting modes. Both the models provided accurate enough determination of natural frequencies to detect damage. The ARMAV method was noted as being very expensive computationally. Mode shapes also seemed to be a viable parameter for damage detection.

Conventional modal testing requires artificial excitation of the test structure under well-controlled conditions. Heyns (1995) presented a technique that utilised time series analysis of the measured response, while assuming the perturbation of the structure through initial displacement, impulse or random excitation. Very good results was obtained when an initial displacement or impulse was applied on the theoretical model used and the responses computed. All modal parameters were found with a high degree of accuracy. For the case of random excitation, especially when some random white noise was introduced, the situation changed drastically however. Although the natural frequencies were still found with a fair degree of accuracy, the damping factors and mode shapes were not. In conclusion the author note that good results could be obtained for random excitation if suitable multi-channel tests were used and the order of the model used was increased.

1.4.2 Frequency domain methods

Hermans and Van der Auweraer (1998) also realised that while modal parameters are traditionally extracted from FRF measurements performed under laboratory conditions, in-operation tests frequently make it impossible to obtain input forces. The frequency domain Maximum Likelihood (ML) identification technique was investigated in this paper. Attention was paid to the modifications that has to be applied to the ML estimator in order to be applicable to output-only data and the derivation of the noise information required for the ML estimator. It was found that the ML estimator could be used to extract the modal parameters from output only data. Instead of using FRFs the ML estimator was fed by power- and cross-spectral density functions. The spectral densities were estimated by making use of the periodogram and the correlogram methods. Special attention was paid to leakage effects that created bias error. In the end the correlogram method was preferred because of better estimates for damping. Contrary to the stochastic subspace method, the ML estimator also provided uncertainties on the modal parameters, which might be of great interest in case of structural monitoring or damage detection applications.

Another frequency domain analysis using ambient vibration data was performed by Felber and Ventura (1996). Data from the Queensborough Bridge was used to do a frequency domain analysis. The authors found that thirteen natural frequencies could be identified between 0 and 10 Hz. Since more than one time signal were available and taken on different locations of the bridge simultaneously, the authors could also reconstruct some of the mode shapes by using TFs and a reference signal. This could only be done because the test had been carefully planned with these types of signal manipulations in mind. The results obtained compared well to results found with time domain techniques.

1.5 Feasibility of using vibration monitoring on a fan

Although the various signal processing, modelling and identification techniques studied up until now were very important, all would be in vain if accurate, repeatable measurements could not be obtained at a reasonable cost. This section describes some of the sensors that have been used, or may be used in future, along with some aspects regarding placement of sensors.

1.5.1 Sensors

A wide variety of sensors exist to measure the dynamic behaviour of systems. These sensors measure variables such as displacement, velocity or acceleration of the structure and converts this information into an electrical (usually analogue) signal that can be processed using various signal transducers. Since the method for damage detection developed has to be implemented on the an actual fan in industry at some stage, it was important to establish the feasibility and cost of using sensors.

The rest of this section describes various types of sensors and the viability of using them for this application.

A. Vibrometer

Laser Doppler vibrometry is a non-contacting optical technique that relies on the Doppler shift of laser light to measure the velocity of structures. The output consists of voltage signals proportional to the structure velocity. These signals are related to the frequency shift of the reflected light and are therefore accurately calibrated, providing accurate, quantitative measurements.

The application of laser Doppler vibrometry to high speed rotating structures has been hampered by technical limitations. Lomenzo *et al.* (1999) introduced a self-tracking laser vibrometry system which overcame these limitations. This method was first proposed by Maddux (1997). The method proposed made use of a series of mirrors, one of which was attached to the rotating structure's centre of rotation. This mechanical connection to the structure gave better results than other more exotic method making use of short measurement intervals.

A schematic of the typical configuration that will be necessary to monitor the vibration of a rotating blade can be seen in Figure 1.4. The measurement point on the bladed disk could the be adjusted by either tilting the vertex mirror or moving the fold mirror closer or further away from the disk.

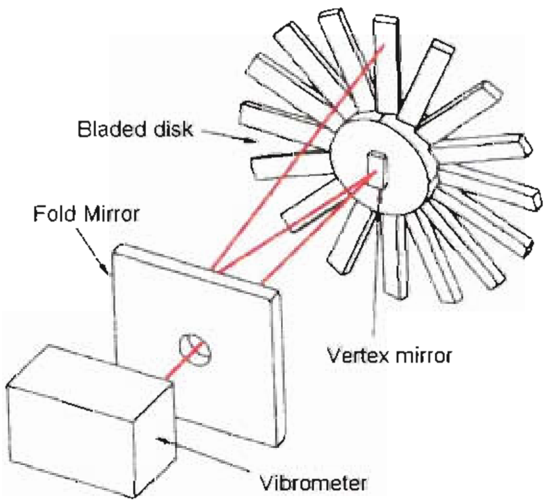

Figure 1.4: The self-tracking system for blade vibration measurements .

Recently a scanning laser vibrometer has been developed. While the entry level laser vibrometers can be acquired for $4500, the scanning vibrometer can cost as much as $80 000. The scanning laser vibrometer has the ability to direct the laser beam through an arc or cone depending on model.

B. Accelerometers

These sensors are the most widely used transducers for vibration measurement in industry. There are two primary types of accelerometers:

- *Piezoelectric:* These make use of a piezoelectric crystal and a seismic mass to measure the acceleration of the sensor and thus the structure. This type usually has a relatively wide frequency range (0.1-10000Hz) and low sensitivity (100mV/g). Because the charge created by the crystals dissipates quickly, lower frequencies can not be measured as accurately as higher frequencies.
- *Capacitive:* These are usually larger (although micro machining techniques are changing that) sensors and can measure very low frequencies (≈0Hz). The sensitivity of these accelerometers is usually higher as well (1-10V/g).

Figure 1.5 shows the trends for accelerometers regarding price, size, frequency response, range, reliability and level of integral electronics. The most exiting development is the advent of MEMS (MicroElectroMechanical Systems) technology (see Figure 1.6).

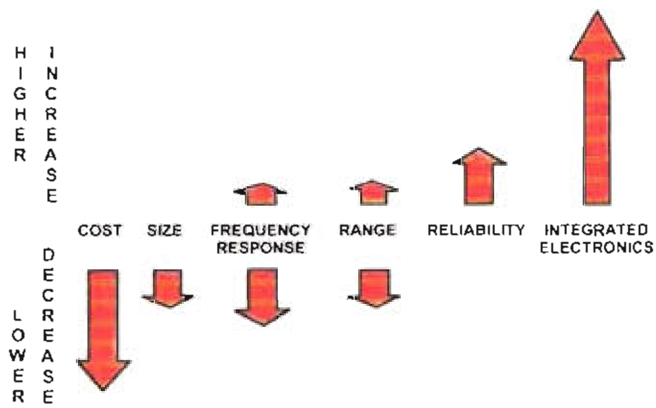

Figure 1.5: Trends regarding accelerometers

Using the same technology as that used by microchips, a very small accelerometer can be constructed and packaged on a circuit board. Furthermore, integrated circuits can be built into the accelerometer, turning it into a "smart sensor". These sensors measure environmental changes around them (such as pressure, acceleration etc.) and use the integrated circuit to amplify, condition, calibrate and process the raw signal from the transducers. Examples of these sensors include the accelerometers used to deploy air bags in cars.

These sensors typically cost less than $10 and makes a decision regarding the deployment of the air bag before sending a signal to the triggering. An example of MEMS capacitive accelerometer can be seen in Figure 1.6.

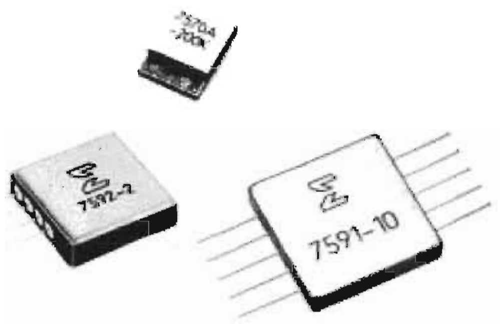

Figure 1.6: Examples of MEMS capacitive accelerometers

The most important aspect of these developments is the fact that while the performance of these devices are getting better and better, the cost is going down dramatically as mass production for MEMS accelerometers come into play. While micro accelerometers such as the one used on the fan blade damage simulator cost around R5000, it is not unreasonable to expect cheaper MEMS accelerometers to be available within the next few years.

The micro accelerometer used for some of the measurements can be seen in Appendix A. The specifications and physical dimensions of the sensor are also provided to give some indications of what is readily available even now.

C. Strain gauges

These devices had been around for some time. Modern strain gauges are inherently sensitive to strain.

The unit output is directly proportional to the unit dimensional change (strain). These generally work by measuring the increase of electrical resistance with increasing strain. The bonded-wire-type strain gauge is the most generally used. Another type work by using the decreasing area of the metal from which the strain gauge is manufactured as electrical resistance. Figure 1.7 shows the most commonly found type schematically.

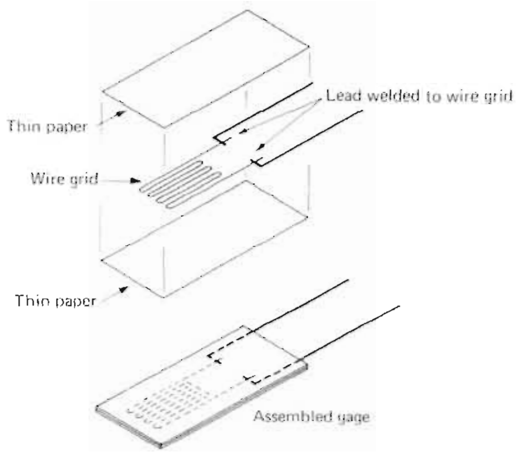

Figure 1.7: Schematic of typical strain gauge (Beckwith (1993))

Recently, the piezoelectric strain gauge has been developed. This sensor can only measure dynamically and is therefore optimised for the dynamic measurement of system response. The strain is measured by using the properties of the piezoelectric crystal. When this crystal deforms it results in a voltage difference across the crystal that can be measured. The big advantage of this sensor is that no balancing circuitry, amplifiers and other peripherals were necessary. The piezoelectric strain gauge used specifications and physical dimensions can be seen in Appendix A.

D. Other sensors

Other sensors that may have been used include various types of displacement and velocity sensors. The vibration of blades has been studied by proximity sensors in the past. The difficulties involved with placement of these sensors make them less than ideal for this particular application however.

1.5.2 Telemetry

One of the biggest problems regarding the monitoring of the dynamic behaviour of fan blades is the transfer of data from the measurement sensor (that will probably be mounted on a blade) to the signal transducer or user interface. The ultimate goal would be to develop an integrated sensor that measures the dynamic behaviour of the blade, process this information, make a decision regarding the conditions of the blade and then send a warning signal to the user if the blade requires maintenance. This scenario is probably still a few years into the future. A more realistic approach would be to either transmit the signal from the sensor directly to a signal transducer, or to store this data and transfer it in bursts whenever the fan is shut down due to lower power demand from the national electricity grid.

Wireless transfer of data has become more and more available as time has gone by. Local area networks between personal computers have already taken the step to a wireless environment by making use of radio wave connections similar to cellular phones. At the moment, only very specialised and expensive wireless-transfer techniques exist for the precision sensor signal that an accelerometer gives as output. A device that use infra red non-visible light can be imported from America at around $10 000 . A good example of how the prices on sensors and telemetry is going down is that a similar device, using radio waves can now be acquired for $4500.

New wireless transfer standards such as Bluetooth being developed by companies such as Nokia, Intel, Ericson, Microsoft, Motorola, 3COM and various others will play a huge role in future communication between various devices. Bluetooth is a high-speed, low power, microwave wireless link technology which enables devices such as phones, laptops and other portable equipment to communicate with each other. Briefly, Bluetooth technology:

- uses radio waves in the 2.4 GHz band, meaning that line of sight is not required.
- supports multipoint communication
- works in small confined area (10 to 15 meters apart)
- is able to support speeds of 1-2 Mbps
- the chipsets are relatively inexpensive ($10 per chip)
- over 1800 members in industry support this technology

This technology is already used in various mobile phones and laptops and is also being developed for applications such as wireless sensors. Nokia recently displayed a Bluetooth headset that allows users wireless communications with their mobile phones over distances up to 10 meters.

For the purposes of this thesis, it was decided to use a locally developed slip ring unit that can be seen if Figure 1.8.

This unit specifications and physical dimensions can be seen in Chapter 3. It performed very well throughout the experimental tests. The units' location in the signal path can also be seen in Chapter 3.

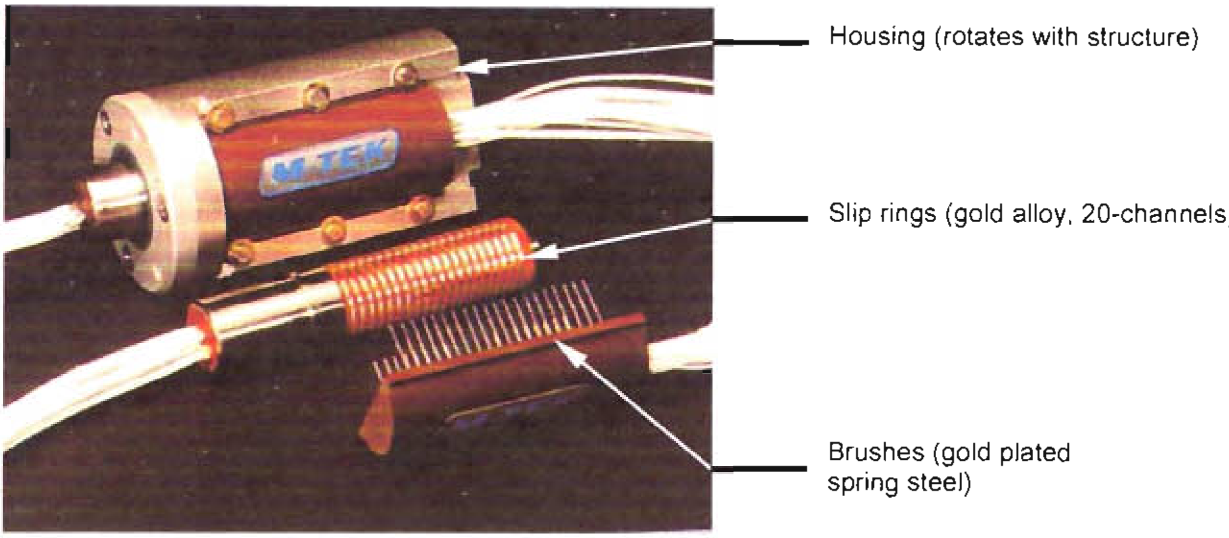

Figure 1.8: The slip ring unit used for transferring data from the rotating transducers to the signal processing unit and personal computer.

1.6 Scope of work

This chapter described an extensive literature study covering:

- Damage detection techniques
- Vibration based damage detection techniques
- Viability of dynamic measurements on a rotating structure such as a fan
- Sensor requirements
- Telemetry requirements

It was found that exhaustive efforts have been made in the field of vibration based damage detection. From these efforts it was apparent that damage could be located and classified provided good quality measurements (repeatable and accurate) was available. Although most applications in industry made it impossible to obtain accurate input forces on structures, the majority of the techniques developed required accurate input data. For an application such as health monitoring of operational structures, especially fan blades, this was not a realistic requirement. Fortunately some methods involving output data had been developed. Time domain techniques offered the best applicable results. Special attention was given to ARMA based techniques, as various researchers have used these techniques to successfully identify modal parameters such as natural frequency.

A great deal of time was spent gathering data on various sensors, especially so-called "smart" sensors. From the vast number of articles on this subject available on the Internet, it seemed reasonable to assume that these sensors are being developed more and more. The integrated sensors used for the deployment of air bags in cars are a good example. These sensors measure the deceleration forces and make a decision as to whether the air bag should be deployed or not within a split second before sending the activation signal to the deployment system. The cost of these sensors have come down to about $10 due to mass production. Wireless sensors are also becoming more and more common and it seems certain that a damage detection technique for fan blades can be developed, knowing that inexpensive transducers are not too far into the future.

Due to the fact that most industries can not afford to make unscheduled maintenance stops, the development of on-line monitoring techniques providing adequate warning of possible failures have become of paramount importance. Failures leading to loss of lives and production can be prevented if these techniques can be developed into reliable and relatively inexpensive solutions.

The feasibility of using vibration-based damage monitoring has been studied in some detail in chapter 1. The next chapter deals with the specific techniques used for damage level monitoring for this project. It became clear at an early stage that it would be necessary to design and build an experimental test structure to facilitate with the development of a damage identification technique. Some of the most important reasons for using an Experimental Fan Blade Damage Simulator (EFBDS) and not the actual fan from industry (such as the FD fan at Majuba) were:

- Most fans in industry can not be switched on and off at will.
- Because of the construction of industrial fans, instrumentation of the blades would have been quite difficult and time consuming.
- The time spend travelling would have been unacceptably much.
- It made sense to develop techniques in an environment that can be controlled to cut down the number of variables that needed to be taken into account.
- In order to test the damage detection techniques the blades would have to be damaged artificially. This would have carried a severe cost and safety penalty if done at a power plant or other industry.
- The minimum of telemetry can be bought because most of the required sensors and measuring equipment are already available in the Gold Fields Dynamics Lab.

After the decision to construct an EFBDS was taken, different concepts were generated, a selection was made and a detailed design done. This also involved the procurement of the necessary telemetry such as the slip ring unit discussed in section 1.5 and the electric motor and control system discussed in chapter 3.

With the EFBDS constructed and assembled, some preliminary measurements were taken followed by a full set of measurements taken at 0, 10, 20, 30 and 40% levels of damage. Statistical techniques were used to determine the required number of data sets that needed to be taken in order to compensate for measuring inaccuracies. All the results found can be seen in Chapter 4. Frequency shifts proved to be a good indicator of blade damage. Time domain damage indicators were also evaluated with a future view for use as features in pattern recognition techniques such as neural networks.

Some of the natural frequencies did not shift by as much as was predicted by the FEMs developed. A postulation that this was due to the global modes of the structure proved to be correct and is discussed in Chapter 5. Final conclusions and recommendations can also be found in Chapter 6.