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MARS - Modal Analysis of Rotating Structures

Development of validated structural dynamic modelling and testing techniques for vibration predictions in rotating machinery

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1. ABSTRACT

The MARS project has developed a set of experimental and analytical techniques for measuring and predicting the dynam-ic behaviour of rotating machine structures, including flexible rotors, foundations and bearing elements.

Modal testing of components and assemblies is a well recognised method of validating Finite Element (FE) models but vibration measurements on rotating components are extremely difficult to make and require additional processing compared with those on non-rotating components. Modal testing and analysis requires measuring the response at selected points on a structure to an input force at a series of known frequencies and known amplitude. Applying such forces to a rotor is difficult, given the need to also provide bearing supports for the rotor.

An excitation system using Active Magnetic Bearings (AMBs) with integral Hall effect force sensors has been developed to supply a controlled sine wave force pattern in the vertical and horizontal directions at each bearing. They allow selective excitation of forward and backward modes of the rotating rotor. an identification algorithm for AMB machinery was developed. Controller design methodology for AMB machinery was further developed.

A shaft-synchronised scanning laser doppler vibrometer has been developed for response measurements enabling motion of a single point on a rotating disc to be measured. Measurements from an array of proximity probes have been used to determine the traveling wave information from a rotating shaft or disc and the wave motion may be displayed in a multi-directional f orm of Campbell diagram.

A pc based modal testing data acquisition and control package has been developed which will adjust the horizontal and vertical forces applied by the two AMBs to provide a set of four sine wave force patterns, even when the structure and excitation system are non-linear. The responses can be separated to determine the Frequency Response functions (FRFs) due to a single force. Accurate measurements can be made, even in the presence of noise from the transducers, or due to additional synchronous response in the rotor.

A new Finite Element programme **LISA** has been specifically developed for analysing rotor dynamics. The programme interfaces with other packages (NASTRAN, PATRAN, & MATLAB), but allows easy modelling of specific rotor dynamics problems such as gyroscopic and centrifugal effects, and the modelling of bearings and seals. High quality graphical output is provided as spatial mode shape displays, frequency response functions or time responses.

A two-stage approach to Model Updating of the FE model, based on non-rotating and rotating FRFs has been developed which may be used to determine properties such as dynamic bearing stiffnesses, or the gyroscopic coupling.

These measurement, analysis and modelling techniques have been demonstrated on a specially designed rotating machine model used to investigate a series of parameters: flexible rotors and stators, foundations and bearing elements, that have major influence on the dynamic properties of rotating machines.

2. INTRODUCTION

The reliability and efficiency of every rotating machine depends on the designer's ability to predict correctly a range of its dynamic characteristics, including stability, vibration response levels and fatigue, and to diagnose faults effectively. For these tasks, reliable structural dynamics models are essential. The current state-of-the-art of dynamic modelling for rotating structures is such that, in almost all cases, experimental confirmation or validation is necessary before the critical design calculations can be performed with confidence. The three stages involved in this process - (i) initial dynamic analysis and modelling, (ii) experimental measurement and (iii) the combination of these two in a validation process - all require development and this was the motivation for the project.

3. OBJECTIVES

Objective 1. To develop new test methods for the study of the structural dynamics of rotating structures, using a non-contacting excitation method provided by Active M-agnetic Bearings (AMBs) and non-contacting measurement methods using laser doppler velocity meter and proximity probes.

Objective 2. To develop refined methods of analysis for the study of the **structural** dynamics of rotating components in a machine. (a) by a theoretical (FE) analysis and (b) by identification from test data.

Objective 3. To develop test/analysis correlation and updating procedures applicable to rotating structures. Hence to demonstrate that the analytical models are reliable by correlating predictions against a series of measured test conditions.

Objective 4. To lay the basis of advanced design procedures which maybe subsequently developed for specific industrial applications.

4. TECHNICAL DESCRIPTION

4.1 Test rig

A specially designed test rig has been built to simulate rotor dynamics problems (see Figure 1). It enables a horizontal flexible rotor with either a flexible or rigid disc mounted at one end to be supported on rolling element bearings, or freely suspended on active magnetic bearings (AMBs). The other end of the shaft is driven via a light-weight coupling from an electric motor with accurate speed control. The whole system is mounted on a heavy base frame.

The outline design was refined by dynamic modelling to ensure that the bending modes of the flexible shaft with an overhung disc do not have node points close to the proposed AMBs, so that they can be used to effectively stimulate the bending modes. The flexible rotor includes the laminated cores for the AMBs, which were shrink fitted onto the shaft. Additional rolling element bearings could be added outside the AMBs to support the shaft if required.

The rolling element bearings may be supported on a flexible platform, mounted onto the heavy base frame, to represent a machine mounted on flexible foundations.

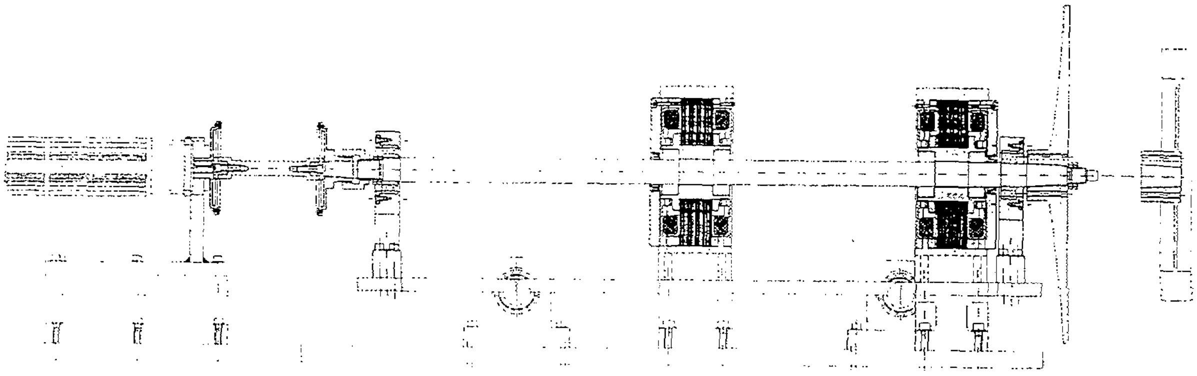

Figure 1: *Arrangement of test rig.*

4.2 **Active** Magnetic Bearing (AMB) exciters

The design of the two AMBs has been tailored to make FRF measurements. The AMB exciters allow the rotor to levitate without contact, and to excite it with user-defined sinusoidal forces at the same time. A specially developed force measurement method using Hall sensors allows the radial forces acting on the rotor to be measured with high accuracy. These features enable high-quality FRF measurements to be made on the rotating rotor. The exciting forces may be adjusted to specifically excite forward or backward traveling modes of the rotating rotor [1, 17, 21] For forces up to 500N, the linearity error in the force measurement is as good as 1.5 %.

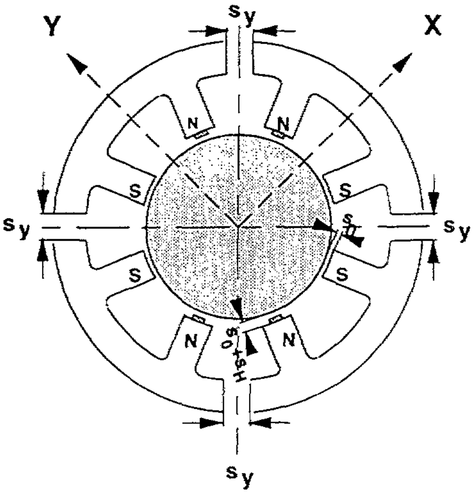

Figure 2: *Cross-section of AMB. A special bearing geometry was developed to optimise the trade-off between bearing performance and force measurement accuracy. The Hall sensors are placed at all north poles.*

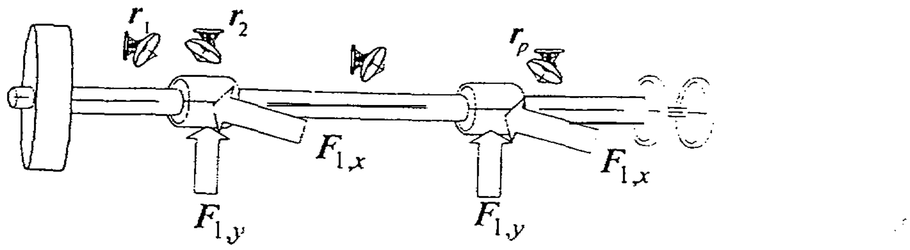

Figure 3: *AMB force input into a rotor.*

Figure 3 shows the four forces applied through the AMBs. To extract the frequency response functions due to each applied force in turn it is essential to produce four independent force patterns for each measurement. The force patterns are checked using singular value decomposition to ensure independence. [6]

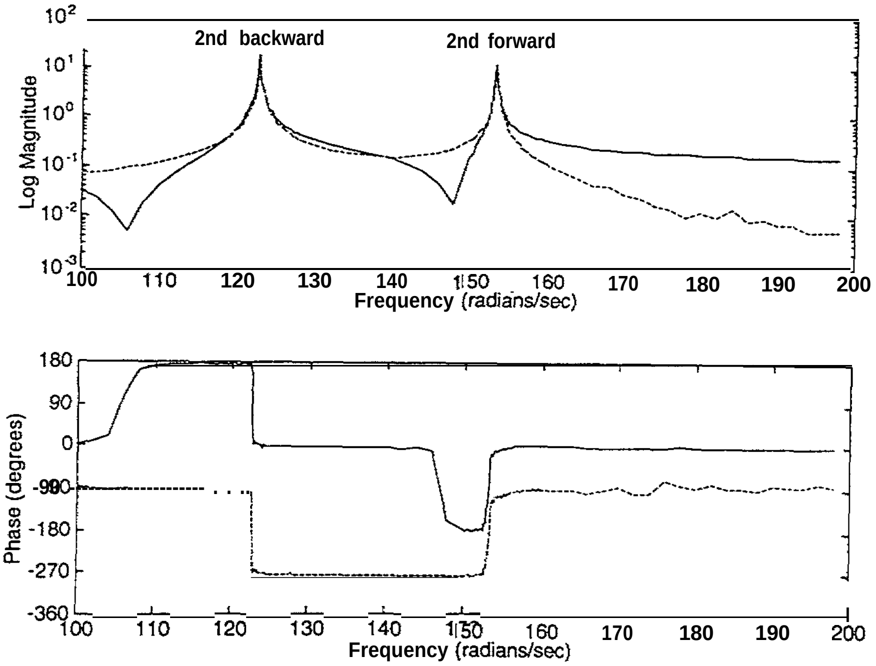

*Figure 4: FRF of the rotor at 2000 rpm. Response (accelerance) to excitation in x direction at bearing A. Two of the elements of the measured full 4*4 FRF matrix are shown in this plot. Solid: point-to-point FRF; dashed: cross-coupling between x and y planes caused by gyroscopic effects. The two resonances are the second backward and forward modes.*

Controller design methodology for AMB systems with highly flexible and gyroscopic rotors has been further developed. The new approach for decentralised controller design mainly consists of shaping the controller phase such that all eigenmodes of the rotor can be stabilised, whilst a low controller gain at high frequencies guarantees robustness and good noise rejection.

A novel algorithm for multivariable identification of AMB systems was developed beyond the scope of the project [2 ,14, 18] It allows faster commissioning of AMB systems and better controller performance. The algorithm for system identification of AMB systems must identify the flexible modes of the system and the unstable rigid-body modes. The new algorithm identifies the eigenvalues from the determinant of the measured FRF. The quality of this identification procedure is shown by the results in Figure 5.

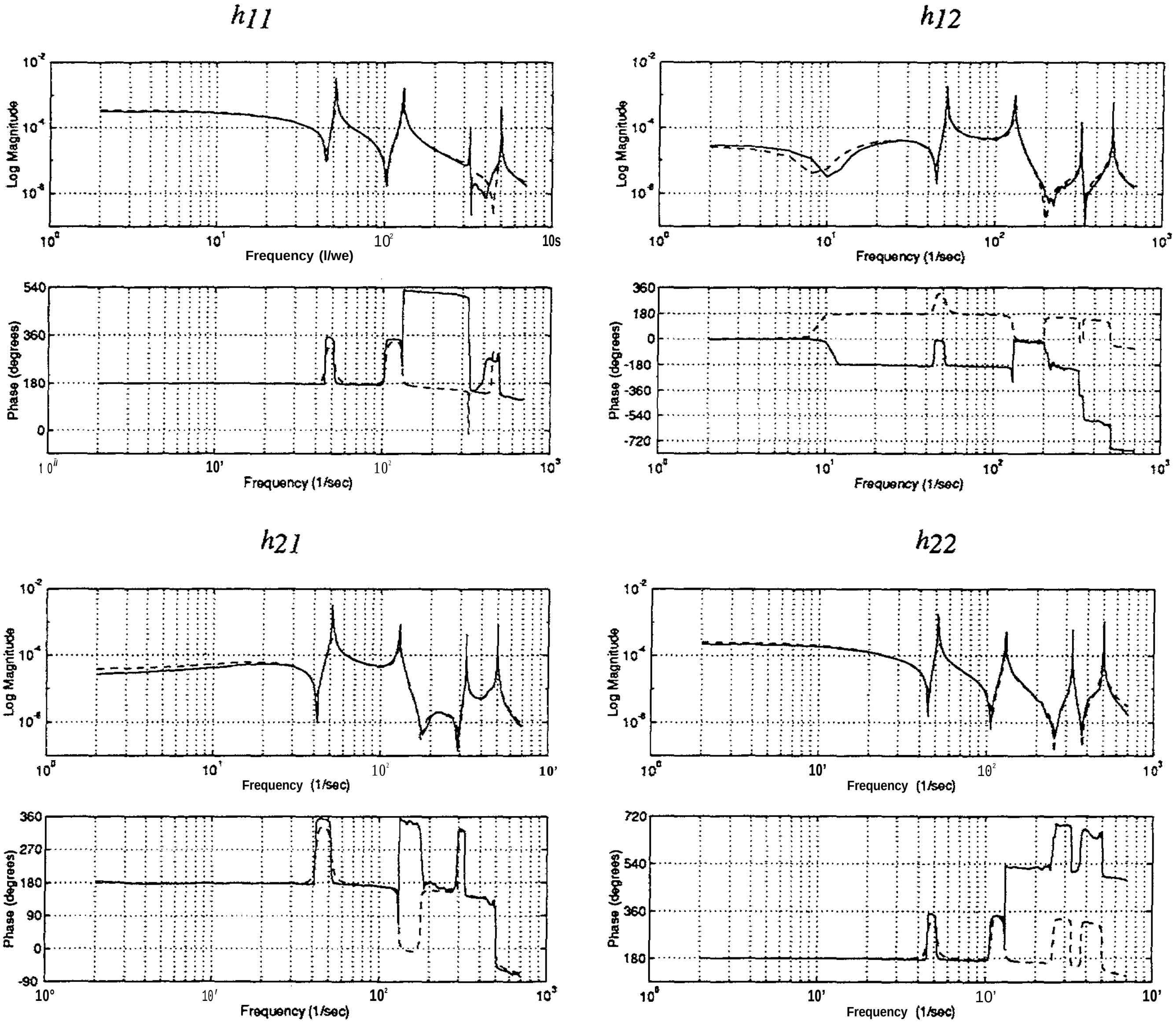

Figure 5 :Identification results. Solid: measured FRF; dashed: FRF of the identified model. The inputs of the identified system are the AMB coil currents, its outputs are the displacements.

4.3 Scanning laser response system

Non-contacting measurements are required for rotating systems and two approaches have been developed, i, a scanning laser doppler vibrometer, and ii, an array of capacitance proximity probes.

The laser system uses a mirror control system synchronised to the rotor's angular position to adjust the scan mirrors on a commercial scanning laser doppler vibrometer supplied by Ometron. The laser is mounted on a heavy machine table and accurately aligned with the shaft axis. Motion of the x and y mirror controls enables the laser beam to trace a circular orbit, which may be synchronised directly to the rotor to measure the axial vibration of a shaft mounted disc. This is equivalent to a point measurement on the rotating disc.

[4, 10] Alternatively the laser beam rotational speed can be set to be non-synchronous to the shaft, in which case it will scan a circle round the disc surface, detecting any axial velocity associated with traveling waves on the disc. The existing laser scanning mirrors allow scanning frequencies up to about 100 Hz.

Other applications of the laser for modal testing have also been investigated' [3, 8, 13,22]

4.4 **Proximity probes - modified Campbell diagrams**

In many applications it is not possible for a laser to have a line of sight onto the disc, e.g. inside a pressurised casing, and proximity probes may be used to detect relative motion between the rotor and a stationary probe. Provided that the probe's motion is very small, or it can be measured, the output from a single probe gives a measure of the rotating component's response. In general, with a sine wave excitation of a rotor, the response will contain frequencies due to the forward and backward traveling waves in the rotor. A single probe will detect the two waves, which will appear as two frequencies.

In normal run-up or run-down test, the frequencies detected by a single probe are plotted against running speed to detect the interference with modes of the stationary structure in a Campbell diagram. However two probes can be used to provide relative phase information about the motion, and it is then possible to separate the motions into backward and forward traveling waves. This technique has been developed [12, 19] and expanded to separate the signal into specific nodal diameter patterns using an array of sensors, providing much more information about the vibrations. The number of modes which can be detected is limited by spatial aliasing, two probes per nodal diameter are required. Figure 6 shows a run-up test on a shaft plus flexible disc using a single probe Campbell diagram and the results obtained using eight probes in an arc round the shaft axis to separate and determine the amplitudes of the various nodal patterns, from n= O to n =3.

4.5 **Modal Testing Data acquisition and measurement control system.**

A pc based multi-channel data acquisition and measurement control system has been developed, which adjusts the demand signal to each AMB to provide the sinusoidal forcing pattern in the four radial bearing directions, and measures the response of 16 transducers. The force pattern is adjusted to provide a virtually sinusoidal force, ***even*** with non-linearity in the structure and AMB system, by extracting the harmonic terms from the forces measured by the Hall sensors [9, 11]. Figure 7a shows the effect of pure sine wave signals on two conventional exciters acting on a rotor with a non-linearity in the measurement system. Figure 7b shows the improvement in response obtained by regenerating the demand signal with higher harmonics to modify the force input.

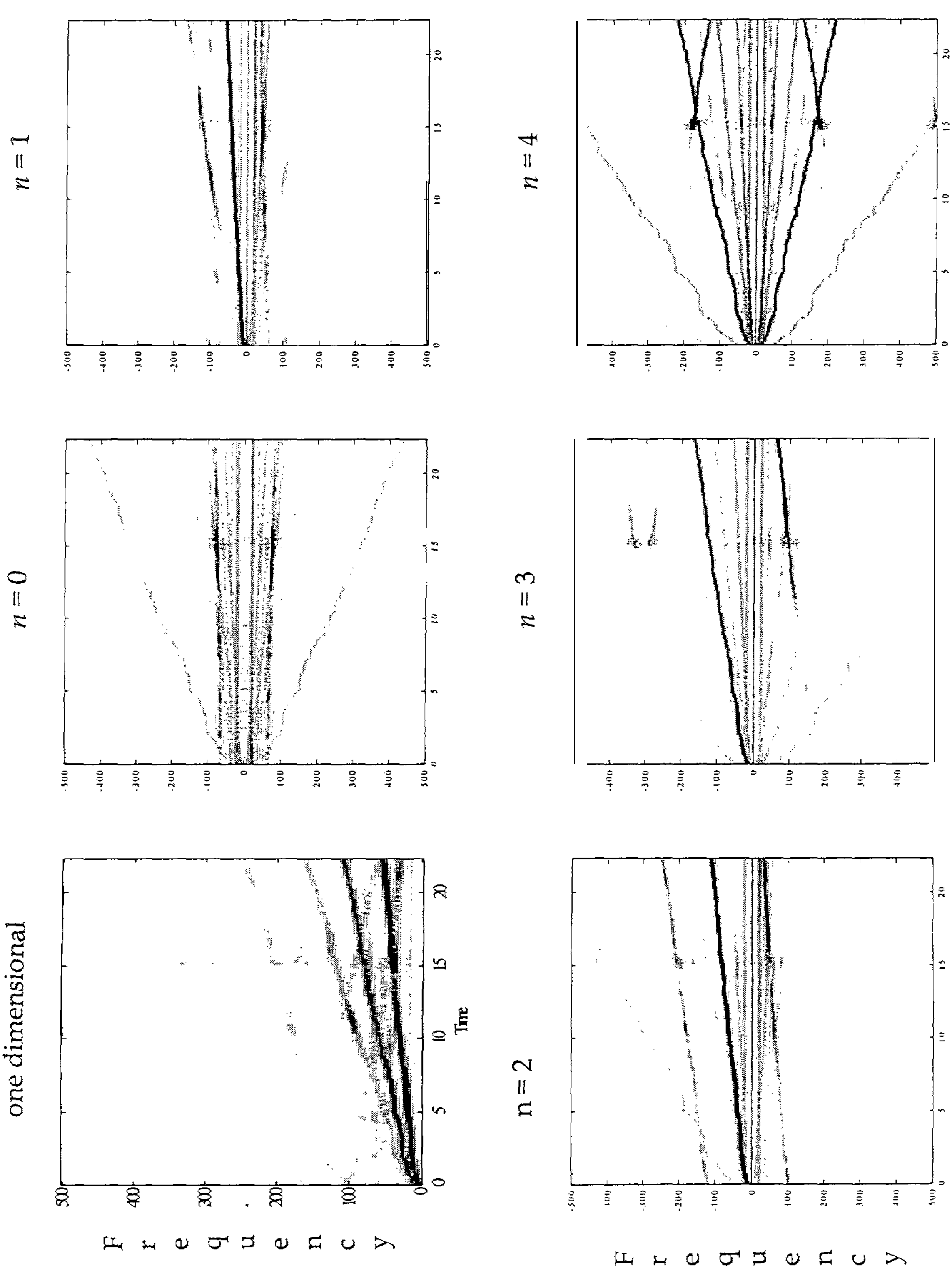

Figure 6: Multi-dimensional Campbell diagrams for a shaft with flexible disc, separating nodal patterns for n= O 1,2,3,4, from the standard plot (one dimensional).

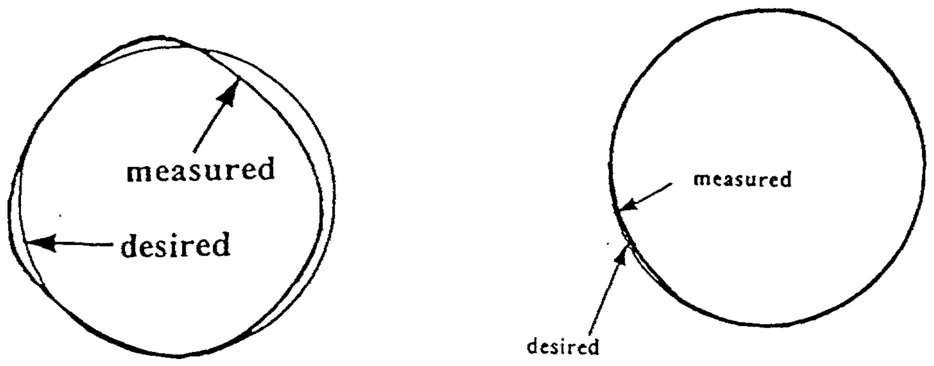

Figure 7: Modifying demand signal to cope with non-linearity in the structure or measurement system. u: with pure sine wave demand signal b: sine wave + harmonic correction.

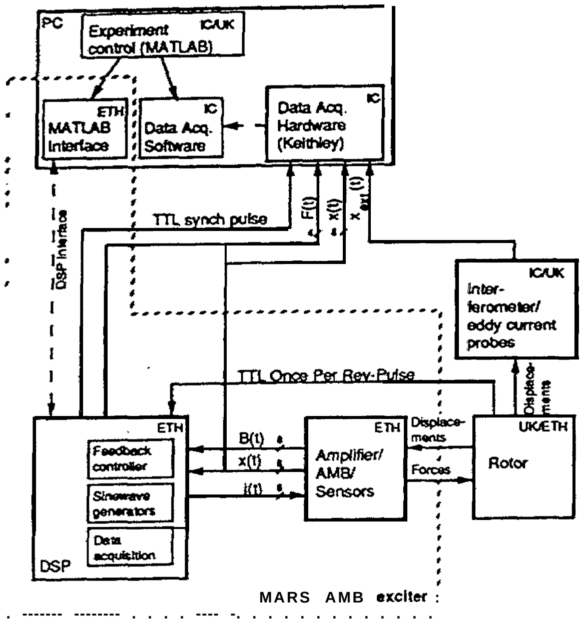

Figure 8 Control interaction for MARS test rig. Communication is via MATLAB commands to facilitate easy development and fault locution.

Figure 8 shows the interaction between the various stages of the measurement and control system on the MARS test rig.

Measurements on rotating systems may detect several frequencies of response, due to bearings, shaft run-out or out-of-balance and due to wave patterns on the rotor, especially a rotor with a flexible disc attached, where forward and backward traveling waves can occur [7]. It is essential to separate these effects when attempting to perform measurements for modal analysis and hence FFT based measurement procedures using random or pseudo random analysis are not satisfactory. Step sine testing has the advantage of concentrating all the input energy into one frequency, hence the force signal and the response signal should correlate well at that frequency. Responses synchronised to rotor speed can be filtered out and bearing noise can be removed by averaging. Non-linear effects can be deduced by harmonic analysis of the actual forces measured to the original pure' sine-wave demand signal [9].

A further problem with testing many rotors is that they are designed to be symmetric about the rotational axis, which leads to pairs of identical modes. However in practice manufacturing variations may lead to slight mistuning. Testing such structures requires several close frequency measurements and the use of more than one exciter to separate the modes. With rotating systems the gyroscopic coupling separates the pairs of modes into forward and backward motion with different frequencies to a stationary observer [20]. It is therefore possible to measure each mode in isolation, and by repeating tests at a range of rotational speeds, the gyroscopic separation and damping effects can be assessed.

Step sine testing to remove non-linearity effects and ensure four independent forcing patterns for each frequency, together with the need to filter out noise and other signals, therefore takes a long time if accurate results are to be obtained. However the step sine approach enables the operator to select frequency bands of major interest e.g. round resonances, and to concentrate the measurement effort in these regions.

Figure 7 shows typical measurements made using the AMBs to support the rotor and to provide the excitation, and using proximity probes to determine the responses.

4.6 Dynamic Modelling

A new Finite Element package LISA has been developed [5], which can accept input from standard FE packages such as NASTRAN, pre and post processor programmed such as PATRAN, or from MATLAB. The complete structure can be modelled as a mixture of stationary and rotating items, joined at specified locations, and is specifically designed to analyse problems related to rotating machines. In particular the modelling of bearings and gyroscopic terms are included. A range of eigenvalue solvers can be accepted, for use in particular classes of problem. Output can be graphical to display normal or complex modes, Frequency Response Functions or time responses. Alternatively output can be passed to other programmed such as SIMULINK in MATLAB for control system assessment. It has been written in an open format to allow additional elements such as seals to be included, and to use alternative solution methods for comparison.

4.7 Model Updating

The problems of model validation and model updating are considerably more complicated for rotating machines, compared with non-rotating systems [16].

In general, the properties of the rotating elements (rotors, discs etc) are time varying as seen by a stationary observer, and in principle to obtain the complete set of left and right hand eigenvectors needed to describe the structure completely, it is required to measure the response at every point on the structure to a force applied at every point in the structure in turn. Apart from the time involved in completing this measurement process, n^2 measurements are required if there are **n** locations to be checked, it is virtually impossible in a practical structure to apply forces at every location and direction. However if the rotor is virtually symmetrical, then its properties are not significantly time varying. If the rotor has gyroscopic coupling terms which are significantly greater than any cross-coupling due to damping then the left hand eigenvectors are directly related to the right-hand eigenvectors and it is possible to reduce the measurements required to just a single row or column, in a similar manner to that used in non-rotating systems.

Measurements round resonance require very small forces, and hence are likely to be of lower accuracy than those away from resonance. In addition the requirement to generate four independent force patterns at each frequency is more difficult close to resonance as the dominant modes tend to cause severe interaction between force and response. With lightly damped rotor systems the AMB control system may have difficulty in producing the required force patterns. Hence although the actual resonance frequencies can be detected with good accuracy, traditional modal analysis using data close to resonance is unlikely to give accurate results, due to the relatively poor data.

As mentioned in the Modal Testing section, running the rotor at a fixed speed does separate the close modes of the rotor into forward and backward motions, and by running the machine at several speeds these effects can be checked with a stationary transducer due to the split in frequencies.

A multi-stage process has been developed to update analytical models using rotating measurements. The initial stage is to minimise the error in the natural frequency predictions by adjusting Young's modulus and density, and secondly to minimise the error in the eigen-vector elements, using data away from resonance to minimise the effect of noise. By making a series of tests at different running speeds to check the Campbell diagram, the gyroscopic coupling term can be accurately determined as a final adjustment.

4.8 Experimental Measurements and Updating

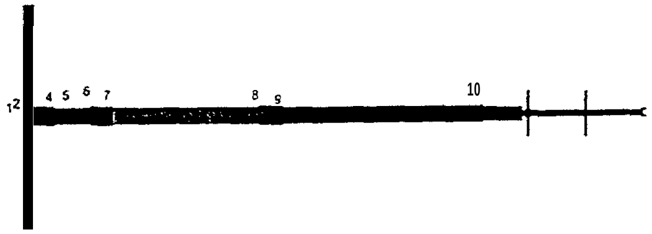

Figure 9: *FE model of rotor plus disc*

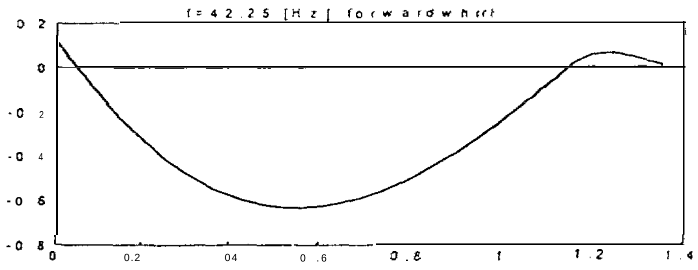

Figure 20: First bending mode predicted by FE model.

Figure 9 shows an FE Model of the rotor plus rigid disc, and a prediction of its first bending mode shape is shown in Figure 10. The predicted rotor speed effects can be seen in a Campbell diagram Figure 11.

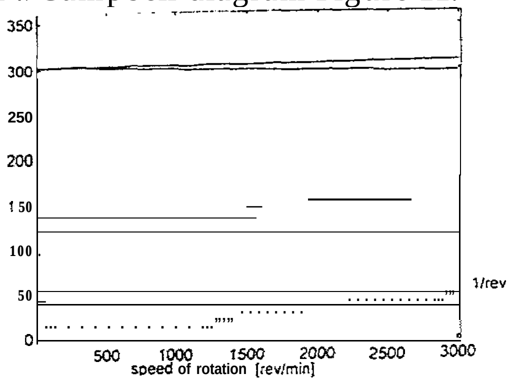

***Figure 11:** Campbell diagram **from** FE prediction,*

Frequency response measurements have been made on the flexible rotor plus rigid disc, using the AMBs to support the rotor and apply the required force inputs. Figure 12 shows four measured FRFs at the bearings and Figure 13 shows the variation in AMB force levels during the step sine measurement at stand-still.

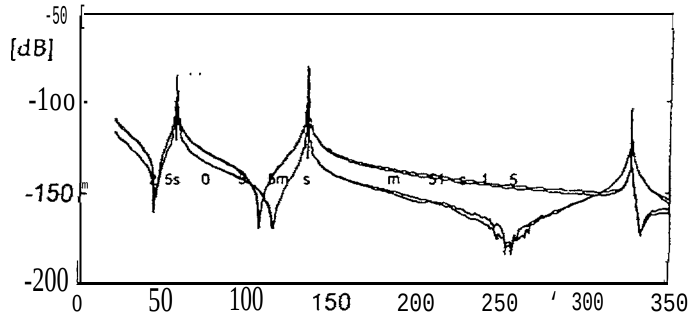

Figure 12: *Four measured FRFs*

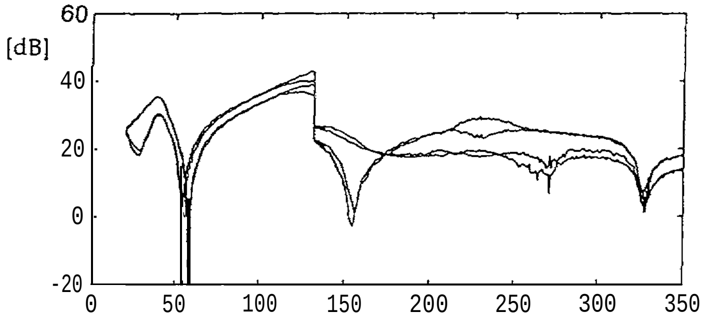

***Figure 13:** Force level variation for AMBs.*

Figure 14a shows the predicted Campbell diagram using the original FE model with the measured non-rotating frequencies marked. Figure 14 b shows the effect of updating using this data.

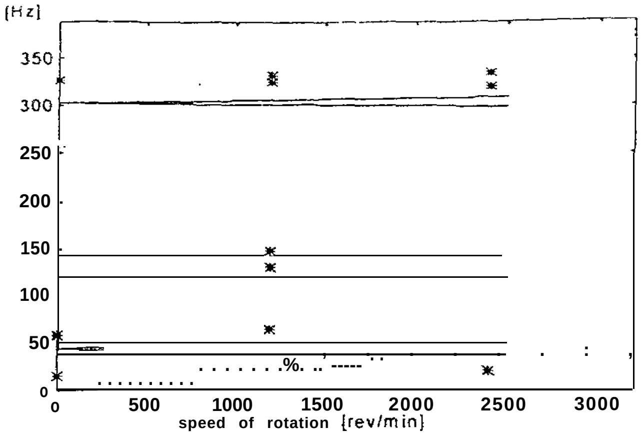

Figure 14a: *Campbell diagram,
Initial FE model*

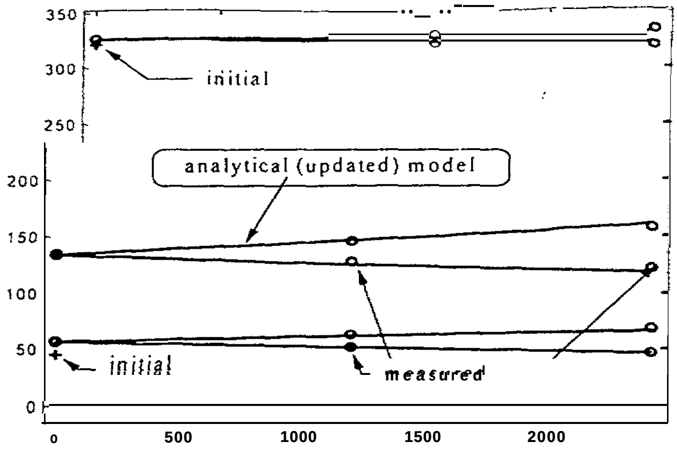

Figure 14b : *Updated using non-rotating measurements.*

Finally figure 15 shows the results of updating the FE model using measurements with the shaft rotating at 1200 rpm, and the close agreement reached in the Frequency Response function based on the adjusted model.

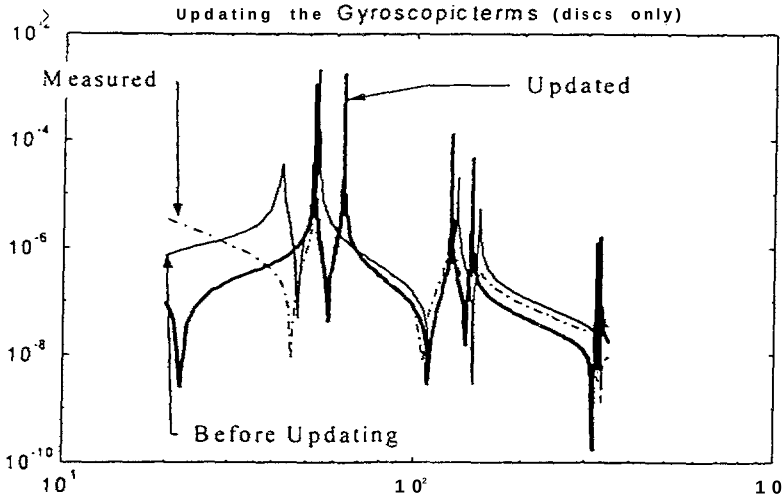

Figure 15 *Updating of FE model using 1200 rpm rotor test.*

The sequence demonstrates the need for high quality data, and the advantages of a multi-stage approach when the gyroscopic terms can be separated.

5. RESULTS

1. A test rig has been designed, manufactured and tested which is capable of representing typical dynamics problems in a form which have been measured and analysed using the tools which were developed as other parts of this project.

2. The Active Magnetic Bearing system has been developed as a fully functional method of exciting a rotating shaft system to enable step sine testing using sinusoidal forces applied through the bearings. A novel

approach for the controller design with AMB systems has been developed, including related software tools. This approach is tailored to systems with highly flexible and gyroscopic rotors, and decentralised control with predefine low controller order, supporting the rotor independently of any other support mechanism.
The control system developed to operate the bearings on the MARS test rig has been demonstrated to perform satisfactorily over the speed range O to 3000 rpm, with a flexible rotor and flexible disc having bending resonance frequencies in this running speed range. A novel identification algorithm for AMB systems was developed which facilitates controller design..

3. A new method for accurate force measurement was developed using Hall sensors, including a new bearing geometry, new sensor configuration, new flux computation method, and a real-time approximation for this flux computation method.

4. Methods for measuring out-of-plane vibration of a rotating disc, using a scanning Laser Doppler Vibrometer have been successfully demonstrated. An unrestricted line of sight from a point on the axis of rotation is always necessary and, using existing hardware, current mirror drive characteristics limit the scan speed to about 100 Hz (6000 rpm).

5. Other techniques which have been developed in considering the potential of a continuously-scanning Laser Doppler Vibrometer:- ‘mode shape measurements defined along circular and straight scan lines, angular vibration measurement, and measurement of vibration direction vectors:- all satisfy real needs in the field of experimental vibration work, and should prove to be genuinely useful.

6. A Finite Element program LISA has been developed which can model stationary and rotating structures with a range of engineering components such as shafts, discs and bearings. The input may be from existing FE models of machine structures, or from built up elements. The output can be displayed graphically or used as the input to further analysis, e.g. for control systems. The structure of the program is such that alternative eigenvalue solvers may be complemented by other routines to speed up the solution for special purposes.

7. A pc based data acquisition and control system has been developed to provide multi-exciter step sine inputs and 16 channel analogue response measurements for rotating machinery. The system can be used to control a scanning laser doppler vibrometer synchronously with a rotating shaft to enable point measurements to be made on rotating disc components. or take inputs from other transducers. Shaft synchronous signals may be removed from the response signals before extracting the sine response and harmonic response. A force controller process adjusts the demand signal to each exciter to produce the required sine wave force pattern. Multi-exciter systems must have the same number of independent force patterns as exciters, and the control system checks for this independence to maximise the accuracy of each force determination. The output is a series of FRFs suitable for Modal Analysis.

8. A new method or rotational response analysis, using an array of stationary response transducers, enables phase information about rotating component vibration to be determined, producing a multi-dimensional spectrogram and Campbell diagram which separated forward and backward traveling waves, enables greater understanding of machine vibration during normal operation. This is suitable for use in many industrial rotating machinery investigations. .

9. The FE modelling and Modal Analysis of the rotors show that it is still important to be able to correct the initial FE model in the light of experimental test measurements, and that additional information about the structure may be obtained from this process to improve modelling of future designs.

10. The MARS test rig provides an invaluable method of demonstrating the various experimental and analytical tools which were developed during the project, and will be used in the future for further investigations into many aspects of rotor dynamics which are not resolved by theoretical modelling alone.

6. CONCLUSIONS

The MARS project has developed a series of experimental and analytical methods which can be applied to rotating machinery:

- Active magnetic bearings to provide controlled excitation to a flexible rotor using a novel controls ystem.
- Accurate force determination for AMBs using Hall effect sensors.
- Shaft synchronised Laser scanning techniques to measure motion of a point on a rotating system, or to measure modes shapes.
- Additional uses of a scanning laser to determine vibration information.
- pc based data acquisition and control system to produce accurate FRFs from rotating system measurements.
- Response measurement for run-up or run-down tests using an array of proximity probes to separate forward and backward waves in a modified Campbell diagram.
- Finite Element program LISA specifically designed for rotating machinery analysis.
- Modal testing methods to provide multi-channel controlled force input and response measurement for non-linear systems.
- Model updating methods applicable to rotating systems tested at different speeds to determine bearing effects and gyroscopic coupling terms.
- A test rig which incorporates the above techniques and which can be used to investigate further rotor dynamics problems.

These techniques will be of major benefit to designers at the design optimisation stage, reducing the development time required for new designs and increasing confidence in the dynamic assessment of the design.
The techniques will also be useful for condition monitoring and fault diagnosis, where accurate analytical models may be used to investigate probable effects of typical faults.

7. ACKNOWLEDGEMENTS

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They also wish to thank the Swiss Bundesamt fur Bildung und Wissenschaft for funding the ETH part of the project.

8. PUBLICATIONS GENERATED BY THE PROJECT

1. *Precise Magnetic Bearing Exciter for Rotordynamic Experiments*
   C **Gähler, P Forth**
   Fourth International Symposium on Magnetic Bearings, Zurich, Switzerland, 23-26 August 1994

2. *Identification of Magnetic Bearing Systems*
   C Gähler, R Herzog.
   Fourth International Symposium on Magnetic Bearings, Zurich, Switzerland, 3-26 August 1994

3. *Measurement of translational and rotational vibration using a scanning laser doppler vibrometer*
   A B Stanbridge, D J Ewins
   First International Conference on vibration measurements by laser techniques, Ancona, Italy, 3-5 October 1994

4. Laser *based measurement system for measuring the vibration of rotating discs*
   I Bucher, P Schmiechen, D A Robb, D J Ewins
   First International Conference on vibration measurements by laser techniques, Ancona, Italy, 3-5 October 1994

5. *On the use* of *finite elements in rotor dynamics*
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6. Modale Analyse an rotierenden Maschinen mittels Magnetlagern
   P Förch, A **Reister, C Gähler, R Nordmann**
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7. *Excitation and measurement of Traveling Waves in Rotating axisymmetric structures*
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   SIRM-Tagung (Vibrations in rotating machinery), Kaiserslautern, Germany, March 1995

8. *Structural modal analysis using a scanning laser doppler vibrometer*
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   RAeS International Forum on Aeroelasticity and Structural dynamics, Manchester, 26-28 June 1995

9. *Automatic force or response adjustment in a multi-shaker excitation system using a non-linear optimisation approach*
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RAeS International Forum on Aeroelasticity and Structural dynamics, Manchester, 26-28 June 1995

10. *Modal testing* of *rotating discs using a scanning LDV*
A B Stanbridge, D **J Ewins**
ASME Conference, Boston, September 1995

11. *Excitation of arbitrary displacement/velocity coalitions in rotationally periodic structures*
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ASME Conference, Boston, September 1995

12. *Multi-dimensional direction spectrograms and Campbell (ZMOD) diagrams for rotating machinery*
I Bucher, D J Ewins, P Schmiechen, G von Groll
ASME Conference, Boston, September 1995

13. *Using a continuously-scanning laser doppler vibrometer for modal t testing*
A B Stanbridge, D J **Ewins**
IMAC 14, Dearborn, USA, 12-15 February 1996

14. *Multivariable Identification of Active Magnetic Bearing Systems*
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15. *Measurement of translational and rotational* vibration *using a scanning laser doppler vibrometer*
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