Defence Science Journal, Vol. 54, No. 4, October 2004, pp. 563-570

Dual-frequency Eddy Current Non-destructive Detection of Fatigue Cracks in Compressor Discs of Aero Engines

B. Sasi, B.P.C. Rao, and T. Jayakumar

Indira Gandhi Centre for Atomic Research, Kalpakkam–603 102

ABSTRACT

Eddy current non-destructive testing is used to inspect the critical aircraft components. The shortcomings of the inspection method identified, based on a few accidents, necessitate the development of high sensitive and reliable testing procedures for inspecting the critical safety related aircraft components. This paper discusses a dual-frequency eddy current testing procedure developed for inspection of compressor discs of aero engines for detecting fatigue cracks with high sensitivity and reliability. This procedure is capable of detecting fatigue cracks smaller than 2 mm in comparison to 4 mm cracks that can be detected with the currently practiced eddy current testing procedure.

Keywords: Dual-frequency eddy current testing, fatigue crack, compressor discs, aero engines, non-destructive testing, aircraft components, non-destructive inspection, NDE, NDT, NDI, eddy current testing, non-destructive evaluation

1. INTRODUCTION

Aircraft components, particularly airframes and aero engines, subjected to static and dynamic loads and changing temperatures, should be inspected regularly for cracks and corrosion by non-destructive testing (NDT) techniques. The NDT of ageing aircraft components is essential for flight safety and keeping the operational costs low. A critical component in aero engine is the compressor disc. The non-destructive inspection (NDI) of aero engine compressor discs is important for the safety of an aircraft. The accident occurred on the United Airlines Flight 232 on 19 July 1989 at Sioux City, Iowa, was attributed to the failure of the aero engine compressor disc[1]. The investigation revealed that the failure was caused due to the unnoticed fatigue crack in the dovetail region of the compressor disc. To avert such accidents, early and reliable detection of small fatigue cracks in aero engine compressor discs using non-destructive evaluation (NDE) techniques is essential. Out of various NDE techniques, eddy current testing is widely used for testing many aircraft components, because of its non-contact, fast, and cost-effective characteristics[2]. Generally, eddy current testing has been accepted as an effective technique for detecting fatigue cracks on aero engine discs[3]. However, the complex geometry of the aero engine compressor disc due to the presence of irregular edges (dovetail regions) makes the detection of defects a difficult task. In eddy current testing, edge effect of the material produces a large amplitude signal, masking the defects present at the edge region. The edge region is the most probable location of fatigue cracks because of its sharp geometry with high stress concentration. This problem can be overcome by

Received 07 November 2003

adopting dual-frequency eddy current testing method. Accordingly, a reliable and high sensitive eddy current testing procedure has been developed for the detection of fatigue cracks in the typical compressor discs of aero engines of defence aircraft. This paper discusses the salient features of a single-and dual-frequency eddy current testing, the development of an inspection procedure, and the results.

2. PRINCIPLE OF EDDY CURRENT TESTING

Eddy current testing method uses the principle of electromagnetic induction to inspect the electrically-conducting components for the detection, sizing, and classification of defects. In eddy current testing, an alternating current (ac) is made to flow in a coil (called probe) which, in turn, produces an alternating magnetic field around it. This coil, when brought close to the electrically-conducting material surface to be inspected, induces eddy currents into the material by electromagnetic induction. These eddy currents are generally parallel to the direction of coil winding as shown in the Fig.1. The

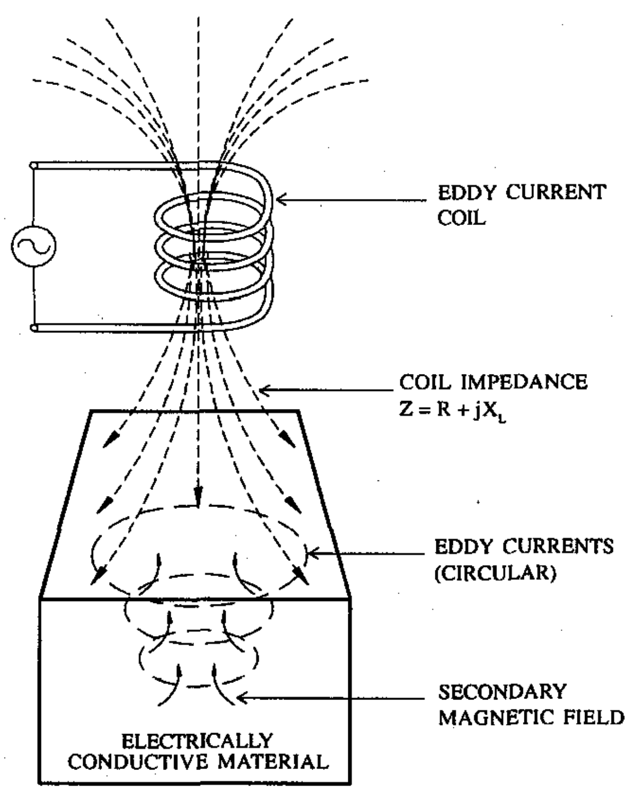


Figure 1. Principle of eddy current testing

presence of any defect in the material, such as cracks, corrosion, wall loss, or any other discontinuity, disrupts the eddy current flow. These eddy currents, in turn, generate an alternating magnetic field which may be detected, either as a voltage across a second coil or by the perturbation of the impedance of the original coil[4]. The coil is usually excited with frequencies in the range 50 Hz–5 MHz. The higher excitation frequencies are used to detect surface and near-surface defects, whereas lower excitation frequencies are used when the detection of deeper and subsurface defects is sought. The locus of impedance change during the movement of a probe coil over a component is called an eddy current signal. Impedance being a complex quantity, eddy current signals are usually displayed as impedance plane trajectories. While the amplitude of the eddy current signal provides information about the severity of the defect, the phase angle wrt lift-off (distance between the coil and the material surface) provides information about the depth of a defect[5]. Reference standard defects are used for establishing correlation between eddy current signal parameters and defect dimensions, and for the detection and sizing of an unknown defect signal [6]. This analysis, using single-frequency excitation, is referred to as conventional single-frequency eddy current testing[7].

Apart from defects, a number of variables, such as changes in material conductivity, permeability, wall thickness, surface roughness; and presence of geometrical features, such as curvature, edges, and grooves influence the coil impedance, in other words, the eddy current signals. As a result, the signals are complex and the process of detection and characterisation of defects may become difficult. Successful detection and assessment of defects relies on keeping the influence of disturbing variables as constant, or eliminating their effects on the analysis of the defect signals. To perform this, excitation at other frequencies is necessary and the conventional single-frequency eddy current testing is inadequate[8]. Elimination of undesired response or disturbing variables using simultaneous multiple-frequency excitation, forms the basis of much of the technology of eddy current inspection, particularly dual-frequency eddy current testing[9].

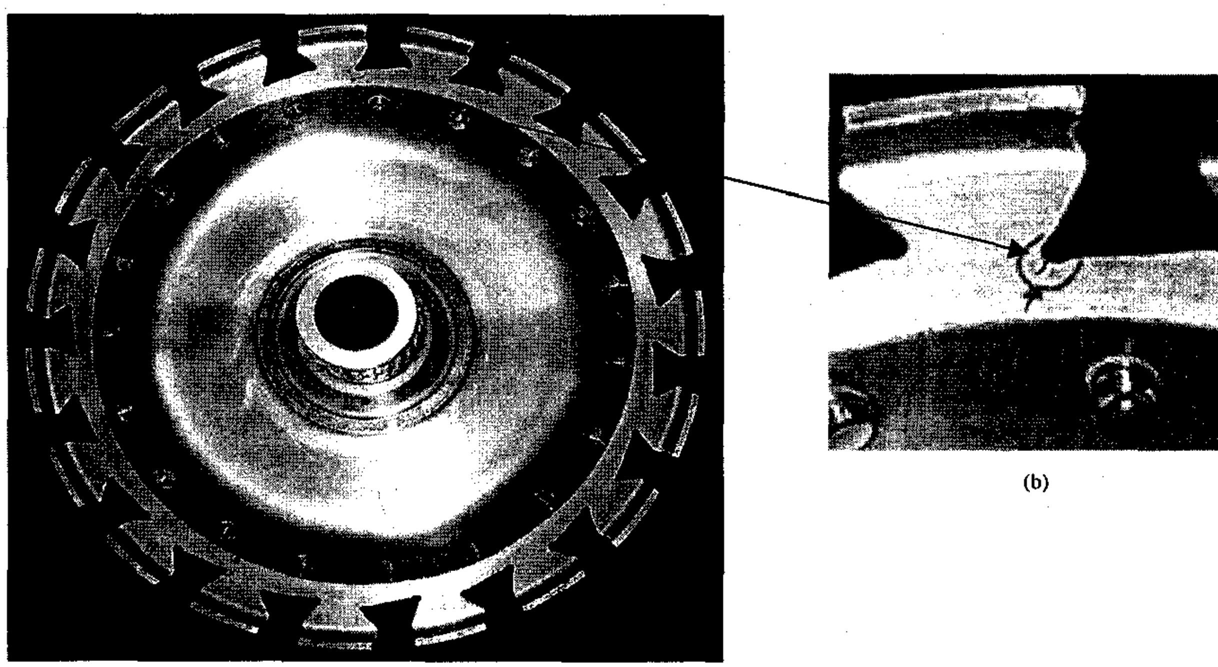
2.1 Dual-frequency Eddy Current Method

In this method, eddy current coil is excited simultaneously with multiple frequencies[6-9]. Most commonly, two frequencies are used which are selected in such a way that one is more sensitive to the desired variable, such as defects, and the other frequency is sensitive to the unwanted or disturbing variables. The ratio of the two frequencies is usually in the range 2:4. By suitably mixing the signals from the two frequencies, subsequent to amplification and phase rotation, the signal from a desired defect is enhanced and the signals from the undesired variables, eg, edge effect and probe tilt, are suppressed. Popular applications of dual-frequency eddy current testing include the detection of corrosion at the second and the third layers in aircraft structures, and the detection of defects under support plates in heat exchangers[10-11].

3. INSPECTION OF AERO ENGINE COMPRESSOR DISC

Aero engine compressor disc assemblies of defence aircraft are subjected to high thermomechanical loads and contain highly stressed components. Aero engine compressor discs have basically three critical regions for which lifetime certification is necessary. These are: (i) dovetail-rim region, (ii) assembly holes or weld areas, and (iii) hub region. The loads associated with these regions are the centrifugal forces of the blades, the self-generated loads applied by spacers, and the assembly bolts and the thermal stresses. These thermomechanical stresses vary during a flight, leading to fatigue cracks in the compressor disc.

In a majority of failed compressor discs, the cracks were initiated from the dovetail regions due to high stress concentration and fretting action at the blade-disc interface[12]. The catastrophic failure of a compressor disc could even cause the larger fragments of the disc to puncture the engine casing. The consequences of such a failure are serious, resulting in the destruction of the engine, and ultimately there is a loss to the aircraft and the human life. Hence, careful inspection of dovetail regions is carried out routinely and it serves as a basis for the integrity of the compressor disc throughout its service life. Therefore, a reliable inspection method, that is sensitive to small fatigue cracks, and also fast and easy to use, is needed.



(a) (b)

Figure 2. Aero engine compressor disc: (a) with a surface crack of 4 mm length in the dovetail region and (b) close view of the crack originating from the dovetail region.

4. DEVELOPMENT OF EDDY CURRENT TESTING PROCEDURE

In the recent past, failures of first-stage compressor discs were experienced in defence aircraft. In these cases, the discs failed due to the cracks originated from the trailing edge of the dovetail slots of the discs. To ensure that such cracks on the compressor discs are detected much before the occurrence of an accident, periodic inspection of first-stage discs, that have completed specified number of hours of flying, is carried out. While carrying out this mandatory checkup using eddy current testing procedure supplied by the manufacturers of the compressor discs, one of the discs that had completed 1200 h of flying was found to have a surface crack of 4 mm length, originating from the dovetail region. The compressor disc with 4 mm crack is shown in Fig. 2. It was decided to examine this disc further for any additional cracks, employing a more sensitive inspection procedure. Accordingly, a reliable and high sensitive eddy current testing procedure employing dual-frequency excitation has been developed.

4.1 Eddy Current Instrument & Probe

The conventional single-frequency eddy current testing was carried out on the disc. During testing, it is essential to distinguish defect signals from those of probe tilt and geometric edges. The surface crack of 4 mm length shown in Fig. 2 was used as the reference defect for instrument calibration. For developing the eddy current procedure, a dual-frequency eddy current tester with computer interface for data acquisition, a storage device, and an analyser was used (Fig. 3). Since the crack was near the edge, an absolute shielded surface eddy current probe (pencil type) of 3 mm outer diameter operating in the frequency range 50 kHz to 500 kHz was chosen, considering the geometry of the compressor disc.

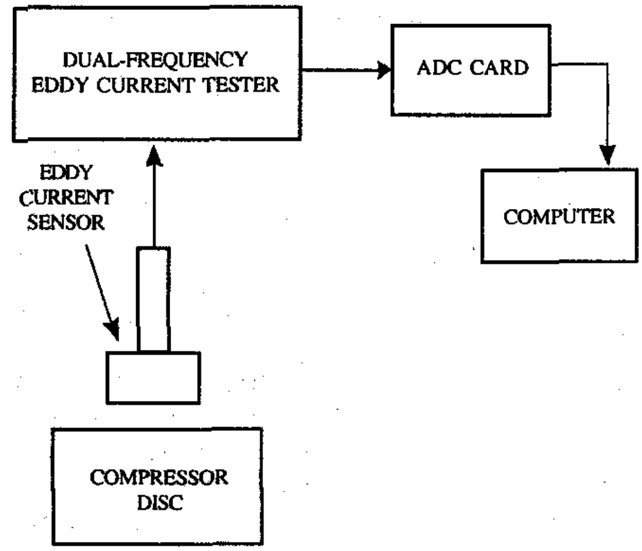


Figure 3. Block diagram of the experimental setup

4.2 Dual-frequency Eddy Current Testing Procedure

As mentioned earlier, the selection of the test frequency is important in eddy current testing, and in general, it is chosen such that maximum amplitude signal is produced by defects, and at the same time, with a good phase separation from probe tilt and edge-effect signals. The single-frequency excitation of 130 kHz was selected to inspect up to 1.3 mm depth from the surface. The instrument gain and phase were adjusted such that probe-tilt signals were parallel to the X-axis (horizontal component) of the cathode-ray tube screen in the eddy current tester. With these conditions, the edge-effect signal (when the coil is moved-off the dovetail region) is formed at a different angle. The typical eddy current signal at 130 kHz corresponding to the edge effect and probe tilt from a dovetail region is shown

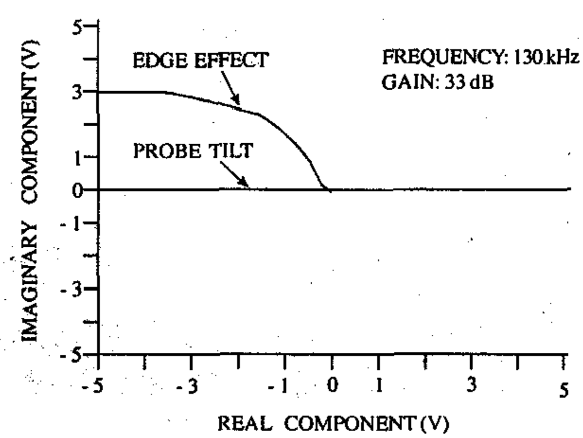


Figure 4. Eddy current signals from probe tilt and edge effect at 130 kHz.

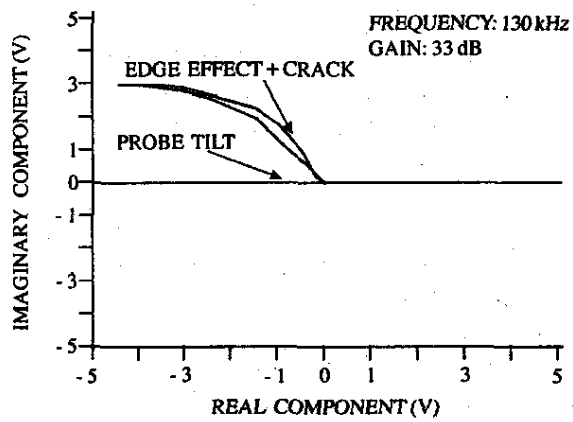


Figure 5. Eddy current signal at 130 kHz for the reference crack of 4 mm length along with signal due to edge effect and probe tilt.

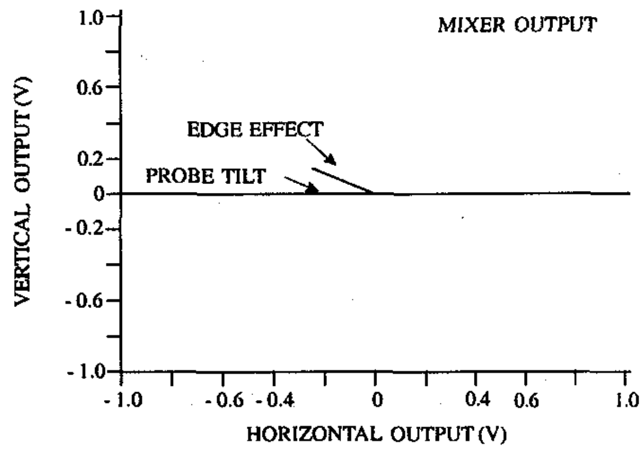


Figure 6. Eddy current signal from probe tilt and edge effect after dual-frequency mixing.

in the Fig. 4. The eddy current probe was moved parallel along the edges and the response from the reference (natural) crack of 4 mm length was obtained and is shown in Fig. 5. It is clearly seen from the Fig. 5 that there is no phase separation between the edge-effect signal and the crack signal. Hence, it is difficult to identify the signals from the cracks. To eliminate the influence of the edge effect, dual-frequency mixing method was employed. The two excitation frequencies were optimised using the following criteria:

(a) Maximum suppression of edge-effect signal response

(b) Maximum amplitude of the eddy current signal from the reference crack

(c) Maximum phase angle separation between the probe tilt and the edge effect.

The optimised instrument parameters meeting the above criteria are given in Table 1.

Table 1. Optimised instrument parameters for detection of cracks in compressor discs

Parameter	Channel 1	Channel 2	Mixer
Test frequency (kHz)	130	67	-
Gain (dB)	33	70	-
Phase angle (deg)	75	110	34
Display (V/div)	1	1	0.5

Results of application of the dual-frequency mixing method in suppressing the edge-effect signal is shown in the Fig. 6. It can be seen from the Fig. 6 that there is considerable reduction in the signal due to edge effect using the dual-frequency mixing. With these optimised parameters, eddy current testing has been carried out on various critical regions of the compressor disc. The eddy current signal from the reference crack of 4 mm length is detected without any ambiguity and the same is shown in the Fig. 7, thus confirming the effectiveness of the optimised parameters for reliable detection of the defects.

Another signal depicted in the Fig. 8 has been observed from another dovetail root region, indicating

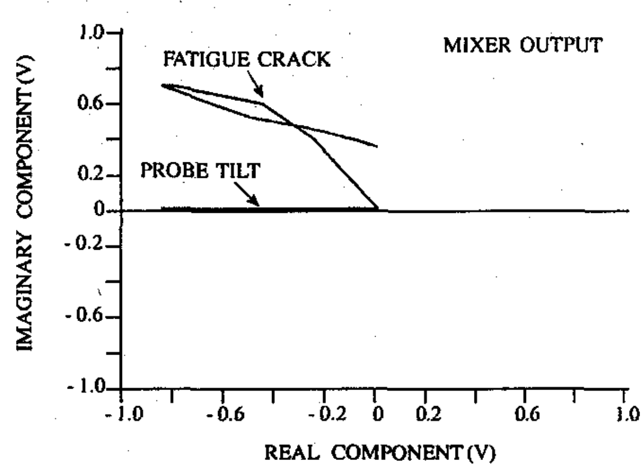


Figure 7. Eddy current signal from reference crack of 4 mm length after dual-frequency mixing.

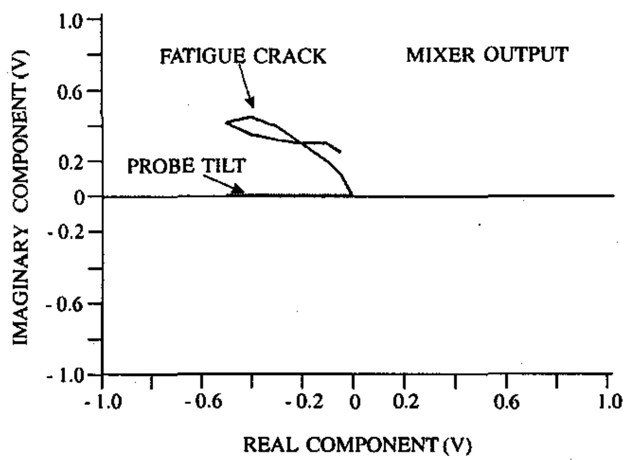


Figure 8. Eddy current signal for a crack of 2 mm length in the compressor disc detected by dual-frequency mixing method.

the presence of a crack. From the signal amplitude, it can be inferred that this crack is smaller than the reference crack signal (Fig. 7).

Both the fluorescent liquid penetrant testing using high sensitive procedure and *in situ* metallography indicated that the length of the second crack is about 2 mm. This finding of the second crack of smaller dimension by the dual-frequency eddy current testing procedure developed, clearly brings out the limitations of the currently practiced eddy current testing method provided by the manufacturer of the compressor discs. As the amplitude of the eddy current signal from the 2 mm long crack is sufficiently high in comparison to the crack-free regions, it may be possible to detect cracks with surface length shorter than 2 mm. This elucidates the high sensitivity of the developed dual-frequency eddy current testing procedure. This study demonstrates that by proper optimisation of testing procedure, early detection of fatigue cracks in compressor discs with high sensitivity, is possible.

5. SUMMARY

The dual-frequency eddy current testing procedure has been developed for the detection of fatigue cracks with high sensitivity in dovetail regions of the compressor discs of aero engines. The dual-frequency mixing method suppresses the disturbing signals due to edge effect and probe tilt that influence testing and analysis. The eddy current testing parameters have been optimised such that signal from crack at the dovetail region is of higher amplitude than the mixed remnant edge-effect signal and is well separated by phase. The developed procedure has proven its performance by detecting a fatigue crack of 2 mm length that could not be detected by the eddy current testing procedure provided by the manufacturer of the compressor discs. Hence, the developed procedure can be implemented for the detection of fatigue cracks with high sensitivity in the dovetail regions of the compressor discs of aero engines.

ACKNOWLEDGEMENTS

Authors thank Shri K.V. Kasiviswanathan, Head, Post Irradiation Examination, Inservice Inspection and Robotics Section (PIRS), Sarvashri N.G. Muralidharan and N. Raghu of Division for PIE and NDT Development (DPEND) for their useful discussions. The experimental support provided by Sarvashri P. Sukumar, N. Dhakshinamurthy, and R. Gnanasekaran of DPEND is thankfully acknowledged. Authors are also thankful to Shri P. Kalyanasundaram, Head, DPEND, Dr S. L. Mannan, Associate Director, Materials Development Group, and Dr Baldev Raj, Director, Materials, Chemical and Reprocessing Groups for their keen interest and encouragement.

REFERENCES

1. Chris, Kirloy. Special report: United Airlines Flight 232.

   www.airdisaster.com/specia/special-ua232.shtml.

2. Robert, D. Shaffer. Historical development of eddy current testing in aircraft maintenance. *Materials Evaluation*, January 1992, **50**, 76-82.

3. Ko, R.T. & Pipenburg, S. J. Automated eddy current detection of edge defects in a complex geometry using a magnitude approach. *In* Review of progress in quantitative non-destructive evaluation, Vol. **14**. Plenum Publishing Corp, New York, 1994. pp. 307-13.

4. Baldev Raj ; Jayakumar, T. & Thavasimuthu, M. *In* Practical NDT testing. Narosha, New Delhi, 1997. pp. 27-42.

5. Hagemaier, D.J. Fundamentals of eddy current testing. American Society for Non-destructive Testing Inc, December 1990. 61p.

6. Rao, B.P.C. & Jayakumar, T. Discontinuity characterisation using electromagnetic methods. *J. Non-destructive Testing Eval.*, 2002, **2**(2), 23-29.

7. Baldev Raj; Jayakumar, T. & Rao, B.P.C. Review of NDT techniques for structural integrity, Sadhana, No. 20. *In* Academy Proceedings in Engineering Sciences, 1995. pp. 5-38.

8. Cecco, V. S.; Van Drunnen, G. & Sharp, F. L. Eddy current manual : Test method, Vol.**1**. AECL-7523. Chalk River, Ontario, November 1981.

9. Bllitz, J. Electrical and magnetic methods for non-destructive testing. Adam Hilger, Bristol, 1995.

10. Hagemaier, D.J.; Wendelbo, A.H.& Bar-Cohen, Y. Aircraft corrosion and detection methods. *Materials Evaluation*, 1985, **43**, 426-37.

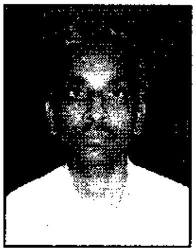
11. de la Pintiere, L. Multi-frequency eddy current examination of heat exchanger tubing. *In* Electromagnetic methods for non-destructive testing. Gordon and Breach Science Publishers, New York, 1985. pp. 195-303.

12. Bhaumik, S. K.; Sujata, M. & Krishnan, R.V. Fatigue failure of engineering structures. *In* Proceedings of 4th Conference on Creep, Fatigue and Creep-fatigue Interaction. Kalpakkam, Tamil Naidu, October 2003. pp. 145-56.

Contributors

Ms B. Sasi obtained her MSc (Applied Physics) from the Gandhigram Rural Institute, Deemed University. She has been working in the area of eddy current non-destructive testing since 1996. She has developed eddy current sensors and signal processing software to be used in nuclear and defence sectors. She has published/presented a number of papers in various journals/conferences.

Dr B.P.C. Rao, Metallurgical Engineer, joined Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, in 1986 after undergoing training at the BARC Training School, Trombay, Mumbai. He has specialised in the area of non-destructive testing of metallic materials for defect detection and characterisation. He has published/presented more than 75 research papers in various journals and conferences. His areas of research include: Electromagnetics, numerical modelling, signal processing, sensor design, imaging, automation and component inspection.



Dr T. Jayakumar, Metallurgical Engineer, joined IGCAR, Kalpakkam, in 1978 after undergoing training at the BARC Training School, Trombay, Mumbai. Presently, he is heading the Non-destrctive Evaluation Section at the IGCAR. He has specialised in the areas of non-destructive evaluation for defects and materials characterisation and failure analysis of engineering components. He has published more than 150 research papers in various international journals.