



شبكة المعلومات الجامعية

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ





شبكة المعلومات الجامعية



# شبكة المعلومات الجامعية

## التوثيق الالكتروني والميكرو فيلم

# جامعة عين شمس

التوثيق الالكتروني والميكرو فيلم

## قسم

نقسم بالله العظيم أن المادة التي تم توثيقها وتسجيلها  
علي هذه الأفلام قد اعدت دون أية تغيرات



## يجب أن

تحفظ هذه الأفلام بعيداً عن الغبار

في درجة حرارة من 15 – 20 مئوية ورطوبة نسبية من 20-40 %

To be kept away from dust in dry cool place of  
15 – 25c and relative humidity 20-40 %



شبكة المعلومات الجامعية



# بعض الوثائق الأصلية تالفة



شبكة المعلومات الجامعية



بالرسالة صفحات  
لم ترد بالأصل

**EVALUATION OF RELIABILITY  
USING RESPONSE SPECTRA  
FOR PREDICTIVE MAINTENANCE APPLICATIONS**

By  
**Roushdy Ahmed Mohamed Ahmed**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfilment of the  
Requirements for Degree of

**Doctor of Philosophy**

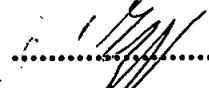
in  
**MECHANICAL ENGINEERING**

**Under Supervision of**

**Prof. Dr. Sayed M. Metwalli**

  
.....  
Professor of Machine Design  
Mechanical Design & production  
Department  
Faculty of Engineering, Cairo University

**Dr. M. Ezz Hassan Ahmed**

  
.....  
Lecturer  
Mechanical Design & Production  
Department  
Faculty of Engineering, Cairo University

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY**

**GIZA, EGYPT**

**May, 1999**



B  
9140

6

1. 1. 1.

2. 2. 2.

3. 3. 3.

4. 4. 4.

5. 5. 5.

6. 6. 6.

7. 7. 7.

8. 8. 8.

9. 9. 9.

**EVALUATION OF RELIABILITY  
USING RESPONSE SPECTRA  
FOR PREDICTIVE MAINTENANCE APPLICATIONS**

By  
**Roushdy Ahmed Mohamed Ahmed**

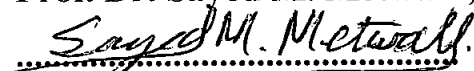
A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfilment of the  
Requirements for Degree of

**Doctor of Philosophy**

in  
**MECHANICAL ENGINEERING**

Approved by the  
Examining Committee:

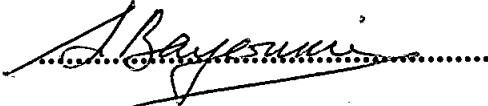
Prof. Dr. Sayed M. Metwalli, Thesis Main Advisor

  
.....

Prof. Dr. Amr Abd El-Hamid, Member

  
.....

Prof. Dr. Salah El-Din Ahmed Bayoumy, Member

  
.....

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY**

**GIZA, EGYPT**

**May, 1999**

7  
17  
17

17

17

# Table of Contents

|                                                                                               | Page   |
|-----------------------------------------------------------------------------------------------|--------|
| <b>Table of Contents.</b>                                                                     | i      |
| <b>List of Tables.</b>                                                                        | v      |
| <b>List of Figures.</b>                                                                       | vi     |
| <b>Nomenclature.</b>                                                                          | x      |
| <b>Acknowledgment.</b>                                                                        | xiv    |
| <b>Abstract.</b>                                                                              | xv     |
| <b>Chapter(1): Introduction and Literature Survey.</b>                                        | 1      |
| 1.1 Maintenance Philosophy.                                                                   | 2      |
| 1.2 Previous Work of Predictive Maintenance.                                                  | 4      |
| 1.3 Problem Statement.                                                                        | 9      |
| <br><b>Chapter(2): Theoretical Development for Rolling<br/>Contact Fatigue Investigation.</b> | <br>11 |
| 2.1 Rolling Contact Fatigue Investigation.                                                    | 11     |
| 2.2 Competing Failure Modes.                                                                  | 15     |
| 2.3 Crack propagation Law.                                                                    | 16     |
| 2.3.1 Local Plastic Strain.                                                                   | 18     |
| 2.3.2 Material Ductility.                                                                     | 19     |
| 2.3.3 Plastic Strain / Ductility Ratio.                                                       | 19     |
| 2.4 Rolling Contact Life Determination.                                                       | 20     |
| 2.5 Rolling Element Life Distribution.                                                        | 21     |
| 2.6 Fundamentals of Reliability Analysis.                                                     | 22     |
| 2.6.1 Reliability Function.                                                                   | 23     |
| 2.6.2 Expected Life.                                                                          | 24     |
| 2.6.3 Hazard Function.                                                                        | 24     |
| 2.6.4 Estimating Reliability from Empirical Data.                                             | 26     |

|                                                                   |           |
|-------------------------------------------------------------------|-----------|
| 2.6.5 Reliability Analysis for Weibull Distribution.              | 27        |
| 2.6.6 Rolling element Damage Accumulation Cases.                  | 28        |
| 2.7 Fundamentals of Spectral Analysis.                            | 30        |
| 2.7.1 Dynamic Impulse Due to Failure.                             | 31        |
| 2.7.2 Torsional Vibration System.                                 | 31        |
| 2.7.3 Modal Analysis.                                             | 33        |
| 2.7.4 State-Space Approach.                                       | 35        |
| 2.7.5 Power Spectral Density Function.                            | 37        |
| 2.7.6 Analog Data Processing.                                     | 38        |
| 2.7.7 Digital Data Analysis.                                      | 38        |
| <b>Chapter(3): Reliability Evaluation Using Response Spectra.</b> | <b>43</b> |
| 3.1 Reliability and Spectral Analyses Interaction.                | 43        |
| 3.2 Scheme of Spectral Reliability Evaluation.                    | 44        |
| 3.3 Weibull Reliability for Rolling Element Bearings.             | 46        |
| 3.3.1 Theoretical Reliability Analysis.                           | 46        |
| 3.3.2 Statistical Reliability Analysis.                           | 47        |
| 3.4 Spectral Analysis to Evaluate Response Spectra.               | 48        |
| 3.4.1 Response Spectra from System Dynamics.                      | 50        |
| 3.4.2 Response Spectra from Trend Analysis.                       | 57        |
| 3.5 Reliability Evaluation from Response Spectra.                 | 58        |
| 3.5.1 Spectral Reliability Function.                              | 60        |
| 3.5.2 Conditional Reliability to Estimate Remaining Life.         | 60        |
| 3.6 Optimum Evaluation of Reliability.                            | 61        |
| 3.7 Illustration of Reliability Evaluation from Response Spectra  | 64        |
| <b>Chapter(4): Computer Aided Fault Diagnostic System (FDS)</b>   | <b>74</b> |
| 4.1 FDS Implemented for Rolling Element Bearings.                 | 74        |

|                                                                                    |     |
|------------------------------------------------------------------------------------|-----|
| 4.1.1 Data Files Manipulation.                                                     | 76  |
| 4.1.2 Reliability Analysis.                                                        | 78  |
| A. Statistical Reliability.                                                        | 78  |
| B. Theoretical Reliability.                                                        | 78  |
| 4.1.3 Spectral Analysis.                                                           | 80  |
| 4.1.4 Fault Diagnosis.                                                             | 80  |
| A. Reliability Level with Response Spectra.                                        | 83  |
| B. Maintenance Optimization.                                                       | 83  |
| C. Report of Reliability Evaluation Using Response Spectra.                        | 86  |
| 4.1.5 Using “Help” and “Options” of FDS for Windows.                               | 86  |
| 4.2 Computer System Requirements.                                                  | 92  |
| <b>Chapter(5): Spectral Reliability Implementation for Predictive Maintenance.</b> | 93  |
| 5.1 Problem Presentation.                                                          | 93  |
| 5.2 Spectral Analysis Results.                                                     | 95  |
| 5.3 Corrective Action Taken.                                                       | 102 |
| 5.4 Historical Data of Failure Occurrences.                                        | 102 |
| 5.5 Weibull Reliability Function.                                                  | 105 |
| 5.6 Measured Reliability with Response Spectra.                                    | 107 |
| 5.7 Optimum Reliability Evaluation Using Response Spectra.                         | 109 |
| 5.8 Results and Recommendations.                                                   | 111 |
| <b>Chapter (6): Results and Discussion.</b>                                        | 117 |
| 6.1 Spectral Reliability Evaluation.                                               | 118 |
| 6.2 Remaining Life Estimation Using Conditional Reliability.                       | 123 |
| 6.3 Maintenance Optimization Results.                                              | 123 |

|                                                  |     |
|--------------------------------------------------|-----|
| <b>Chapter(7): Conclusions.</b>                  | 132 |
| <b>References.</b>                               | 135 |
| <b>Appendix A: Leakage Reduction Techniques.</b> | 145 |
| A.1 Hanning Lag Weighting.                       | 147 |
| A.2 Modified Boxcar Weighting.                   | 147 |
| <b>Appendix B: Spectral Analysis via FFT.</b>    | 151 |
| B.1 Fast Fourier Transform (FFT).                | 151 |
| B.2 Power Spectral Estimates via FFT Algorithm.  | 152 |

ment Be  
st the

and

to

for

Re  
-ing

## List of Figures

|                                                                                               | Page |
|-----------------------------------------------------------------------------------------------|------|
| <b>Figure (1.1):</b> Classification of Maintenance.                                           | 3    |
| <b>Figure (2.1):</b> Rolling Contact Fatigue Life Prediction Model.                           | 13   |
| <b>Figure (2.2):</b> Hazard Function Over System Life.                                        | 25   |
| <b>Figure (2.3):</b> Weibull Reliability Function.                                            | 29   |
| <b>Figure (2.4):</b> Weibull Hazard Function.                                                 | 29   |
| <b>Figure (2.5):</b> Fundamental Block Diagram of Power Spectral Density Function.            | 39   |
| <b>Figure (2.6):</b> Analog Data Processing.                                                  | 40   |
| <b>Figure (2.7):</b> Sampling of the Acceleration $a(t)$ .                                    | 41   |
| <b>Figure (3.1):</b> Scheme of Spectral Reliability Evaluation.                               | 45   |
| <b>Figure (3.2):</b> Schematic Diagram of Spectral Reliability Technique.                     | 49   |
| <b>Figure (3.3):</b> Modeling of a Multi-degree of Freedom System.                            | 51   |
| <b>Figure (3.4):</b> Load Distribution of a Rolling Element Bearing.                          | 53   |
| <b>Figure (3.5):</b> Peak Value Represented Against the Bearing Life.                         | 59   |
| <b>Figure (3.6):</b> Spectral Reliability Analysis and Remaining Life Estimation.             | 62   |
| <b>Figure (3.7):</b> Maintenance Optimization to Evaluate the Optimum Reliability.            | 65   |
| <b>Figure (3.8):</b> System Response Spectra for Different Values of Spall Size.              | 68   |
| <b>Figure (3.9):</b> Illustration of Spectral Reliability Functions of the Ball Bearing 6408. | 72   |

19 101

10 101

10 101

10 101

10 101

10 101

10 101