

---

|   |      |
|---|------|
| <i>Preface</i>  | xiii |
| <i>About the author</i>   | xv   |
| 1 Reliability analysis of rolling-element bearings  | 1    |
| 1.1 A general review  | 1    |
| 1.2 Introduction  | 1    |
| 1.3 Detection of bearing malfunction and determination of defect frequencies                | 2    |
| 1.4 Resonant frequencies  | 3    |
| 1.5 Experimental procedure  | 3    |
| 1.6 Instrumentation details and techniques  | 4    |
| 1.7 Determination of defect frequencies and energy levels                                   | 7    |
| 1.8 Results and discussion  | 9    |
| 1.9 Conclusions and recommendations   | 19   |
| 1.10 References   | 20   |
| 1.11 Nomenclature   | 20   |
| 2 Functional performance of rolling-element bearings for acceptance in routine applications | 22   |
| 2.1 A general review  | 22   |
| 2.2 Introduction  | 22   |
| 2.3 Bearing test philosophy   | 23   |
| 2.4 Bearing test machine  | 25   |
| 2.5 Experimental procedure  | 26   |
| 2.6 Data deduction  | 27   |
| 2.7 Results and discussion  | 30   |
| 2.8 Overall vibration levels of bearings  | 37   |
| 2.9 Predicted life of bearings  | 37   |
| 2.10 Comparison of performance of bearings  | 38   |

|      |  |    |
|------|--|----|
| vi   | Contents   |    |
| 2.11 | Conclusions  | 38 |
| 2.12 | References   | 39 |
| 3    | Cage and roller slip of rolling-element bearings   | 40 |
| 3.1  | A general review   | 40 |
| 3.2  | Introduction   | 40 |
| 3.3  | Characteristic defect frequencies  | 41 |
| 3.4  | Experimental procedure   | 41 |
| 3.5  | Spectral analysis technique  | 42 |
| 3.6  | Determination of defect frequencies and energy levels  | 43 |
| 3.7  | Results and discussion   | 44 |
| 3.8  | Comparison of bearings   | 51 |
| 3.9  | Conclusions  | 52 |
| 3.10 | References   | 53 |
| 3.11 | Appendix   | 53 |
| 3.12 | Nomenclature   | 54 |
| 4    | Diagnosis and cause analysis of rolling-element bearings failure in electric power equipment | 56 |
| 4.1  | A general review   | 56 |
| 4.2  | Introduction   | 56 |
| 4.3  | Bearing arrangement and nature of bearing failure  | 57 |
| 4.4  | Investigations, observation of failures and data collection                                  | 57 |
| 4.5  | Results and discussion   | 61 |
| 4.6  | Conclusions  | 64 |
| 4.7  | References   | 65 |
| 5    | Localized electrical current in rolling-element bearings                                     | 67 |
| 5.1  | A general review   | 67 |
| 5.2  | Introduction   | 67 |
| 5.3  | Bearing arrangement and the nature of bearing failure  | 69 |
| 5.4  | Investigations, observations and data collection   | 70 |
| 5.5  | Theoretical model and approach to determine the flow of localized current in a bearing       | 72 |
| 5.6  | Field strength on track surfaces of races and rolling-elements                               | 75 |
| 5.7  | Magnetic flux density  | 75 |
| 5.8  | Determination of time span for the appearance of flutes on track surfaces                    | 76 |
| 5.9  | Data deduction   | 76 |
| 5.10 | Results and discussion   | 77 |

|      |   |     |
|------|---|-----|
| 5.11 | Conclusions   | 80  |
| 5.12 | References  | 81  |
| 5.13 | Nomenclature  | 82  |
| 6    | Response and performance of a rolling-element bearing under the influence of an electric current                                    | 84  |
| 6.1  | A general review  | 84  |
| 6.2  | Introduction  | 84  |
| 6.3  | Behaviour of grease in non-insulated bearings   | 86  |
| 6.4  | Effect of current on formation of corrugated patterns on the roller track of races of roller bearings                               | 90  |
| 6.5  | Effect of current leakage on electro-adhesion forces in rolling friction and magnetic flux density distribution on bearing surfaces | 92  |
| 6.6  | Effect of operating parameters on the threshold voltages and impedance response of non-insulated rolling-element bearings           | 94  |
| 6.7  | Impedance, capacitance and charge accumulation on roller bearings   | 95  |
| 6.8  | Contact temperature, contact stresses and slip bands initiation on roller track of races  | 96  |
| 6.9  | Effects of instantaneous charge leakage on roller tracks of roller bearings lubricated with high-resistivity lubricants             | 98  |
| 6.10 | Capacitive effects of roller bearings on repeated starts and stops of a machine   | 99  |
| 6.11 | Mechanism of bearing failures   | 100 |
| 6.12 | Conclusion  | 102 |
| 6.13 | References  | 102 |
| 6.14 | Nomenclature  | 103 |
| 7    | Effect of oil grades and clearance ratios on the reliability of cylindrical hydrodynamic bearings                                   | 106 |
| 7.1  | A general review  | 106 |
| 7.2  | Introduction  | 106 |
| 7.3  | Background  | 107 |
| 7.4  | Theoretical   | 109 |
| 7.5  | Evaluation of viscosity coefficients  | 110 |
| 7.6  | Determination of viscosity integral   | 112 |
| 7.7  | Assessment of bearing performance   | 114 |
| 7.8  | Effect of oil grades on temperature rise and safe load-carrying capacity of bearings  | 116 |

|      |   |     |
|------|---|-----|
| viii | Contents  |     |
| 7.9  | Bearing turbulence and transition speed   | 117 |
| 7.10 | Results and discussion  | 120 |
| 7.11 | Conclusions and recommendations   | 126 |
| 7.12 | References  | 128 |
| 7.13 | Nomenclature  | 128 |
| 8    | Spherical seating of hydrodynamic journal bearings  | 130 |
| 8.1  | A general review  | 130 |
| 8.2  | Introduction  | 130 |
| 8.3  | Theoretical basis of the simplified design methodology  | 131 |
| 8.4  | Evaluation of minimum values of constant of moment of friction and optimum values of the design parameters of spherical seating | 133 |
| 8.5  | Functional nomographs for evaluation of optimum values for spherical seating design parameters                                  | 134 |
| 8.6  | Guidelines for choosing the optimum values for spherical seating design parameters  | 136 |
| 8.7  | Conclusions and recommendations   | 136 |
| 8.8  | References  | 137 |
| 8.9  | Nomenclature  | 137 |
| 9    | Life estimation of turbine oils: a methodology and criterion for acceptance or rejection  | 139 |
| 9.1  | A general review  | 139 |
| 9.2  | Introduction  | 139 |
| 9.3  | Experimental investigations   | 140 |
| 9.4  | Data deduction  | 141 |
| 9.5  | Results and discussion  | 142 |
| 9.6  | Conclusions and recommendations   | 147 |
| 9.7  | References  | 148 |
| 10   | Axial force on motor bearings: a tool for performance evaluation  | 149 |
| 10.1 | A general review  | 149 |
| 10.2 | Introduction  | 149 |
| 10.3 | Axial force measurement technique   | 150 |
| 10.4 | Experimental determination of axial force   | 152 |
| 10.5 | Results and discussion  | 152 |
| 10.6 | Conclusions and future studies  | 153 |
| 10.7 | Bibliography  | 153 |

|       |  |     |
|-------|--|-----|
| 11    | An analysis of the progressive increase in vibration of a large synchronous electric motor               | 154 |
| 11.1  | A general review   | 154 |
| 11.2  | Introduction   | 154 |
| 11.3  | Possible sources of vibration  | 155 |
| 11.4  | Diagnosis of causes of vibrations  | 156 |
| 11.5  | System design, bearing assembly and characteristic features of the synchronous motor under investigation | 157 |
| 11.6  | Investigations and analysis  | 158 |
| 11.7  | Results and discussion   | 161 |
| 11.8  | Conclusions and recommendations  | 163 |
| 11.9  | References   | 164 |
| 12    | A study of the causes of failure of rolling-element bearings in alternators                              | 165 |
| 12.1  | A general review   | 165 |
| 12.2  | Introduction   | 165 |
| 12.3  | Design features of the alternators   | 166 |
| 12.4  | The nature of bearing failure  | 166 |
| 12.5  | Data collection and investigations   | 167 |
| 12.6  | Causes of shaft voltage and flow of current through bearings   | 171 |
| 12.7  | Results and discussion   | 172 |
| 12.8  | Conclusions and recommendations  | 175 |
| 12.9  | References   | 175 |
| 13    | The diagnosis of the cause of a bearing problem in a synchronous condenser                               | 177 |
| 13.1  | A general review   | 177 |
| 13.2  | Introduction   | 177 |
| 13.3  | Technical details of the synchronous condenser   | 178 |
| 13.4  | Experimental procedure   | 178 |
| 13.5  | Measurement obtained   | 179 |
| 13.6  | Theoretical  | 180 |
| 13.7  | Comparison of theoretical and experimental data  | 183 |
| 13.8  | Results and discussion   | 184 |
| 13.9  | Conclusions and recommendations  | 185 |
| 13.10 | References   | 185 |
| 13.11 | Nomenclature   | 186 |

|       |   |     |
|-------|---|-----|
| x     | Contents  |     |
| 14    | The cause of noise at the top bearings of vertical pump-motor sets  | 187 |
| 14.1  | Introduction  | 187 |
| 14.2  | Sump layout and construction  | 187 |
| 14.3  | System layout   | 188 |
| 14.4  | System behaviour  | 189 |
| 14.5  | Factors causing the unusual system behaviour  | 191 |
| 14.6  | Vibration spectra and analysis  | 191 |
| 14.7  | Results and discussion  | 193 |
| 14.8  | Design of the bearing used and its significance   | 199 |
| 14.9  | Explanation of the cause of noise at the motor top bearing  | 200 |
| 14.10 | Conclusions and recommendations   | 200 |
| 14.11 | Bibliography  | 202 |
| 15    | Modifications to the design and bearings of horizontal axis windmills used for pumping water, to achieve trouble-free, reliable operation | 203 |
| 15.1  | A general review  | 203 |
| 15.2  | Introduction  | 203 |
| 15.3  | Design features   | 204 |
| 15.4  | Operational philosophy  | 204 |
| 15.5  | Transmission system   | 205 |
| 15.6  | Bearings and performance of the reciprocating pump  | 205 |
| 15.7  | Recommendations   | 209 |
| 15.8  | Conclusions   | 213 |
| 15.9  | References  | 213 |
| 16    | Magnetic suspension bearings for AC energy meters   | 214 |
| 16.1  | A general review  | 214 |
| 16.2  | Introduction  | 214 |
| 16.3  | Design considerations   | 216 |
| 16.4  | Mechanical requirements   | 220 |
| 16.5  | Typical construction  | 221 |
| 16.6  | Frictional torque studies   | 222 |
| 16.7  | Conclusions and discussion  | 226 |
| 16.8  | Bibliography  | 227 |
| 17    | A new generation of rolling-element bearing with an outline of its performance advantages   | 228 |
| 17.1  | A general review  | 228 |
| 17.2  | Introduction  | 228 |

|       |  |     |
|-------|--|-----|
| 17.3  | Basic concept and principle of operation of DDHPB  | 229 |
| 17.4  | Theoretical analysis   | 230 |
| 17.5  | Theory behind performance evaluation of bearings   | 232 |
| 17.6  | Design and test conditions of DDHPB  | 233 |
| 17.7  | Bearing test set-up and experimental details for testing DDHPB vis-à-vis conventional bearings | 235 |
| 17.8  | Data deduction   | 235 |
| 17.9  | Results and discussion   | 237 |
| 17.10 | Brief summary of the published research on DDHPB   | 239 |
| 17.11 | Conclusions  | 239 |
| 17.12 | References   | 240 |
| 17.13 | Nomenclature   | 241 |
|       | <i>Index</i>   | 243 |