

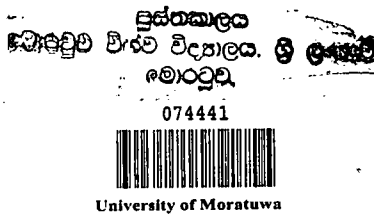
Title Page

# Vibration Diagnostic of Rotor Mechanisms in Ships



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This Thesis was submitted to the Department of Mechanical Engineering of the University of Moratuwa on the in partial fulfillment of the requirements for the Degree of Master of Philosophy.



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November, 2001.

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## Declaration

Here with, I certify that the work included in the Thesis in part or whole, has not been submitted for any other academic qualification at any institution.

***UOM Verified Signature***

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**Dr. P.A.B.A.R. Perera**  
(Supervisor)



## ABSTRACT

In ships, there are so many sources of noise and Vibration such as propulsion engines and electric generators in restricted spaces and structures of ships, which are made of steel, transmit vibration well. By the reasons, noise and vibration of ships are very big by nature and reduction of noise and vibration is important subject for ships. Regarding noise reduction, reduction of noise cause by vibration has difficulty and the major part of such noise is structure born noise.

"*Vibration*" is not a problem. It is a physical manifestation of machinery imperfection. It is used to help find obvious and subtle deviations in machines. No machine runs perfect. "*Diagnosis*" is the Method of Detection. If, a fault develops and goes undetected, then, at best, the problem will not be too serious and can be remedied quickly and cheaply; at worst, it may result in expensive damage and down-time, injury, or even loss of life. There is no reason or excuse to have machinery operate unprotected. The areas of interest in vibration measuring in plant maintenance are general measurement, analysis, and corrective.

All rotor mechanisms in ships consist of shafts, bearings, couplings, gears etc. These machinery operate under various load conditions from light to heavy. Ship propulsion system comparatively works under very heavy load conditions with rolling and pitching of the ship which may tend to cause overstressing of shafts.

### **Objective of the Research:**

The aim of the project is to identify the vibration analysis of a ship transmission system. A ship transmission system is the link between the crank shaft (or thrust block) end and the propeller of the vessel. As it contains number of shafts, couplings and bearings it tends to cause severe vibrations due to various running and incipient defects. These defects can be diagnosed by measuring the level of vibration to the extent they excited.

### **Methodology Adopted:** A Test Rig:

The test rig is a model of the transmission system of the ship "M/V Lanka Mahapola" made in to a scale of 1:10. Level and condition of lubrication maintained. Accelerometers are mounted over the bearing casings to trace the excitement of individual bearings.

Diagnosis of the misaligned and unbalanced shafts and defected sleeve (fluid film) bearings are done by using the "AUTOVIB" software package which is a vibration monitoring method introduce by this project.

### **Final Outcome of this research :**

Although spectrum analysis method is not in use, similar demodulation techniques, will be practical, for the diagnostics of Sleeve (Fluid Film) bearings.

Measurement of the vibrations excited by bearing friction forces present all the necessary information for Diagnostics of bearing condition including installation problems and the quality of lubrication.

## ACKNOWLEDGEMENT

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This project wouldn't have been possible without the concerted effort (on importing Vibration measuring equipment) of Former Dean/ Engineering Prof. L.L.Rathnayake.

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Of course without the support of the staff in Maritime Division Mr. M.D.D. Gunathilake and Mr. Sunil Wickramasinghe, the Test Bed made for the project would be nothing more than a dream.

# CONTENTS



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# CONTENTS

	<b>PAGE</b>
<b>LIST OF FIGURES AND TABLES</b> . . . . .	XIV - XX
<b>LIST OF ABBREVIATIONS</b> . . . . .	XXI - XXVIII
<b>PREFACE</b> . . . . .	XXIX - XXXVIII
<b>CHAPTER I</b> LITERATURE SURVEYS . . . . .	1 - 13
I . 1 INTRODUCTION . . . . .	2
I . 2 PREVIOUS LITERATURE REVIEWS AND SURVEYS . . . . .	3
I . 2 . 1 MASS UNBALANCE . . . . .	6
I . 2 . 2 BENT SHAFTS . . . . .	8
I . 2 . 3 CRACKED SHAFTS . . . . .	9
I . 2 . 4 CAN ONE AFFORD PLANT DOWNTIME ? . . . . .	9
I . 2 . 5 WHAT IS 'CONDITION MONITORING'? . . . . .	10
I . 2 . 6 WHERE CAN IT BE APPLIED . . . . .	10
I . 3 LITERATURE SURVEY . . . . .	10
I . 3 . 1 APPLICATION OF SHOCK PULSE METHOD . . . . .	10
(SPM) FOR ROLLING BEARING AND ITS DRAWBACKS AS A MONITORING METHOD	
I . 3 . 2 DIFFERENCE BETWEEN SHOCK PULSE AND . . . . .	11
VIBRATION	
I . 3 . 3 PROCESSING SHOCK PULSE SIGNALS . . . . .	11
I . 3 . 4 SHOCK PULSE PATTERNS . . . . .	12
I . 3 . 5 MEASURING OPERATION CONDITION . . . . .	13
<b>CHAPTER II</b> CODE ON NOISE LEVELS ON BOARD SHIPS . . . . .	14 - 18
II . 1 SCOPE . . . . .	15
II . 2 PURPOSE . . . . .	15
II . 3 NOISE LEVEL LIMITS . . . . .	15

<b>Chapter III</b>	<b>ROTOR MECHANISMS IN SHIPS; CLASSIFICATION; ELEMENTS; SOURCES OF VIBRATION</b>	19 - 20
III . 1	CLASSIFICATION OF SHIPS ROTOR MECHANISMS	20
III . 2	ELEMENTS OF ROTOR MECHANISMS IN SHIPS	20
<b>Chapter IV</b>	<b>MODES OF VIBRATION</b>	21 - 25
IV . 1	TORSIONAL VIBRATION	22
IV . 1 . 1	HOLZER ANALYSIS OF TORSIONAL SYSTEM	23
IV . 1 . 2	DRIVE TRAIN ANALYSIS	23
IV . 1 . 3	VIBRATION AMPLITUDES	24
IV . 2	RANDOM VIBRATION	24
IV . 2 . 1	WHY DO WE CARE ABOUT RANDOM VIBRATION?	25
IV . 2 . 2	WHAT IS FREQUENCY RESPONSE ANALYSIS ?	25
<b>CHAPTER V</b>	<b>MAIN CAUSE OF SHIP VIBRATION</b>	26 - 31
V . 1	INTRODUCTION	27
V . 1 . 1	THE ACTION OF THE SEA	27
V . 1 . 2	VIBRATION IN SHIPS	27
V . 1 . 3	OUT OF BALANCE FORCES IN RECIPROCATING MACHINERY	31
<b>CHAPTER VI</b>	<b>VIBRATION ANALYSIS</b>	32 - 35
VI . 1	INTRODUCTION	33
VI . 2	ANALYSIS FREQUENCY	34
VI . 3	ADVANTAGES / LIMITATIONS	35

<b>CHAPTER VII</b>	<b>FOURIER ANALYSIS</b>	<b>36 - 75</b>
VII . 1	CLASSIFICATION OF DATA	37
VII . 1 . 1	DIFFERENCES BETWEEN DETERMINISTIC AND RANDOM DATA	37
VII . 1 . 2	STATIONARY AND ERGODIC RANDOM DATA	38
VII . 1 . 3	NON-STATIONARY DATA	38
VII . 1 . 4	NATURE OF TRANSIENT DATA	38
VII . 1 . 5	FREQUENCY SPACING AND LENGTH CONSIDERATIONS	41
VII . 1 . 6	PADDING WITH ZEROS	42
VII . 1 . 7	EFFECT OF RECORD LENGTH	42
VII . 1 . 8	COMPUTATIONAL VERSUS RESOLUTION BANDWIDTH	43
VII . 1 . 9	RESOLUTION LIMITS	44
VII . 1 . 10	NONZERO MEAN VALUES	44
VII . 1 . 11	TIME WEIGHTING FUNCTIONS AND SPECTRAL LEAKAGE	45
VII . 1 . 12	ANALYZING SHORT DURATION TRANSIENTS	45
VII . 1 . 13	EFFECTS OF ZERO PADDING	46
VII . 1 . 14	EFFECTS OF RECORD LENGTH	46
VII . 1 . 15	EFFECTS OF TIME WEIGHTING FUNCTIONS (WINDOWING)	46
VII . 1 . 16	HANDLING NON-ZERO MEAN VALUES	47
VII . 1 . 17	PRACTICAL EXAMPLES USING DETERMINISTIC AND RANDOM TRANSIENT WAVE FORM	47
VII . 1 . 18	CONTINUOUS SINE WAVE	50
VII . 2	THE COMPLEX FOURIER TRANSFORMS	54
VII . 2 . 1	THE COMPLEX FOURIER TRANSFORMS (IN DETAIL)	54
VII . 2 . 2	TIME AND FREQUENCY REPRESENTATION	55
VII . 2 . 3	TIME AND FREQUENCY DOMAINS	55



VII . 3	DISCRETE FOURIER TRANSFORM AND THE FFT	59
VII . 3 . 1	INTRODUCTION	59
VII . 3 . 2	THE DISCRETE FOURIER TRANSFORMS.	59
VII . 3 . 3	FAST FOURIER TRANSFORMS	61
VII . 3 . 4	FILTERS	62
VII . 3 . 4 . 1	FILTERING	62
VII . 3 . 4 . 2	ANTI-ALIASING FILTERS	62
VII . 3 . 5	FOURIER TRANSFORM PROPERTIES	65
VII . 3 . 5 . 1	SCALING PROPERTY	65
VII . 3 . 5 . 2	SHIFTING PROPERTY	66
VII . 3 . 6	APPROXIMATION OF CONTINUOUS TRANSFORMS WITH THE DFT	66
VII . 4	SAMPLING THEOREM	67
VII . 5	REAL TIME ANALYSIS	69
VII . 6	C-PROGRAM FOR FAST FOURIER TRANSFORMATION	70

**CHAPTER VIII** TYPES OF BEARINGS 76 - 79

VIII . 1	ROLLING BEARINGS	77
VIII . 1 . 1	DEEP GROOVE BALL BEARINGS	78
VIII . 1 . 2	SELF-ALIGNING BALL BEARINGS	78
VIII . 1 . 3	ANGULAR CONTACT BALL BEARINGS	78
VIII . 1 . 4	NEEDLE ROLLER BEARINGS	78
VIII . 1 . 5	SPHERICAL ROLLER BEARINGS	78
VIII . 1 . 6	TAPER ROLLER BEARINGS	78
VIII . 1 . 7	THRUST BALL BEARINGS	79
VIII . 1 . 8	CYLINDRICAL ROLLER THRUST BEARINGS	79
VIII . 1 . 9	NEEDLE ROLLER THRUST BEARINGS	79
VIII . 2	HYDRO-DYNAMIC BEARINGS	79
VIII . 3	SLEEVE BEARINGS	79


<b>CHAPTER IX</b>	<b>LIFE OF BEARINGS</b>	80 - 87
IX . 1	INTRODUCTION	81
IX . 2	IRREGULARITIES OF BALL BEARINGS	82
IX . 3	BEARING WEAR AND ITS CAUSES	83
IX . 3 . 1	WEAR CAUSED BY ABRASIVE PARTICLES	83
IX . 3 . 2	WEAR CAUSED BY INADEQUATE LUBRICATION	83
IX . 3 . 3	WEAR CAUSED BY VIBRATION	84
IX . 3 . 4	SURFACE DISTRESS AND ITS CAUSES	85
IX . 3 . 5	IONS AND THEIR CAUSES	85
IX . 3 . 6	INDENTATIONS CAUSED BY FAULTY MOUNTING OR OVERLOADING	85
IX . 3 . 7	DAMAGE CAUSED BY THE PASSAGE OF ELECTRIC CURRENT	85
IX . 4	BEARING CRACKS	86
IX . 4 . 1	CRACKS CAUSED BY ROUGH TREATMENT	86
IX . 4 . 2	CRACKS CAUSED BY SMEARING	86
IX . 4 . 3	CRACKS CAUSED BY FRETTING CORROSION	86
IX . 5	BEARING CORROSION	87
IX . 5 . 1	CORROSION	87
IX . 5 . 2	FRETTING CORROSION	87
<b>CHAPTER X</b>	<b>VIBRATION MONITORING</b>	88 - 91
X . 1	INTRODUCTION	89
X . 2	CORRECTIVE MEASURES	89
<b>CHAPTER XI</b>	<b>CONDITION MONITORING AND FAULT DIAGNOSTICS</b>	92 - 100
XI . 1	MACHINE MONITORING SYSTEMS - MAINTANANCE PROCEDURE	93
XI . 1 . 1	PREDICTIVE MAINTANANCE	93
XI . 1 . 2	CONDITION MONITORING	94
XI . 2	FORMS OF TECHNICAL MAINTANANCE	98
XI . 2 . 1	METHODS FOR CONTROLLING THE CONDITION OF MACHINES AND MECHANISMS	98



<b>CHAPTER XII</b>	<b>VIBRATION MEASURING EQUIPMENT</b>	<b>101 - 114</b>
XII . 1	INTRODUCTION	102
XII . 2	ACCELEROMETERS	104
XII . 2 . 1	THE PIEZOELECTRIC EFFECT, THEORY, DESIGN AND USAGE	104
XII . 3	CHARGE AMPLIFIERS	109
XII . 3 . 1	TIME CONSTANT AND DRIFT	110
XII . 3 . 2	FREQUENCY AND TIME DOMAIN CONSIDERATION	110
XII . 4	LOW IMPEDANCE PIEZOELECTRIC TRANSDUCERS	111
XII . 4 . 1	TIME CONSTANT	112
XII . 5	LOW IMPEDANCE POWER SUPPLY (COUPLER)	113
XII . 5 . 1	TIME CONSTANT	113
XII . 5 . 2	SELECTION METRIX	113
XII . 5 . 3	DUAL MODE CHARGE AMPLIFIERS	113
XII . 6	HIGH AND LOW IMPEDANCE SYSTEM COMPARISON	114
XII . 6 . 1	SIMILARITIES	114
XII . 6 . 2	HIGH IMPEDANCE SYSTEMS HIGH	114
XII . 6 . 3	LOW IMPEDANCE SYSTEMS	114
XII . 7	EXTERNAL IMPEDANCE CONVERTERS	114
<b>CHAPTER XIII</b>	<b>VIBRATION MEASURING EQUIPMENT USED</b>	<b>115 - 119</b>
XIII . 1	PIEZOELECTRIC ACCELEROMETER, DESIGN & USE	116
XIII . 1 . 1	MEASURING ACCELERATION	116
XIII . 1 . 2	ACCELEROMETER MOUNTING	118
XIII . 1 . 2 . 1	STUD MOUNTING	118
XIII . 1 . 2 . 2	ADHESIVE MOUNTING	118
XIII . 1 . 2 . 3	TRIAxIAL MOUNTING	119
XIII . 1 . 2 . 4	STRAIN RELIEVING CABLE	119
XIII . 1 . 3	CALIBRATION TECHNIQUES	119
XIII . 1 . 3 . 1	ACCELEROMETERS	119

<b>CHAPTER XIV</b>	<b>VIBRATION MONITORING SYSTEM</b>	120 - 124
XIV . 1	INTRODUCTION	121
XIV . 2	WHY SEELVE BEARINGS ARE SELECTED ?	123
XIV . 2 . 1	COMMENT	123
XIV . 2 . 2	OBSERVATIONS:	124
<b>CHAPTER XV</b>	<b>DATA ACQUISITION CARD : ACL - 812PG</b>	125 - 130
XV . 1	INTRODUCTION	126
XV . 2	A SELECTION OF MEASUREMENT LOCATION	127
XV . 3	SELECTION OF THE INTERVALS BETWEEN MEASUREMENTS	127
XV . 4	C-PROGRAMME FOR CONVERSION OF ANALOG SIGNAL INTO DIGITAL VALUES	127
XV . 5	PROJECT DATA	127
XV . 6	CONVERSION OF DIGITAL VALUE TO ACCELERATION UNITS	129
XV . 7	RESULTS OBTAINED FROM FAST FOURIER TRANSFORMATION - ACCELERATION IN $\text{mm/s}^2$	130
<b>CHAPTER XVI</b>	<b>'AUTOVIB' - VIBRATION ANALYSING PROGRAMME</b>	131 - 137
XVI . 1	INTRODUCTION	132
XVI . 2	'AUTOVIB' - VIBRATION ANALYSING PROGRAMME	135
XVI . 3	EXAMPLES OF GRAPHS OBTAINED FROM 'AUTOVIB' PROGRAM	135
XVII . 4	FAULT DETECTION IN ROTATING MACHINERY	136
XVII . 5	OVERALL MEASUREMENT AND SPECTRUM COMPARISON	136
XVII . 6	HOW SPECTRUM CHANGES ARE RELATED TO THE CONDITION OF A MACHINE	136



<b>CHAPTER XVII DATA ANALYSIS</b>	138 - 168
XVII . 1 ENVELOPE SPECTRA OBTAINED FROM ELECTRIC MOTOR (EMO2, EMRI AND ECUP)	139
XVII . 2 COMPARISON OF GRAPHS AL_B11, AL_B21 AND AL_B31	144
XVII . 3 THE MAIN FAULTS CAUSING VIBRATIONS AT MACHINE ROTATING FREQUENCY	146
XVII . 4 FINDINGS	165
 <b>CHAPTER XVIII CONCLUSION</b>	 169 - 173
CONCLUSION	170
 <b>APPENDIX - A C-PROGRAM FOR FAST FOURIER                 TRANSFORM</b>	 174 - 177
 <b>APPENDIX - B C-PROGRAMME FOR CONVERSION OF                 ANALOG SIGNAL INTO DIGITAL VALUES</b>	 178 - 183
 <b>APPENDIX - C</b>  <b>AUTOVIB - VIBRATION ANALYSING                 PROGRAMME</b>	 184 - 194
 <b>APPENDIX - D AUTO SPECTRA AND ENVELOPE SPECTRA.                 AT DIFFERENT CONDITIONS OF A MACHINE</b>	 195 - 239
 <b>APPENDIX - E ENVELOPE SPECTRA AT DIFFERENT                 CONDITIONS OF A MACHINE</b>	 240 - 285
 <b>APPENDIX - F VIBRATION MONITORING TEST BED</b>	 286 - 303
 <b>REFERENCES</b>	 304 - 311
 <b>GLOSSARY</b>	 312 - 320
GLOSSARY	313

# LIST OF FIGURES AND



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# TABLES

# LIST OF FIGURES AND TABLES

## LIST OF FIGURES

FIG NO.	FIGURE	PAGE NO.
FIG. I . 3 . 3 . 1	Shock Pulse Transducer and its Vibration Signal	11
FIG. I . 3 . 4 . 1	Filtered Transducer Signals	12
FIG. I . 3 . 5 . 1	Measurements using Shock Pulse Meter	13
FIG. II . 1	Allowable Daily and Occasional Noise Exposure Zones	16
FIG. II . 2	Resonance Curve	17
FIG. VII . 1 . 10 . 1	Sine Shock Pulse	44
FIG. VII . 1 . 17 . 1	Half Cycle Sine Pulse, Its Fourier Transform Magnitude, and Imaginary Component (scale shifted).	48
FIG. VII . 1 . 17 . 2	One Cycle Sine Pulse, and Its Fourier Transform Magnitude.	49
FIG. VII . 1 . 17 . 3	Sine Wave and Its Fourier Transformation Curves	51
FIG. VII . 1 . 17 . 4	Fourier Transform of 1Hz	53
FIG. VII . 2 . 3 . 1	Time Domain Signal	56
FIG. VII . 2 . 3 . 2	Frequency Domain	56
FIG. VII . 2 . 3 . 3	Example of a Non - Harmonic Periodic Motion (Piston Acceleration of a Combustion Engine)	57
FIG. VII . 2 . 3 . 4	Illustration of How the Waveform can be "Broken Up" into a Sum of Harmonically Related Sine-Waves	57

FIG. VII . 2 . 3 . 5	Illustration of How the Signal can be Described in Terms of a Frequency Spectrum	58
FIG. VII . 4 . 1	Undersampled, Oversampled, and Critically-Sampled Unit Area Gaussian Curves.	68
FIG. VII . 6 . 1	Recording an Array (Here of Length 8) by Bit Reversal, (A) between Two Arrays, versus (B) In Place.	73
FIG. VII . 6 . 2	Input and Output Arrays for FFT	75
FIG. XI . 2 . 1 . 1	Measured Vibration from Tests of Periodic Conditions	99
FIG. XI . 2 . 1 . 2	A Typical Model of a Mechanism, in Absence of Prophylactic Maintenance	99
FIG. XII . 2 . 1 . 1	Thin Slab Representation of Crystals	106
FIG. XII . 2 . 1 . 2	Various Effects on Crystals	106
FIG. XII . 2 . 1 . 3	Typical Frequency Response Curve	108
FIG. XII . 3 . 1	Simplified Charge Amplifier Model	109
FIG. XII . 4 . 1	PIEZOTRON Circuit & Coupler	111
FIG. XIII . 1 . 1 . 1	Typical Compression Mode Accelerometer	116
FIG. XIII . 1 . 1 . 2	K-SHEAR Accelerometer	117
FIG. XIII . 1 . 2 . 4 . 1	Cable Strain Relief	119
FIG. XIV . 1 . 1	Vibration Monitoring System	122
FIG. XIV . 2 . 1 . 1	Sleeve Bearing Assembly	123
FIG. XIV . 2 . 1 . 2	Ball Bearing Assembly	123
FIG. XVI . 1 . 1	Illustrating of View Ports	134
FIG. XVI . 3 . 1	Example of Graph Obtained from 'AUTOVIB' Program	135
FIG. XVI . 3 . 2	Example of Graph Obtained from 'AUTOVIB' Program	135
FIG. XVII . 1 . 1	Characteristics of Electric Motor with No Speed	140
FIG. XVII . 1 . 2	Characteristics of Electric Motor in Running	142



FIG. XVII . 1 . 3	Characteristics of Electric Motor with Coupling attached	143
FIG. XVII . 2 . 1	Characteristics of Aligned Shaft – Vibration Measured on First Bearing	145
FIG. XVII . 2 . 2	Characteristics of Aligned Shaft – Vibration Measured on Second Bearing	145
FIG. XVII . 2 . 3	Characteristics of Aligned Shaft – Vibration Measured on Third Bearing	146
FIG. XVII . 3 . 1	Characteristics of Bearing No. 1 with Loosen Coupling No. 1	147
FIG. XVII . 3 . 2	Characteristics of Electric Motor with Loosen Coupling No. 2	148
FIG. XVII . 3 . 3	Characteristics of Bearing No. 2 with Loosen Coupling No. 1	149
FIG. XVII . 3 . 4	Characteristics of Bearing No. 3 with Loosen Coupling No. 2	150
FIG. XVII . 3 . 5	Typical Spectrum – Summary of Graphs XVII . 3 . 2, 3 and 4	150
FIG. XVII . 3 . 6	Characteristics of Bearing No. 1 without Lubrication	151
FIG. XVII . 3 . 7	Characteristics of Bearing No. 2 without Lubrication	152
FIG. XVII . 3 . 8	Characteristics of Bearing No. 3 without Lubrication	153
FIG. XVII . 3 . 9	Typical Spectrum – Summary of the Graphs made Out of FIG. XVII . 3 . 6, 7 and 8	153
FIG. XVII . 3 . 10	Characteristics of Bearing No. 1 with Loosen Coupling No. 1	154



LIST OF FIGURES AND TABLES

FIG. XVII . 3 . II	Characteristics of Bearing No. 2 with Loosen Coupling No. 2	154
FIG. XVII . 3 . 12	Characteristics of Electric Motor with Loosen Coupling No. 2	155
FIG. XVII . 3 . 13	Characteristics of Bearing No. 1 with Loosen Bearing No. 1	156
FIG. XVII . 3 . 14	Characteristics of Bearing No. 1 with Loosen Bearing No. 2	157
FIG. XVII . 3 . 15	Characteristics of Bearing No. 1 with Loosen Bearing No. 3	158
FIG. XVII . 3 . 16	Effects of Soft Foot	158
FIG. XVII . 3 . 17	Characteristics of Bearing No. 1 with Loosen Cap No. 1	159
FIG. XVII . 3 . 18	Characteristics of Bearing No. 3 with Loosen Cap No. 1	160
FIG. XVII . 3 . 19	Characteristics of Electric Motor with Loosen Cap No. 1	160
FIG. XVII . 3 . 20	Characteristics of Electric Motor with Loosen Cap No. 2	161
FIG. XVII . 3 . 21	Characteristics of Bearing No. 1 with Loosen Cap No. 2	161
FIG. XVII . 3 . 22	Characteristics of Bearing No. 2 with Loosen Cap No. 2	162
FIG. XVII . 3 . 23	Characteristics of Bearing No. 1 with Loosen Cap No. 3	162
FIG. XVII . 3 . 24	Characteristics of Bearing No. 2 with Loosen Cap No. 3	163



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FIG. XVII . 3 . 25	Characteristics of Bearing No. 3 with Loosen Cap No. 3	163
FIG. XVII . 3 . 26	Characteristics of Electric Motor with Loosen Cap No. 3	164
FIG. XVII . 3 . 27	Typical Spectrum – Summary of the Graphs made Out of FIG. XVII . 3 . 18,19,20,21,22 and 23	164



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## LIST OF TABLES

<b>TABLE NO.</b>	<b>TABLE</b>	<b>PAGE NO.</b>
TABLE VII . 1 . 4 . 1	BASIC FORMS OF FOURIER TRANSFORME	40
TABLE VII . 3 . 4 . 2 . 1	SYMMETRY PROPERTIES OF THE FOURIER TRANSFORM	64
TABLE XI . 1 . 2 . 1	MONITORING PARAMETERS	97
TABLE XV . 5 . 1	DATA OBTAINED AFTER ANALOG / DIGITAL CONVERSION	128
TABLE XV . 7 . 1	RESULTS OBTAINED FROM FAST FOURIER TRANSFORMATION	130



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## CHAPTER I

dBsv	Decibel shock value
dB <sub>i</sub>	Initial shock value
dB <sub>N</sub>	Normalized shock value

## CHAPTER II

v	impact velocity
dB(A)	Vibration energy measurement
L	Length of the structure
M	Function of the mass at the structure and its distribution
I	Second moment of area of the material of the structure about its neutral axis.
f	Frequency of applied force
f <sub>n</sub>	Frequency of Natural Structure



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## CHAPTER IV

m	Mass or inertia (in Spring-mass system) ( kg )
J	Mass or inertia (in Torsional system) ( kg m <sup>2</sup> )
K <sub>m</sub>	Spring (in Spring-mass system) ( Nm )
K <sub>T</sub>	Spring (in Torsional system) (Nm/rad )
c <sub>m</sub>	Damping (in Spring-mass system) (Ns/m )
c <sub>T</sub>	Damping (in Torsional system) ( Nms/rad )
a	Acceleration (in Spring-mass system) ( m /s <sup>2</sup> )
ö	Acceleration (in Torsional system) ( rad/s <sup>2</sup> )
v	Velocity (in Spring-mass system) ( m /s )
ò	Velocity (in Torsional system) ( rad/s )
y	Displacement (in Spring-mass system) ( m )
θ	Displacement (in Torsional system) ( rad )

## CHAPTER VII

$F(t)$	Fourier Transform – Time response function
$T$	Periodic time
$\omega_T$	Angular velocity
$t$	Time
$a_0, a_n, b_n$	Fourier transform coefficients
$n$	Integral multiplier
$f_0$	Fundamental frequency (first harmonic)
$\Delta f$	Frequency interval
$f(t)$	Fourier time response
$N$	Number of discrete values
$\Delta t$	Sampling interval
$f_s$	Sampling rate
$f_{Ny}$	Nyquist frequency
$F(f)$	Fourier Transform – Frequency response function
$u_{r12}(t)$	Boxcar time response function
$U_{r12}(f)$	Boxcar frequency response function
$\Delta N$	Number of padded zeros
$N'$	Number of data values in time series
$\Delta f'$	Frequency Increment
$B_e$	Resolution bandwidth
$f_{max}$	Highest frequency
$X(f)$	Fourier transform
$x(t)$	Inverse fourier transform
$k$	Integral coefficient
$a_k, b_k$	Fourier transform coefficients
$f(x), g(x)$	Original functions
$F(s), G(s)$	Function after convolution
$X(mF)$	Discrete frequency transform function



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$x(nT)$	Time response function
realOut	Array of coefficients of cosine waves in the Fourier formula.
imagOut	Array of coefficients of sine waves in the Fourier formula.
$h(t)$	Impulse response
$x(t)$	Input time domain
$y(t)$	Output time domain
$X(f)$	Input frequency domain
$Y(f)$	Output frequency domain
$H(f)$	Impulse frequency domain
$f(w)$	Fourier transform function
$f(x)$	Continuous time function
$E(x)$	Even part of function $f(x)$
$O(x)$	Odd part of function $f(x)$
$f^*(-x)$	Imaginary Function
$F^*(-s)$	Complex Conjugate of Function $f(x)$
$F(s)$	Fourier Transform function of $f(x)$
$\mathcal{P}_c$	Cosine Transform
$\mathcal{P}_s$	Sine Transform
$i$	Numerous
$x_0$	A Real constant
$\beta$	$= (x - x_0)$
$B$	A frequency in Hz
$H_n$	Discrete Fourier transform of N-points
$W$	A Complex Number
$h_k$	A Vector
$F_k$	$k^{\text{th}}$ component of fourier transform
$F_k^c$	$k^{\text{th}}$ Component of Fourier transform of length $n/2$
$data[1]$	Real part of $f_0$
$data[2]$	Imaginary part of $f_0$



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**CHAPTER IX**

$L_{10}$  Basic rating life of bearing

**CHAPTER XII**

$f_n$  Undamped natural (resonant) frequency (Hz)  
 $f$  Frequency at any given point of the curve (Hz)  
 $a_o$  Output acceleration  
 $a_b$  Mounting base or reference acceleration  
 $Q$  Factor of amplitude increase at resonance  
 $C_t$  Transducer capacitance  
 $C_c$  Cable capacitance  
 $C_r$  Range (or feedback) capacitor  
 $R_t$  Time constant resistor (or insulation of range capacitor)  
 $R_i$  Insulation resistance of input circuit (cable and transducer)  
 $q$  Charge generated by the transducer  
 $V_o$  Output voltage  
 $A$  Open loop Gain  
 $TC$  Time Constant  
 $q$  Charge generated by piezoelectric element  
 $V_i$  Input signal at gate  
 $C_q$  Transducer capacitance  
 $C_G$  MOSFET GATE capacitance

**CHAPTER XIII**

$F$  Force  
 $m$  Mass  
 $a$  Acceleration



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**CHAPTER XIV**

T1, T2, T3	Accelerometers
EM	Electric motor
B1, B2, B3	Bearings
TS	Tail shaft
IS	Intermediate shaft
C1, C2	Couplings

**CHAPTER XVII**

N	Motor speed (rps)
n	Number of balls
d	Ball diameter
D	Pitch diameter
B	Contact angle of ball
Z	Number of balls
$F_L$	Line frequency
$N_s$	Synchronous speed
$F_{rot}$	Rotational frequency
$F_s$	Slip frequency
$F_p$	Pole frequency
$F_z$	Slot frequency
$F_z \pm F_{rot}$	Side bands
$F_z - 2 F_L \pm F_{rot}$	Side bands
$F_m$	Main supply frequency
EMO	Characteristics of electric motor at 0 rpm
ECUP	Characteristics of electric motor running with attached coupling only
EMR	Characteristics of electric motor running with shafting and propeller



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LIST OF ABBREVIATIONS

CAP1_B11	Characteristics of bearing no. 1 with loosen cap no.1
CAP1_B21	Characteristics of bearing no. 2 with loosen cap no.1
CAP1_B31	Characteristics of bearing no. 3 with loosen cap no.1
CAP1_EM1	Characteristics of electric motor with loosen cap no.1
CAP2_B11	Characteristics of bearing no. 1 with loosen cap no.2
CAP2_B21	Characteristics of bearing no. 2 with loosen cap no.2
CAP2_B31	Characteristics of bearing no. 3 with loosen cap no.2
CAP2_EM1	Characteristics of electric motor with loosen cap no.2
CAP3_B11	Characteristics of bearing no. 1 with loosen cap no.3
CAP3_B21	Characteristics of bearing no. 2 with loosen cap no.3
CAP3_B31	Characteristics of bearing no. 3 with loosen cap no.3
CAP3_EM1	Characteristics of electric motor with loosen cap no.3
LB1_B11	Characteristics of bearing no. 1 with loosen bearing no.1
LB1_B21	Characteristics of bearing no. 2 with loosen bearing no.1
LB1_B31	Characteristics of bearing no. 3 with loosen bearing no.1
LB1_EM1	Characteristics of electric motor with loosen bearing no.1
LB2_B11	Characteristics of bearing no. 1 with loosen bearing no.2
LB2_B21	Characteristics of bearing no. 2 with loosen bearing no.2
LB2_B31	Characteristics of bearing no. 3 with loosen bearing no.2
LB2_EM1	Characteristics of electric motor with loosen bearing no.2
LB3_B11	Characteristics of bearing no. 1 with loosen bearing no.3
LB3_B21	Characteristics of bearing no. 2 with loosen bearing no.3
LB3_B31	Characteristics of bearing no. 3 with loosen bearing no.3
LB3_EM1	Characteristics of electric motor with loosen bearing no.3
LC1_B11	Characteristics of bearing no. 1 with loosen coupling no.1
LC1_B21	Characteristics of bearing no. 2 with loosen coupling no.1
LC1_B31	Characteristics of bearing no. 3 with loosen coupling no.1
LC1_EM1	Characteristics of electric motor with loosen coupling no.1
LC2_B11	Characteristics of bearing no. 1 with loosen coupling no.2
LC2_B21	Characteristics of bearing no. 2 with loosen coupling no.2



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LIST OF ABBREVIATIONS

LC2_B31	Characteristics of bearing no. 3 with loosen coupling no.2
LC2_EM1	Characteristics of electric motor with loosen coupling no.2
UM_B11	Characteristics of bearing no. 1 with unbalance mass
UM_B21	Characteristics of bearing no. 2 with unbalance mass
UM_B31	Characteristics of bearing no. 3 with unbalance mass
UM_EM1	Characteristics of electric motor with unbalance mass
NOL1_B11	Characteristics of bearing no. 1 without lubrication
NOL2_B21	Characteristics of bearing no. 2 without lubrication
NOL3_B31	Characteristics of bearing no. 3 without lubrication
ECUP	Characteristics of electric motor with coupling attached
AL_B11	Characteristics of bearing no. 1 with shaft aligned
AL_B21	Characteristics of bearing no. 2 with shaft aligned
AL_B31	Characteristics of bearing no. 3 with shaft aligned



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# **P R E F A C E**

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## P R E F A C E

A ship is the home of the crew for months at a time and of her passengers perhaps for weeks. The influence of vibration upon comfort is therefore extremely important and will be a factor in the reputation of any passenger ship.

Vibration Problems on ships such as mast, foundation, and propeller shaft vibration excited by propulsion system frequencies can lead to structural fatigue, damage to machinery, and can be annoying, uncomfortable, and dangerous for persons on the ship.

Vibration has been a matter of concern to ship designers since the end of the 19th century although its presence in ship characteristics was known long before that time and its importance has become much emphasized over the last half century. Some sailing warships, particularly the lightly-built frigates, suffered from serious vibration aft when driven hard, probably as a result of flow interaction while there are accounts of mast/sail combinations causing such severe vibration that crewmen were thrown from their feet or, worse, from their mast-top positions.

Today, an increasing number of new or alternative ships is launched - very large and very fast container ships, cruise ships, tankers with modern propulsion systems. Due to little experience with such ships, living conditions can be adversely affected by vibration if the frequencies of major excitations are close to a natural frequency of the superstructure or a part of it.

In ships, there are so many sources of noise and Vibration such as propulsion engines and electric generators in restricted spaces and structures of ships, which are made of steel, transmit vibration well. By the reasons, noise and vibration of ships are very big by nature and reduction of noise and vibration is important subject for ships.

### **Effect of Vibration :**

One can distinguish two areas, where standards have been developed to assess the effect of vibration, applied to the human body: vibration passing to hand and whole body. The vibration passes to hand, can cause the disease, called as "white finger disease," the latter can lead to variety of health problems, ranging from motion sickness to tissue damages. It should be noted, that the relationship between exposure and the disease is complex and many questions in this area, remain unanswered. A number of standards incorporating the latest state of knowledge have been introduced over the last few years with the object of giving guidance to those, who required to assess the importance of human vibration exposure.

It is now generally believed that vibration causes damage to blood vessels, which are thus made incapable of circulating blood to the extremities. There is no known cure and symptoms, which are irreversible. So it is clearly important to establish the levels of vibration and the duration of exposure, which are statically likely to cause the disease and to take precautions.



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### **Noise:**

Noise has been recognized as a nuisance (in the legal sense) for many years. Nuisance can be either public or private. A private nuisance is commonly defined as an unlawful interference with a person's use or enjoyment of land or of some right over it or in connection with it. A public noise is an unlawful act or omission causing interference with the health and safety of the public at large. A noisy operation can be both a public and a private nuisance. It is not always easy to answer the question of whether the nuisance complained of is a public or a private one. If the noise nuisance affects just one person or a household, it is clearly a private nuisance. If it affects a class of the public, such as the residents of a community or of the passers-by of a noisy factory, it is likely to be a public nuisance.

A private action can only be brought by the occupier of the land or by someone who has a legal interest in the land, and he can only take action against the person who cause the nuisance. A public nuisance is a crime, and proceedings can be taken by public bodies such as the local authority or Attorney-General or both. All the criminal sanctions are available to the court, an in addition it has power to issue an abatement order, which may take the form of restricting the noise to certain hours, or levels, or to cease entirely.

It is well known that much of modern technology is derived from projects ordered by the military industry of the developed countries. The deepest research of machines and equipment vibration is done initially in countries with strong naval forces, which have important needs to minimize noise and vibration. A number of naval research centers that deal with using and developing analytical tools for vibration measurement and reduction exist in Developed Countries. These centers are equipped with modern instrumentation for measurement and analysis of signals ,mostly using instruments produced by Bruel & Kjaer (Denmark) and Kistler (Norway). A number of highly qualified experts work in these centers and prepare specialists for navy and shipbuilding industry.

The greatest advances can make in the condition diagnostics of machines using vibration., The AUTOVIB monitoring method for condition diagnostics of machines using vibration can be successfully used in a number of civil industries including energy, nuclear power plants, paper and pulp, metallurgy, transport including ships, aviation and railways.

One of the main problems in Sri lanka is a great shortage of specialists who can efficiently use condition monitoring and diagnostics systems, including those with expert systems that are supplied by the leading Western companies. To prepare these specialists would take too much time. This fact has defined the main peculiarities of the vibration diagnostics in Sri lanka. The strategy of AUTOVIB, is to develop a system for condition diagnostics of sleeve bearings (fluid film bearings) that can be applied equally for ball bearings as well.



### The main problems peculiar to the Sri lankan market

The changes associated with the introduction of market relations in the number of industries in Sri Lanka were started at the end of the 1950s and after 1980s with the introduction of Open economy. Plans for restructuring the economy included plans to decrease production costs and excess labour energy. The drawbacks prevail in improving of the efficiency of production processes is based on three main assumptions:

- The absence of financial resources in the country to renew the machinery and equipment in the majority of industries for at least five to ten years. The natural wear of the equipment should significantly increase its maintenance costs and the introduction of the condition diagnostics systems is likely to be the most practical way to decrease these costs.
- Relatively high investments over high level diagnostic systems (Automatic Condition monitoring Systems) prevent owners by utilizing such a system.
- Significant limitations of existing condition diagnostic technologies from leading Western companies.

The following reasons that limit the use of modern condition monitoring and diagnostics systems of American and West-European production in Sri Lanka

- The absence in most regions of qualified personnel who can use these systems, despite the existence of a number of scientific centers with experts of higher qualification. The problem is that to prepare a person to be a qualified expert takes several years and would require significant financial resources.
- The high relative price of the common monitoring and diagnostic systems in Importing. For example, in the West the price of the diagnostic instrumentation needed for an expert to work on the enterprise is less than or equal to compared to the labor costs of an expert for the enterprise during a year. In Sri Lanka, taking into account the tax policy, the price for the diagnostic equipment equals the income of an expert for about ten years. This makes the survival of small companies specialized in diagnostic services impossible.

- One more reason, which is also economic is the high costs of mounting permanent transducers on existing equipment. Typically, the construction of units should be redesigned to assure appropriate mounting and protection of the transducers so as not to destroy them in the process of standard maintenance of the equipment.
- The last reason is connected to the existence of various standards and regulations that differ in each industry that define the requirements for different parameters of the main equipment and methods for their control. These regulations do not allow making a decision for maintenance and repair of the equipment without conducting standard measurements that usually require the shutdown of the equipment and partial disassembly of the units. That's why these regulations make it impossible to use modern condition monitoring systems and use condition based maintenance.

This analysis of the current situation led to a recommendation to speed up the development of the methods for mass condition diagnostics that can be carried out by a user with no special training in condition diagnostics. These methods were developed over a period of several years based on the analysis of machine vibrations in the shipbuilding industry and the resultant extraction of diagnostic information signals. The methods developed were intended to be used for condition diagnostics of supplementary machines and equipment the maintenance of which was not governed by the existing standards and regulations.

This analysis was the base of this project. At the same time, a number of problems became evident during the detailed market research stage:

- The first problem was the need for application software based on the developed methods that would efficiently replace a qualified expert. The system should ask the customer to describe the equipment for diagnostics, define what data should be measured, process the measured data, make condition diagnostic and prediction for the machines and equipment under control.

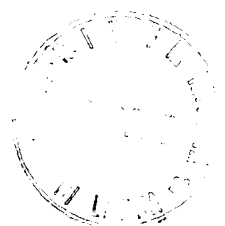
- The second problem occurred after the start of the exploitation by the customers of the automatic diagnostic systems consisting of the measurement device, personal computer and the application software . This was the problem of the customers support in those rare situations when the automatic diagnostics did not answered the question of what is the defect in the machine and how dangerous it is.

## Noise Generated From Machine Vibrations

If you want to reduce maintenance costs you must improve equipment maintainability and reliability. The premise being, if the equipment does not fail as often, it costs less to repair. When equipment does fail, longer life can be achieved if proper repairs are made. Proper repairs means the cause of failure must be identified and eliminated. If this is not done the equipment will fail again. These objectives can be accomplished during the acquisition phase of new equipment, the purchase of spare parts, and accurate diagnosis of all rotating machinery problems. If either of these items are not properly managed the objectives may not be achieved. Executive evaluations, payment of bonuses, production objectives and other brownie point systems tend to focus management's attention on the short term instead of the long term. This can also affect maintainability and reliability.

In field balancing machines with high vibrations, the use of common methods of determining balance weights often does not yield satisfactory results. An analysis of the reasons for this shows that there are two main groups of constraints on the balancing efficiency: The forces of different nature from simple unbalance that excite vibration at the rotating frequency and the existence of certain defects in the machine that can change the mechanical properties of the machine.

The technology on how to diagnose problems in rotating machinery is equally unparalleled. The technology has progressed from amplitude measuring and trending to using the time domain signal, phase, and frequency domain spectra for accurate diagnosis of specific problems. In fact, it may be time to



progress to the next step beyond predictive maintenance to equipment maintainability and reliability.

Consideration of the reliability and service life of a machine suggests that low frequency vibrations present the greatest source of danger to a machine. For machines with rotating parts (rotors), this is typically a vibration at the rotation frequency. This vibration may significantly increase during the machine operation. Usually, when the vibration level exceeds certain limits, the users conduct maintenance of the machine. The inertial forces due to the unbalance of the rotating parts relative to the rotation axis are typically considered to be the reasons for the vibration increase. That's why the users try field balancing the machine when possible. Unfortunately, attempting to balance the machine may not always produce acceptable results. The main reasons for this are other problems of the machine or of its supports. To eliminate additional expenses and delays, the customer should have the information about the various possible defects of the machine that can be responsible for the machine vibration at the rotating frequency and this information should be available before or at least during the balancing.

The factor, the vibration still remains as an actual problem with increase in speed and load of machines in ships. The technical diagnostic is the process of testing the machine, in order to test the condition of it. Therefore the technical diagnostic helps to detect the faults of machines while they operate. The change in condition of vibration of machines may cause the change in technical condition of ship machinery then the condition of the ship.

The term **Diagnostic** is a Greek word, and means the ability to discern. It is used in Medical Science. That is the section, which indicates the symptoms of diseases and methods using to identify the diseases.

### **Accurate Diagnosis**

Accurate diagnosis of machinery problems provides the intelligence for new equipment acquisitions, spare parts purchasing, and necessary repairs. This is why this very important function must be part of the Equipment Maintainability and Reliability group.

Once a problem has been identified the necessary maintenance and engineering talent must be available to determine the proper fix. Accurate diagnosis of machinery problems requires a lot more than condition monitoring and trending. Accurate diagnosis requires the proper hardware, software, technology, and skilled people. This includes the use of frequency domain spectra, time domain signals, and phase relationships of frequencies. The first response is "we can't afford that." The fact is that you can't afford not to do accurate diagnosis.

If the right hardware, software, and technology are placed in the hands of skilled people, the payback period is the shortest, and the return on investment (ROI) is more than for any other investment today. These savings are realized by a reduction in maintenance cost and increased production. Managers should realize they may have to purchase new equipment analyzers and transducers. High quality personnel should be assigned to the program. These people must be trained in the best technology. People's attitude should be changed from condition monitoring and trending to accurate diagnosis with vibration analysis. If these objectives are achieved, the increase in profits for a medium plant should be at least one million dollars per year.

Imbalance is a linear problem. Linear problems behave in a linear manner. If a machine is out of balance, you should be able to balance it in three or four runs. If balancing is so simple, what is the problem? The problem is inaccurate diagnosis. There are a lot of vibration "experts" that cannot tell the difference between imbalance, looseness, bent shaft, misalignment, softfoot, broken rotor bars, and loading. All of these problems can cause a high amplitude at rotor speed, however these problems cannot be solved by balancing.

The program "AUTOVIB" gives a broad range of options to diagnose above mentioned disorders and irregularities of the machinery.

