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The application of Eulerian laser Doppler vibrometry to the on-line condition monitoring of axial-flow turbomachinery blades

by

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Submitted in partial fulfilment of the requirements for the degree Philosophiae Doctor (Mechanical Engineering) in the Faculty of Engineering, the Built Environment and Information Technology, University of Pretoria, Pretoria

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Summary

The on-line condition monitoring of turbomachinery blades is of utmost importance to ensure the long term health and availability of such machines and as such has been an area of study since the late 1960s. As a result a number of on-line blade vibration measurement techniques are available, each with its own associated advantages and shortcomings. In general, on-blade sensor measurement techniques suffer from sensor lifespan, whereas non-contact techniques usually have measurement bandwidth limitations. One non-contact measurement technique that yields improvements in the area of measurement bandwidth is laser Doppler vibrometry.

This thesis presents results and findings from utilizing laser Doppler vibrometry in an Eulerian fashion (i.e. a fixed reference frame) to measure on-line blade vibrations in axial-flow turbomachinery. With this measurement approach, the laser beam is focussed at a fixed point in space and measurements are available for the periods during which each blade sweeps through the beam. The characteristics of the measurement technique are studied analytically with an Euler-Bernoulli cantilever beam and experimental verification is performed. An approach for the numerical simulation of the measurement technique is then presented.

Associated with the presented measurement technique are the short periods during which each blade is exposed to the laser beam. This characteristic yields traditional frequency domain signal processing techniques unsuitable for providing useful blade health indicators. To obtain frequency domain information from such short signals, it is necessary to employ non-standard signal processing techniques such as non-harmonic Fourier analysis.

Results from experimental testing on a single-blade test rotor at a single rotor speed are presented in the form of phase angle trends obtained with non-harmonic Fourier analysis. Considering the maximum of absolute unwrapped phase angle trends around various reference frequencies, good indicators of blade health deterioration were obtained. These indicators were verified numerically.

To extend the application of this condition monitoring approach, measurements were repeated on a five-blade test rotor at four different rotor speeds. Various damage cases were considered as well as different ELDV measurement positions. Using statistical parameters of the abovementioned indicators as well as time domain parameters, it is shown that with this condition monitoring approach, blade damage can successfully be identified and quantified with the aid of artificial neural networks.

Keyterms: *Laser Doppler vibrometry, Eulerian measurements, Lagrangian measurements, on-line blade vibration, condition monitoring, non-harmonic Fourier analysis, phase angle trends, finite element modelling, artificial neural networks.*

Die toepassing van Euler laser Doppler vibrometrie op die operasionele toestandsmonitering van aksiaalvloei turbomasjinerie lemme

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Opsomming

Die operasionele toestandsmonitering van turbomasjinerie lemme is van uiterste belang met betrekking tot die langtermyn integriteit en beskikbaarheid van hierdie masjiene en is 'n gebied wat al sedert die laat 1960's bestudeer word. Gevolglik is daar 'n aantal operasionele lemvibrasie meettegnieke beskikbaar, elk met sy eie sterk- en swakpunte. In die algemeen word sensors wat direk op die lemme geïnstalleer word, hoofsaaklik beperk deur sensorleeftyd. Nie-kontak tegnieke aan die ander kant, het gewoonlik meetbandwydte beperkings. 'n Nie-kontak meettegniek wat verbeterings bied op die gebied van meetbandwydte, is laser Doppler vibrometrie.

Hierdie proefskrif bied resultate en bevindings aan ten opsigte van die implementering van laser Doppler vibrometrie in 'n Euler verwysingsraamwerk, ten einde operasionele lemvibrasies te meet op aksiaalvloei turbomasjinerie. Met hierdie meetbenadering word die laserstraal gefokus op 'n vaste ruimtelike punt en is metings dan beskikbaar vir die periodes waartydens elke lem deur die laserstraal beweeg. Die eienskappe van die meettegniek word analities bestudeer met behulp van 'n Euler-Bernoulli kantelbalk waarna eksperimentele verifiëring uitgevoer word. 'n Metode om die meettegniek numeries te simuleer word dan aangebied.

Gepaardgaande met hierdie meettegniek is die kort periodes waartydens elke lem blootgestel word aan die laserstraal. Tradisionele seinprosesseringstegnieke is as gevolg daarvan nie geskik om bruikbare lemtoestandsaanwysers te lewer nie. Om frekwensiedomein inligting vanaf sulke kort seine te kry, is dit nodig om van nie-standaard seinprosesseringstegnieke soos nie-harmoniese Fourier analise gebruik te maak.

Resultate vanaf eksperimentele toetse op ’n enkellem toetsrotor by ’n vaste rotorspoed word aangebied in die vorm van fasehoek grafieke wat verkry is deur nie-harmoniese Fourier analise. Deur die maksimum van die absolute van ontvoude fasehoek grafieke te evalueer, word goeie aanduiders van lemtoestandsverswakking verkry. Die resultate word numeries geverifiëer.

Om hierdie toestandsmoniteringtegniek verder te verifiëer, word die metings herhaal op ’n vyf-lem toetsrotor teen verskillende rotasiesnelhede. Verskeie lemskade gevalle word beskou so wel as verskillende Euler meetposisies. Deur statistiese karakteristieke van die bogenoemde aanduiders asook tyddomein aanduiders te evalueer, word dit bewys dat met hierdie toestandsmoniteringtegniek lemskade suksesvol geïdentifiseer en gekwantifiseer kan word deur gebruik te maak van kunsmatige neurale netwerke.

<u>Sleutelterme:</u> Laser Doppler vibrometrie, Euler metings, Lagrange metings, operasionele lemvibrasie, toestandsmonitering, nie-harmoniese Fourier analise, fasehoek grafieke, eindige element modellering, kunsmatige neurale netwerke.

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"The fear of the LORD is the beginning of knowledge" (Proverbs 1:7)

Table of contents

Summary ii
Opsomming iv
Acknowledgements vi
Table of contents vii
Glossary xi
  Abbreviations xi
  Symbols xii
  Greek symbols xv
Chapter 1 Introduction and Literature Study 1
  1.1 Introduction 1
  1.2 Blade vibration 2
    1.2.1 Operational blade excitation 2
    1.2.2 Rotational effects 3
    1.2.3 Blade manufacturing tolerances 4
      1.2.3.1 Blade roots 4
      1.2.3.2 Mistuning 5
  1.3 Blade damage and failure modes 6
    1.3.1 Fatigue 7
    1.3.2 Stress-corrosion 7
    1.3.3 Foreign object damage 8
    1.3.4 Flutter 8
    1.3.5 Transient load events 8
  1.4 Blade health indicators 9
    1.4.1 Natural frequencies 9
    1.4.2 Damping 10
    1.4.3 Amplitude 10
    1.4.4 Phase angle 10
    1.4.5 Operational modal analysis 11
  1.5 Blade vibration measurement techniques 11
    1.5.1 Strain gauges 12
    1.5.2 Blade tip TOA 12
      1.5.2.1 Probe Types 14
      1.5.2.2 Aliasing 15
      1.5.2.3 Probe configuration 15
      1.5.2.4 Assumptions 16
      1.5.2.5 Signal processing 16

1.5.3 Pressure signals......16
1.5.4 Shaft torsional vibration measurements......17
1.5.5 Audio signals......17
1.5.6 Fibre Bragg Grating sensors......17
1.5.7 Interferometry......17
1.5.8 Laser Doppler velocimetry......18
1.5.9 Laser Doppler Vibrometry......18
1.5.9.1 Eulerian Laser Doppler Vibrometry......19
1.5.9.2 Lagrangian Laser Doppler Vibrometry......20
1.5.9.2.1 Tracking Laser Doppler Vibrometry......20
1.5.9.2.2 Continuous Scanning Laser Doppler Vibrometry......21
1.5.10 Radar proximity sensors......22
1.6 Blade vibration measurement systems......22
1.6.1 Available systems......22
1.6.2 Shortcomings of available systems......23
1.7 Experimental related issues......23
1.7.1 Non-contact blade excitation techniques......23
1.8 Finite element modelling......24
1.8.1 Model updating based on Frequency Response Functions......25
1.9 Issues with regards to Laser Doppler Vibrometry......25
1.9.1 Speckle noise......25
1.9.1.1 The nature of speckle noise......26
1.9.1.2 Noise cancellation......27
1.9.2 Effect of geometry on measurements......28
1.9.3 Practical issues......28
1.10 Signal processing......28
1.11 Scope of research......31
1.12 Document layout......33
1.13 Publications......34
Chapter 2 Eulerian Laser Doppler Vibrometry......36
2.1 Introduction......36
2.2 Analytical and numerical study......36
2.2.1 Cantilever beam theory......36
2.2.2 ELDV analytical formulation......37
2.2.3 Numerical simulation of ELDV......38
2.2.4 Effect of scanning speed......41
2.2.4.1 Modulation frequency......42
2.2.4.2 Frequency resolution......46

2.2.5 Condition monitoring feasibility study 48
2.3 Experimental study of ELDV 49
2.3.1 Discrete frequency excitation 51
2.3.2 White noise excitation..52
2.4 ELDV on rotating axial-flow blades..53
2.4.1 Rotor-circumferential ELDV 53
2.4.2 Rotor-axial ELDV..55
2.5 Conclusions...56
Chapter 3 Rotor-axial Eulerian Laser Doppler Vibrometry applied to a single-blade axial-flow test rotor...58
3.1 Introduction...58
3.2 Experimental setup..58
3.2.1 Measurement and control..61
3.2.2 Laser alignment...63
3.3 Experimental measurements 65
3.4 Finite element model..65
3.5 Phase angle as a damage indicator..70
3.6 Non-Harmonic Fourier Analysis...72
3.6.1 Signal shift detection using NHFA 75
3.6.2 Sensitivity analysis..76
3.6.3 Damping...79
3.7 Results comparison 81
3.8 Experimental measurement uncertainty...83
3.9 Conclusions...86
Chapter 4 Rotor-axial Eulerian laser Doppler vibrometry applied to a five-blade axial-flow test rotor..88
4.1 Introduction...88
4.2 Test setup 89
4.3 Test control and measurement 91
4.4 FEM 93
4.4.1 Model updating 95
4.4.2 TLDV simulation 96
4.5 Experimental results...99
4.5.1 MAUPAT analysis..99
4.5.2 Time domain analysis 104
4.5.3 ANN implementation..106
4.5.4 Natural frequency estimation...108
4.6 Measurement uncertainty sensitivity analysis 110

4.6.1 MAUPAT results 112
4.6.2 Time domain results 114
4.6.3 Discussion 114
4.7 Conclusions 115
Chapter 5 Conclusions and further work 117
5.1 Conclusions 117
5.2 Further work 118
References 120
Appendix A Rotor-Circumferential ELDV 131
A.1 Introduction 131
A.2 RC ELDV mathematical definition 132
A.2.1 Vector-loop equations 132
A.2.2 Rigid Body Velocity Component 135
A.2.3 The influence of BLEP variance from the MBLEC 138
A.3 Experimental verification 138
A.4 Response matrix interpolation for non-constant scanning speeds 142
A.5 Conclusions 142

Glossary

Abbreviations

Abbreviation	Description
AC	Alternating Current
ADC	Analogue to Digital Converter
AIC	Akaike Information Criterion
ANN	Artificial Neural Network
AR	Autoregressive
ARMA	Autoregressive Moving Average
BLEP	Blade Leading Edge Profile
BPF	Blade Pass Frequency
CLSF-IO	Combined Non-Linear Least Squares Frequency Method On Input Output Spectra
CSLDV	Continuous Scanning Laser Doppler Vibrometry
DC	Direct Current
DEN	Denominator
ELDV	Eulerian Laser Doppler Vibrometry
ESPI	Electronic Speckle Pattern Interferometry
EV	Eigenvector
EVR	Eulerian Vibration Response
FBG	Fibre Bragg Grating
FEM	Finite Element Model
FFT	Fast Fourier Transform
FOD	Foreign Object Damage
FPE	Final Prediction Error
FRF	Frequency Response Function
HCF	High Cycle Fatigue
HFA	Harmonic Fourier Analysis
HI	Holographic Interferometry
HP	High Pressure
INVE	Iterative Noise Variance Estimation
LCF	Low Cycle Fatigue
LDV	Laser Doppler Vibrometer / Vibrometry

LP	Low Pressure
LVR	Lagrangian Vibration Response
LVRM	Lagrangian Vibration Response Matrix
MAUPAT	Maximum Absolute Unwrapped Phase Angle Trend
MBLEC	Mean Blade Leading Edge Curve
MDL	Minimum Description Length
MPC	Multi-Point Constraint
MUSIC	Multiple Signal Classification
MW	Megawatt
mW	milliwatt
NExT	Natural Excitation Technique
NHFA	Non-Harmonic Fourier Analysis
NOM	Nominator
ODS	Operational Deflection Shape
PI	Proportional-Integral
PPCRE	Predicted Percent Reconstruction Error
PPR	Pulses-Per-Revolution
PSD	Power Spectral Density
RBVC	Rigid Body Velocity Component
RC	Rotor Circumferential
RMS	Root-Mean-Square
RPM	Revolutions Per Minute
SCC	Stress Corrosion Cracking
SLDV	Scanning Laser Doppler Vibrometer / Vibrometry
SNR	Signal to Noise Ratio
TLDV	Tracking Laser Doppler Vibrometry
TOA	Time-Of-Arrival
UPA	Unwrapped Phase Angle
VI	Virtual Instrument

Symbols

Symbol	***Description***
A	ELDV measurement position
a	Fourier cosine coefficient

B	ELDV measurement position
b	Blade number
C	Cosine operator
c	Scanning speed
c_{ref}	Reference scanning speed
$c_{\max}$	Maximum scanning speed
D_b	Blade-specific damage level [mm]
d	Fourier sine coefficient
E_j	j^{th} modal constant
F	Force
F_b	Simulated blade force
f	Frequency
f_{actual}	Actual frequency
$f_{aliased}$	Aliased frequency
f_{NQ}	Nyquist frequency
f_R	MAUPAT reference frequency
f_s	Sampling frequency
$\Delta f_{\min}$	Minimum required ELDV frequency resolution
Δf	Frequency resolution
G	NHFA signal approximation
g	Probe group size
H	Mobility FRF amplitude
h	Vector-loop diagram vector number
J	ELDV RMS run-down peak number
j	Mode / natural frequency number
k	Scanning speed ratio
l	Cantilever beam length
m	Harmonic number
N	Sample length
N_k	Interpolation sample length

N_{ref}	Reference sample length
n	Sample number
P_b	Average nozzle back-pressure waveform
q_j	j[th] generalized modal coordinate
$\bar{R}_1$	MBLEC offset vector
$\bar{R}_2$	Relative MBLEC measurement position vector
$\bar{R}_3$	Laser orientation vector
$\bar{R}_4$	Laser offset vector
$\bar{R}_5$	Absolute MBLEC measurement position vector
$\bar{R}_h$	Vector-loop diagram vector
R_h	$\bar{R}_h$ amplitude
r	Angular ELDV measurement radius
S	Sine operator
t	Time
t_0	Zero-based time vector
t_N	Sample time span
Δt	Time increment
$\hat{V}_{L,c_{ref}}$	LVRM
$\hat{V}_{L,\psi_{ref}}$	Angular LVRM
v_E	Eulerian vibration velocity
$\vec{v}_E$	EVR vector
v_L	Lagrangian vibration velocity
$\vec{v}_L$	LVR vector
v_{RB}	RBVC
W_j	j[th] characteristic function
w_E	Eulerian vibration displacement
w_L	Lagrangian vibration displacement
X	X-axis

x_E	Eulerian measurement position
x_L	Lagrangian measurement position
Δx	Measurement position increment
Y	Y-Axis
y	Time signal
Z	Z-axis

Greek symbols

Symbol	Description
β_j	j^{th} modal root
δ	$\bar{\varepsilon}$ offset
$\bar{\varepsilon}$	Rotor order vector
Φ	NHFA detected phase angle
ϕ	Phase angle
ϕ_d	Damped phase angle
η_h	$\overline{R}_h$ angle
ϑ	Angular measurement range
φ_E	Eulerian angular measurement position
φ_L	Lagrangian angular measurement position
μ_b	Pressure waveform normalization constant
θ	Rotor angle
σ	Standard deviation
σ_{CORR}	Correlation coefficient standard deviation
σ_{MAUPAT}	MAUPAT standard deviation
σ_{RMS}	RMS standard deviation
$\tilde{\sigma}_{MAUPAT}$	Mean MAUPAT standard deviation
τ	Total signal time span
ϖ	Arbitrary frequency
ϖ_0	Signal fundamental frequency
ϖ_{ref}	NHFA reference frequency
$\Delta\varpi$	Frequency offset

Ω_j	j[th] modulation frequency
$\overline{\omega}$	ω_1 estimate vector
ω_d	Damped natural frequency
ω_j	j[th] natural frequency
ω_1	Blade first bending mode frequency
$\omega_{1,est}$	ω_1 estimate
$\overline{\Psi}$	Rotation speed vector
ψ	Rotor speed
ψ_{ref}	Reference rotor speed
ζ	Structural damping coefficient