The Development of an On-line Fan Blade Damage Detection Methodology

by

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Summary

This dissertation entails the development of an on-line fan blade damage detection methodology. The aim is to use a minimal number of sensors to measure in-operation blade vibrations in order to qualify and quantify fan blade damage in terms of blade root crack length for multiple blades. An experimental setup namely the Fan Blade Condition Monitoring Test Structure (FaBCoM TeSt) was used to develop such a methodology.

A Finite Element Model (FEM) of the FaBCoM TeSt was developed to study the feasibility of using Global Mode Shape Frequency (GMSF) shifts for damage quantification and qualification, to identify GMSFs useful for damage detection in the FaBCoM TeSt and to select features from Frequency Response Functions (FRFs) of the FEM for training neural networks to be used on the FaBCoM TeSt.

The feasibility study was done by performing modal analyses on the FEM for different levels of damage for two blade damage scenarios. Also, the influences of typical fan operating condition variables such as temperature and rotational velocity were investigated. The results of these modal analyses were used to identify GMSFs that are sensitive damage indicators in terms of frequency shifts.
In order to verify the validity of the FEM, an Experimental Modal Analysis (EMA) was performed on the FaBCoM TeSt. A Modal Assurance Criterion (MAC) matrix of the FEM was calculated, the results of which led to a decision to update the model by means of frequency tuning and adjusting material properties.

Piezoelectric accelerometers and strain sensors were used as transducers during experimental testing due to their compactness and low masses. As no suitable wireless vibration data transmission system for testing could be found, it was decided to make use of a slip ring assembly for signal transmission. Operational vibration measurements were taken on the FaBCoM TeSt by means of strain sensors on three of the four blades as well as a radially orientated piezoelectric accelerometer. Measurements were taken for different blade damage scenarios, levels of damage and sensor location scenarios.

The suitability of using neural networks for damage identification using less than one sensor per blade was studied for two different approaches. The first approach was to train neural networks with features obtained form the experimental measurements. Very satisfying results were obtained, proving the ability of neural networks to do damage detection on a fan for all the above-mentioned scenarios when experimental supervision is employed.

For expensive and critical industrial equipment however, neural networks cannot necessarily be trained using this type of supervision due to cost implications. Therefore, the second approach was to train neural networks with features obtained from FRFs calculated using the FEM. Normalization of the FEM features was needed and for this, a single set of feature normalizing constants were calculated from a single set of experimental measurements obtained from an undamaged structure. Very good results were obtained proving the feasibility of using this approach on an operating structure.

Keywords: *On-line blade vibration; damage detection; experimental modal analysis; frequency sensitivity analysis; neural networks; finite element modelling; model updating; feature normalization; numerical testing; experimental testing*

Die Ontwikkeling van `n Operasionele Waaierlemskade Opsporingsmetodologie

deur

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Opsomming

Hierdie verhandeling handel oor die ontwikkeling van `n operasionele waaierlemskade opsporingsmetodologie. Die doel was om gebruik te maak van `n minimum aantal sensors om die operasionele vibrasies van lemme te meet om sodoende skade kwalifisering en kwantifisering te kan doen in terme van lemwortel kraaklengte vir `n meervoudige aantal lemme. Ten einde so `n metodologie te ontwikkel is gebruik is gemaak van `n eksperimentele opstelling genaamd die Waaierlem Toestandsmonitering Toets Struktuur (WTTS).

`n Eindige Element Model (EEM) van die WTTS is ontwikkel om die moontlikheid van die gebruik van Globale Modusvorm Frekwensie (GMF) skuiwe vir skade kwanitifisering en kwalifisering te bepaal, om GMFs te identifiseer vir gebruik van skade opsporing in die WTTS en om kenmerke te selekteer vanaf Frekwensie Responsie Funksies (FRFs) verkry van die EEM om neurale netwerke op te lei vir gebruik op die WTTS.

Die moontlikheid om gebruik te maak van GMF skuiwe vir skade opsporing, is ondersoek deur modale analises te doen op die EEM vir verskeie skadevlakke vir twee lemskade gevalle. Die invloed van tipiese waaier werkstoestandveranderlikes, naamlik temperatuur en rotasiesnelheid is ook ondersoek. Die resultate van hierdie modale analises is ook dan gebruik vir `n GMF sensitiwiteitsanalise om sodoende GMFs te identifiseer wat sensitiewe skade-aanduiders is.

Die geldigheid van die EEM is geverifiëer deur `n eksperimentele modale analise op die WTTS gedoen. `n Modale versekeringskriterium matriks van die EEM is bereken en die resultate hiervan het gelei tot die besluit om die EEM op te dateer deur middel van frekwensie instemming en materiaaleienskap verfyning.

Daar is besluit om gebruik te maak van piezo-elektriese versnellingsmeters en vervormingsmeters as sensors na aanleiding van hulle kompaktheid en lae massas.

Aangesien geen geskikte draadlose vibrasie data sender stelsel geïdentifiseer kon word vir toets doeleindes nie, is die besluit geneem om van sleepringe gebruik te maak vir seingeleiding. Vibrasiemetings is geneem op die WTTS deur middel van vervormingsmeters wat op drie van die vier lemme geïnstalleer is asook `n piezo-elektriese versnellingsmeter wat radiaal georiënteer is. Metings is geneem vir verskeie lemskade gevalle, skadevlakke en meetposisie gevalle.

Die geskiktheid daarvan om neurale netwerke te gebruik vir skade opsporing deur gebruik te maak van minder as een sensor per lem is bestudeer deur middel van twee verskillende benaderings. Die eerste hiervan was om neurale netwerke op te lei met eienskappe wat verkry is vanaf die eksperimentele metings. Baie goeie resultate is verkry wat bewys dat neurale netwerke die vermoë het om skade opsporing uit te voer op `n waaier vir al die genoemde gevalle wanneer eksperimentele opleiding gebruik word.

Vir duur en kritieke industriële masjinerie, kan neurale netwerke nie noodwendig opgelei word deur gebruik te maak van hierdie tipe opleiding nie as gevolg van koste implikasies. Die tweede benadering was dus om neurale netwerke op te lei met eienskappe wat verkry is vanaf FRFs wat bereken is met die EEM. Normalisering van die EEM eienskappe was nodig en daarvoor is normaliseringskonstantes bereken vanaf `n enkele stel eksperimentele metings wat verkry is vanaf `n onbeskadigde struktuur. Baie goeie resultate is verkry wat bewys dat hierdie benadering wel gebruik kan word op 'n operasionele struktuur.

Sleutelterme: *Operasionele lemvibrasie; skade opsporing; eksperimentele modale analise; frekwensie sensitiwiteitsanalsise; neurale netwerke; eindige element modellering; model opdatering; eienskap normalisering; numeriese toets; eksperimentele toets*

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Nomenclature

Symbols

A	Area [m^2]
c	Constant
$CW(f)$	Coherence-window function
$C_{pxx}(\tau)$	Power cepstrum
df	Frequency derivative
dt	Time derivative
E_y	Young's modulus [GPa]
$E[x^2]$	Mean-Square value
f	Frequency [Hz]
H	Transfer function
I	Second moment of inertia [m^4]
i	Integer [#]
j	Integer [#]
$[K]$	Stiffness matrix
$[K_g]$	Geometric stiffness matrix
k	Discrete frequency number [#]
l	Length [m]
$[M]$	Mass matrix
$M_{a,b}(f)$	Modal Ratio Function
N	Number of data points
n	Number of discrete frequencies [#]
$PW(f)$	Phase-window function
p	Number of group elements [#]
R^2	Squared Pearson Product Moment Correlation Coefficient
T	Time period [s]
t	Time variable [s]
$TF_{a,b}(f)$	Transmissibility function
$\overline{U}$	Random variable vector
$[V]$	Linear combination matrix
$[W]$	Covariance matrix
$x(t)$	Time signal
$\ddot{x}(t)$	Second derivative of $x(t)$
$X(f)$	Fourier transform of the time signal $x(t)$
$X^*(f)$	Complex conjugate of $X(f)$

$X_{\max}$	Peak value of the time signal $x(t)$
X_{RMS}	Root-Mean-Square value of the time signal $x(t)$
βl	Transverse beam vibration boundary condition value
Δt	Time sampling interval [s]
$\gamma^2(f)$	Coherence function
$\gamma_c{}^2$	Coherence cut-off
λ	Eigenvalue matrix
$\theta(f)$	Phase angle function
θ_c	Phase angle cut-off
ρ	Density [kg.m^{-3}]
σ^2	Variance
ω	Frequency [rad.s^{-1}]
$\{\psi\}$	Eigenvector matrix

Abbreviations

AD	Analogue to Digital
ANPSD	Averaged Normalized Power Spectral Density
ARMAX	Autoregressive Moving Average with Exogenous input
Cov	Covariance
DOF	Degree of Freedom
EFBDS	Experimental Fan Blade Damage Simulator
EMA	Experimental Modal Analysis
EMS	Experimental Mode Shape
FaBCoM TeSt	Fan Blade Condition Monitoring Test Structure
FD	Forced Draught
FEM	Finite Element Model
FRF	Frequency Response Function
GMSF	Global Mode Shape Frequency
ID	Induced Draught
LDV	Laser Doppler Vibrometer
LTF	Linear Transfer Function
LWIM	Low Power Wireless Integrated Microsensors
MAC	Modal Assurance Criterion
MEMS	Micro-electromechanical Systems
MPC	Multi-Point Constraint
MRF	Modal Ratio Function
NExT	Natural Excitation Technique
NMS	Numerical Mode Shape

NPSD	Normalized Power Spectral Density
PCA	Principal Component Analysis
PSD	Power Spectral Density
PSDRMS	Power Spectral Density Root-Mean-Square
RMS	Root-Mean-Square
SDT	Structural Dynamics Toolbox
SL	Sensor Location
TSTF	Tan-Sigmoid Transfer Function
Var	Variance
WLAN	Wireless Local Area Network