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FAN BLADE DAMAGE DETECTION USING ON-LINE VIBRATION MONITORING

by

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Summary

The high cost of unscheduled maintenance on critical machinery has led to the need for on-line monitoring of equipment condition. This study investigated on-line vibration monitoring of fan blades to detect and classify the damage levels of the blades. Due to the loads acting on a fan blade, and the resulting distribution of stress, the maximum stress will nearly always be found at the root of the blade. For this reason the location of damage due to fatigue will also be in this region for normal operating conditions. The condition of the blade can then be determined if the level of damage can be detected. An experimental fan blade damage simulator was designed and built to develop a damage detection technique that will eventually be implemented on an industrial fan.

Prior to the construction of the damage simulator a feasibility study was done to determine the sensitivity of the natural frequencies of the fan blade to damage, by making use of a finite element model. Results obtained from the finite element model showed that certain natural frequencies were substantially more sensitive to damage at the root of a blade. Both piezoelectric lightweight accelerometers and piezoelectric dynamic strain gauges were used as vibration sensors during measurements taken on the blade damage simulator. These sensors were mounted on the blade to give the best possible data regarding the damage level of the blade. A slip ring unit was used to connect the sensors to signal processing equipment and a desktop computer.

The autoregressive moving average, with exogenous signal algorithm was used to fit a polynomial through the power spectral density plots obtained from time domain data. Statistical methods were used to determine the number of measurements and measurement time necessary to detect the natural frequencies with sufficient accurcy to observe small percentage shifts. Results obtained showed very good correlation with that predicted by making use of the finite element model. Damage levels of as low as 10% could be detected by measuring the frequency shift of most modes.

Some descrepencies with predicted shifts were found on certain modes. An extended finite element model was developed to confirm the hypothesis that global mode shapes were responsible for this behaviour. Time domain damage indicators such as Root Mean Square values, Kurtosis, Crest Factors and standard deviation were also evaluated as damage level indicators. Only strain gauge measurements gave usable results as damage level indicators under some operating conditions.

The various damage level indicators, particularly frequency shifts, should make very good features for pattern recognition algorithms such as neural networks or self organising maps. Damage levels can definitely be detected on individual fan blades using one sensor per blade only and possibly less if global mode shapes are used in conjuction with the pattern recognition algorithms.

Keywords: On-line monitoring, Damage detection, Frequency shift, Fan blades, Vibration, Damage level indicator, Local mode, Global mode, Stochastic input.

OPSPORING VAN WAAIERLEMSKADE DEUR GEBRUIK TE MAAK VAN AANLYN VIBRASIEMONITERING

deur

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Opsomming

Ongeskeduleerde onderhoud van kritieke toerusting kan tot groot finansiële verliese lei. Dit kan verminder word deur aanlyn monitering van hierdie toerusting. Hierdie studie ondersoek die gebruik van aanlyn vibrasiemetings op waaierlemme om skade aan die lemme te bepaal en te klassifiseer. Die maksimum spanning in 'n waaierlem sal meestal by die wortel van die lem voorkom, weens die lastoestande en gevolglike spannings wat op 'n lem inwerk. Die posisie van die skade as gevolg van vermoeidheid is om hierdie rede bekend vir 'n struktuur soos 'n waaier en slegs die vlakke van skade hoef bepaal te word. 'n Eksperimentele waaierlem skade simulator is ontwerp en gebou om 'n tegniek vir die opsporing van skade te ontwikkel wat in die toekoms op 'n industriële waaier geïmplementeer sal word.

'n Eindige Element Model is voor die ontwerp en bou van die simulator gebruik om die sensitiwiteit wat die natuurlike frekwensies van die waaierlem het vir skade te bepaal. Volgens resultate wat van die eindige elementanalise verkry is, is sekere natuurlike frekwensies beduidend meer sensitief vir skade by die wortel van die lem as ander. Daar is van sowel pieso-elektriese versnellingsmeters as pieso-elektriese dinamiese rekstrokies gebruik gemaak tydens vibrasiemetings op die skade-simulator. Hierdie sensors is op die waaierlemme gemonteer om die beste moontlike inligting rakende skade aan die lemme te gee. 'n Sleepring eenheid is gebruik om die sensors te koppel aan 'n seinverwerker en persoonlike rekenaar.

'n *Outo-regressiewe bewegende gemiddelde met eksterne sein* algoritme is gebruik om 'n polinoom deur die drywingspektraaldigtheid (PSD) grafieke wat verkry is van tyddomein data, te pas. Statistiese metodes is gebruik om die aantal- en lengte van metings wat benodig is vir die akkurate bepaling van natuurlike frekwensieverskuiwings te bepaal. Voorspelde natuurlike frekwensies wat verkry is deur gebruik te maak van die eindige elementmodel het 'n baie goeie korrelasie getoon met eksperimentele resultate. Skadevlakke van so laag as 10% kan opgespoor word deur die natuurlike frekwensieverskuiwings van die meeste modusse te monitor.

Die natuurlike frekwensie van sommige van die modusse het wel afgewyk van die voorspelde natuurlike frekwensieverskuiwings. 'n Uitgebreide eindige elementmodel is toe ontwikkel om die hipotese dat globale modusse verantwoordelik was vir die afwykings, te bevestig. Tyddomein skade-indikators soos die Wortel Gemiddelde Waarde, Kurtose, Kruinfaktore en standaardafwykings is ook as moontlike skadevlak indikators getoets. Slegs die metings wat deur die rekstrokies geneem is kon onder sekere in-bedryf omstandighede.bruikbare resultate vir skadevlak-indikasie gee.

Die verskillende skadevlak indikators, veral die frekwensieverskuiwings, behoort baie goeie kenmerke te maak vir patroon-herkenningsalgoritmes soos neurale netwerke en *selfskikkaarte (Self Organising Maps).* Skadevlakke kan sonder twyfel bepaal word deur van een sensor per lem gebruik te maak. Minder sensors mag nodig wees indien globale modusvorme gebruik word in samewerking met patroonherkenningsalgoritmes.

Trefwoorde: Aanlyn monitering, Skade-opsporing, Frekwensieverskuiwing, Waaierlemme, Vibrasie, Skadevlak indikator, Lokale modus, Globale modus, Stogastiese Insette.

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NOMENCLATURE

Uppercase

A	Cross sectional area of uniform beam
A_f	Constant value for analytical calculation of natural frequencies
E	Modulus of elasticity
F_{Blade}	Force acting on blade due to change of momentum
I	Moment of inertia
L	Length of uniform beam
M_{air}	Mass flow of air
M_{shaft}	Moment around shaft due to aerodynamic forces acting on blade
N	Number of elements in $x(k)$
P	Pressure
P_{Blade}	Power absorbed by blade rotating at ω
T	Temperature, Time interval
X_{rms}	*rms* value of $x(t)$
X_{max}	Maximum value of $x(t)$

Lowercase

$a_1, a_2, \ldots, a_n$	AR coefficients
$b_1, b_2, \ldots, b_n$	MA coefficients
$c_1, c_2, \ldots, c_n$	ARMA coefficients
d	Distance from rotational centre
$e(t)$	Sequence of white noise
f_n	Sequence of natural frequencies
n	Number of coefficients in AR, MA, ARMA model, Equal to N-1
na	Number of AR coefficients
nb	Number of MA coefficients
nc	Number of ARMA coefficients
p	Order of AR model
q	Order of MA model
r	Distance from rotational centre
rms	Root Mean Square value
s	Variance
t	Time index
t_n	Normal distribution curve
v	Velocity of blade at distance r from rotational centre
$x(k)$	Random variables
$x(t)$	Function values
$\bar{x}$	Mean of $x(k)$

Greek symbols

α	Empirically calculated value for normal distribution curves
θ	Parameter vector
ρ	Density
σ_x	Standard deviation of x
μ_x	Average value of x
ω	Circular frequency
η	Efficiency factor

Abbreviations

ADSM	Absolute Difference of Strain Mode shapes
AR	AutoRegressive
ARMA	AutoRegressive Moving Average
ARMAV	AutoRegressive Moving Average Vector
ARMAX	AutoRegressive Moving Average with eXogenous variables
ARX	AutoRegressive with eXogenous inputs
CF	Crest Factor
CPU	Central Processing Unit
COMAC	Coordinate MAC
DLAC	Damage Location Assurance Criterion
DOF	Degree Of Freedom
ECOMAC	Enhanced COMAC
EFBDS	Experimental Fan Blade Damage Simulator
ETR	Energy Transfer Ratio
FD	Forced Draft
FEA	Finite Element Analysis
FEM	Finite Element Model
FRF	Frequency Response Function
ID	Induced Draft
IMAC	Inverse MAC
MA	Moving Average
MAC	Modal Assurance Criteria
Mbps	MegaBytes Per Second
MEMS	MicroElectroMechanical Systems
ML	Maximum Likelihood
PMAC	Partial MAC
SOM	Self Organising Maps
TF	Transfer Function