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Condition Monitoring of Gearboxes Operating Under Fluctuating Load Conditions

by

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Summary

Conventional gearbox vibration monitoring techniques are based on the assumption that changes in the measured structural response are caused by deterioration in the condition of the gears in the gearbox. However, this assumption is not valid under fluctuating load conditions, since the fluctuating load will amplitude modulate the measured vibration signal and cause the rotational speed of the system to change. In general monitoring of machines subject to fluctuating load conditions is dealt with by considering the constant load conditions on gearboxes or during free rotational tests.

The need to monitor the condition of large gearboxes in mineral mining equipment has attracted greater interest in order to improve asset management. An inherent need for signal processing techniques, with the ability to indicate degradation in gear condition, under fluctuating load conditions exist. Such techniques should enable the online monitoring of gearboxes that operate under fluctuating load conditions. A continued flow of up to date information should consequently be available for asset and production management.

With this research, a load demodulation normalisation procedure was developed to remove the modulation caused by fluctuating load conditions, which obscures the detection of an incipient gear fault conditions.

A rotation domain averaging technique is implemented which combines the ability of computer order tracking and time domain averaging to suppress the spectral smearing effect caused by the fluctuation in speed, as well as to suppress the amplitude of the vibration which is not synchronous with the rotation of the gear shaft.

It is demonstrated that the instantaneous angular speed of a gearbox shaft can be utilised to monitor the condition of the gear on the shaft. The instantaneous angular speed response measurement is less susceptible to phase distortion introduced by the transmission path when compared to conventional gearbox casing vibration measurements.

A phase domain averaging approach was developed to overcome the phase distortion effect of the transmission path under fluctuating load conditions. The load demodulation normalisation and rotation domain averaging signal processing procedures were applied to both the conventional gearbox casing vibration and instantaneous angular speed measurements prior to the calculation of a smoothed pseudo Wigner-Ville distribution of the data. Statistical parameters such as the energy ratio were calculated from the distribution. These parameters could be monotonically trended under different load conditions to indicate the degradation of gear conditions.

Keywords: Gearbox, condition monitoring, vibration, fluctuating load, modulation, order tracking, rotation domain averaging and normalisation.

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Nomenclature

Symbols

$\overline{a}$	Output vector
$a(t)$	Real signal
$\overline{a}(t)$	Analytical signal
$\tilde{a}(t)$	Hilbert transform of the real signal
$\overline{a}^{*}(t)$	Complex conjugate of the analytical signal
$\overline{b}$	Bias vector
C_1	Structural damping coefficient
C_2	Bearing damping coefficient
C_3	Gear mesh damping coefficient
c	Damping coefficient of a SDOF system
$d^2(\overline{x},\overline{y})$	Mahalanobis distance
E	Energy of the PWV distribution
E_D	Energy in the order band in which the amplitude of the distribution increases when gear damage is introduced
E_{ND}	Energy in the gear mesh order band, which is present when no gear fault condition is induced
ER	Energy ratio
e	Complex exponential
f	Low pass filter frequency or shaft order / frequency
GR	Gear ratio
H	Hilbert transform
h	Frequency smoothing window
K_1	Structural stiffness
K_2	Bearing stiffness

K_3	Gear mesh stiffness function
k	Stiffness of a SDOF system
L_I	Load intensity
L_O	Load order
M_1	Translating mass
M_2	Pinion mass
M_3	Gearwheel mass
$\overline{M}(\overline{y})$	Average mean value vector for the Mahalanobis distance
m	Mass of a SDOF system
$m(\overline{y})$	Mean scalar value for the Mahalanobis distance
$m_\beta(\theta)$	Rotation marginal of the PWV
$m_\theta(\beta)$	Order marginal of the PWV
N	Number of load conditions / Number of values in a vector / Number of gear teeth
N_S	Number of samples per shaft revolution
NSP	Normalised statistical parameter
$\overline{n}$	Input to the hard limit transfer function
$OFV(f)$	Objective function value
$PWV_a(t,f)$	Pseudo Wigner-Ville function
$\overline{p}$	Input vector
RP	Reference parameter
R_g	Gearwheel base circle radius
R_N	Rotation number
R_p	Pinion base circle radius
r	Frequency ratio
S	Number of statistical parameters
SP	Statistical parameter
T_1	Input torque

T_2	Torque load
t	Time
$\bar{t}$	Target vector
W	Weight matrix
X_1	Displacement of the translating mass
$\dot{X}_1$	Velocity of the translating mass
$\ddot{X}_1$	Acceleration of the translating mass
X_2	Displacement of the input pinion
$\dot{X}_2$	Velocity of the input pinion
$\ddot{X}_2$	Acceleration of the input pinion
X_3	Displacement of the gear wheel
$\dot{X}_3$	Velocity of the gear wheel
$\ddot{X}_3$	Acceleration of the gear wheel
x	Mass displacement of a SDOF system
$\bar{x}$	Vector to which the Mahalanobis distance is calculated
$\bar{y}$	Mean reference vector for the Mahalanobis distance
y	Base displacement of a SDOF system
α	Constant modulation phase shift
β	Order
$\Delta\theta$	Angular increment
μ	Mean value of the statistical parameter
ϕ	Modulation phase shift per revolution / Phase of a SDOF system
θ	Angle of shaft rotation
θ_1	Angular rotation of the input pinion
$\dot{\theta}_1$	Instantaneous angular speed of the input pinion
$\ddot{\theta}_1$	Angular acceleration of the input pinion
θ_2	Angular rotation of the gear wheel
$\dot{\theta}_2$	Instantaneous angular speed of the gear wheel

$\ddot{\theta}_2$	Angular acceleration of the gear wheel
τ	Time delay
ζ	Damping ratio

Abbreviations

ANN	Artificial Neural Network
COT	Computer Order Tracking
ER	Energy Ratio
FM	Frequency Modulation
FRF	Frequency Response Function
GMS	Gear Mesh Signal
IAS	Instantaneous Angular Speed
ICP	Integrated Circuit Piezoelectric
LDN	Load Demodulation Normalisation
LNA	Load Normalised Acceleration
MAS	Measured Acceleration Signal
NMGMS	Narrowband Modulated Gear Mesh Signal
NRDV	Normalised Relative Difference Value
NSP	Normalised Statistical Parameter
OFV	Objective Function Value
PDA	Phase Domain Averaging
PWV	Pseudo Wigner-Ville
RDA	Rotation Domain Averaging
RMS	Root Mean Square
RP	Reference Parameter
SDOF	Single Degree Of Freedom
SP	Statistical Parameter
SPWV	Smoothed pseudo Wigner-Ville
TDA	Time Domain Averaging

List of publications based on this research

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