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An investigation into the condition monitoring of large slow speed slew bearings

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An Investigation into the Condition Monitoring of Large Slow Speed Slew Bearings

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For Lesley

Declaration

I, Craig Alexander Simpson Moodie, declare that this thesis, submitted in partial fulfillment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical, Materials and Mechatronic Engineering, Faculty of Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged.

The document has not been submitted for qualifications at any other academic institution.

Craig Alexander Simpson Moodie

21 January 2009.

Craig Moodie

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Abstract

The condition monitoring of slow speed roller bearings has been investigated. A test-rig was designed and constructed to enable detailed measurement of horizontal rotating bearing acceleration forces in both the axial and radial plane in the speed range of 0.5 to 10 revolutions per minute. These accelerations were carried out at both sonic and ultrasonic sampling rates to establish which technique is the most appropriate. Overall bearing displacement and surface temperatures were measured. Strains generated in the stress frame by the loading of the bearing were monitored along with the power used to drive the test-rig. Measurements were obtained from two full-size slew bearings operating in Bluescope Steel Limited. One bearing operated at 4.3 rpm continuously in the vertical plane. The other slew bearing operated intermittently and with partial rotation at approximately 1 rpm in the horizontal plane. During this project, the concepts of Symmetry and Stability have been developed as a fundamental approach to information analysis. A considerable number of novel signal processing methods including; Kurtosis/Correlation dimension plots, Symmetry State Space (SSS), Symmetric Wave Decomposition (SWD), Compressed Eigenvector Deconvolution Spectral Analysis (CEDSA), Ring Matrix Fault Values (RMFV) have been developed. These methods all utilize symmetry, antisymmetry, symmetry 'breaking', stability and enable the assessment of which sensor methodology combination is best for the situation considered. It will be shown, among other things, that ultrasonic measurements using sensors designed for Acoustic Emission (AE) permit an implementation of an early warning system for slow speed bearings. This will enable the operator to carry the minimum inventory in bearings and to plan shut downs without incurring additional costs from unplanned outages resulting from failed bearings.

List of Publications

Craig Moodie, Kiet Tieu, George Wood, *Analysis of Complex Systems for the Condition Monitoring of a Rolling Mill*, 5th International Congress on Industrial and Applied Mathematics (ICIAM2003) CTAC CTL09$_0$H-091, July 2003, Sydney, Australia

C.A.S. Moodie, A. K. Tieu, S. Biddle, *Symmetry methods applied to the condition-monitoring of slow speed slew bearings*, 4th Int. Conf. on Condition Monitoring, June 2007, Harrogate UK

C.A.S. Moodie, A. K. Tieu, S. Biddle, *Deconvolution of time series data using translational symmetry and eigenstate analysis*, 4th Int Conf on Condition Monitoring, June 2007, Harrogate UK

C.A.S. Moodie, A. K. Tieu, S. Biddle, *Symmetric Wave Decomposition as a means of identifying the number of damaged elements in a slow speed bearing*, Proceedings of 14th International Congress on Sound and Vibration, July 2007, Cairns, Australia, paper 265.

C.A.S. Moodie, A. K. Tieu, S. Biddle, *Vibration Event Detection: A Monitoring Method for Slow Speed Bearings*, Proceedings of 14th International Congress on Sound and Vibration, July 2007, Cairns, Australia, paper 266.

Contents

Notation and Glossary

$\mathbf{0}$	Zero vector.
$\mathbf{a}$	A rank 1 group or vector.
$\overset{>}{\mathbf{a}}$	A left-to-right rank 1 group or vector.
$\overset{<}{\mathbf{a}}$	A reverse (right-to-left) rank 1 group or vector.
$\overset{>+}{\mathbf{a}}$	Symmetry of original time vector $\mathbf{a}$ where time increases from t (start) to T (finish).
$\overset{>-}{\mathbf{a}}$	Anti-symmetry of original time vector $\mathbf{a}$ where time increases from t (start) to T (finish).
$\mathbf{b}$	Another rank 1 group or vector.
$\overset{>}{\mathbf{b}}$	Another left-to-right rank 1 group or vector.
$\overset{<}{\mathbf{b}}$	Another reverse (right-to-left) rank 1 group or vector.
$\overset{>+}{\mathbf{b}}$	Symmetry of original time vector $\mathbf{b}$ where time decreases from t (start) to T (finish).
$\overset{>-}{\mathbf{b}}$	Anti-symmetry of original time vector $\mathbf{b}$ where time decreases from t (start) to T (finish).
c_n	Number of compression steps.
C	Compression operator.
C_L	Local compression operator.
C^ψ	Continuous symmetry breaking operator.
$C(l)$	Correlation dimension of a vector containing l elements.
$\mathfrak{d}_e$	Euclidean distance.

$\mathfrak{d}_x$	Distance in the x coordinate.
$\mathfrak{d}_y$	Distance in the y coordinate.
D	Downsampling operator.
efs	Effective sampling rate.
e_k	Cumulative energy for the k^{th} sub-vector/wave.
etc	A rank 1 group or vector function of *etc*.
$\overset{>}{\mathbf{etc}}$	Original vector **etc** where etc proceeds from etc_i (start) to etc_n (finish).
$\overset{<}{\mathbf{etc}}$	Original vector **etc** where etc proceeds from etc_n (finish) to etc_i (start).
fs	Original sampling rate.
f_{spd}	Computational speed-up factor that can result from compressing data.
E	Total energy for a group of waves.
H	Entropy of a group of waves.
i	Index to an element of an array/vector or matrix.
$\Im(\boldsymbol{\omega})$	Imaginary number vector for frequencies.
j	Complex number $= \sqrt{-1}$. Is also used as an index to an element of an array/vector or matrix.
k	Index to an element of an array/vector or matrix.
$K(l)$	Kurtosis of a vector containing l elements.
len	Number of items in the group/set/vector.
$nsym$	Reference pointer to the mid-point of a dataset.
$\aleph$	Vector normal resulting from a vector product.
$\mathfrak{o}$	'of' operator. For example, the symmetry of antisymmetry. This is not the algebraic multiply. Similar to recursion and/or iteration.

p_k	Energy probability for the k^{th} sub-vector/wave.
$\mathbf{p}(\boldsymbol{\omega})$	Power vector for frequencies.
$\mathbf{p}$	A power vector where frequency increases from ω_0 (lowest) to ω_n (highest).
$\overset{>}{\mathbf{p}}$	A power vector where frequency increases from ω_0 (lowest) to ω_n (highest).
$\overset{<}{\mathbf{p}}$	A power vector where frequency reverses from ω_n (lowest) to ω_0 (highest).
$\overset{>+}{\mathbf{p}}$	Symmetry of original power vector $\mathbf{p}$ where frequency increases from ω_0 (lowest) to ω_n (highest).
$\overset{<+}{\mathbf{p}}$	Symmetry of original power vector $\mathbf{p}$ where frequency decreases from ω_n (highest) to ω_0 (lowest).
$\overset{>-}{\mathbf{p}}$	Anti-symmetry of original power vector $\mathbf{p}$ where frequency increases from ω_0 (lowest) to ω_n (highest).
$\overset{<-}{\mathbf{p}}$	Anti-symmetry of original power vector $\mathbf{p}$ where frequency decreases from ω_n (highest) to ω_0 (lowest).
$\mathbf{Q}$	A quadrant of a matrix.
$\mathbf{r}_k$	k^{th} sub-vector obtained from symmetric wave decomposition (SWD).
$\Re(\boldsymbol{\omega})$	Real number vector for frequencies.
$\mathbf{S}$	Any two dimensional state space.
SSS_z	A symmetric/antisymmetric state space on domain z of a vector $\mathbf{x}$.
$\mathbf{t}$	A time vector where time increases from t (start) to T (finish).
$\overset{>}{\mathbf{t}}$	A time vector where time increases from t (start) to T (finish).
$\overset{<}{\mathbf{t}}$	A time vector where time reverses from T (start) to t (finish).
$\overset{>+}{\mathbf{t}}$	Symmetry of original time vector $\mathbf{t}$ where time increases from t (start) to T (finish).

$\overset{<+}{\mathbf{t}}$	Symmetry of original time vector $\mathbf{t}$ where time decreases from T (start) to t (finish).
$\overset{>-}{\mathbf{t}}$	Anti-symmetry of original time vector $\mathbf{t}$ where time increases from t (start) to T (finish).
$\overset{<-}{\mathbf{t}}$	Anti-symmetry of original time vector $\mathbf{t}$ where time decreases from T (start) to t (finish).
$\overset{>+\Psi}{\mathbf{t}}$	Broken symmetry of original time vector $\mathbf{t}$ where time increases from t (start) to T (finish).
$\overset{<+\Psi}{\mathbf{t}}$	Broken symmetry of original time vector $\mathbf{t}$ where time decreases from T (start) to t (finish).
$\overset{>-\Psi}{\mathbf{t}}$	Broken anti-symmetry of original time vector $\mathbf{t}$ where time increases from t (start) to T (finish).
$\overset{<-\Psi}{\mathbf{t}}$	Broken anti-symmetry of original time vector $\mathbf{t}$ where time decreases from T (start) to t (finish).
$\overset{>-\Psi_C}{\mathbf{t}}$	Broken anti-symmetry of original vector $\mathbf{t}$ and compressed it where time increases from t (start) to T (finish).
$\overset{<-\Psi_C}{\mathbf{t}}$	Broken anti-symmetry of original Vector $\mathbf{t}$ and compressed it where time decreases from T (start) to t (finish).
$\mathbf{u}$	A rank 1 group or vector function of u.
$\overset{>}{\mathbf{u}}$	Original vector $\mathbf{u}$ where u proceeds from u_i (start) to u_n (finish).
$\overset{<}{\mathbf{u}}$	Original vector $\mathbf{u}$ where u proceeds from u_n (finish) to u_i (start).
U	Up-sampling operator.
$\mathbf{v}$	A rank 1 group or vector function of v.
$\overset{>}{\mathbf{v}}$	Original vector $\mathbf{v}$ where v proceeds from v_i (start) to v_n (finish).
$\overset{<}{\mathbf{v}}$	Original vector $\mathbf{v}$ where v proceeds from v_n (finish) to v_i (start).

$\mathbf{w}$	A rank 1 group or vector function of w.
$\overset{>}{\mathbf{w}}$	Original vector $\mathbf{w}$ where w proceeds from w_i (start) to w_n (finish).
$\overset{<}{\mathbf{w}}$	Original vector $\mathbf{w}$ where w proceeds from w_n (finish) to w_i (start).
$\mathbf{x}$	Any rank 1 group or vector.
$\overset{0}{\mathbf{x}}$	Upsampled ring vector. The stretched-out/unraveled ring matrix.
$\overset{n}{\mathbf{x}}$	Vector $\mathbf{x}$ at step n where time increases from t start to T.
$\overset{n-1}{\mathbf{x}}$	Vector $\mathbf{x}$ at step $n-1$ where time increases from t start to T.
$\overset{>}{\mathbf{x}}$	Original vector $\mathbf{x}$ where time increases from t (start) to T (finish).
$\overset{<}{\mathbf{x}}$	Original vector $\mathbf{x}$ where time decreases from T (start) to t (finish).
$\overset{>+}{\mathbf{x}}$	Symmetry of original vector $\mathbf{x}$ where time increases from t (start) to T (finish).
$\overset{<+}{\mathbf{x}}$	Symmetry of original Vector $\mathbf{x}$ where time decreases from T (start) to t (finish).
$\overset{>-}{\mathbf{x}}$	Anti-symmetry of original vector $\mathbf{x}$ where time increases from t (start) to T (finish).
$\overset{<-}{\mathbf{x}}$	Anti-symmetry of original Vector $\mathbf{x}$ where time decreases from T (start) to t (finish).
$\overset{>+\Psi}{\mathbf{x}}$	Broken symmetry of original vector $\mathbf{x}$ where time increases from t (start) to T (finish).
$\overset{<+\Psi}{\mathbf{x}}$	Broken symmetry of original Vector $\mathbf{x}$ where time decreases from T (start) to t (finish).
$\overset{>-\Psi}{\mathbf{x}}$	Broken anti-symmetry of original vector $\mathbf{x}$ where time increases from t (start) to T (finish).
$\overset{<-\Psi}{\mathbf{x}}$	Broken anti-symmetry of original Vector $\mathbf{x}$ where time decreases from T (start) to t (finish).

$\overset{>-\Psi_C}{\mathbf{x}}$	Broken anti-symmetry of original vector $\mathbf{x}$ and compressed it where time increases from t (start) to T (finish).
$\overset{<-\Psi_C}{\mathbf{x}}$	Broken anti-symmetry of original Vector $\mathbf{x}$ and compressed it where time decreases from T (start) to t (finish).
$X(\omega)$	The Fourier transform of the time waveform, $\mathbf{x}$.
$\mathbf{X}$	Any rank 2 group or Matrix.
$\overset{<}{\mathbf{X}}$	Original Matrix $\mathbf{X}$ where time decreases from T (start) to t (finish).
$\overset{>h+}{\mathbf{X}}$	Row symmetry of original matrix $\mathbf{X}$ where index increases from i (start) to j (finish).
$\overset{<h+}{\mathbf{X}}$	Row symmetry of original matrix $\mathbf{X}$ where index decreases from j (start) to i (finish).
$\overset{>h-}{\mathbf{X}}$	Row anti-symmetry of original matrix $\mathbf{X}$ where index increases from i (start) to j (finish).
$\overset{<h-}{\mathbf{X}}$	Row anti-symmetry of original matrix $\mathbf{X}$ where index decreases from j (start) to i (finish).
$\overset{>v+}{\mathbf{X}}$	Column symmetry of original matrix $\mathbf{X}$ where index increases from i (start) to j (finish).
$\overset{<v+}{\mathbf{X}}$	Column symmetry of original matrix $\mathbf{X}$ where index decreases from j (start) to i (finish).
$\overset{>v-}{\mathbf{X}}$	Column anti-symmetry of original matrix $\mathbf{X}$ where index increases from i (start) to j (finish).
$\overset{<v-}{\mathbf{X}}$	Column anti-symmetry of original matrix $\mathbf{X}$ where index decreases from j (start) to i (finish).
$\overset{0>}{\mathbf{X}}$	Ring matrix of original vector $\mathbf{x}$ where time increases from t (start) to T (finish).
$\overset{0<}{\mathbf{X}}$	Ring matrix of original vector $\mathbf{x}$ where time decreases from T (start) to t (finish).

$\overset{\overset{0}{>}}{\mathbf{X}}$ Ring matrix formed from original vector $\mathbf{x}$ where time increases from t (start) to T (finish).

$\overset{\overset{0}{<}}{\mathbf{X}}$ Ring matrix formed from original vector $\mathbf{x}$ where time decreases from T (start) to t (finish).

$\overset{>v+h+}{\mathbf{X}}$ Column and row symmetry of original matrix $\mathbf{X}$ where index increases from i (start) to j (finish).

$\overset{>v-h+}{\mathbf{X}}$ Column anti-symmetry and row symmetry of original matrix $\mathbf{X}$ where index increases from i (start) to j (finish).

$\overset{>v+h-}{\mathbf{X}}$ Column symmetry and row anti-symmetry of original matrix $\mathbf{X}$ where index decreases from i (start) to j (finish).

$\overset{>v-h-}{\mathbf{X}}$ Column anti-symmetry and row anti-symmetry of original matrix $\mathbf{X}$ where index decreases from i (start) to j (finish).

$\overset{>h+v+}{\mathbf{X}}$ Row and column symmetry of original matrix $\mathbf{X}$ where index increases from i (start) to j (finish).

$\overset{>h-v+}{\mathbf{X}}$ Row anti-symmetry and column symmetry of original matrix $\mathbf{X}$ where index increases from i (start) to j (finish).

$\overset{>h+v-}{\mathbf{X}}$ Row symmetry and column anti-symmetry of original matrix $\mathbf{X}$ where index decreases from i (start) to j (finish).

$\overset{>h-v-}{\mathbf{X}}$ Row anti-symmetry and column anti-symmetry of original matrix $\mathbf{X}$ where index decreases from i (start) to j (finish).

$\overset{<h-v-}{\mathbf{X}}$ Row anti-symmetry and column anti-symmetry of original matrix $\mathbf{X}$ where index decreases from j (start) to i (finish).

$\overset{0>h+v+}{\mathbf{X}}$ Row and column symmetry of Ring matrix formed from original vector $\mathbf{x}$ where index increases from i (start) to j (finish).

$\overset{0>h-v+}{\mathbf{X}}$ Row anti-symmetry and column symmetry of Ring matrix formed from original vector $\mathbf{x}$ where index increases from i (start) to j (finish).

$\overset{0>h+v-}{\mathbf{X}}$ Row symmetry and column anti-symmetry of Ring matrix formed from original vector $\mathbf{x}$ where index decreases from i (start) to j (finish).

$\overset{0>h-v-}{\mathbf{X}}$ Row anti-symmetry and column anti-symmetry of Ring matrix formed from original vector $\mathbf{x}$ where index decreases from i (start) to j (finish).

$\mathbf{y}$ A rank 1 group or vector function of x.

$\overset{>}{\mathbf{y}}$ Original vector $\mathbf{y}$ where x proceeds from x_i (start) to x_n (finish).

$\overset{<}{\mathbf{y}}$ Original vector $\mathbf{y}$ where x proceeds from x_n (finish) to x_i (start).

$\overset{>+}{\mathbf{y}}$ Symmetry of original vector $\mathbf{y}$ where time increases from x_i (start) to x_n (finish).

$\overset{>-}{\mathbf{y}}$ Antisymmetry of original vector $\mathbf{y}$ where time increases from x_i (start) to x_n (finish).

ð A designed direction vector containing ones and zeros. For example, one for right and zero for left.

ψ_C A compression operator. A particular form of global symmetry breaking.

ψ_G Represents a global broken symmetry.

ψ_L Represents a locally broken symmetry.

ω A frequency.

$\boldsymbol{\omega}$ Vector of frequencies, ω.

$\subset_i$ Reduced subset, i, of $\overset{>+}{\mathbf{x}}$ and/or $\overset{>-}{\mathbf{x}}$.

$\overset{\leftrightarrows}{\mathbf{x}}$ Side shifting operator on vector $\mathbf{x}$.

Δ Determinant of a matrix.

λ An eigenvalue.

$+$ A shorthand representation of a symmetry.

-	A shorthand representation of an antisymmetry.

Glossary

The glossary has been constructed by the author and from the following sources:

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- `http://eu.wikipedia.org/wiki/Raleigh_wave`.

ADC	Analog-to-digital converter. Electronic device that transforms continuous signals into signals with discrete values.
Affine transformation	The sum of a linear transformation and a translation. In Euclidean spaces, this is matrix multiplication plus a vector addition.

Antisymmetric — A system (A, B) is antisymmetric if $A = -B$. see *Symmetry*.

Attractor — An object in state space to which trajectories are eventually attracted. A geometrical form in phase space showing the characteristics of the dynamic system.

Autocorrelation — Describes the general dependence of the values of the data at one time on the values at another time.

Bilateral symmetry — The property of having two similar sides. Each side is a 'mirror image' of the other.

Box-counting dimension — See *Dimension, box-counting.*

CEDSA — Compressed Eigenvector Deconvolution Spectral Analysis. Short for *CEDCDFFT*.

CECDFFT — Compressed Eigenvector Deconvolution Compressed Discrete Fast Fourier Transform. A novel method for obtaining the power spectra of any signal or data. The method incorporates up sampling via translational symmetry, down sampling for sampling frequency reduction, compression by global symmetry breaking of both time/precedence and magnitude, translational symmetry to enforce invariance and the solution of the resulting Ring matrix as an eigen-problem to produce the associated eigen-vectors that require the compressed, discrete, fast Fourier Transform to recover the spectra of each eigenvector.

CDFFT — Compressed discrete fast fourier transform. A novel method for determining the frequency spectra of a symmetrically compressed time series.

Chaos — Irregular, unpredictable behaviour of a deterministic nonlinear dynamical system caused by sensitivity to initial conditions (see *SDIC*). Some researchers believe that chaos theory offers a mathematical framework for understanding much of the noise and turbulence that is seen in experimental science.

Clifford algebras	Some times referred to as Geometric Algebra. In mathematics, Clifford Algebras are a type of associative algebra. They can be thought of of as one of the possible generalisations of the complex numbers and quaternions. The elements of a Clifford algebra constitute a 2^n-dimensional algebra over the reals, in the sense that quaternions form a 4-dimensional vector space over the reals, because there are just four independent 'basis' quantities $1, \mathbf{i}, \mathbf{j}, \mathbf{k}$ that span the entire space of quaternions.
Cyclostationary	Is a stochastic process that exhibits some hidden periodicities in its structure. Formally, a stochastic process $\mathbf{x}(t)_{t\in\mathbb{R}}$ is said to be *strict-sense cyclostationary* with cycle T if its joint probability density function, $p_{\mathbf{x}}(x_1, \cdots, x_n; t_1, \cdots, t_n)$ is periodic in t with period T, that is, if $p_{\mathbf{x}}(x_1, \cdots, x_n; t_1, \cdots, t_n) = p_{\mathbf{x}}(x_1, \cdots, x_n; t_1+T, \cdots, t_n+T)$. In this equation t stands for a generic variable which is not necessarily time.
Cyclostationarity	Is a property that characterises stochastic processes whose statistical properties vary with respect to some generic variable. By definition, this embodies a class of non-stationary stochastic processes, with stationary and deterministic periodic processes as special cases.
Diffusion	The process by which fluids and solids mix intimately with one another due to the kinetic motions of thermally agitated particles such as atoms, molecules, or group of molecules.
Dimension, box-counting	Consider a geometrical object A in n-dimensional space. Denote by $N(\varepsilon)$ the minimum number of n-dimensional cubes of side length ε needed to contain A. The box-counting dimension of A is $\lim_{\varepsilon\to 0} \frac{\log(N(\varepsilon))}{\log(\frac{1}{\varepsilon})}$.
Dimension, correlation	A measure of the probability that two points in a fractal set are near one another.
Dimension, fractal	A measure of a fractal's space-filling properties.

Downsampling	Is a process that involves selecting new data, as a subset of the original data at, successive, fixed intervals. With data sampled at a fixed rate, f_s, downsampling, m, reduces the effective sampling rate, $f_{eff} = \frac{f_s}{m}$.
Embedding	A method of accessing the attractor of a dynamical system via a time series generated by that system.
Embedding space	The space in which an attractor resides when reconstructed from time delay variables in which each point in the time series is plotted versus a number of its preceding points.
EMD	Empirical Mode Decomposition. An empirical method for hierarchically decomposing a signal into many subcomponents via a sifting process.
Entropy	Every finite scheme describes a state of uncertainty. Entropy, $H(p)$, is a measure of the uncertainty of a finite scheme. Given a set of probabilities,$(p_1, p_2, \cdots, p_n)$, the entropy, $H(p_1, p_2, \cdots, p_n) = -\sum_{k=1}^{n} p_k \log p_k$.
Fixed point	A point that is left unchanged by the evolution of a dynamical system. A point that is invariant under a mapping.
Fractals	Objects (or sets of points, or curves, or patterns) which exhibit increasing detail ("'bumpiness"') with increasing magnification. Many fractals are self-similar.
Fundamental frequency	The lowest frequency component of a complex signal.
Gaussian white noise	White noise that is subsequently altered so that it has a bell-shaped distribution of values. Gaussian noise is often approximated by summing random numbers. The following formula generates a Gaussian distribution: $r = \sqrt{-\log(r_1)}\cos(2\pi r_2)\sigma + \mu$, where $r_1$and r_2 are two random numbers from a [0,1] uniform distribution, and σ and μ are the desired standard deviation and mean of the Gaussian distribution.
IGC	Independent Geometric Component is a structure that contributes to the overall structural response to an excitation. For example, a ball in a roller bearing.

Lyapunov exponent	A measure of the average rate of exponential separation of nearby trajectories in a dynamical system. The Lyapunov exponent also can be thought of as a quantity, sometimes represented by the Greek letter λ, used to characterise the divergence of trajectories in a chaotic flow.
Mahalanobis distance	The Mahalanobis distance is the distance of a case from the centroid in the multi-dimensional space, defined by the correlated independent variables (if the independent variables are uncorrelated, it is the same as the simple Euclidean distance). This measure provides an indication of whether or not an observation is an outlier with respect to the independent variable values.
Moment	The weighted average of the variate x to a specified power. The nth moment of distribution $P(x)$ is then $< x^n >= \int_{-\infty}^{\infty} x^n P(x) dx$. The mean value is given by $n = 1$. The second moment is given by $n = 2$, and so on.
Neutral state	The neutral state occurs when the symmetric, anti-symmetric pair are both zero.
Phase space	Given a flow $\mathbf{x}(t) = (x_1(t), \cdots, x_n(t))$ describing a solution to a differential equation in n-dimensional Euclidean space, phase space is the space of all the vectors of the form $(x_1(t), \dot{x_1}(t), \cdots, x_n(t), \dot{x_n}(t))$ in $2n$-dimensional Euclidean space.
Probability density	The probability that an event in an interval $(x, x+dx)$ occurs is given by $P(x)dx$, where $P(x)$ is the probability density and the derivative of $F(x)$ with respect to x.
Quaternion	The general quaternion is defined as $\mathbf{q} = t + u\mathbf{i} + v\mathbf{j} + w\mathbf{k}$ where t, u, v and w are real numbers and $\mathbf{i}^2 = \mathbf{j}^2 = \mathbf{k}^2 = \mathbf{ijk} = -1$.
Rayleigh waves	Rayleigh waves are a type of elastic surface wave that travel on solids. They are produced on the Earth

	by earthquakes, in which case they are also known as "ground roll", or by other sources of seismic energy such as an explosion or even a sledgehammer impact. They are also produced in materials by acoustic transducers, and are used in non-destructive testing for detecting defects. When guided in layers they are referred to as Rayleigh-Lamb waves, Lamb waves or generalized Rayleigh waves.
Recursive	An object is said to be recursive if it partially consists of or is defined in terms of itself. A recursive operation invokes itself as an intermediate operation.
Renormalisation	A process in which some property of a map is rescaled so as to reproduce the same map.
Ring matrix	Is a novel time invariant matrix of a signal or invariant matrix of a set of data. It is derived from the translational symmetry of the original signal or data.
RMFV	Ring matrix fault values. Is a novel method for producing the power at selected frequencies contained in a dataset. The method does not involve the Fourier transform.
Self-similar	A shape made up of copies of itself, each similar to (though smaller than) the original. Self-similarity can be thought of as the property of looking the same under repeated magnifications.
SDIC	Sensitive dependence on initial conditions. The property of chaotic dynamics by which the distance between nearby points increases (initially) as the dynamics proceed.
Spectogram	Some times known as spectrogram. Is a graphic representation of the time variability of the power spectra in a timeseries. See STFFT.
SNR	Signal to noise ratio. A measure of the degradation of a signal when, for example, represented by a model. In engineering SNR is a term for the power ratio between a signal and the background noise. $SNR = \frac{P_{signal}}{P_{noise}} =$

	$(\frac{A_{signal}}{A_{noise}})^2$ where the power, P, is the average power and A is the root mean square (RMS) amplitude. In decibel terms (dB), $SNR_{dB} = 20\log_{10}(\frac{A_{signal}}{A_{noise}}) = 20\log_{10}(\frac{meanvalue}{standarddeviation})$.
Sifting	Is a process that allows the separable components of a system to pass (or be separated) through a filter/sieve. For example to separate the coarse parts with a sieve.
SN_z	A Symmetry Number for the domain z is a novel non-dimensional number that is based on the global (or local), z, bilateral symmetry embedded in all data. see F for the mathematical definition. If x is a function of time then SN_z is also a function of time.
Stability	Is defined as the amplification of change in a local neighborhood.
STFFT	Short Time Fast Fourier Transform. Is a method for producing the power versus frequency relationship over consequetive time windows of a timeseries
SWD	Symmetric Wave Decomposition. A novel, empirical method for non-hierarchical decomposition of a signal into many sub-components via a local symmetry breaking transformation.
Symmetric	A system (A, B) is symmetric if $A = B$. see *Symmetry*.
Symmetry	Symmetry encompasses two primary states. These primary states are the symmetric, antisymmetric pair or the special, neutral state (see *neutral state*). Other sub-states based on these two groups can be derived.
Timeseries	Some times known as time series. A function of time such as an audio signal trajectory. A time series also can be thought of as the path of a system's state through statespace.
Upsampling	Is a process that enables the number of members in a dataset to increase with the same sampling rate as the original dataset.

Variance — The variance of a distribution σ^2 is a measure of the width of the distribution in terms of the first two moments: $\sigma^2 =< x^2 > - < x >^2$ where the brackets denote the average over the probability density $P(x)$.

White noise — White noise requires only that noise spikes be independent of one another in time or that they be statistically uncorrelated. There are infinitely many types of white noise and each has a flat frequency spectrum because all the noise spikes are independent of one another. White noise can be chaotic as well as impulsive and the two can combine in ways that we have not imagined. Real noise cannot be white because pure white noise requires infinite energy.