

Application of the Hilbert-Huang Transform in Machine Tool Fault Detection

Gary G. Leisk

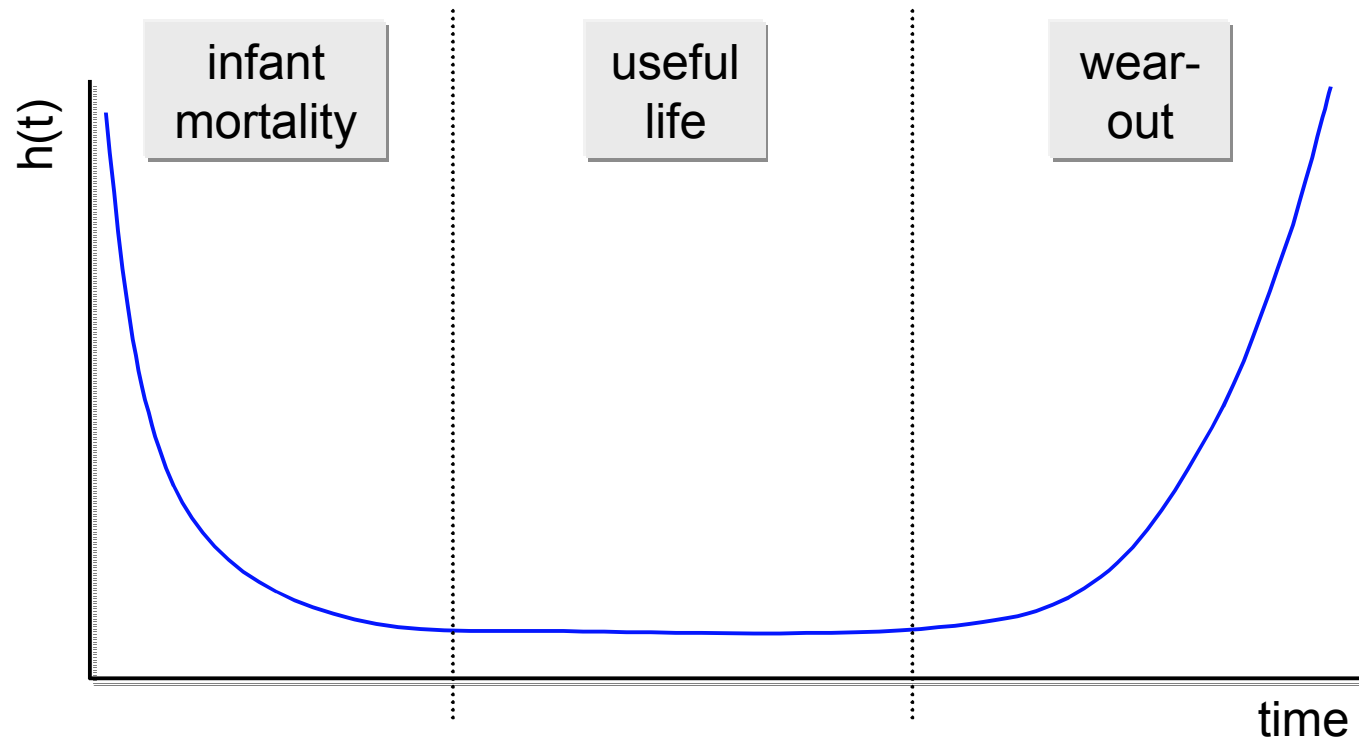
*Tufts University
Mechanical Engineering*



Consolidated B-24 Liberator (1944)



The Simple Bathtub



Automobiles
Electronics
Machine tools
Bearings
Framostats

.....

“It’s tough to make predictions, especially about the future.”

“The future ain’t what it used to be.”

-Lawrence Peter “Yogi” Berra

Circular Logic

Boeing 777-200LR

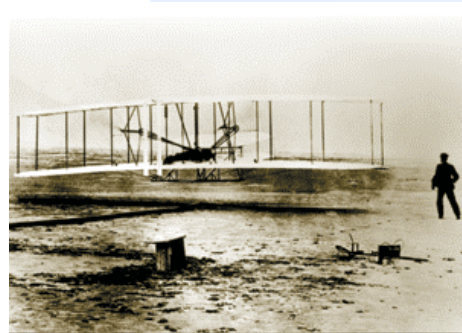


Complete knowledge of performance and failure?



AA Flight 587 Airbus A300

Human error?



December 17, 1903 Wright Flyer

Significant engineering is required!!

Boeing 777 glass cockpit

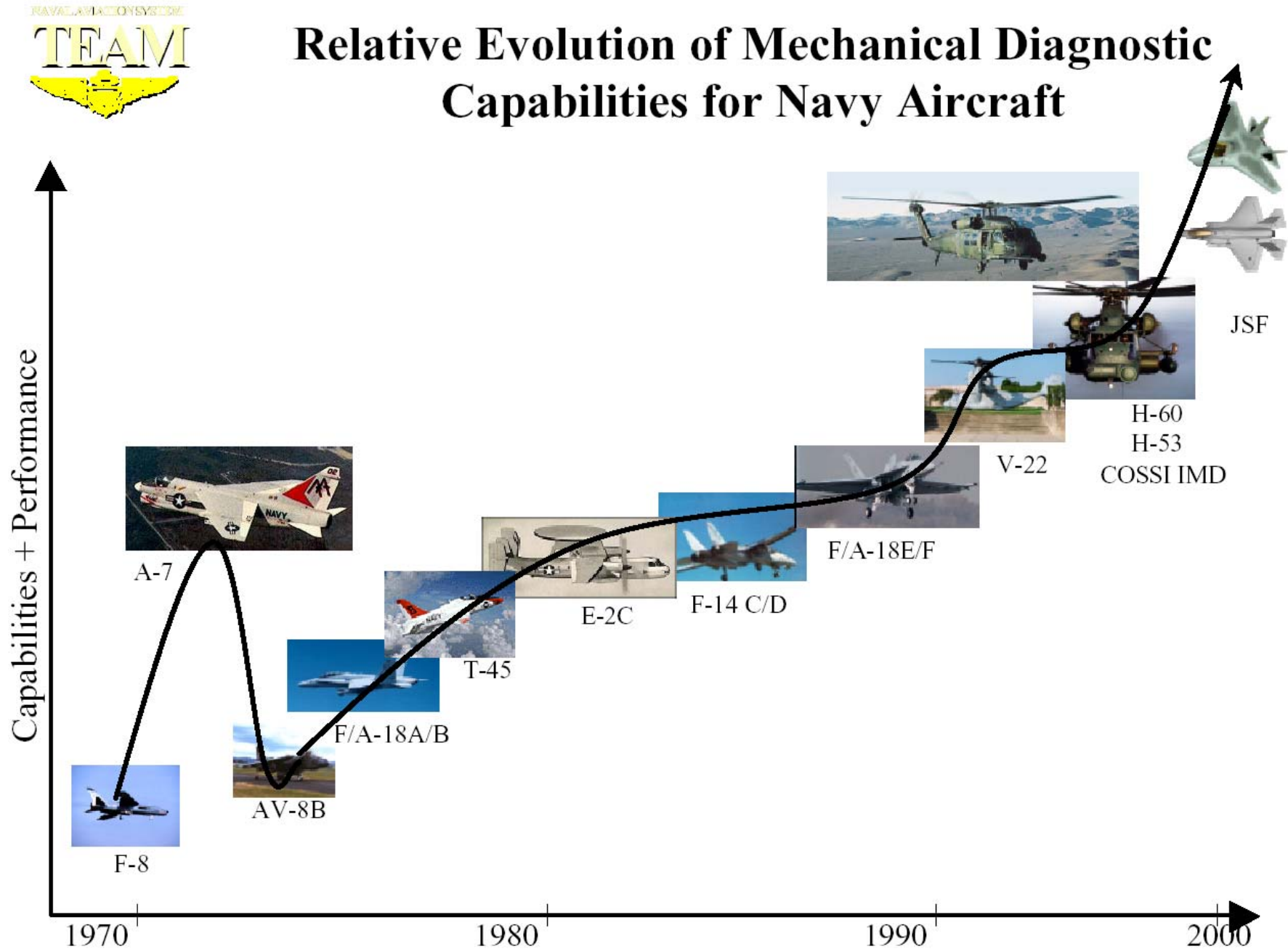


Reliance on computers for operation & performance monitoring.

	Boeing 777-200LR	1903 Wright Flyer
Passengers	300+	1+
Engines	(2) 110,000 lb thrust GE 90-110B1	4-cylinder, 12 hp Wright engine
Max. Takeoff Wt.	750,000 lb	605 lb (+ pilot)
Cruise Speed	0.84 Mach	30 mph
Range	8865 mi	852 feet
Wingspan	212' 7"	40' 4"
Height	60' 11.5" (tail)	7'

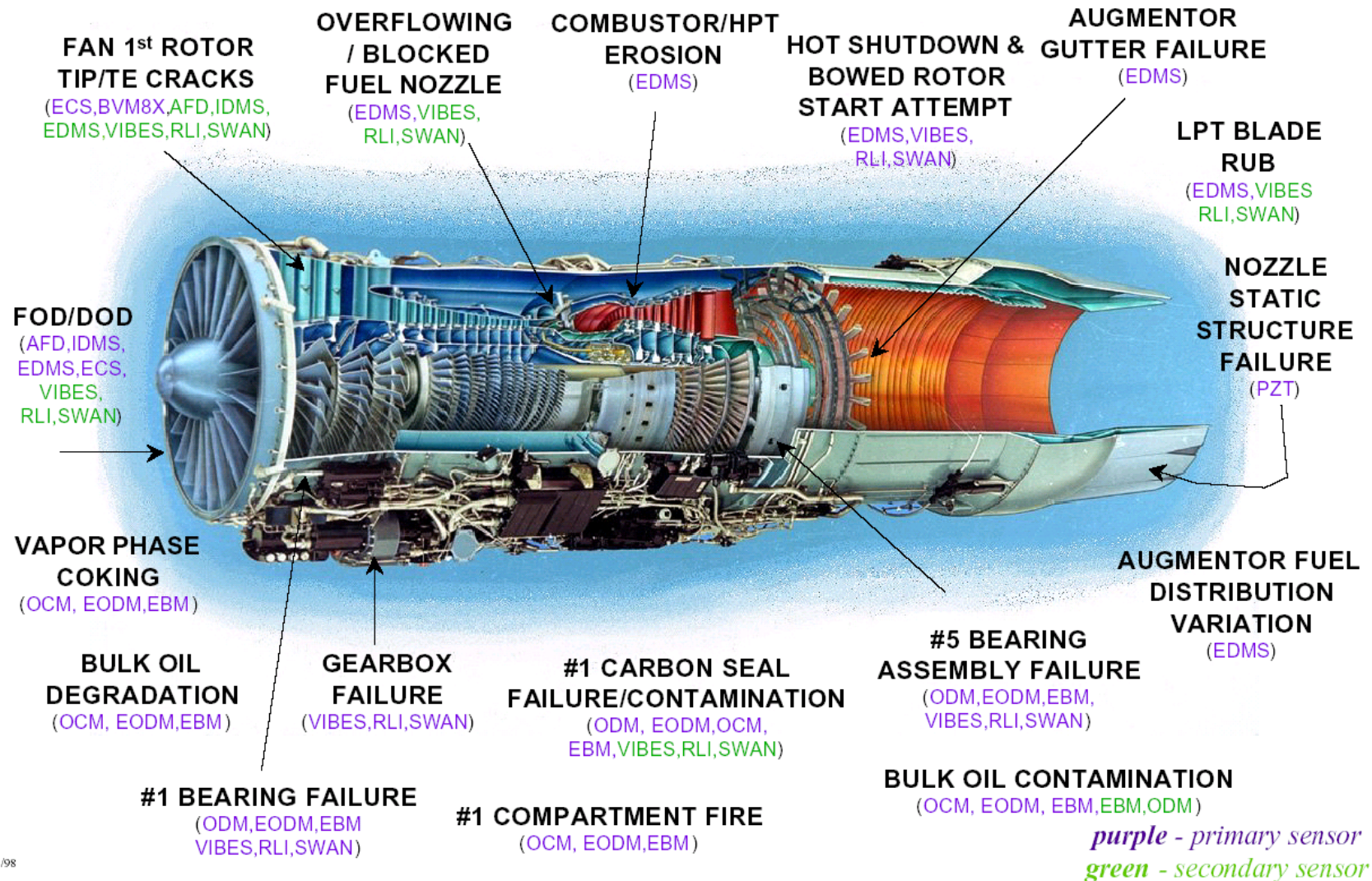
It's evolutionary!

From: A. Hess, "The Joint Strike Fighter (JSF) Prognostics and Health Management," Program Presentation.





F100 Seeded Fault Engine Test Plan





Machines Online

By Patrick Waurzyniak, Senior Editor

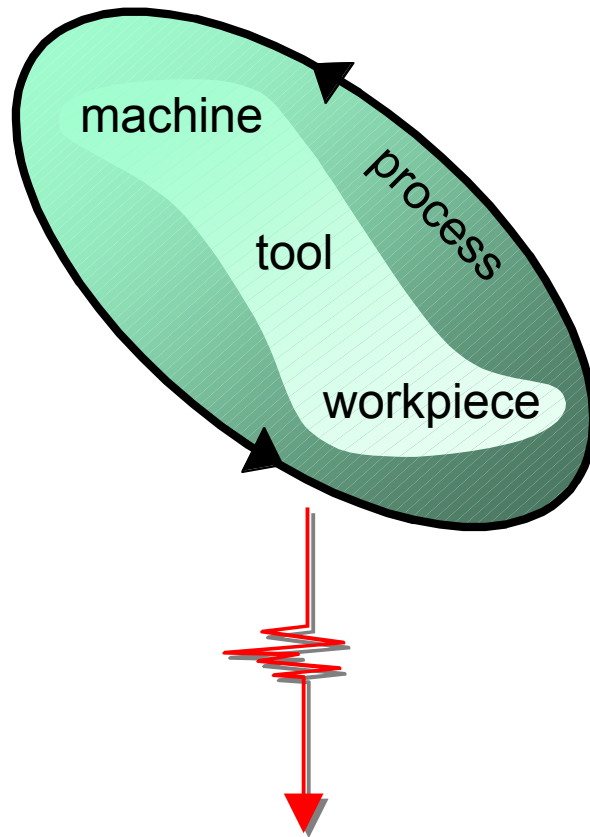
With its Interactive Techsupport system, a Cincinnati Machine-based support technician or application engineer can connect to a machine-tool customer's PC-based Siemens A2100 control to bidirectionally transfer video, voice, and data.

While remote diagnostics and maintenance capabilities for machine-tool customers have been available for years, recent advances in Internet-based monitoring systems using Web technology are making interactive technical support even more widespread.

Remote monitoring and diagnostics... users either the choi...

- Sophistication lacking in existing remote monitoring applications
- Future directions:
 - Predictive maintenance capabilities
 - Sensor-based approach
 - Reporting of everything happening to control

Life is never easy...



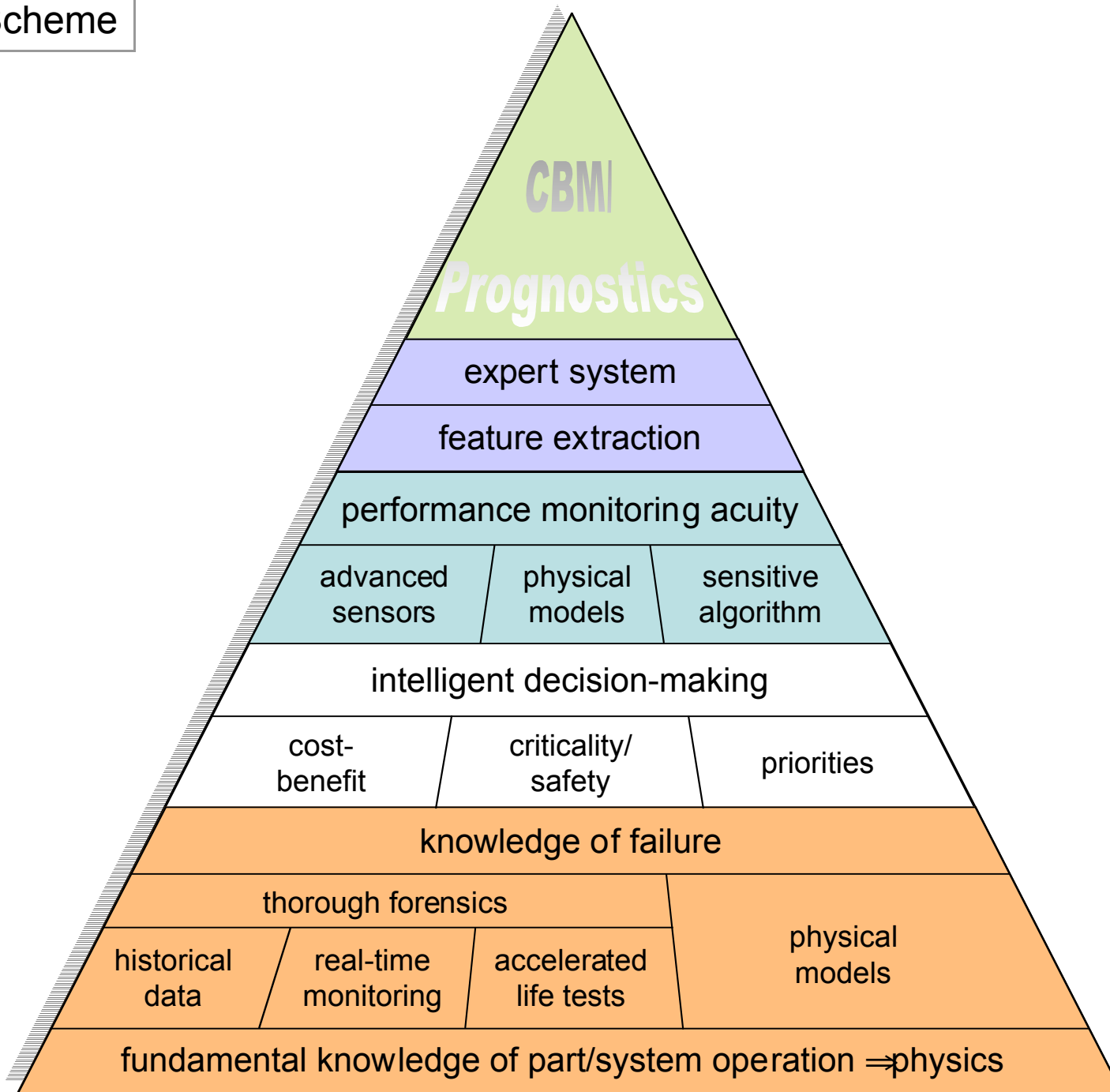
Non-linear, non-stationary data is tough to analyze.

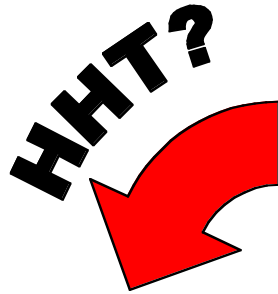
The machine tool is a complex dynamic system.

A collection of analysis methods is listed, grouped by a large curly brace on the left:

- ARMA**
- pattern recognition
- fuzzy logic*
- thresholding*
- Hilbert**
- zero-crossings
- RMS
- Fourier**
- SVD
- cepstrum*
- STFT
- Wigner-Ville**
- wavelet**
- neural net*

Pyramid Scheme





Litmus test:

- Cope with non-linearity, non-stationarity
- Operate in noisy environment
- Provide decent time- and frequency-resolution
- Objective and autonomous (hands-off)
- Real-time implementation
- Reliable
- Practical for machine tool

Essential theory

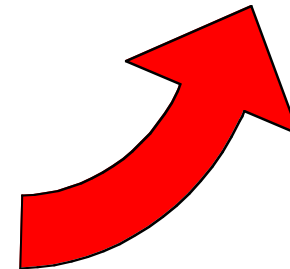
$$Y(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{X(t')}{t - t'} dt'$$

$$Z(t) = X(t) + iY(t) = a(t)e^{i\theta(t)}$$

$$a(t) = \sqrt{X^2(t) + Y^2(t)}, \quad \theta(t) = \arctan \frac{Y(t)}{X(t)}$$

$$\omega = \frac{d\theta(t)}{dt}$$

so far, so good...

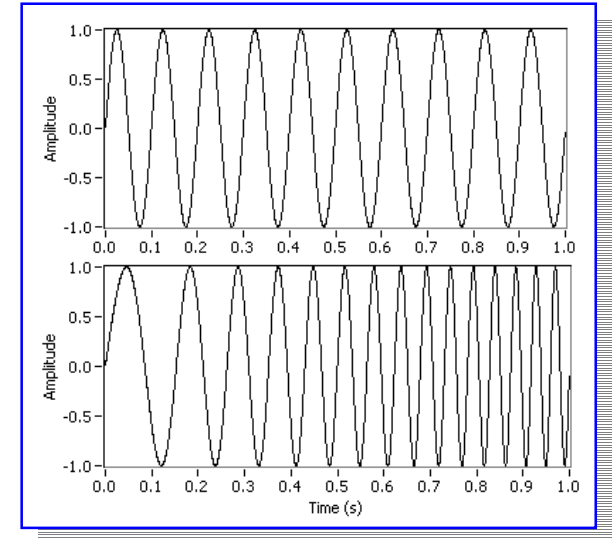


Empirically Speaking

Meaningful Hilbert spectra require:

- number of extrema = number of zero crossings (± 1)
- mean value of waveform envelopes = 0

Huang developed empirical preprocessor to “sift” time-series into “Hilbert-friendly” waveforms.



Philosophy:

- Physical data – time scale, energy distribution most important
- Need clear definition of local time scale
- Extrema vs. zero-crossings
- Weak oscillations/hidden scales \Rightarrow curvature

**Local time scale representing
one mode of oscillation**

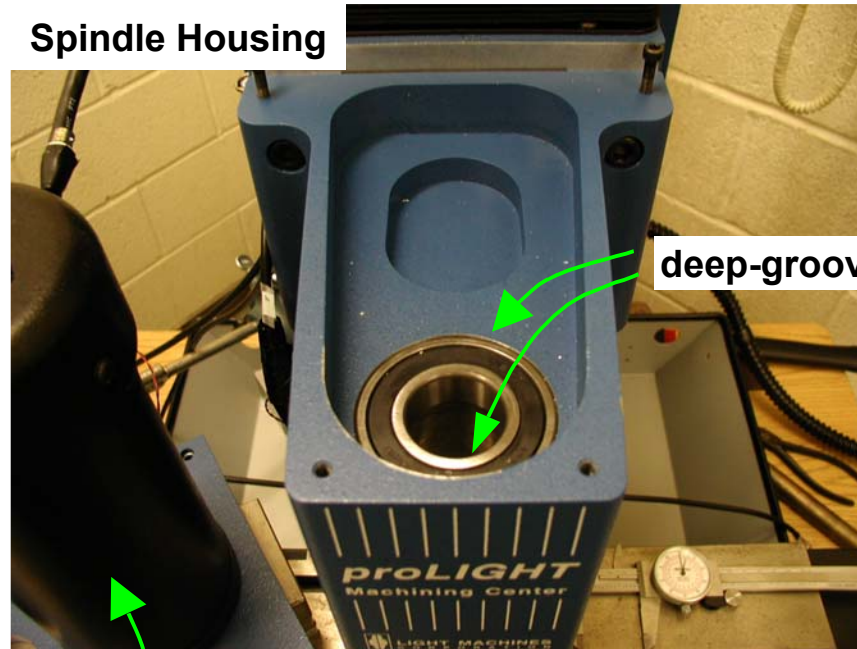
“Intrinsic Mode Function”

The CNC



Light Machines Corp. ProLIGHT 2000

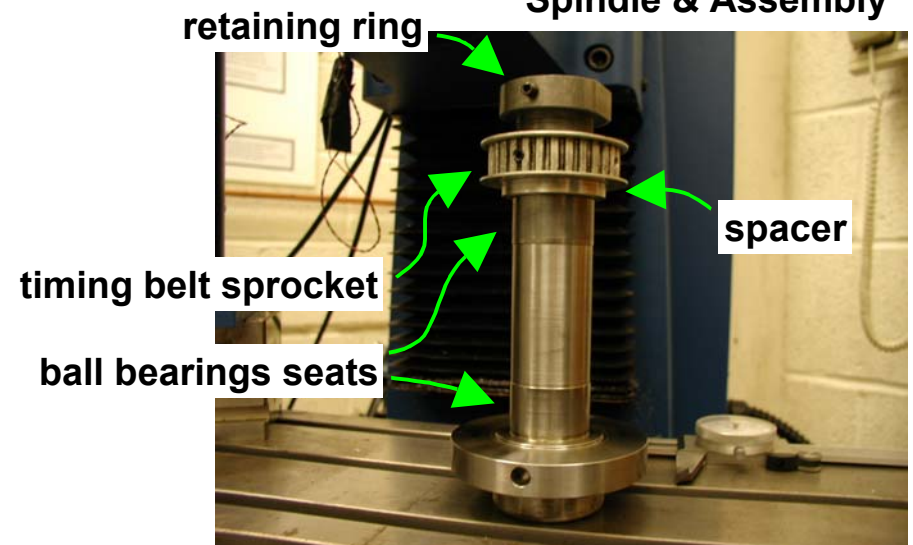
Spindle Housing



deep-groove ball bearings

spindle motor

Spindle & Assembly



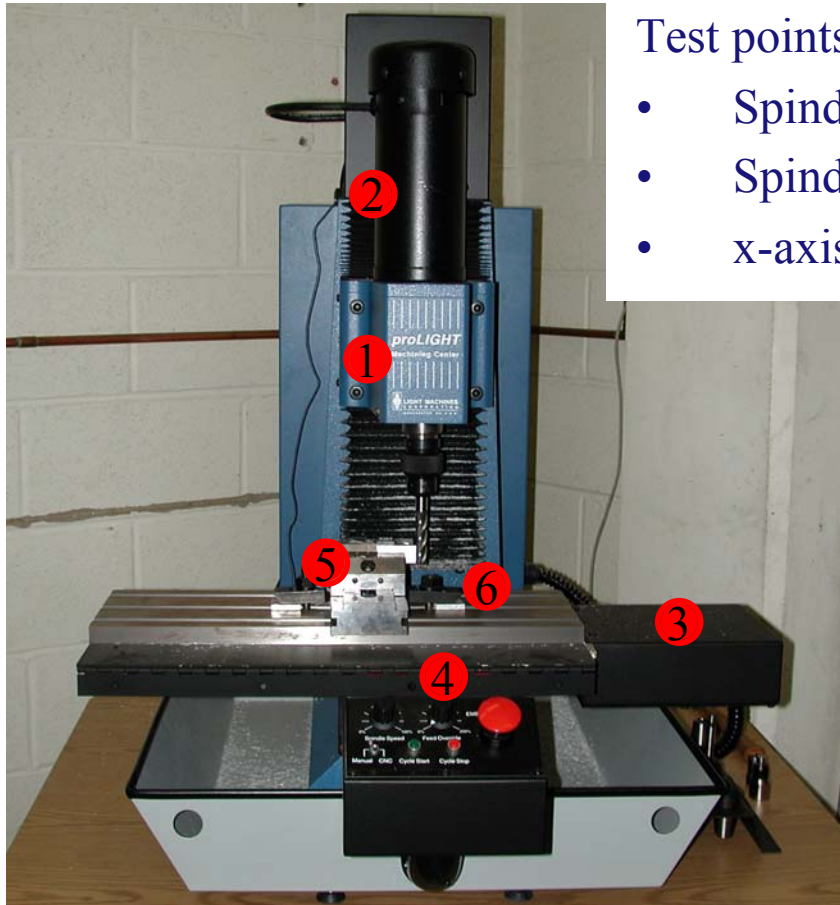
retaining ring

spacer

timing belt sprocket

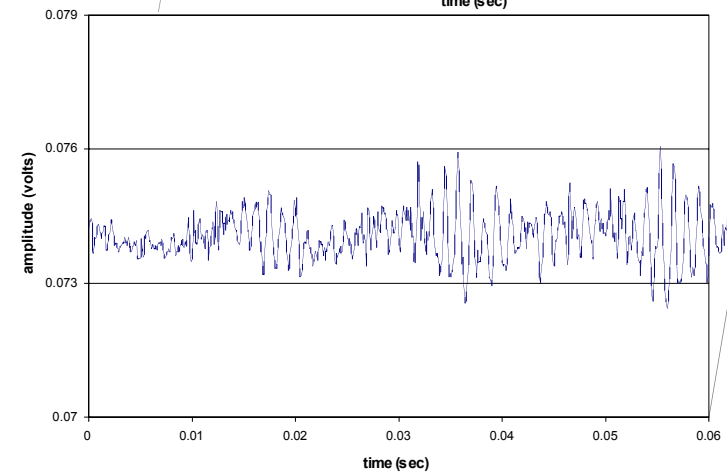
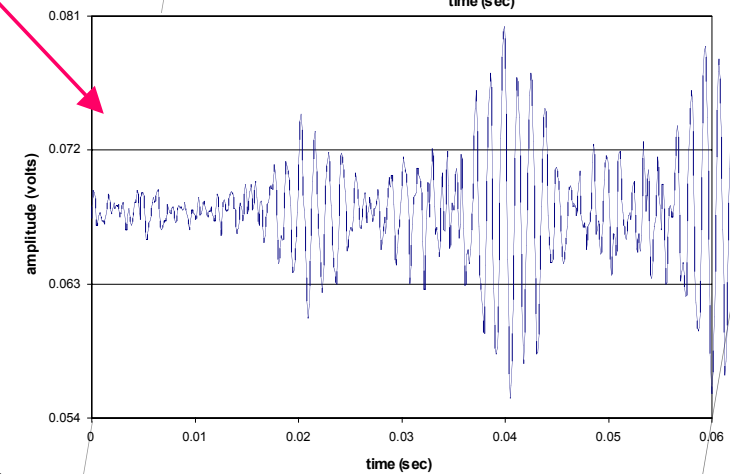
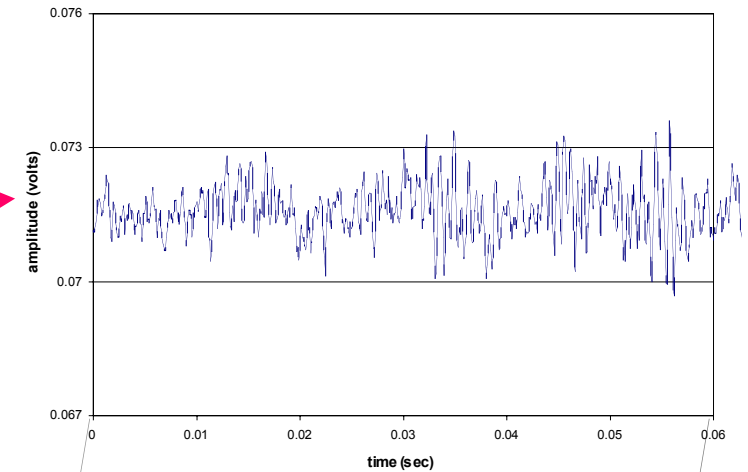
ball bearings seats

Vibration Data



Test points:

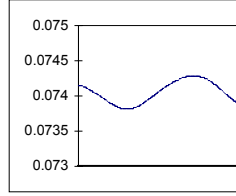
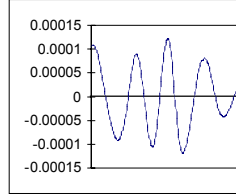
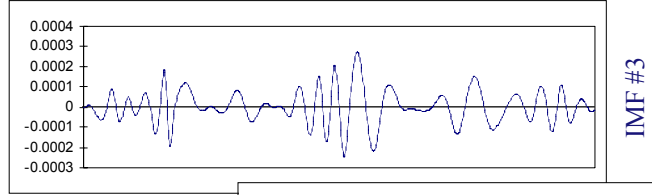
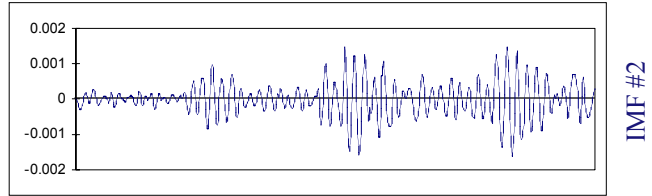
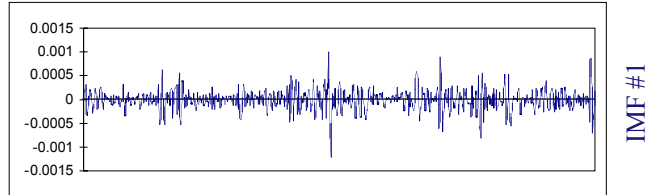
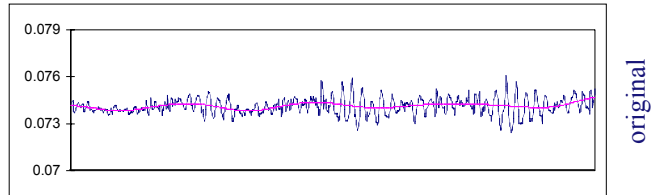
- Spindle housing
- Spindle motor
- x-axis drive



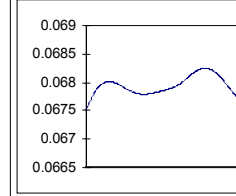
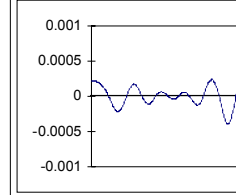
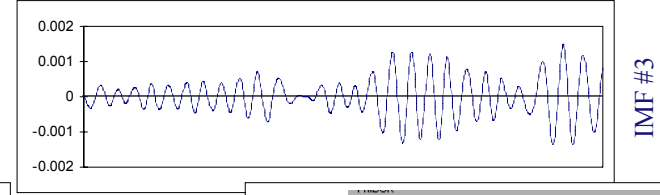
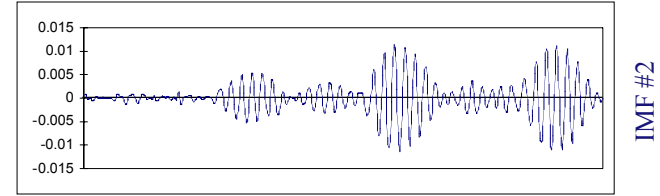
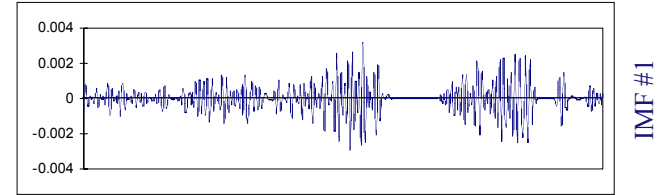
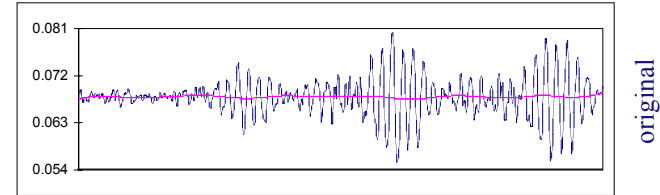
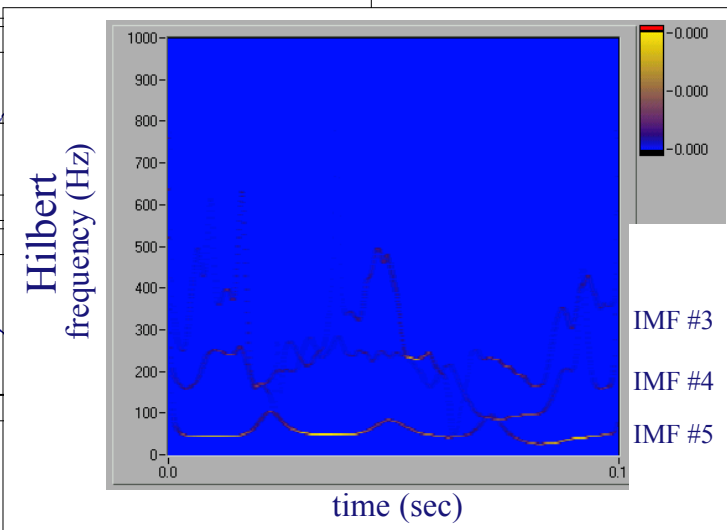
- 1200 RPM
- 8 ipm, -x direction
- 0.1"-wide, 0.02" DOC
- conventional cut
- 1/8" HSS, 4-flute endmill
- Al 2024 workpiece

- y-axis drive
- Workpiece
- Machine bed

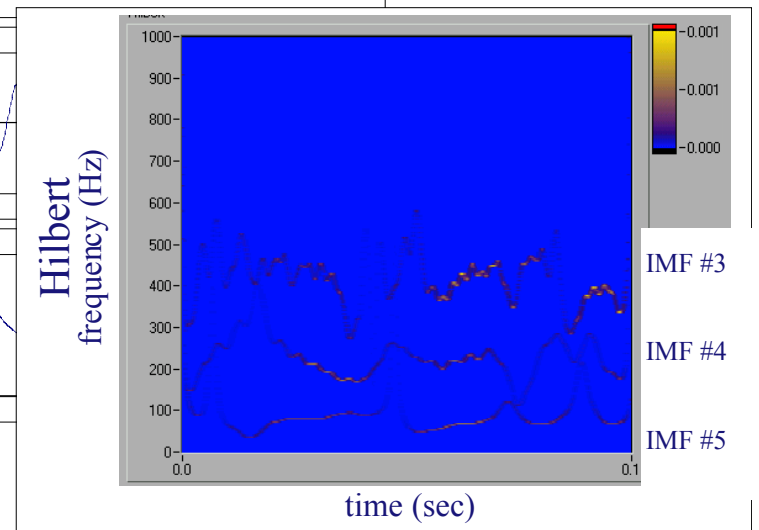
IMFs Galore



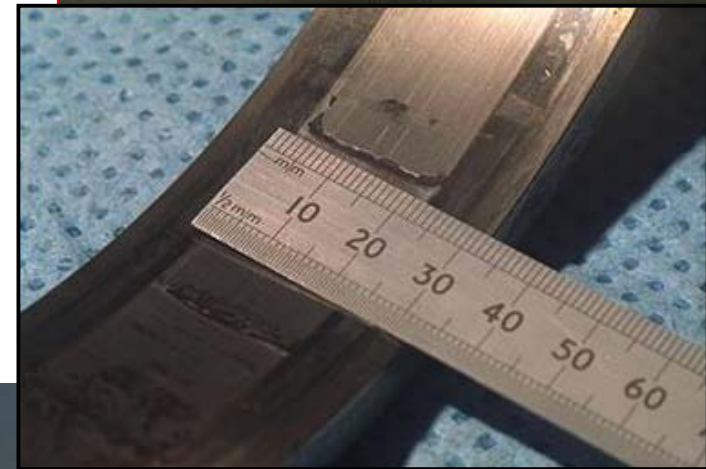
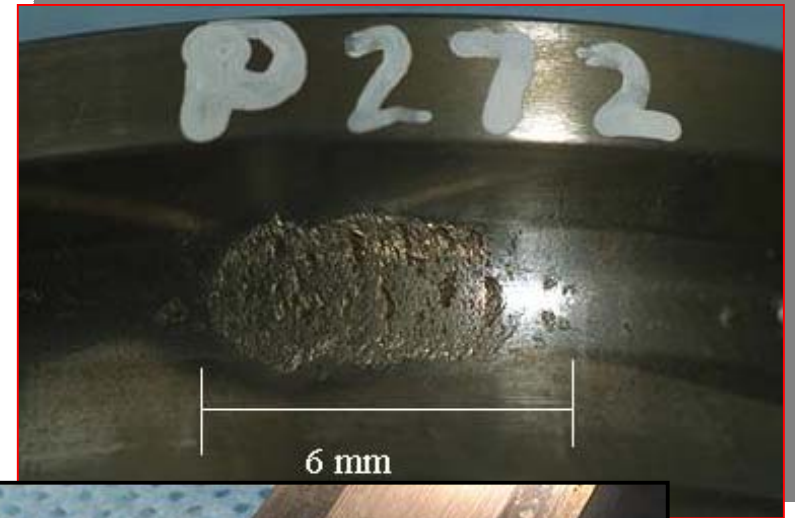
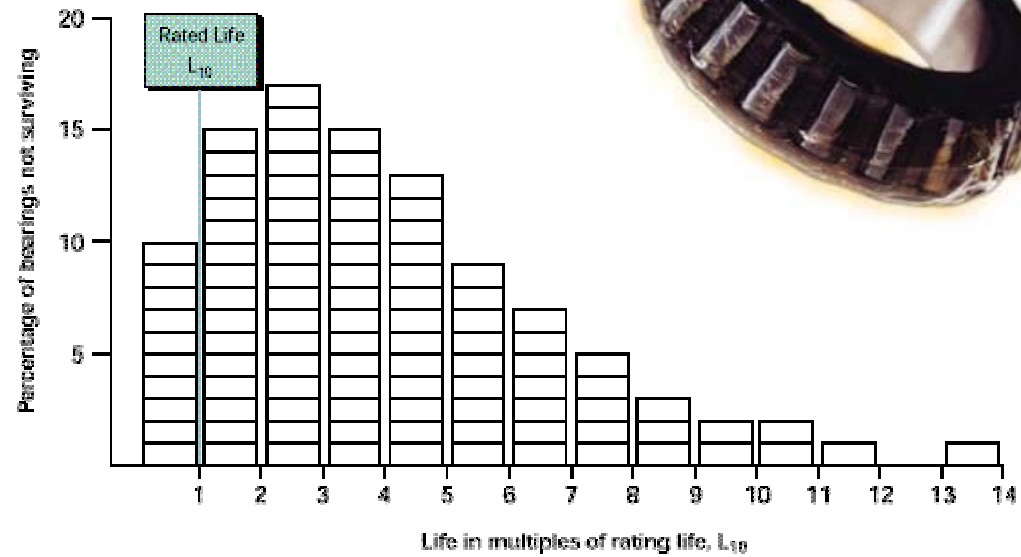
**HHT of
workpiece
vibration**



**HHT of
x-axis drive
vibration**



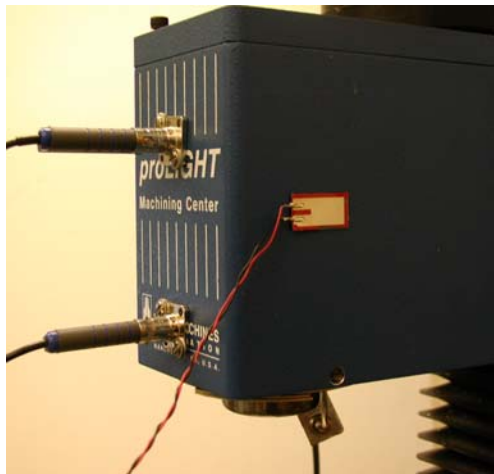
Getting one's bearings



Details, Details...



- Spindle bearings are high-risk
- Bearing tests can be simplified



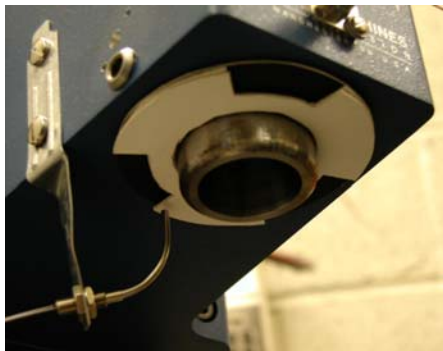
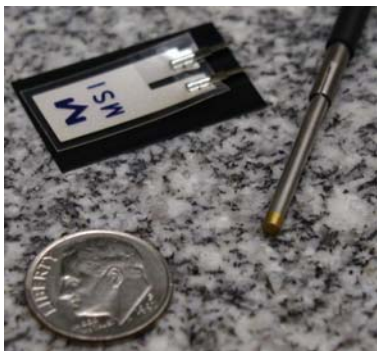
- Strong negative correlation between vibration and life



- PVDF films are “flexible”;
pinducers are small



- Vibration signals are
nonlinear, non-stationary



- HHT could provide prognostic
acuity

Keepin' it simple, *stupid*

Bearing
Characteristic Frequencies

$$BPFI = \frac{N}{2} \left[\frac{d}{D_t} \right] + \frac{d}{D_t} \cos \alpha \sqrt{\frac{2}{N}} f_n$$

$$BSF = \frac{D_t}{d} \left[\frac{d}{D_t} \right] - \frac{d}{D_t} \cos \alpha \sqrt{\frac{2}{N}} f_n$$

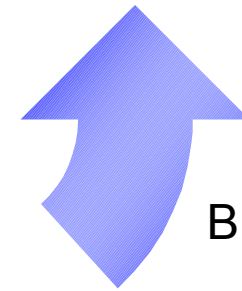
$$BPFO = \frac{N}{2} \left[\frac{d}{D_t} \right] - \frac{d}{D_t} \cos \alpha \sqrt{\frac{2}{N}} f_n$$

Potential Problems

- Spectra complex due to rotor dynamics
- Impurity indistinguishable from pit
- Non-uniform defect development:
 - Symptoms of cavity \Rightarrow wear
 - Symptom disappears by smoothing

General Knowledge

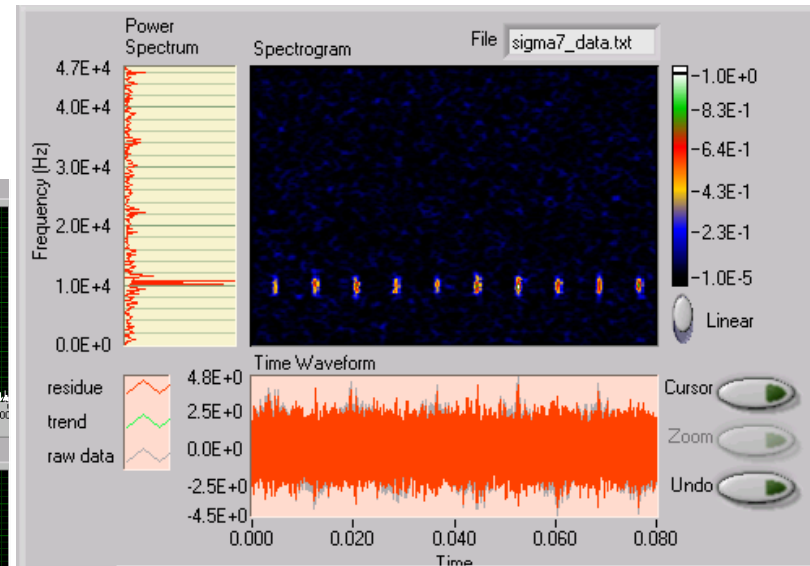
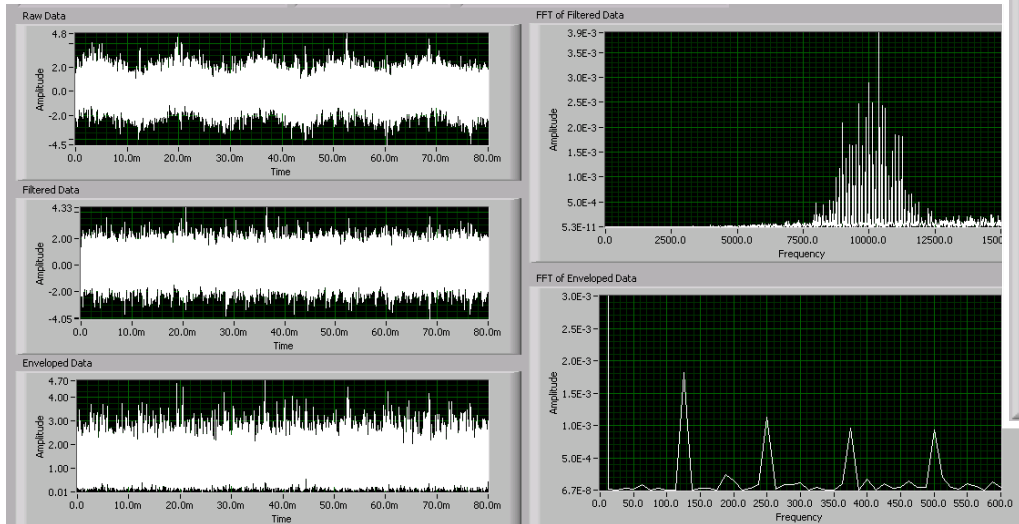
- Spalls/cavities indicated at BPFI, BSF or BPFO
- IR defects occur at much lower amplitude than OR
- Internal looseness components at shaft RPM
- Bearing misalignment at multiple of shaft RPM
- Vibration amplitude increases with degradation
- Baseline energy may increase & bandwidth broaden



BUT...

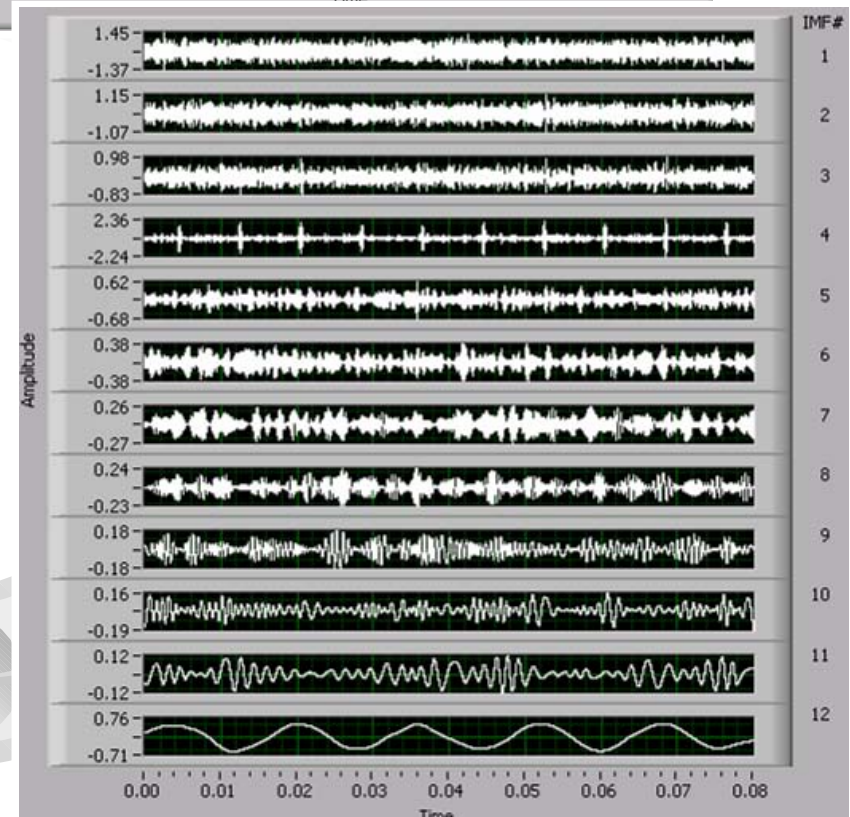
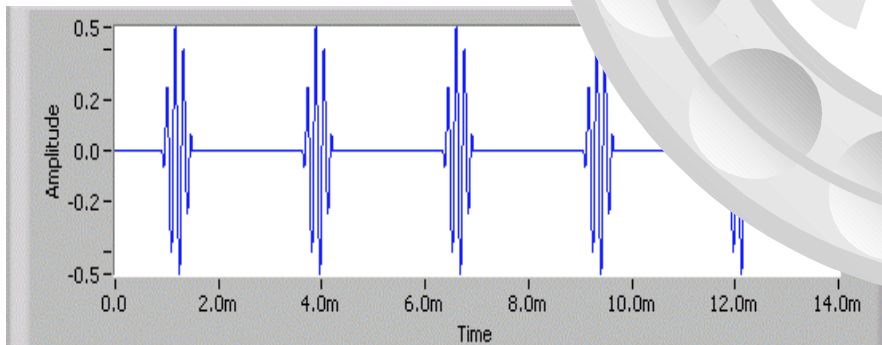
Land of the data-less

STFT



Envelope Detection (FFT)

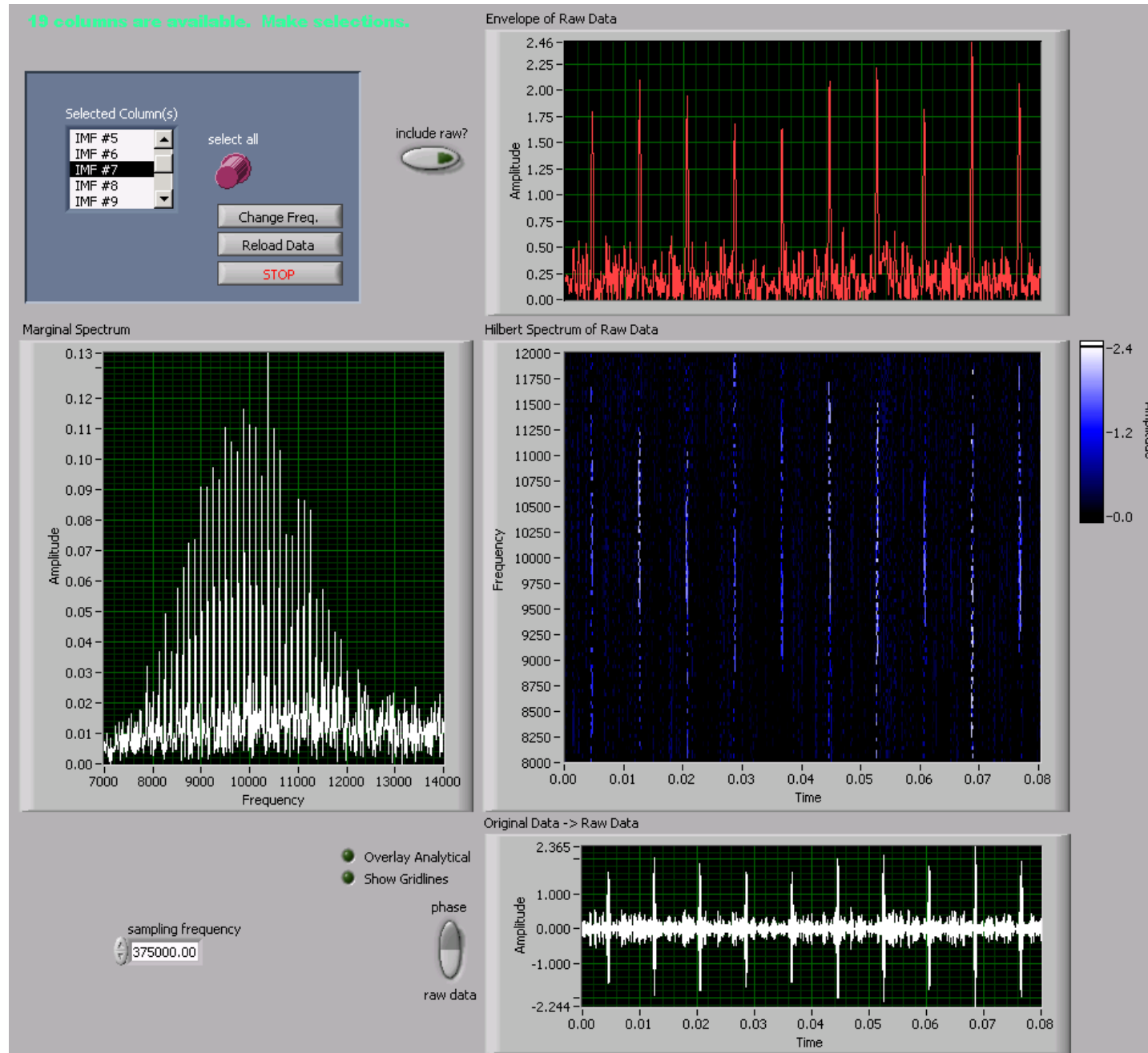
Idealized Signal (10 kHz @ 125 Hz rep.)



EMD Preprocessor

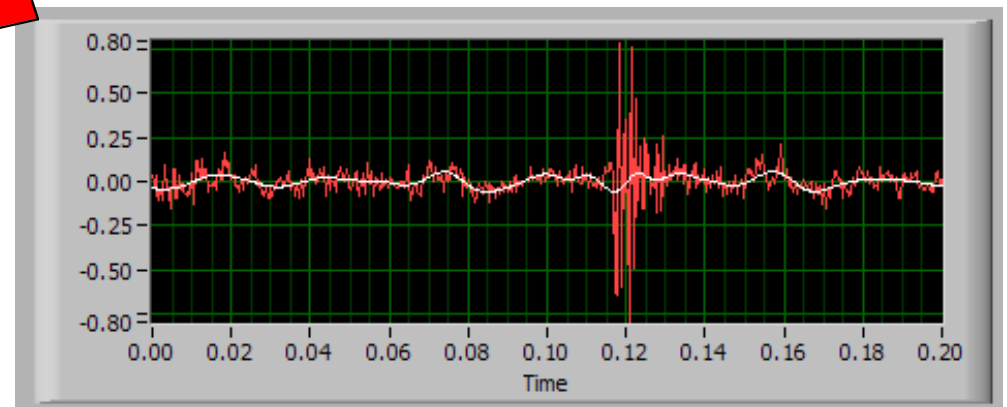
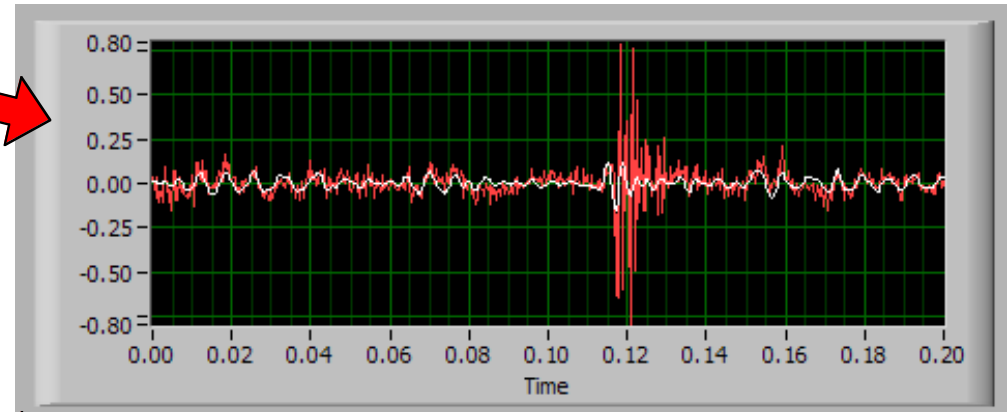
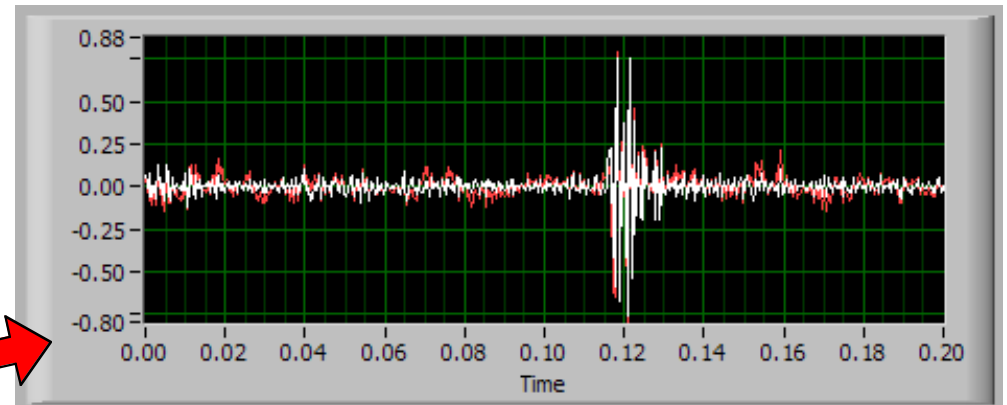
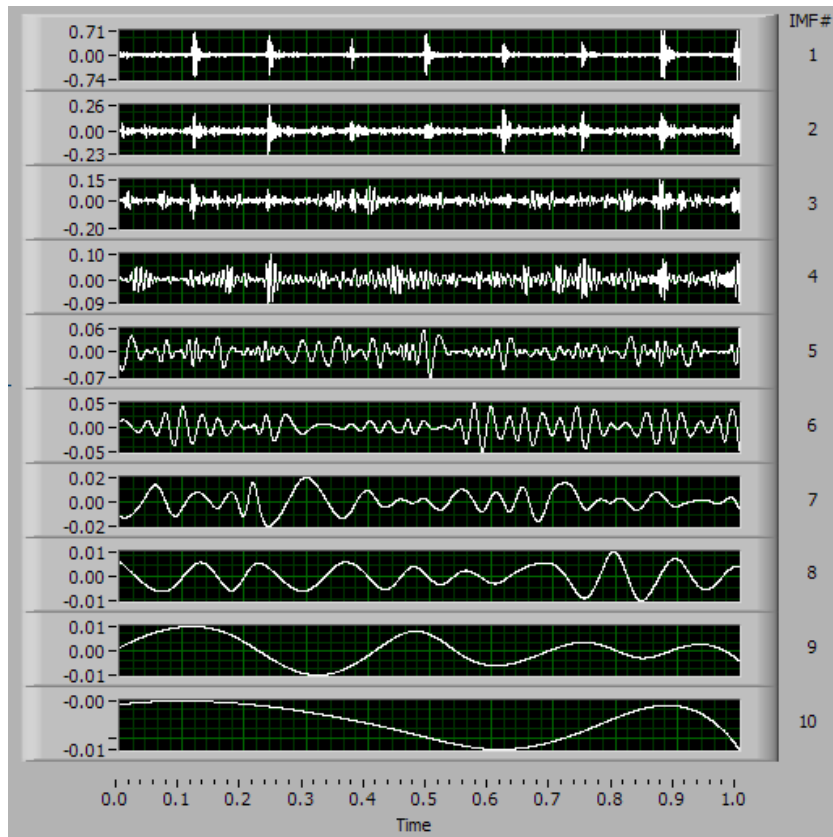
Sanity Check

Hilbert Spectrum



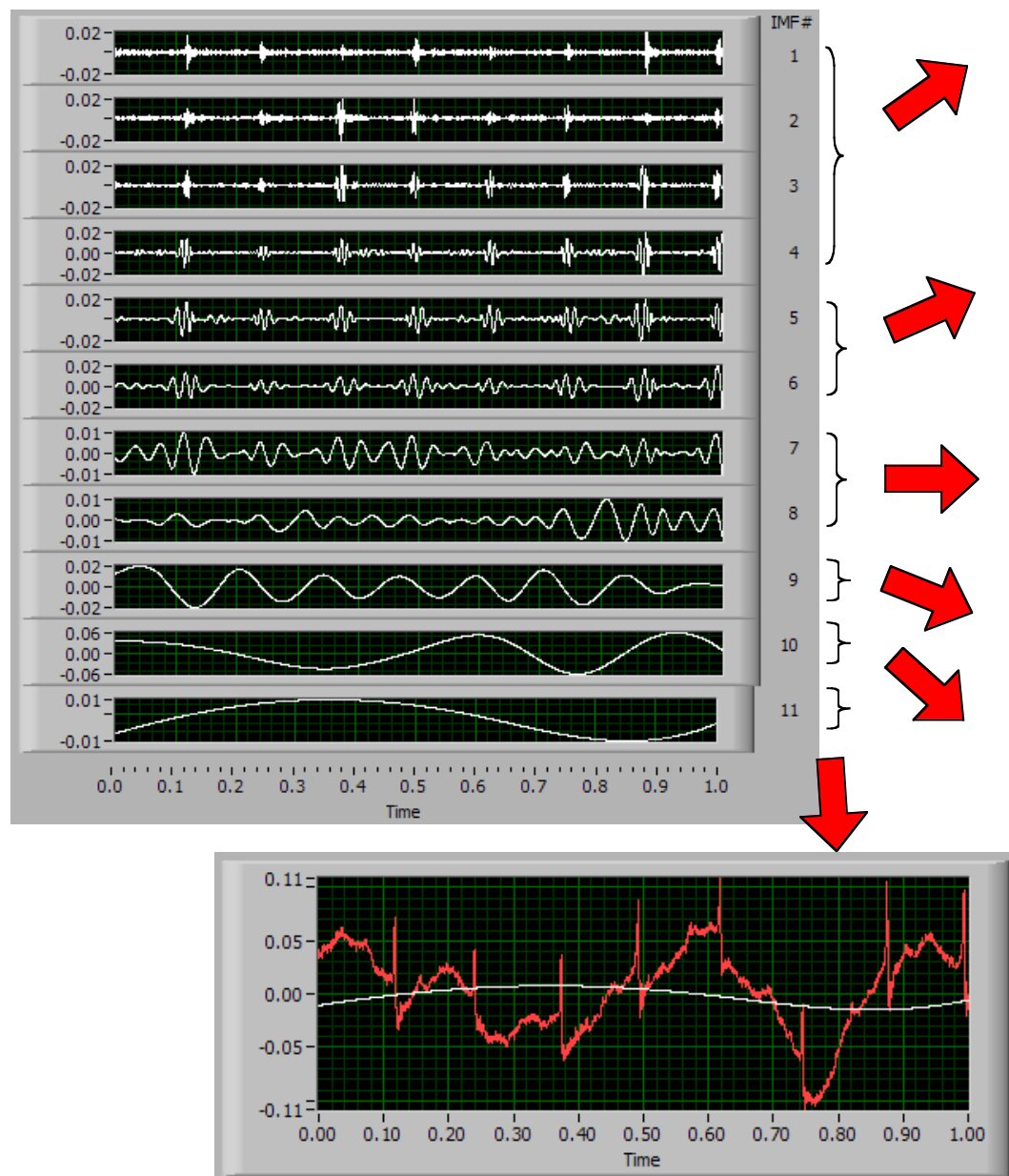
Fresh Data

Outer Ring Defect
(accelerometer, 750 RPM)



Fresh Data II

Outer Ring Defect (piezo-film, 750 RPM)



Data Generation

Code Development

Benchmarking

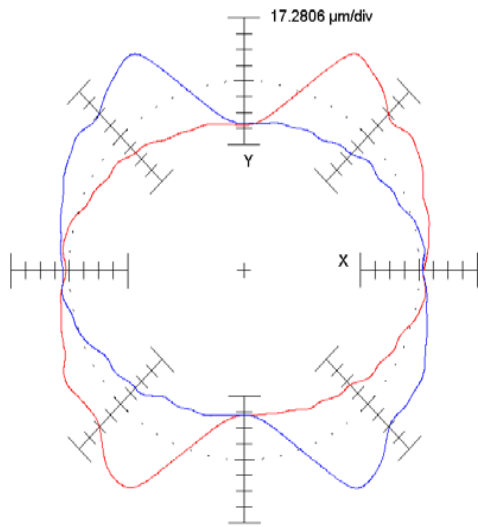
Expert System Development

*The Hilbert-Huang Transform in
Time-Frequency Analysis:*
**implications for
machine tool prognostics**

Special Projects

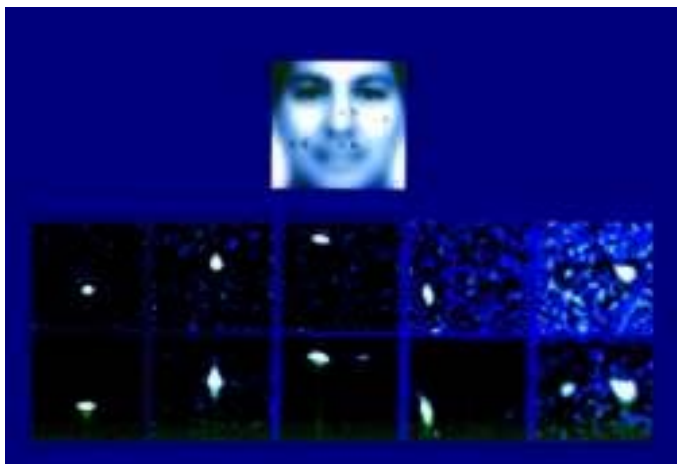
In our spare time...

Circular Error



Measurement 1:	cr_01_1000s.kgk
Type of machine:	
Year of mnt.:	4/10/01
Remark:	
Date/Time:	10.04.2001 19:05:54
Eccentricity:	-0.0058 / -0.0507 mm
Radius Nom./Act.:	1 / 0.907325 mm
Feed rate:	1000 mm/min
Direction of rot.:	CCW
Measurement 2:	cr_01_1000s.kgk
Type of machine:	
Year of mnt.:	4/10/01
Remark:	
Date/Time:	10.04.2001 19:07:46
Eccentricity:	-0.0050 / -0.0503 mm
Radius Nom./Act.:	1 / 0.906803 mm
Feed rate:	1000 mm/min
Direction of rot.:	CCW

Feature Identification



Edge Detection

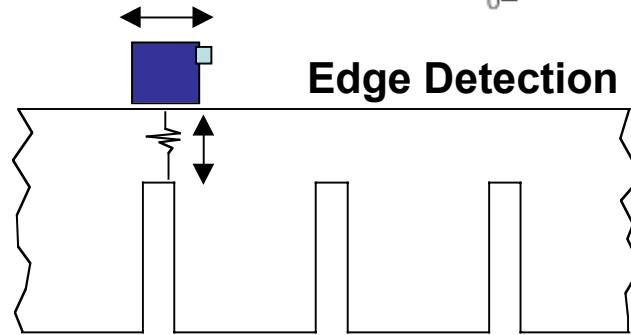
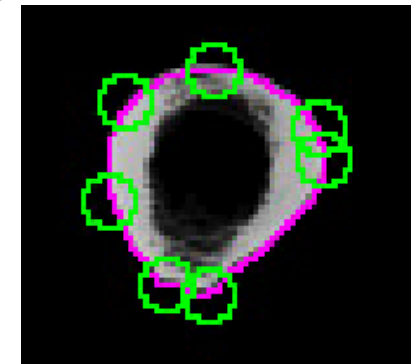
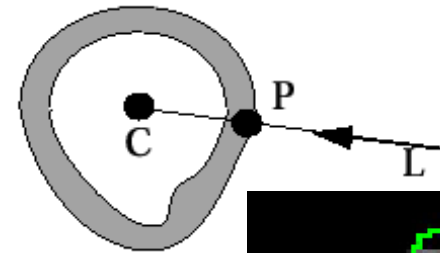
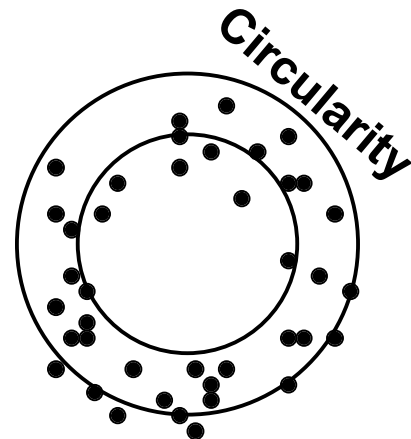
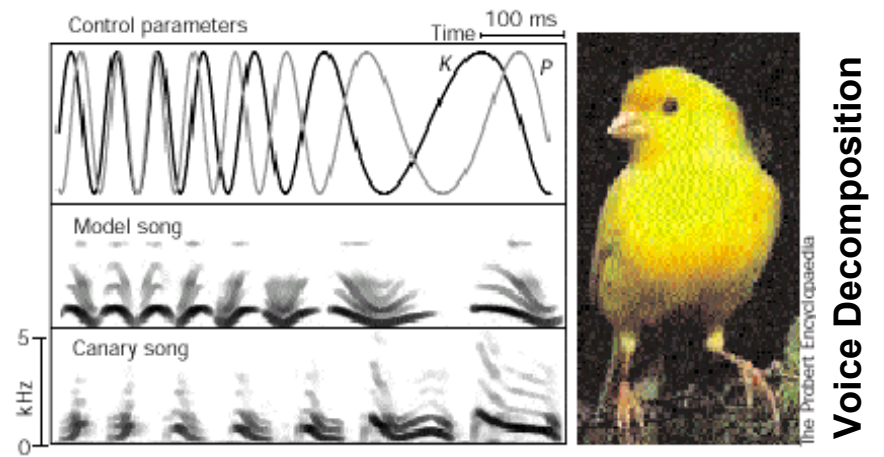


Figure: E. Lerner, "Bird Songs, Human Speech," The Industrial Physicist, Feb/Mar 2002, 8(1), pp. 11-12.



CT Corner-Finding

Figure: W.B. Scott, "Israeli Screening System Exploits Biometric ID," AWST, Feb. 25, 2002, p. 50.

Figure: T. Ault, M.W. Siegel, "Frameless Patient Registration Using Ultrasonic Imaging."