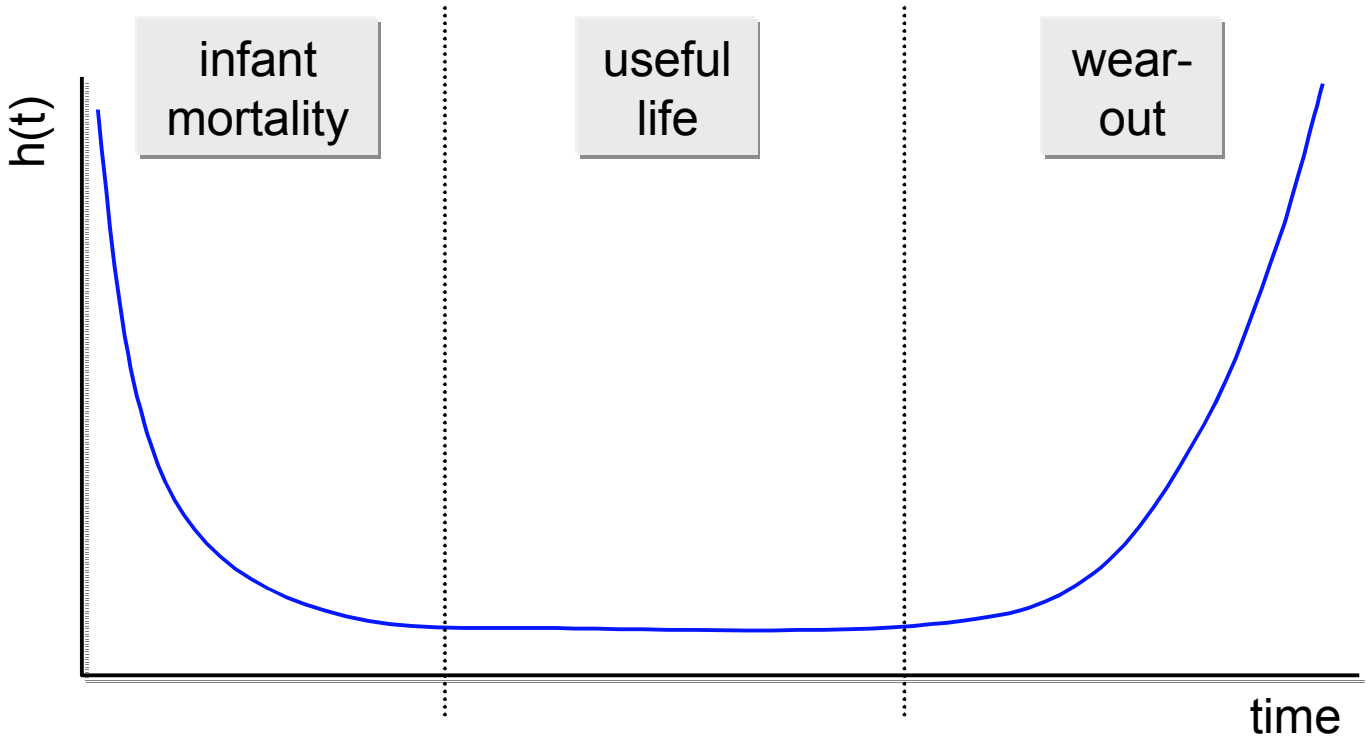
Application of the Hilbert-Huang Transform in Machine Tool Fault Detection

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?

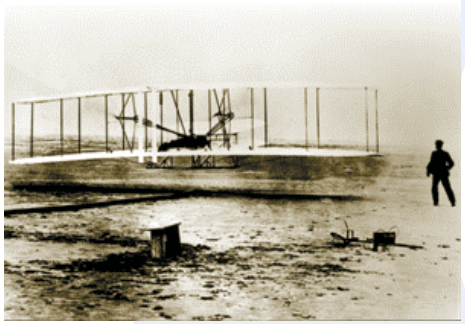
	Boeing 777-200LR	1903 Wright Flyer
Passengers	300+	1+
Engines	(2) 110,000 lb thrust GE 90-110B1	4-cylinder, 12 hp Wright engine
Max. Takeoff Wt.	750,000 lb	605 lb (+ pilot)
Cruise Speed	0.84 Mach	30 mph
Range	8865 mi	852 feet
Wingspan	212’ 7”	40’ 4”
Height	60’ 11.5” (tail)	7’

Reliance on computers for operation & performance monitoring.

Boeing 777 glass cockpit

Significant engineering is required!!

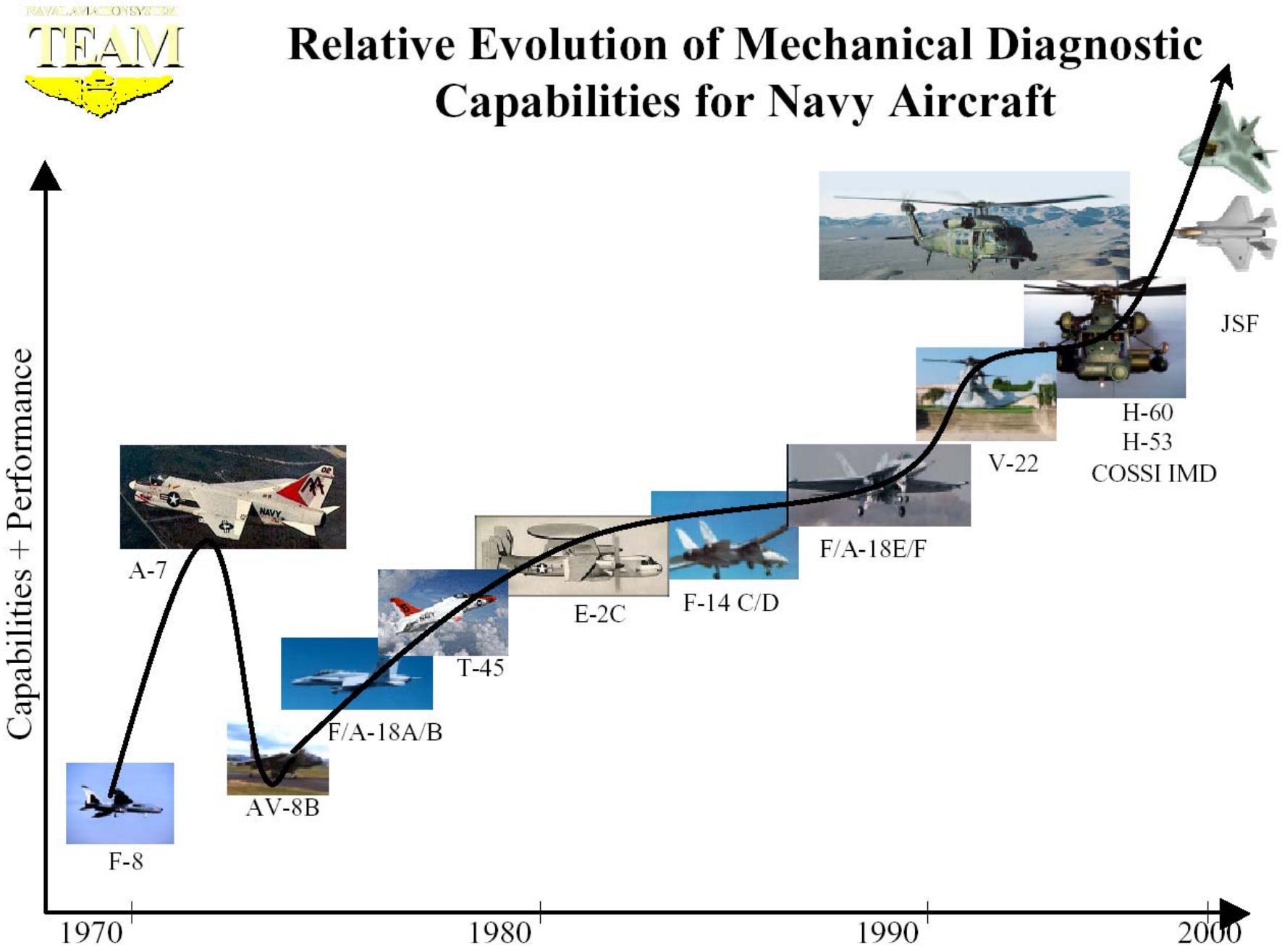
A century of powered, heavier-than-air flight.



December 17, 1903 Wright Flyer

It's evolutionary!

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

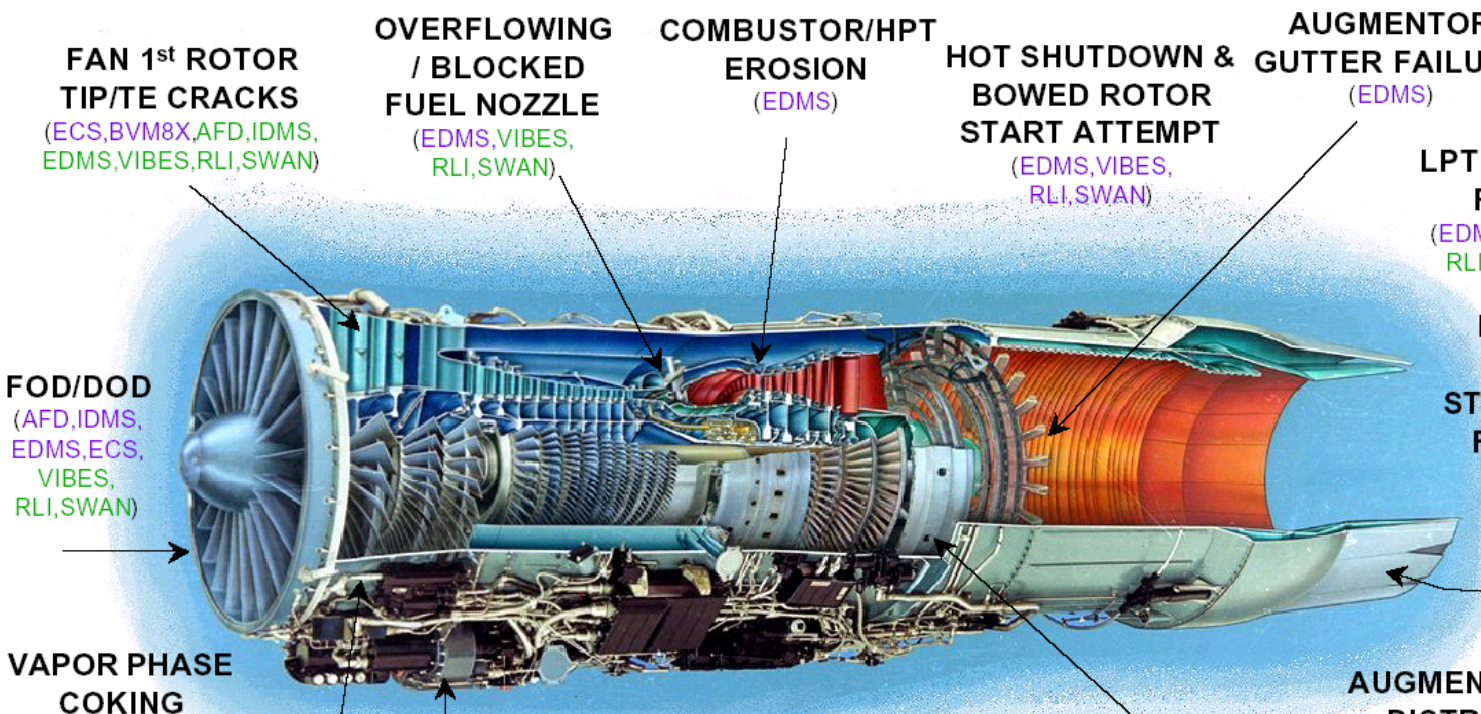


Money talks…

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

Approved for Public Release

F100 Seeded Fault Engine Test Plan



FAN 1st ROTOR TIP/TE CRACKS
(ECS,BVM8X,AFD,IDMS, EDMS,VIBES,RLI,SWAN)

OVERFLOWING / BLOCKED FUEL NOZZLE
(EDMS,VIBES, RLI,SWAN)

COMBUSTOR/HPT EROSION
(EDMS)

HOT SHUTDOWN & BOWED ROTOR START ATTEMPT
(EDMS,VIBES, RLI,SWAN)

AUGMENTOR GUTTER FAILURE
(EDMS)

LPT BLADE RUB
(EDMS,VIBES RLI,SWAN)

NOZZLE STATIC STRUCTURE FAILURE
(PZT)

FOD/DOD
(AFD,IDMS, EDMS,ECS, VIBES, RLI,SWAN)

VAPOR PHASE COKING
(OCM, EODM,EBM)

AUGMENTOR FUEL DISTRIBUTION VARIATION
(EDMS)

BULK OIL DEGRADATION
(OCM, EODM,EBM)

GEARBOX FAILURE
(VIBES,RLI,SWAN)

#1 CARBON SEAL FAILURE/CONTAMINATION
(ODM, EODM,OCM, EBM,VIBES,RLI,SWAN)

#5 BEARING ASSEMBLY FAILURE
(ODM,EODM,EBM, VIBES,RLI,SWAN)

#1 BEARING FAILURE
(ODM,EODM,EBM VIBES,RLI,SWAN)

#1 COMPARTMENT FIRE
(OCM, EODM,EBM)

BULK OIL CONTAMINATION
(OCM, EODM, EBM,EBM,ODM)

purple - primary sensor
green - secondary sensor

7/31/98

Modern Machines

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.

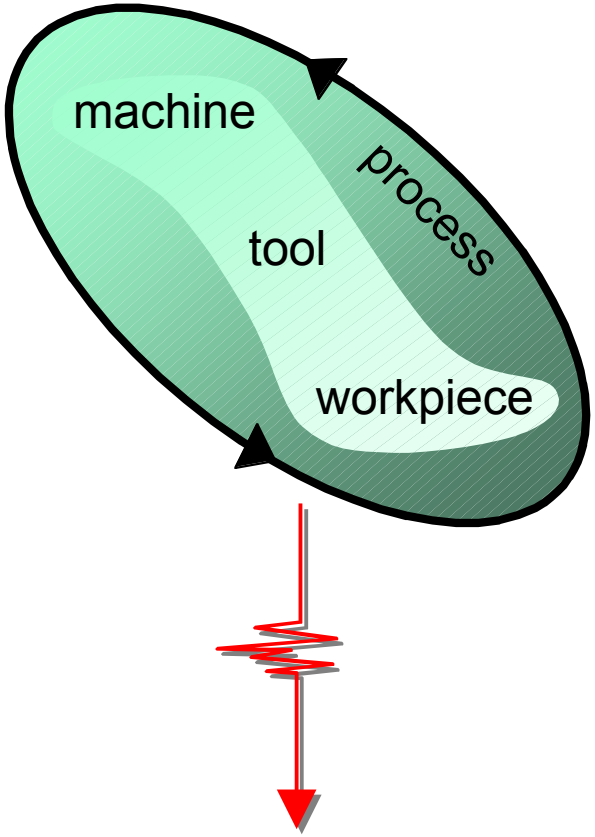
While remote diagnostics and maintenance capabilities for machine-tool customers have been available for years, recent advances in Internet-based monitoring systems using Web technology are making interactive technical support even more widespread.

Remote monitoring and diagnostics
users either the

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

From: Waurzyniak, P., Manufacturing Engineering Vol. 125, No. 5, November 2000.

Life is never easy…



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

The machine tool is a complex dynamic system.

ARMA

fuzzy logic

pattern recognition

thresholding

Hilbert

zero-crossings

SVD

RMS

Fourier

STFT

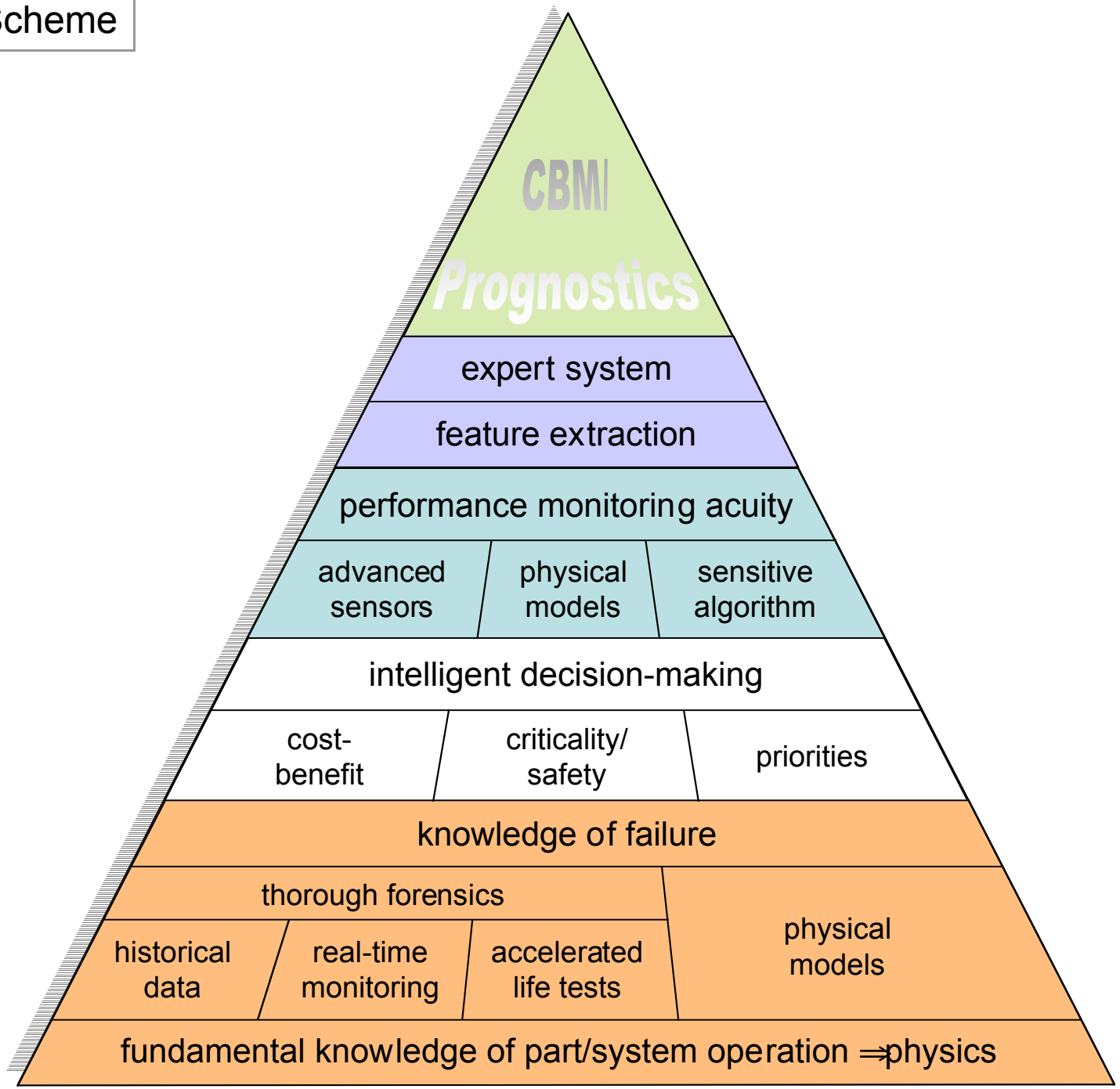
cepstrum

Wigner–Ville

wavelet

neural net

Pyramid Scheme



HHT or Bust

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

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

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

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

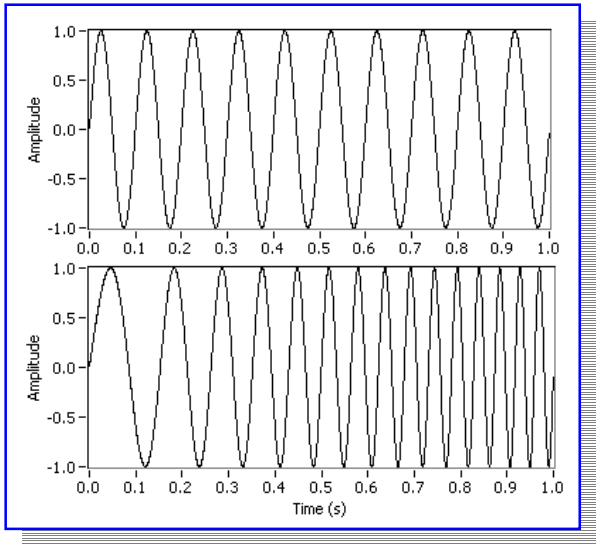
$$\omega = \frac{d\theta(t)}{dt}$$

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 ⇒ curvature

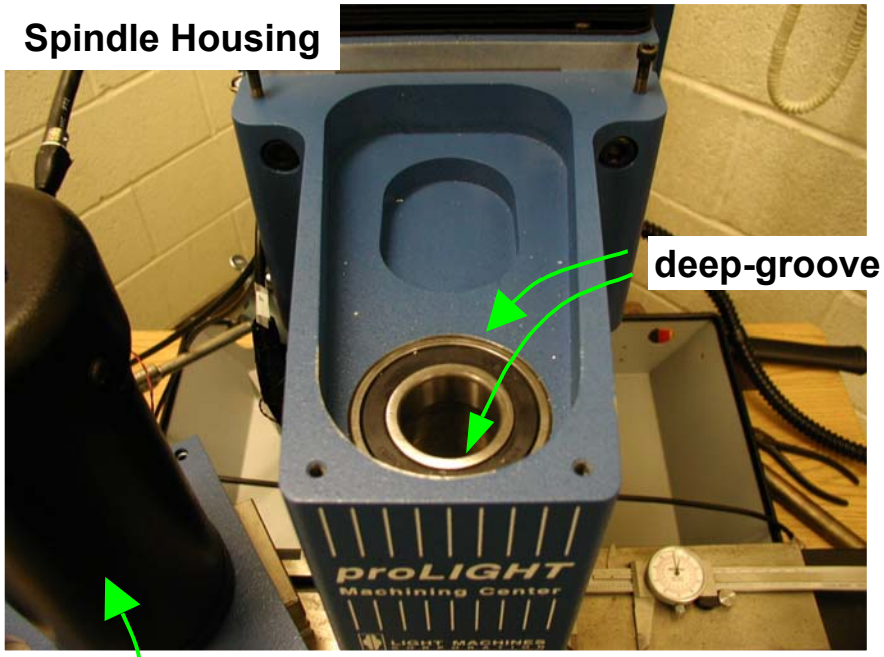
Local time scale representing one mode of oscillation

"Intrinsic Mode Function"

The CNC

Light Machines Corp. ProLIGHT 2000

Spindle Housing

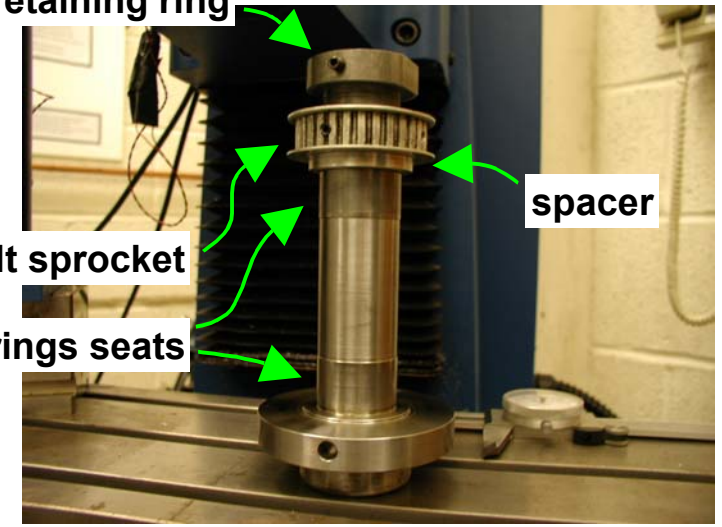


deep-groove ball bearings

spindle motor

Spindle & Assembly

retaining ring

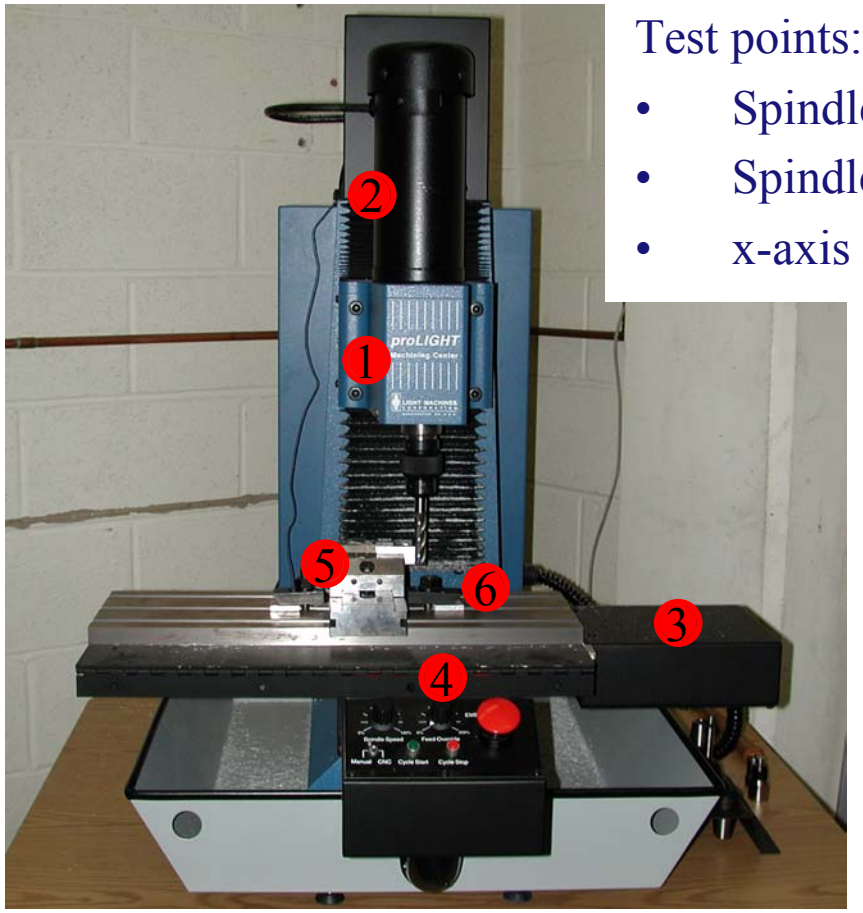


spacer

timing belt sprocket

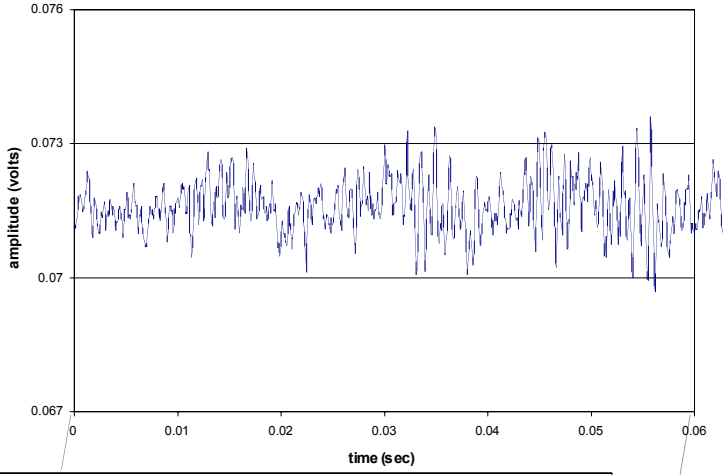
ball bearings seats

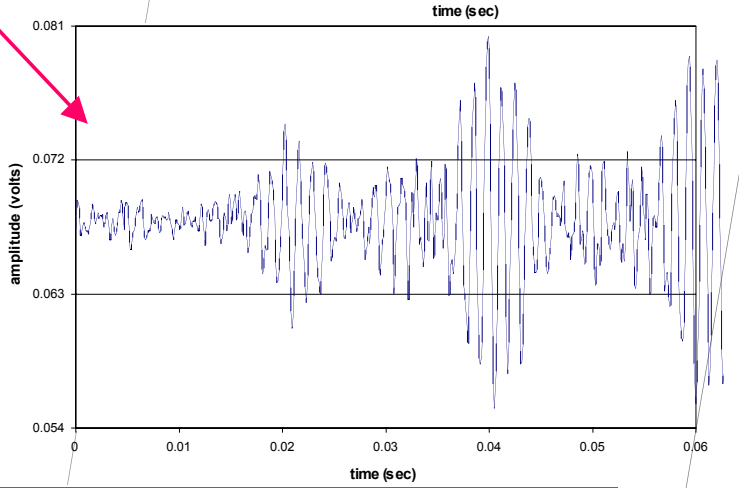
Vibration Data



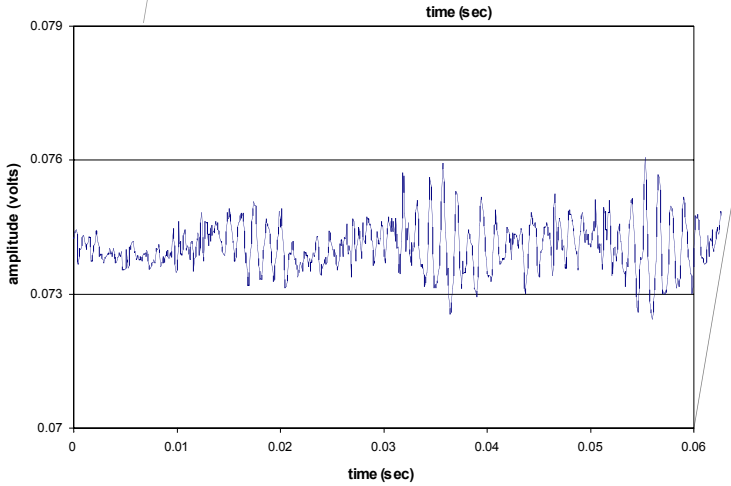
Test points:

- Spindle housing
- Spindle motor
- x-axis drive



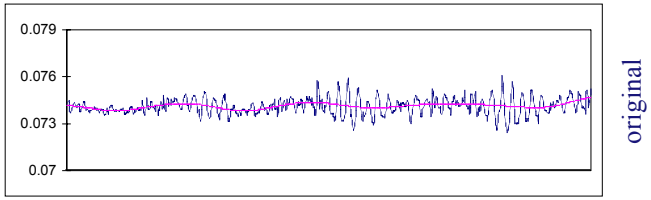


- y-axis drive
- Workpiece
- Machine bed

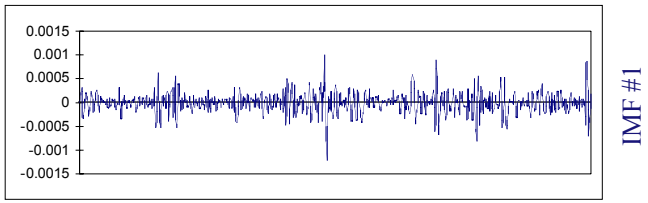


- 1200 RPM
- 8 ipm, -x direction
- 0.1”-wide, 0.02” DOC
- conventional cut
- _” HSS, 4-flute endmill
- Al 2024 workpiece

IMFs Galore



original



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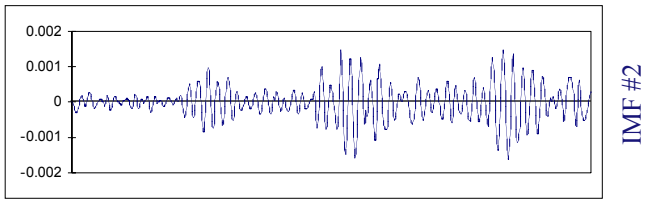
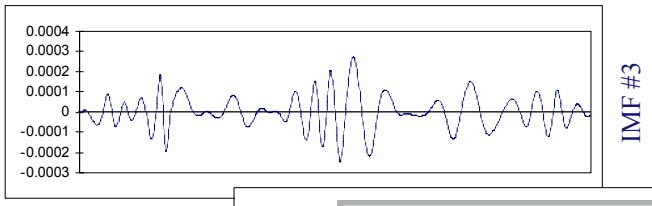


IMF #2



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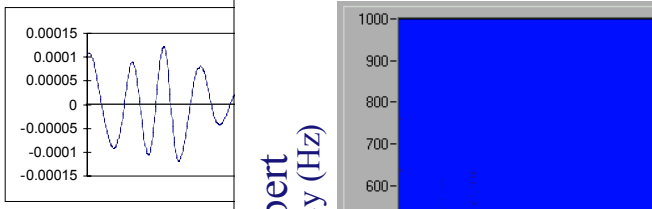
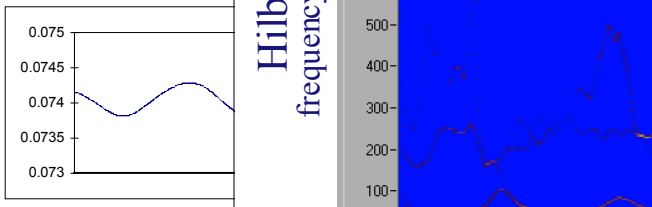
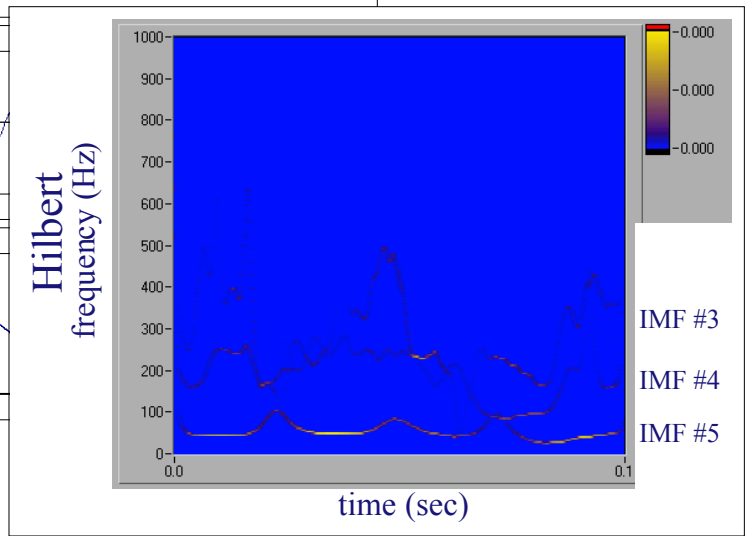
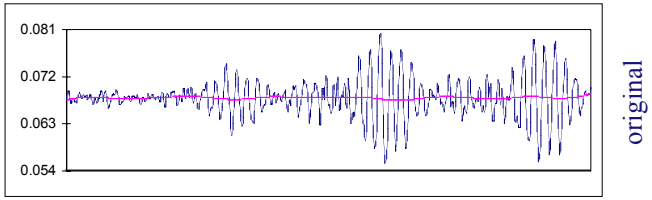


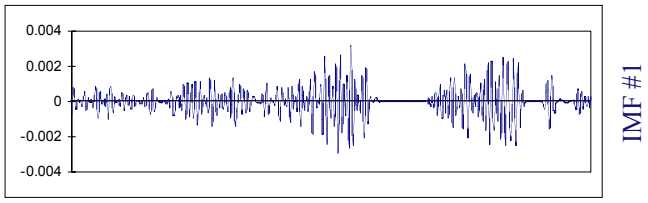


HHT of workpiece vibration

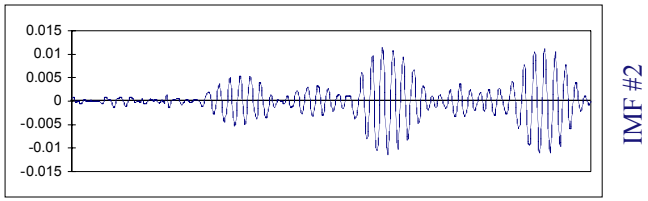




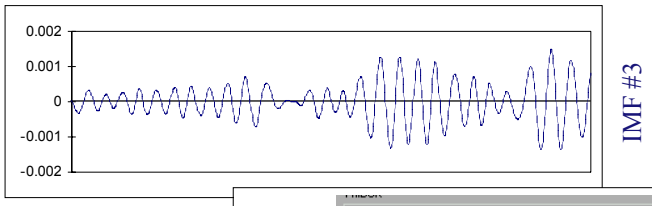
original



IMF #1



IMF #2



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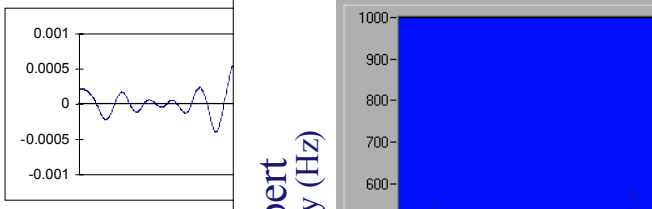
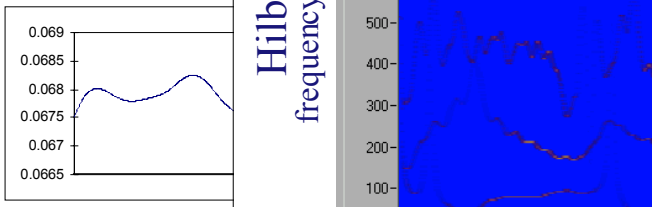
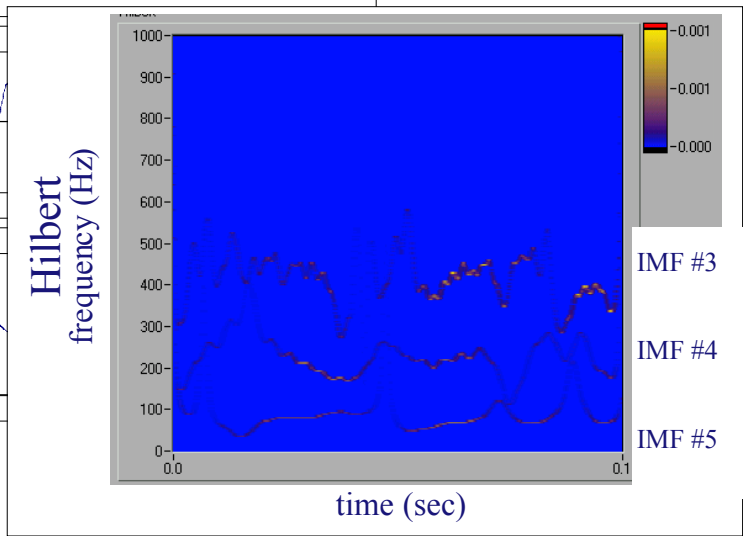
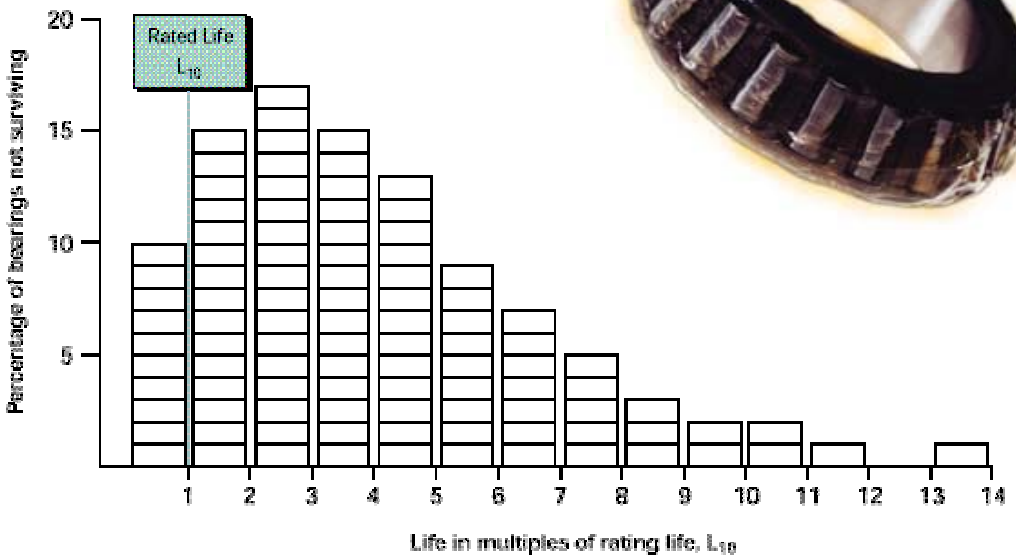


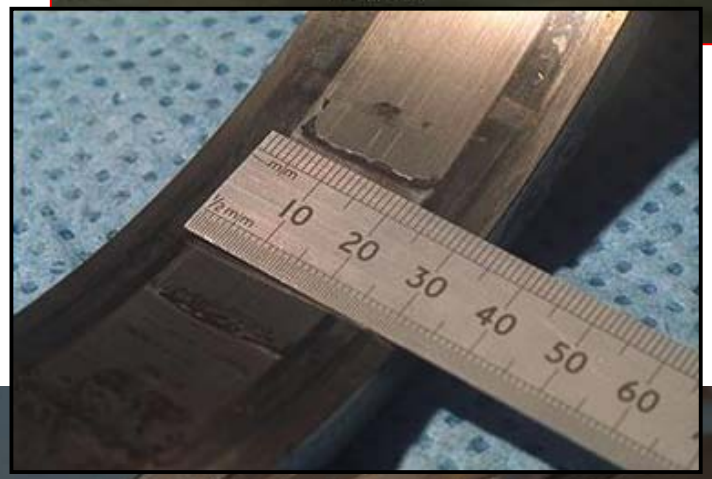


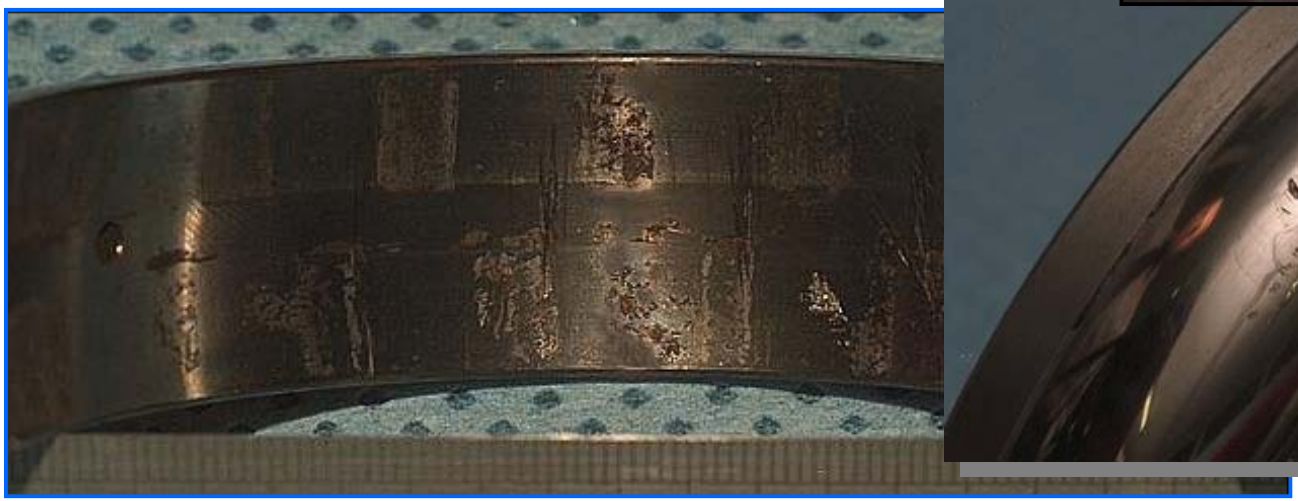
HHT of x-axis drive vibration



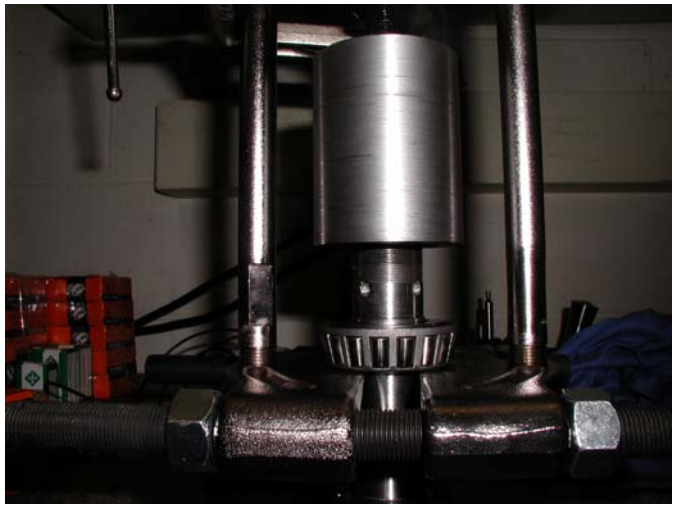
Getting one's bearings





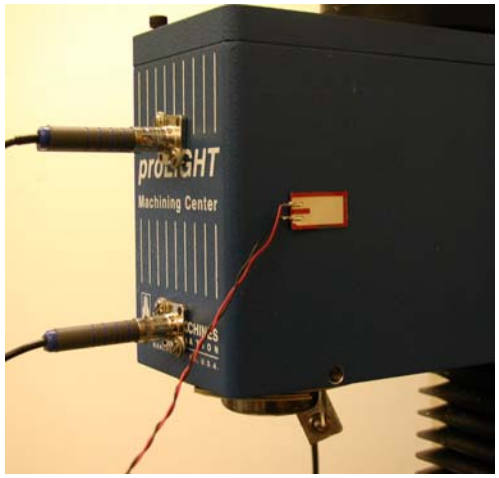


Details, Details…

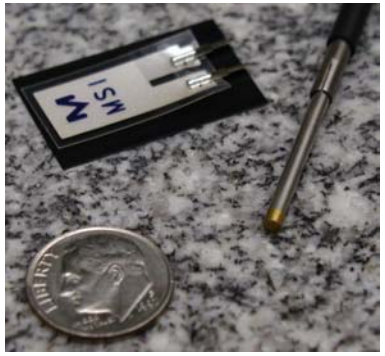


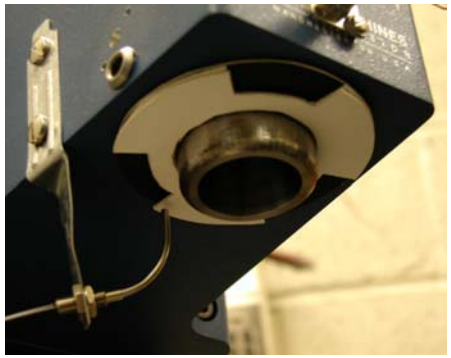
- Spindle bearings are high-risk
- Bearing tests can be simplified

- 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

$$BPFI = \frac{N}{2}\left(1 + \frac{d}{D_t}\cos\alpha\right) f_n$$

$$BSF = \frac{D_t}{d}\left(1 - \left(\frac{d}{D_t}\cos\alpha\right)^2\right) f_n$$

$$BPFO = \frac{N}{2}\left(1 - \frac{d}{D_t}\cos\alpha\right) f_n$$

Potential Problems

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

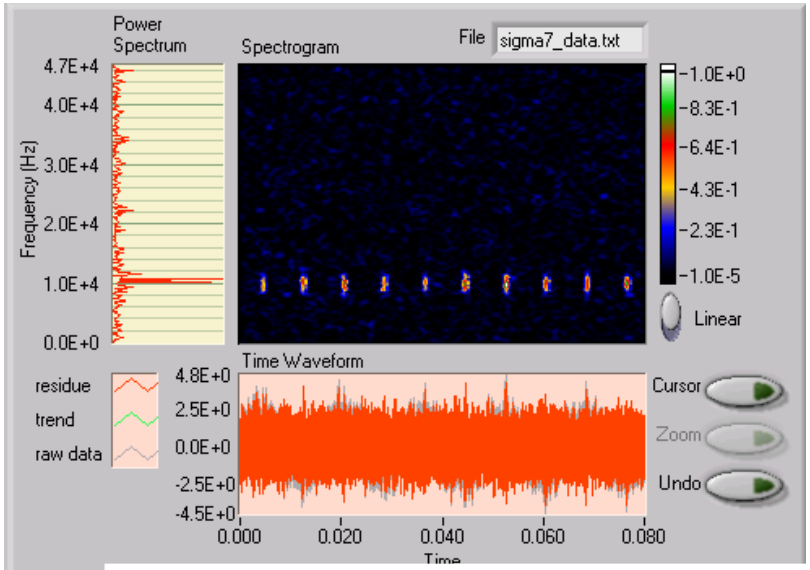
General Knowledge

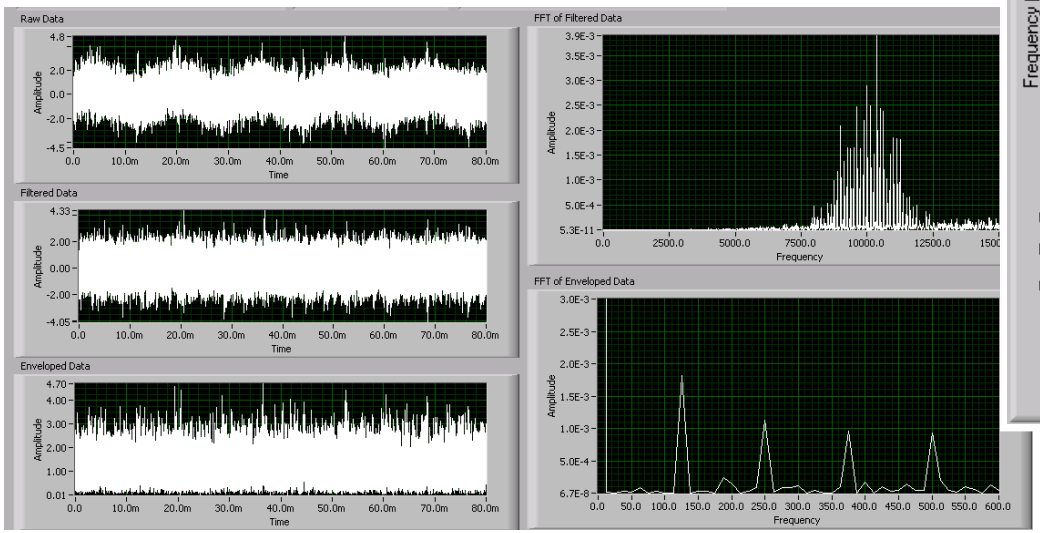
- Spalls/cavities indicated at BPFI, BSF or BPFO
- IR defects occur at much lower amplitude than OR
- Internal looseness components at shaft RPM
- Bearing misalignment at multiple of shaft RPM
- Vibration amplitude increases with degradation
- Baseline energy may increase & bandwidth broaden

BUT…

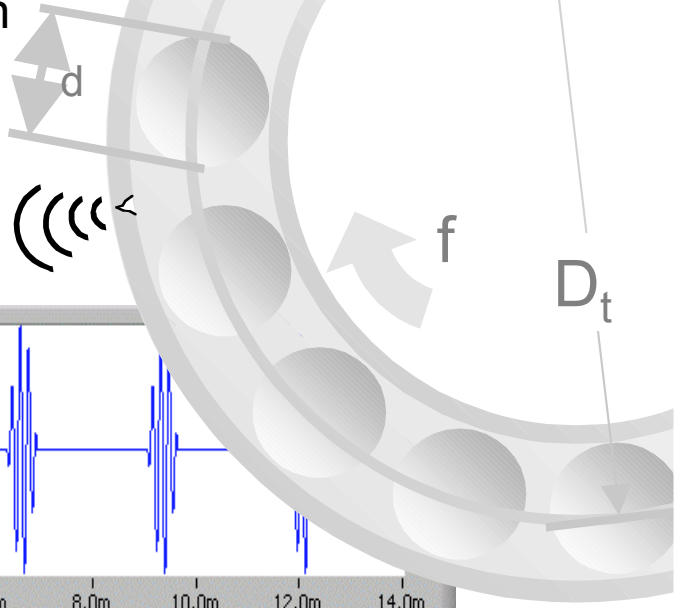
Land of the data-less

STFT

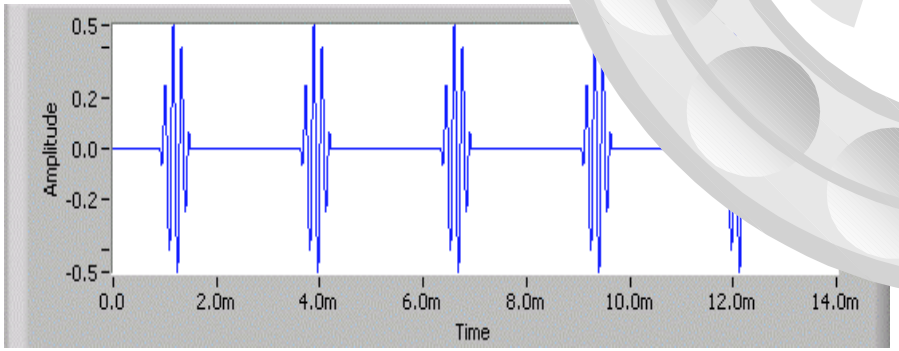


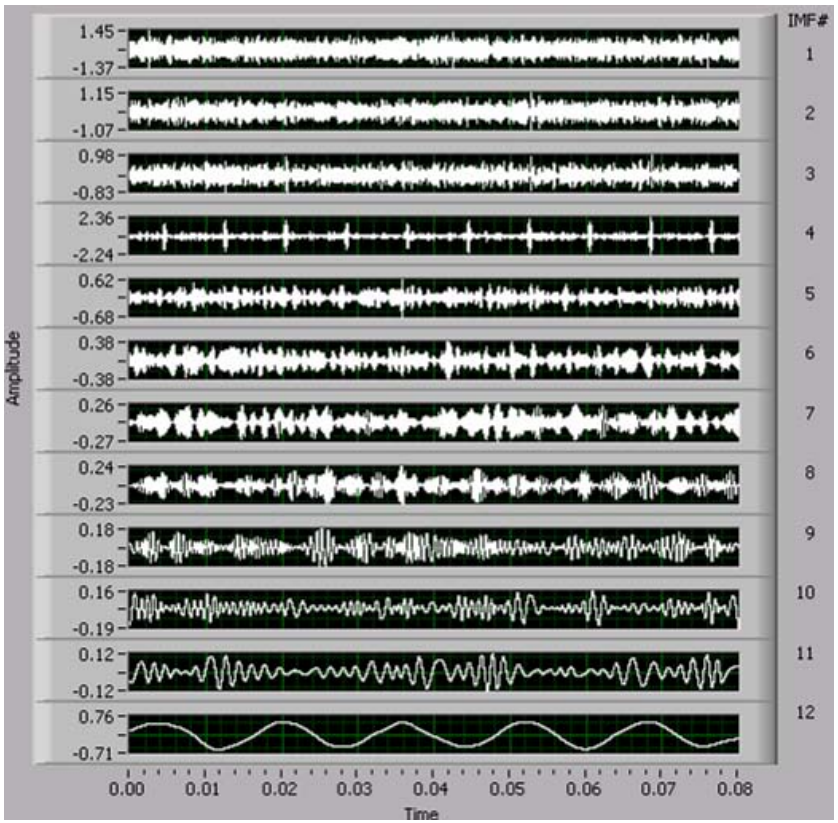


Envelope Detection (FFT)



Idealized Signal
(10 kHz @ 125 Hz rep.)

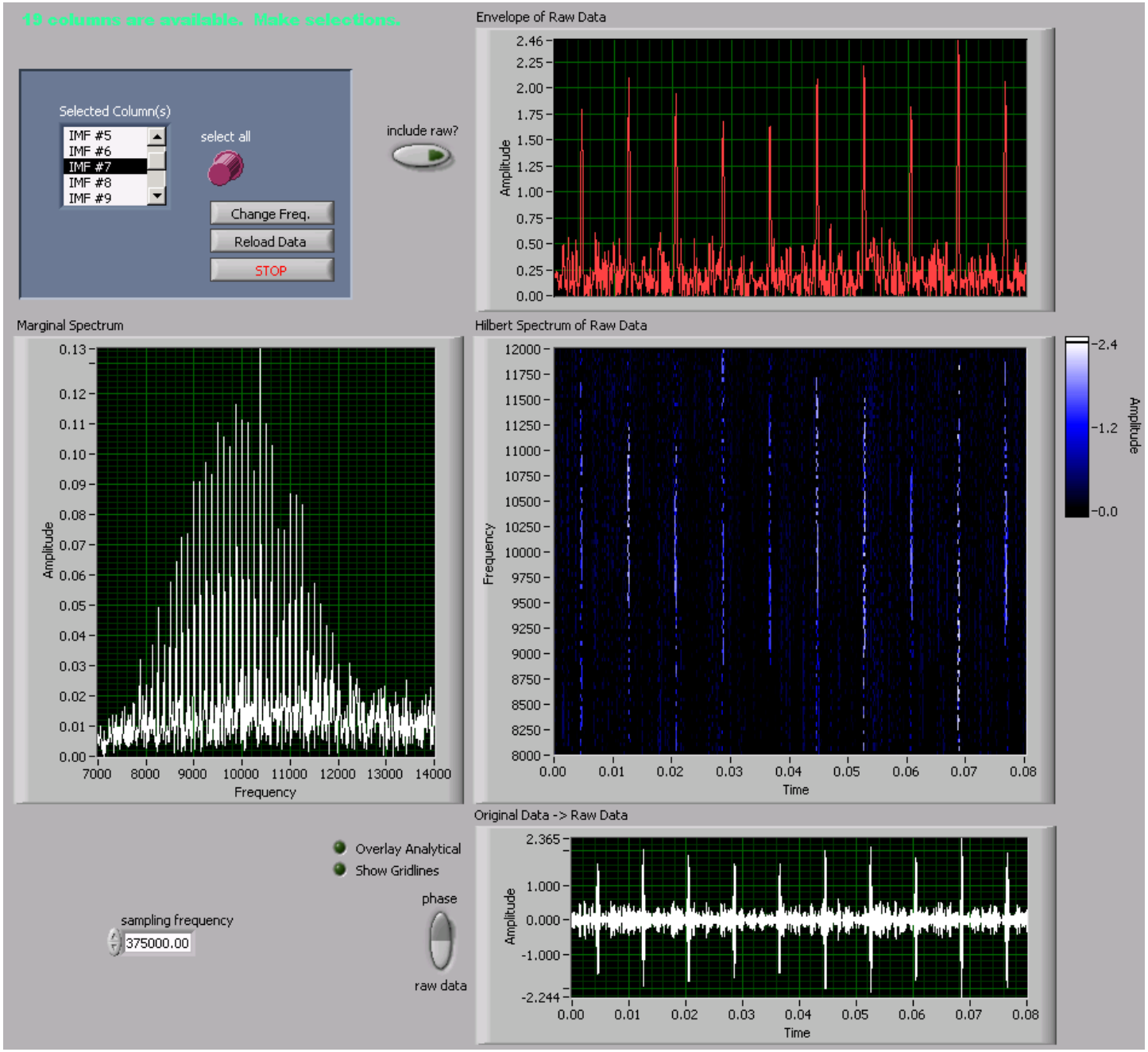




EMD Preprocessor

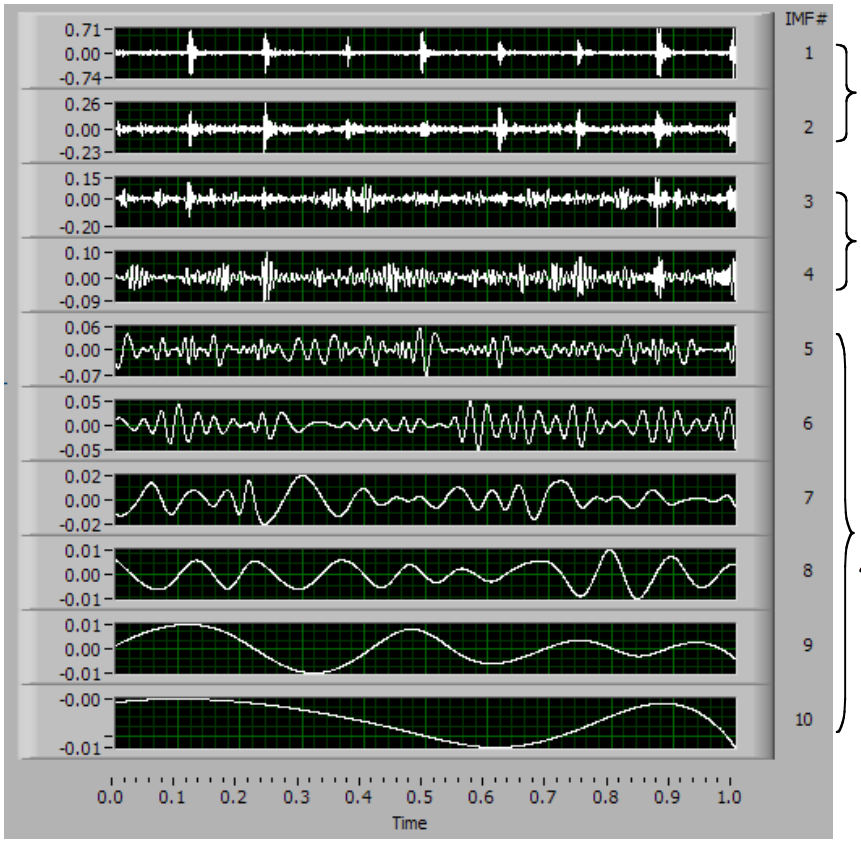
Sanity Check

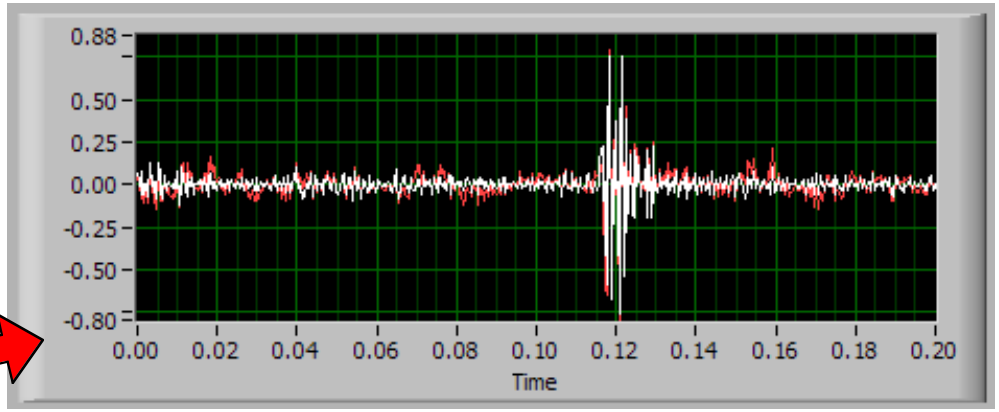
Hilbert Spectrum

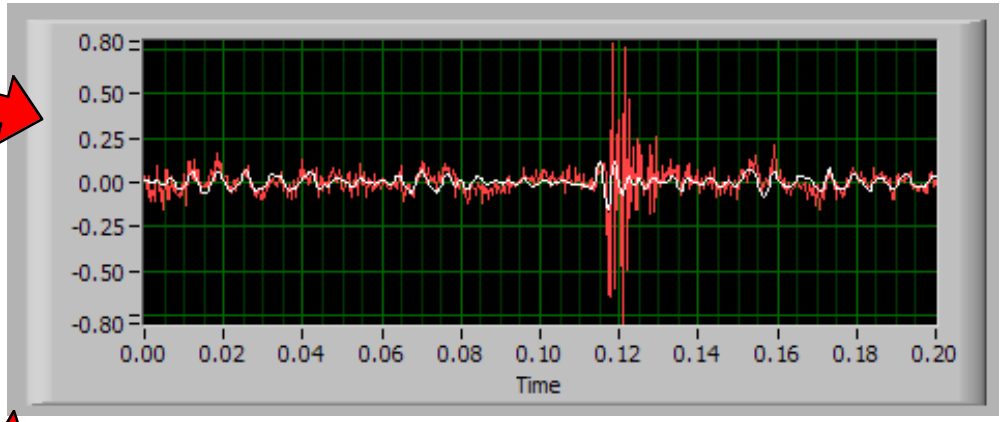


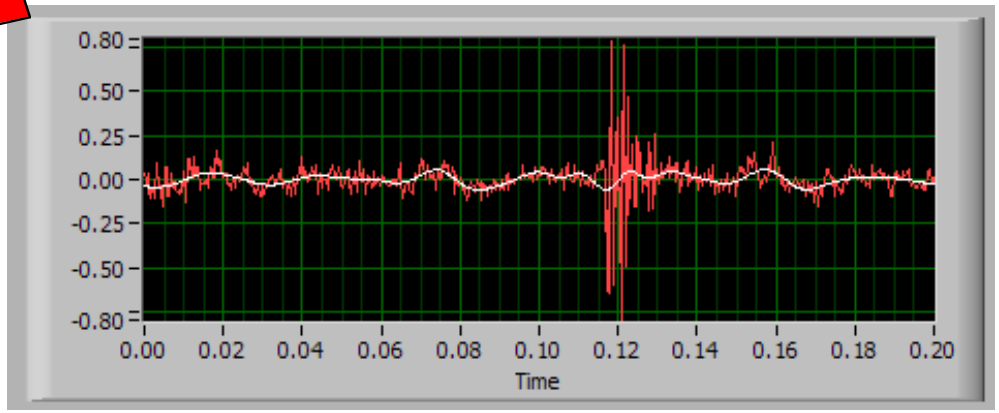
Fresh Data

Outer Ring Defect
(accelerometer, 750 RPM)



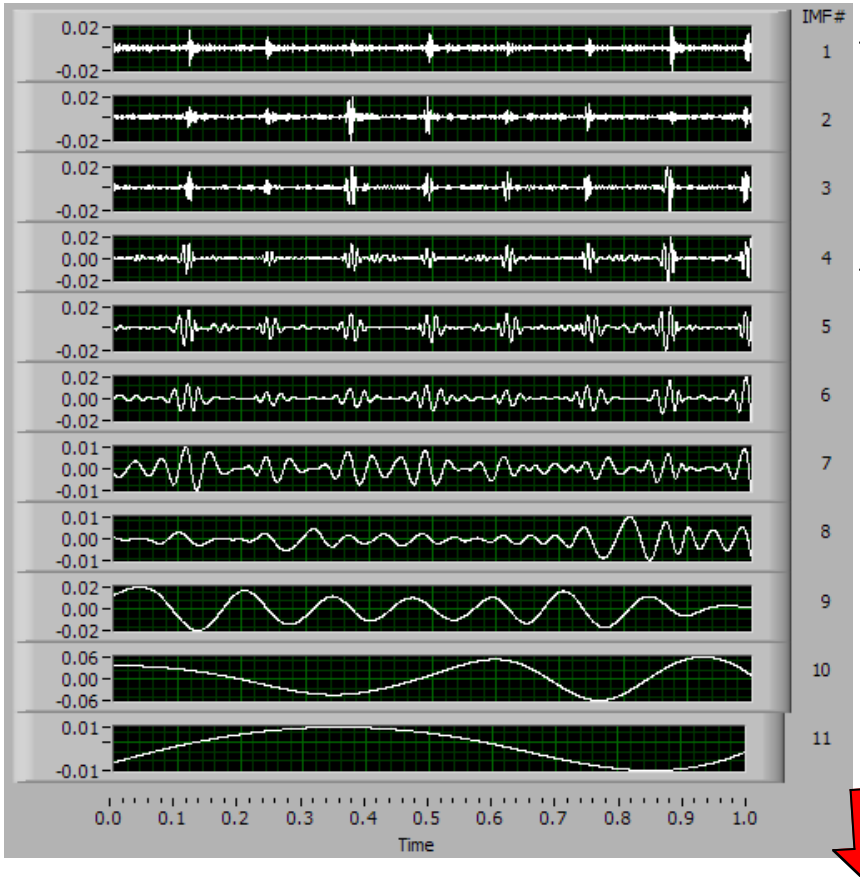


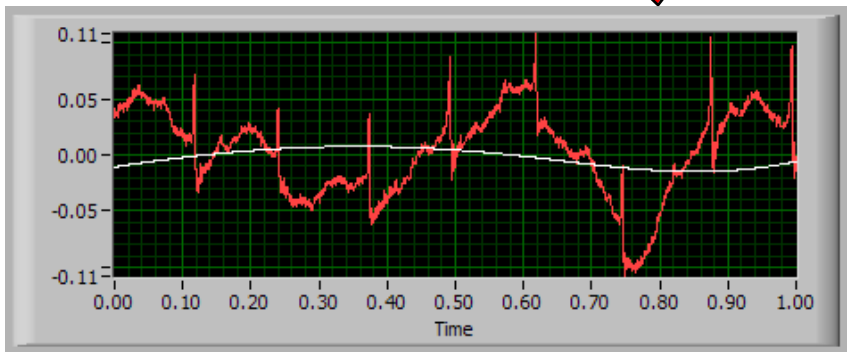


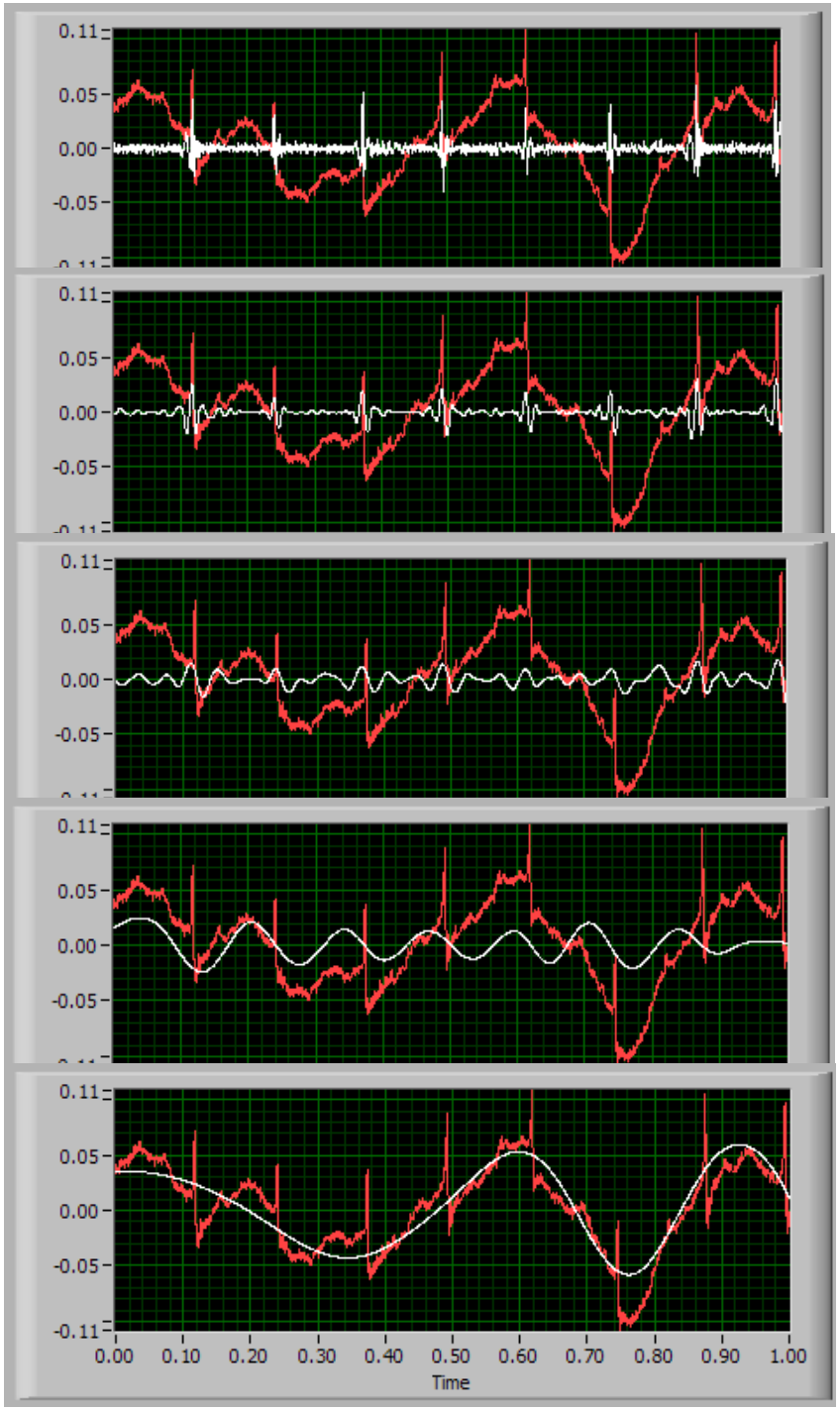


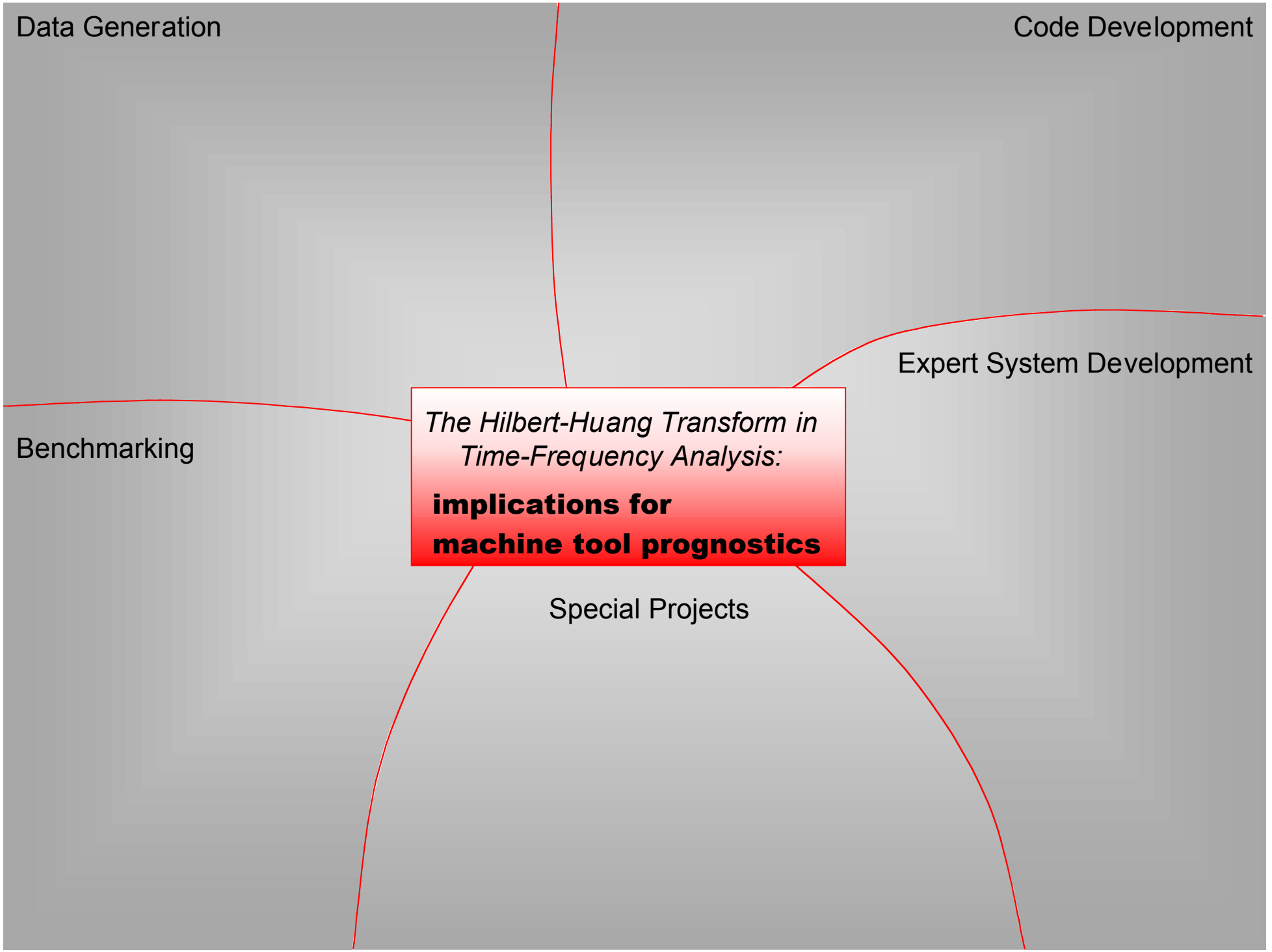
Fresh Data II

Outer Ring Defect
(piezo-film, 750 RPM)





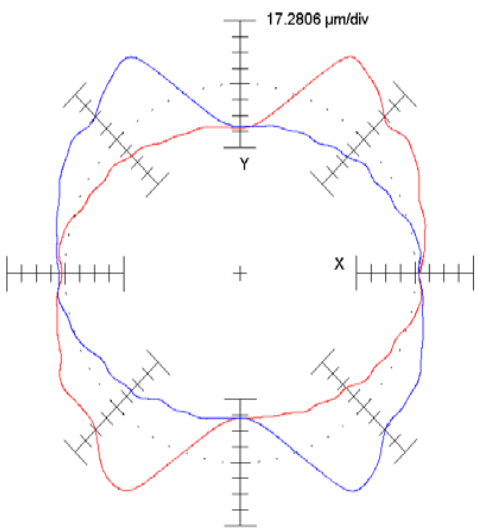


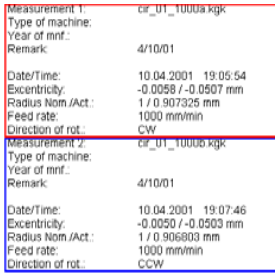

Data Generation
Code Development
Expert System Development
Benchmarking
The Hilbert-Huang Transform in Time-Frequency Analysis:
implications for machine tool prognostics
Special Projects

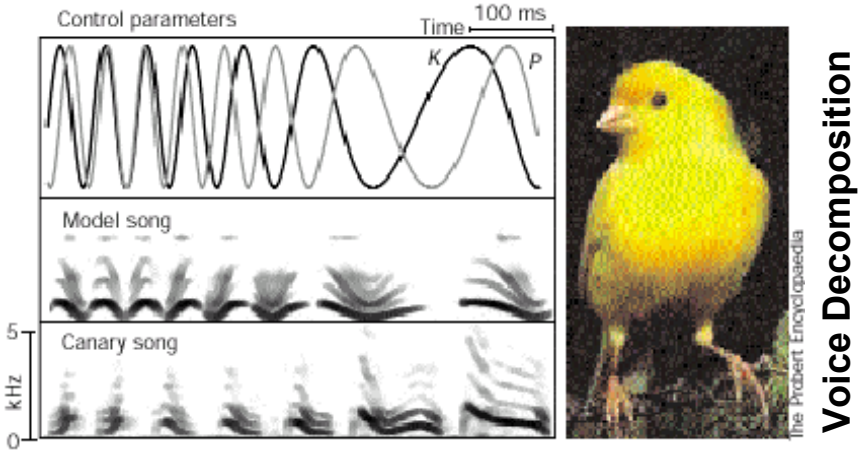
In our spare time…

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

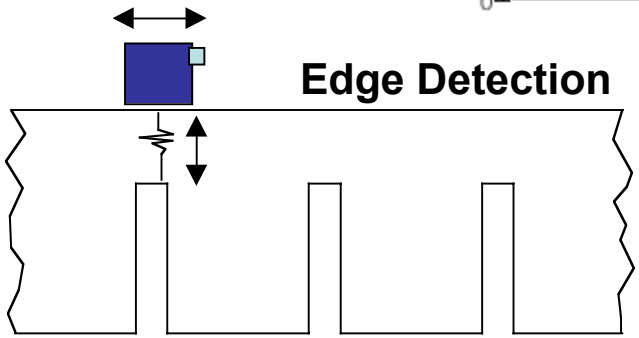
Circular Error

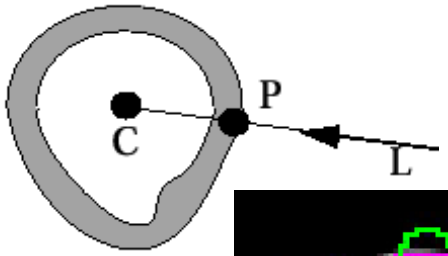






Edge Detection





Feature Identification

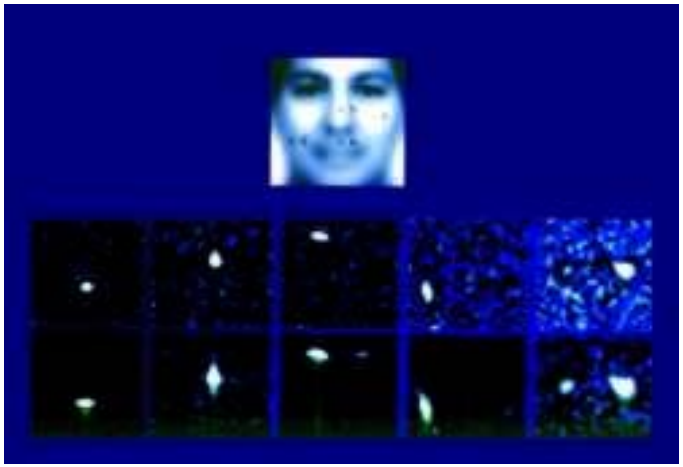
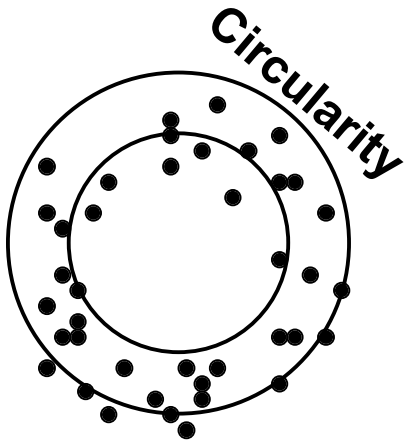
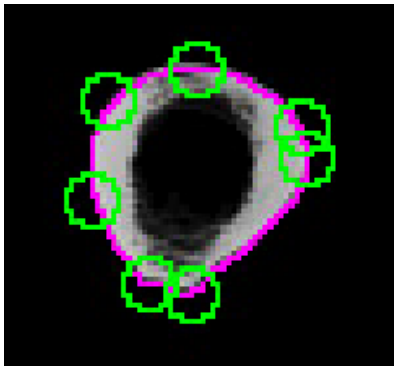


Figure: W.B. Scott, "Israeli Screening System Exploits Biometric ID," AWST, Feb. 25, 2002, p. 50.





CT Corner-Finding

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