A Leading Indicator enables better life test and prognostication

During life test, how to further reduce ("accelerate") test time and to provide earlier & richer feedback. During normal operation, how to use a leading indicator to prognosticate future failures, to sharpen maintenance, to improve system reliability. This describes a mechanical example, but these concepts are more widely applicable.

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Frequent challenges in life test & maintenance

Available test population is too few

Available test time is too short

Allowable stress exaggeration is too mild

Lifetime test results & engineering response are too late

Maintenance is expensive and disruptive

Mismatch between generality and specificity

- Often measure & estimate
  {Average status across population}
- Often need
  {Real-time status of specific unit}

Vision driving this work

Find a "Wideband Leading Indicator" for a specific mechanism of "Wear, Fatigue and Future Failure" (WF^3)

Validate and calibrate this Leading Indicator

During exaggerated ("accelerated") stress testing, also monitor this Leading Indicator. (patent pending)

- Thus provides better feedback, enables shorter life test

Compared to classical

- life test until manifest failure with exaggerated stress

During normal operation, also monitor this Leading Indicator. Thus

- Prognosticate future failures
- Guide conditional maintenance

Disclaimer: Please tolerate this presentation of novel work. Clearly this is a beginning, and much remains to do.

Overview of Presentation

1) Introduce VSA & MCSA
Vibration and Motor Current Spectrum Analysis

2) Leading Indicator to enhance ALT and HALT.
=> Briefer tests, better feedback (patent pending)

3) Generalize to other mechanisms for Wear, Fatigue, and Future Failure

4) Leading Indictor enable conditional maintenance
=> prognostication, time-elective and unit-selective

5) Conclusions

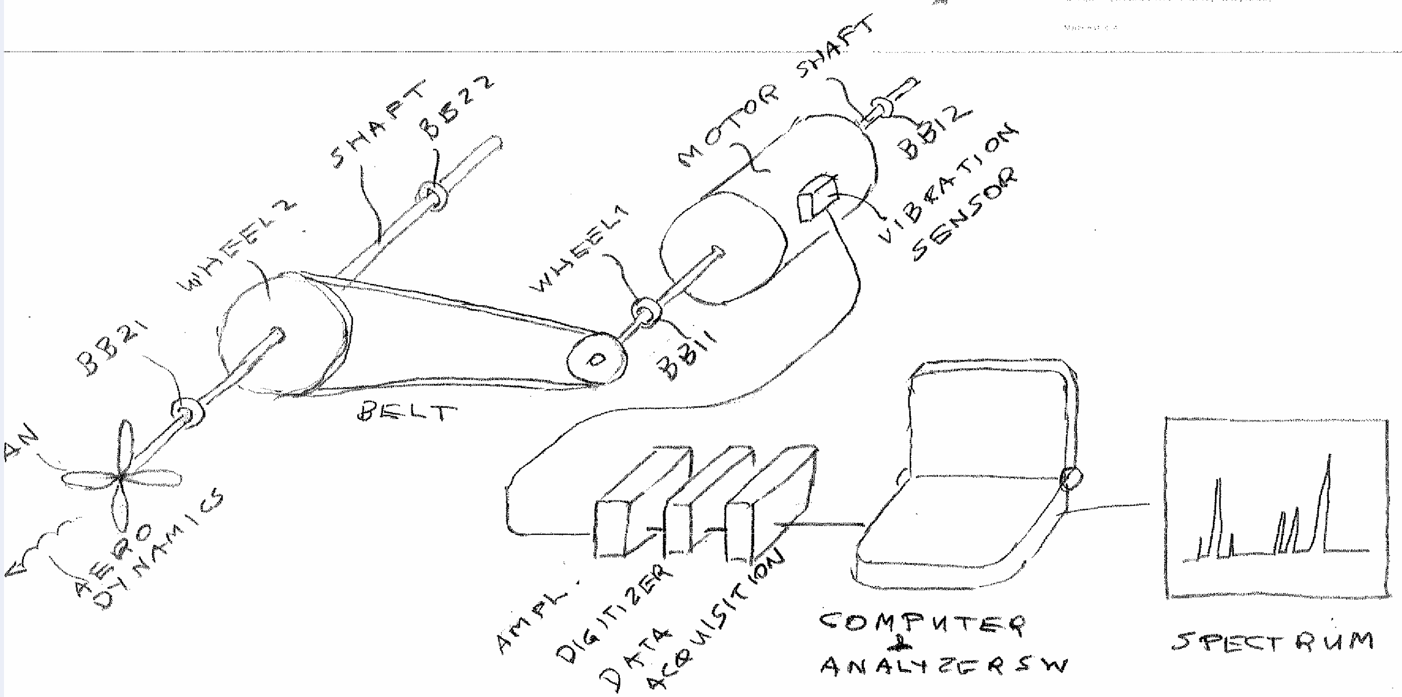
Introduce VSA 1
Vibration Spectrum Analysis

VSA for mech. rotary system uses accelerometer and signal analyzer to sense vibrations. For many dynamic modes, VSA readily enables mode separation, identification, measurement, monitoring

VSA was/is well known in mechanical engng. & mech. maintenance but

VSA was not previously used in life test and rel. engng.

Introduce VSA 2
Vibration Spectrum Analysis



V.S.A. Vibration Spectrum Analysis can readily separate & measure many motions by separate frequencies

2007.11.02 AKZ

Introduce MCSA 1
Motor Current Spectrum Analysis

ASTR 2007

For an electrical motor and drive train, **MCSA** uses stator current as a sensor for drive train loads & vibrations

- From electrical motor, its stator current is demodulated, then fed into a signal analyzer.
- MCSA is more compatible cousin of VSA Vibration Spectrum Analysis

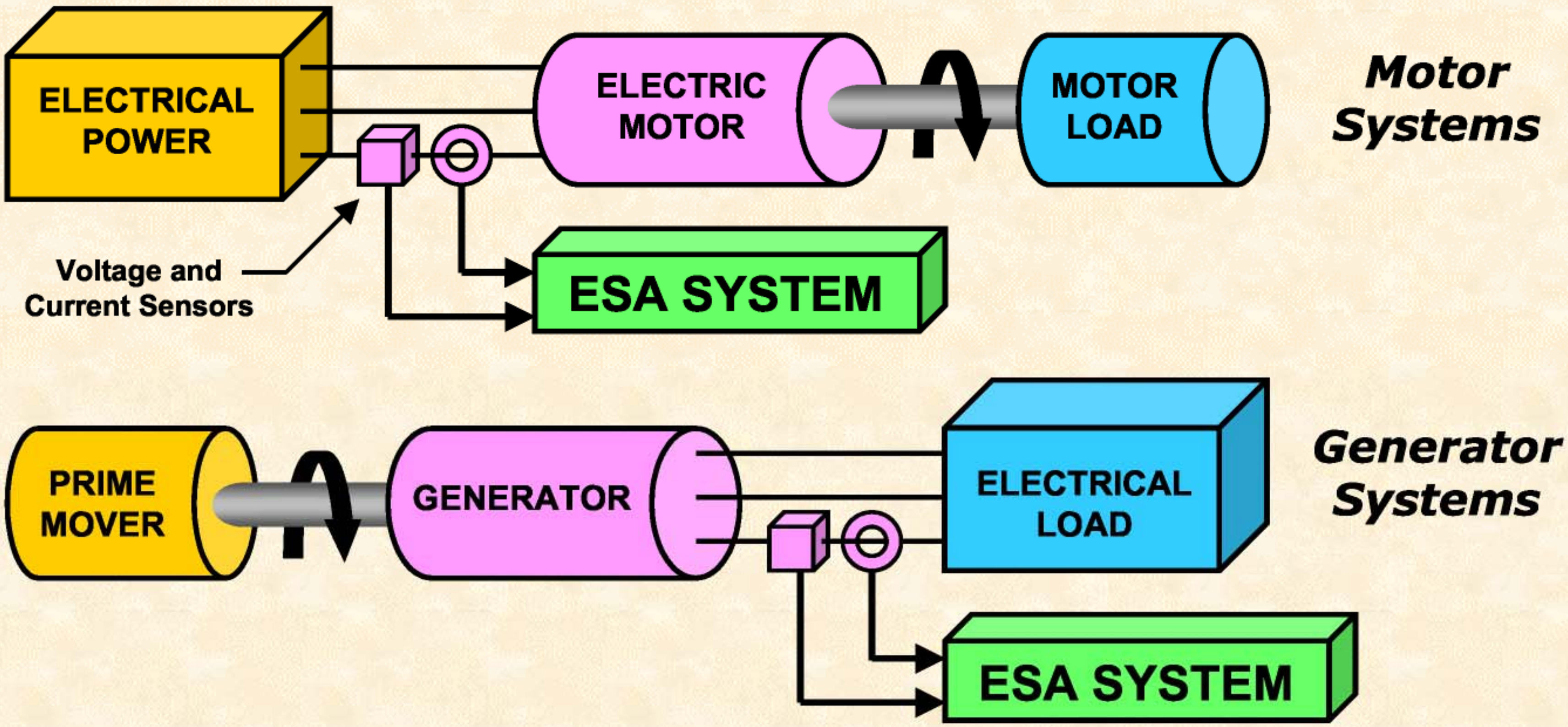
MCSA readily enables separation, observation, identification & measurement of many periodic modes

Oak Ridge National Lab. invented & developed MCSA for aircraft maintenance. They call it **ESA** Electrical Signal Analysis

MCSA is valuable for **conditional maintenance** in large systems: military, transportation, power, factories & more.

How Does ESA Work?

- A motor (or generator) of the system under test is used to provide diagnostic signals, much like a built-in transducer.

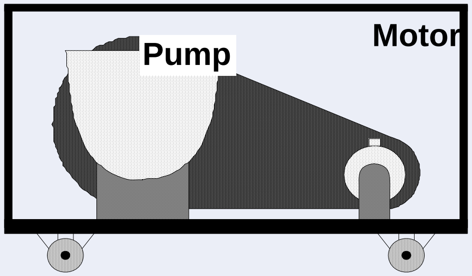


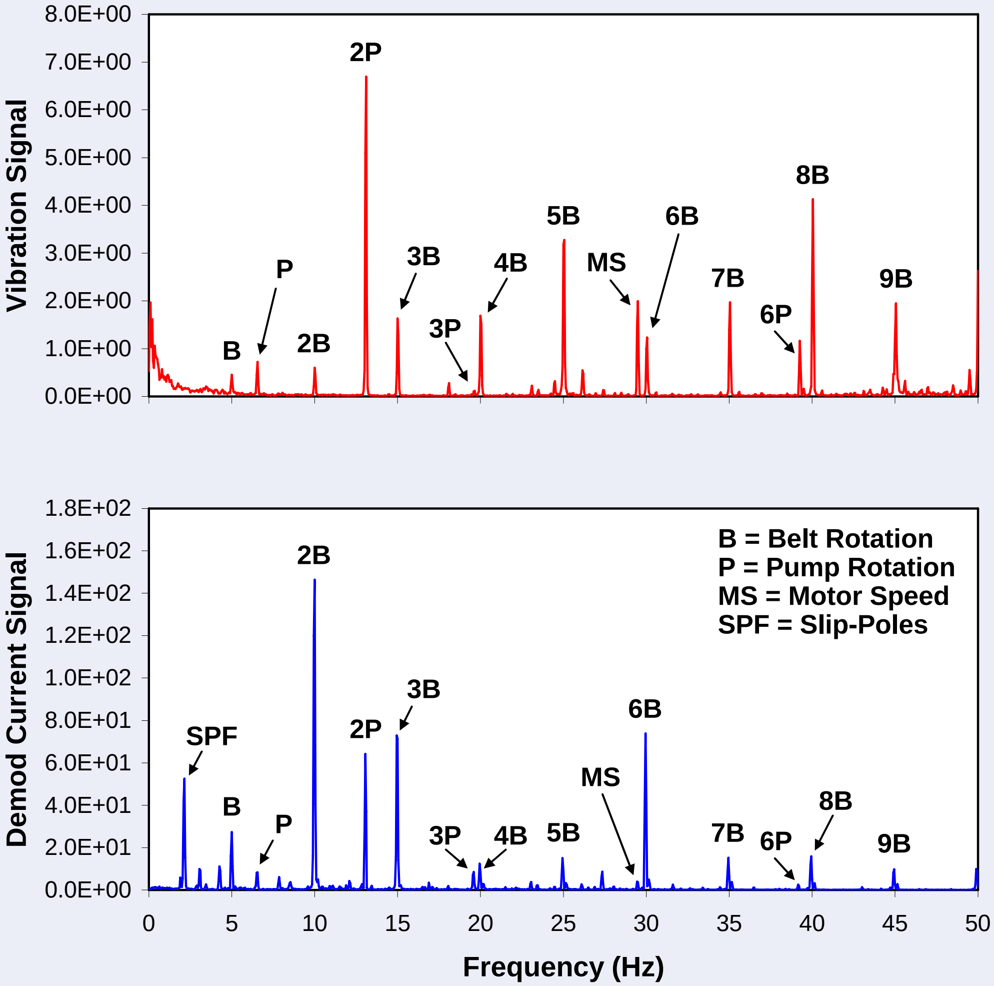
- Variations in electric current or voltage are analyzed and related to the electrical and mechanical condition of the tested system.

Compare VSA & MCSA

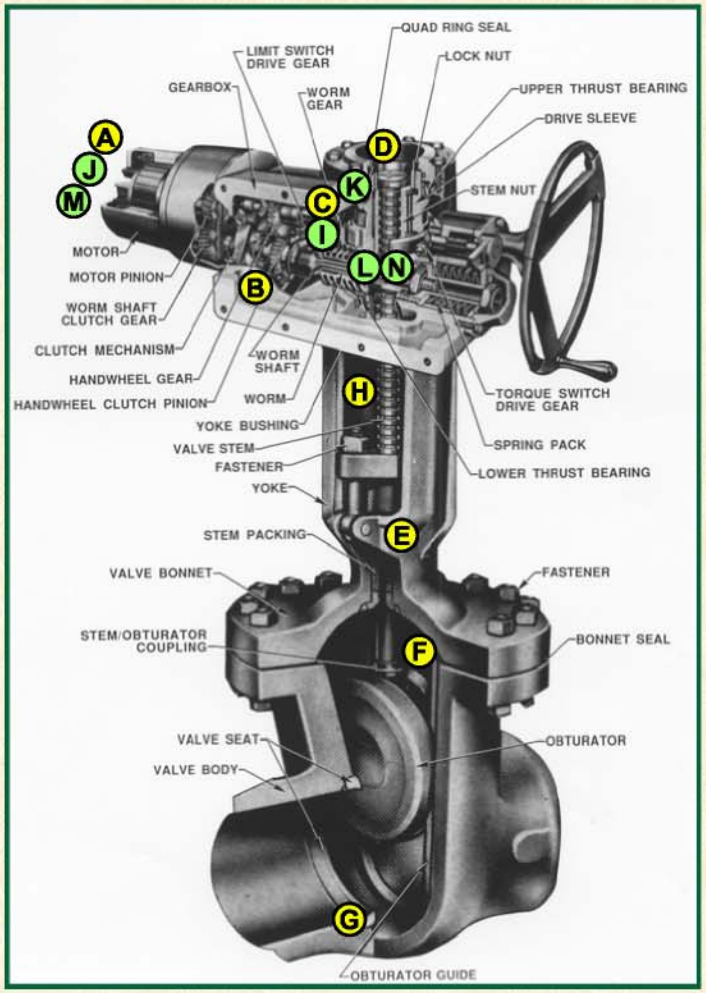
(example: vacuum pump)

- VSA uses explicit vibn. sensor
- MCSA uses demodulated stator current
- Periodic mechanical events associated with the motor, belt, and pump produce periodic vibrations and periodic variations in motor stator current.
- All key mechanical events are sensed by both the accelerometer and motor current.



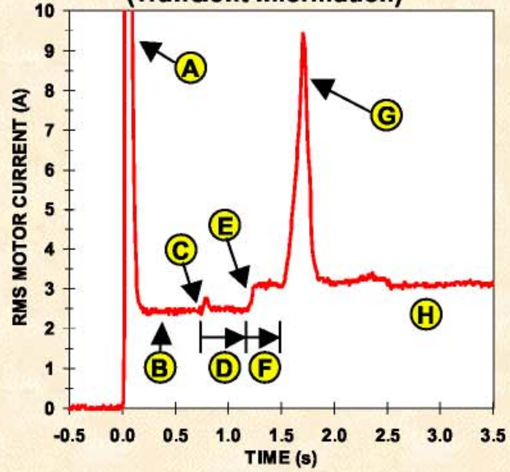


ESA Can Reveal Detailed Information at the Subcomponent Level



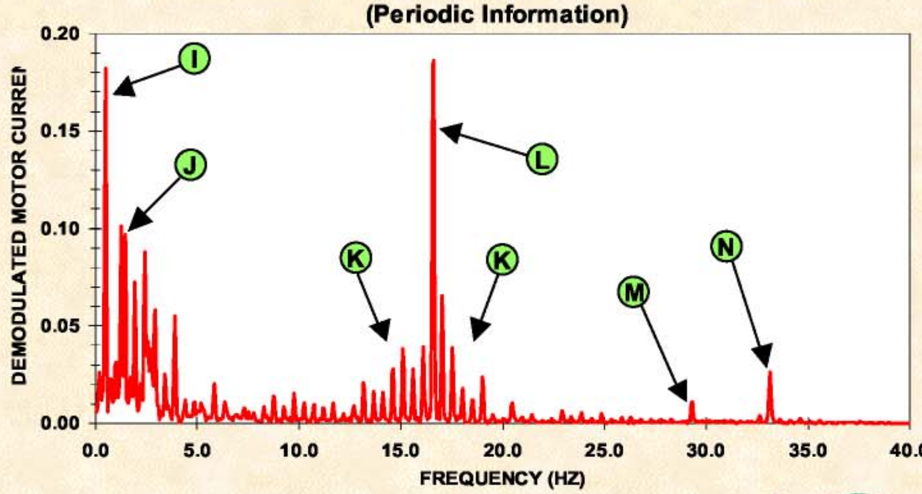
Motor-Operated Valve

Motor Current Time Waveform
(Transient Information)



- (A) Motor inrush current
- (B) No - load current
- (C) Hammerblow current
- (D) Stem nut clearance time
- (E) Packing drag current
- (F) Stem coupling time
- (G) Unseating current
- (H) Total running current
- (I) Worm gear rotation
- (J) Motor slip
- (K) Worm gear rotation sidebands
- (L) Worm gear tooth meshing
- (M) Motor speed
- (N) Worm gear mesh harmonic

Demodulated Motor Current Frequency Spectrum
(Periodic Information)



Overview of Presentation

1) Introduce VSA & MCSA

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2) Leading Indicator to enhance ALT and HALT.

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4) Generalize to other mechanisms for Wear, Fatigue, and Future Failure

4) Leading Indictor enable conditional maintenance

=> prognostication, time-elective and unit-selective

6) Conclusions

WF^3: Wear, Fatigue and Future Failure 1

"WF^3" = "Wear, Fatigue, and Future Failure"

VSA or MCSA can easily observe dynamics and WF^3 of drive-train etc:

- WF^3 of Bearings
- WF^3 of Drive Belt, Drive Chain, Drive Shaft
- WF^3 of Pulleys & Shafts
- WF^3 of Mechanical Loads
- WF^3 of Frames & Supports
- WF^3 effects of Alignments, Adjustments, Pathologies

Systems vintage 2007 often include a pre-amortized digital network. Often this can be adapted to measure & monitor VSA or MCSA

WF^3: Wear, Fatigue and Future Failure 2

To understand WF^3 process, compare

- Using MCSA or VSA to observe WF^3 versus
- Using failure histogram to summarize WF^3

Compare bandwidths relevant to WF^3:

- BW (Electronics) is giant
- BW (MCSA or VSA measurement) is moderate
- BW (WF^3 mechanism) is small
- BW (Failure histogram measurement) is microscopic

Wide BW potentially enables MCSA or VSA simultaneously

- to monitor, separate, observe, track many mechanisms for WF^3
- to provide much more information & insight into WF^3
- compared to failure histogram

WF^3: Wear, Fatigue and Future Failure 3

MCSA & VSA each offer:

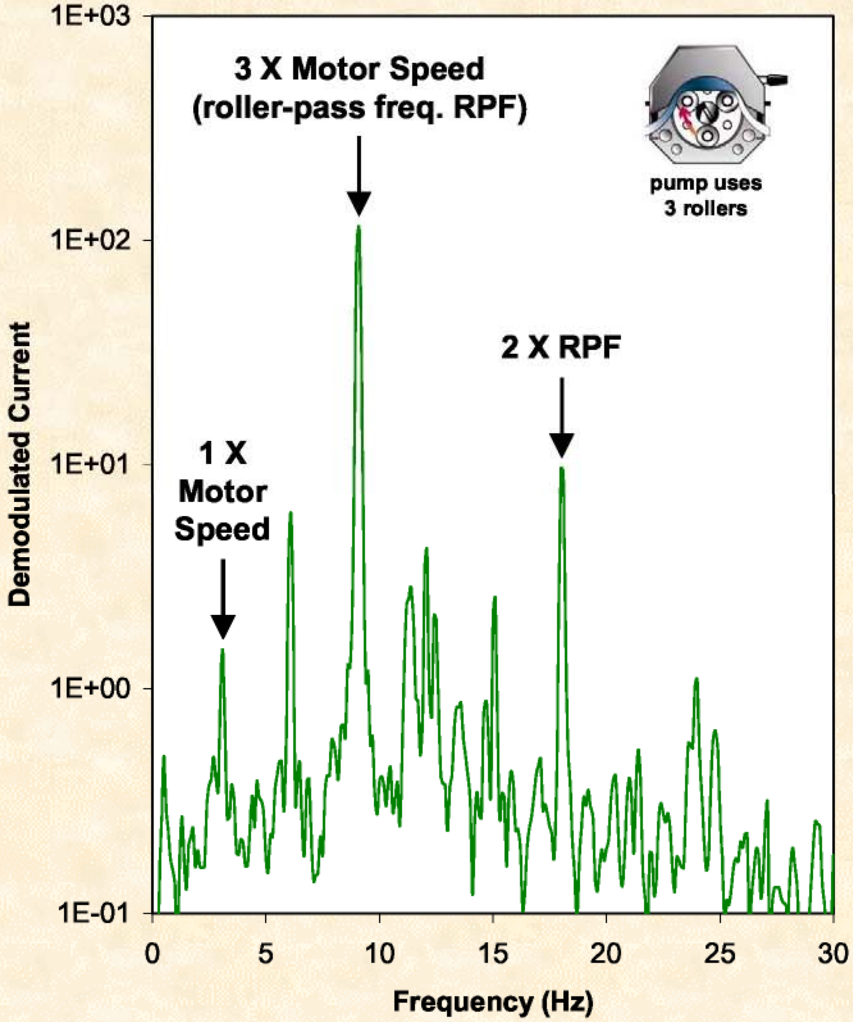
- Wideband observation of WF^3 mechanisms
- Contemporary indication of wear
- Leading indicator of future failure

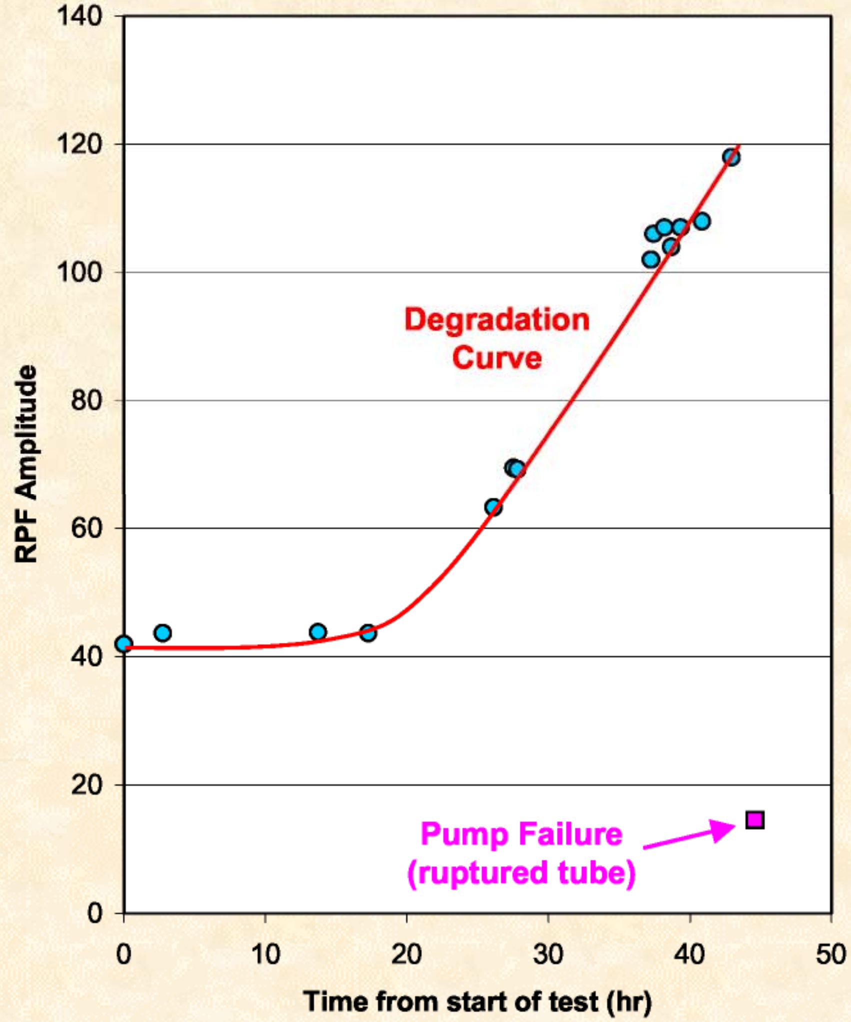
These properties are useful for reliability engineering & generalization

This wideband “Leading Indicator” needs
to be calibrated against future failure

ESA Can Detect Changes in Component Condition Before Failure

(example: peristaltic pump)





These provide important potential

Calibrate a Leading Indicator 1

How to calibrate a Leading Indicator against Future Failure

In an preliminary test, use an early-version subsystem

with a simulated exaggerated load:

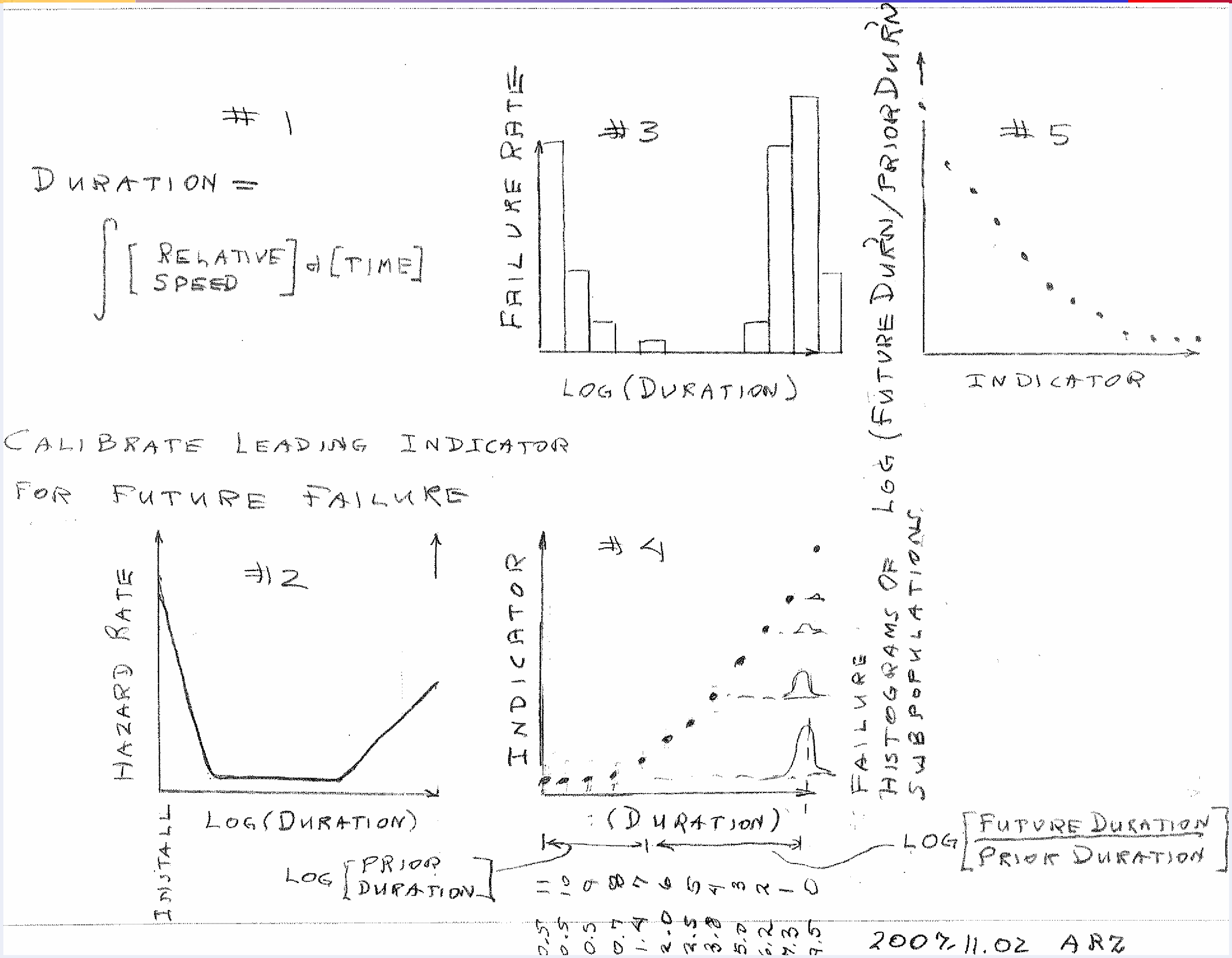
[1] Use MCSA or VSA to measure spectrum

[2] Identify each peak in spectrum

[3] Select most relevant peak(s)

[4] Measure and calculate peak strength (peak area or height or width)

Calibrate a Leading Indicator 3



Calibrate a Leading Indicator 2

Throughout calibration test (first reliability & lifetime test),

especially accelerated stress test on an early subunit:

[5] Measure duration. Duration is the operating time integral, adjusted for duty factor and load intensity

[6] Draw graph of measured peak strength versus operating duration

[7] Draw histogram of cumulative failures versus operating duration

[8] Compare these two graphs

Thus calibrate Leading Indicator against Future Failures

Subsequently use this Leading Indicator & Calibration

to predict (prognosticate) Future Failure

Useful Implications of a Leading Indicator 1

Construct and compare

- Graph of measured indicator versus operating duration
- Histogram of measured failures versus operating duration

In some cases, **both are “bathtub curves”**

- Both show **SAME** intervals for wear-in, useful lifetime, wear-out
- Both show **SAME** mechanism for WF^3

Advantages, compared to failure histogram for same WF^3

- Leading Indicator provides earlier data about WF^3
- Leading Indicator provides richer data about WF^3

Useful Implications of a Leading Indicator 2

Useful Implications

Context: Testing until manifest failure often is difficult, slow, costly, although desirable

Calibrate & Predict: Calibration establishes measurement as Leading Indicator for specified mechanism for WF^3. Thereafter use “to prognosticate” future operating duration until future failure

Life Testing Advantage: During life tests, Leading Indicator eases need to test until manifest failure

- Test each specimen until Leading Indicator predicts future failure (“prognosticated failure”)
- Enables test to operate until “prognosticated failure”, rather than operating until manifest failure

Multiplication of test-time (acceleration) factors:

- Exaggerated stress reduces (accelerates) test-time until manifest failure
- A Leading Indicator reduces (accelerates) test-time until prognosticated failure
- We propose using both simultaneously for life testing (patent pending)
- In some cases, the WF^3 mechanism is one-dimensional
- Therefore time-reduction (acceleration) factors combine by multiplication
- This can be quite useful: (1/8) * (1/3) = (1/24)

Sharper observation of WF^3 with a Leading Indicator 1

Medical analogy: Medical checkup that is personal & frequent typically tells more about a patient than actuarial tables

Automotive Analogy: Buying a used car incurs uncertainty:

- {A familiar car you have owned & driven for many miles} versus
- {An unfamiliar car of a similar model and similar mileage}
- For the original owner & driver, a familiar car is more predictable than a unfamiliar car with same model & same vintage

Leading Indicator (L.I.) with calibration provides better insight into WF^3, rather than classical testing and failure histogram

Sharper observation of WF^3 with a Leading Indicator 2

Leading Indicator (L.I.) provides better feedback

- This provides wide-band feedback throughout product life
- Classical failure test typically provides just time to failure

L.I. may provide smaller measurement uncertainty:

- {Standard deviation of measured indicator}

often is narrower than

- {Poisson statistics of manifest failures}

L.I. may provide smaller intrinsic uncertainty: For an individual specimen, its WF^3 is

- {more predictable given an indicator that is leading, real-time and individual} versus
- {less predictable given only population-wide failure histogram}

Earlier calibration 1

Calibration of Leading Indictor often can be done ahead of final complete system. See “Early Reliability Test” also at ASTR07

- Calibrate subsystem with a L.I. and exaggerated load or stress to simulate the remainder of system
- Validate & calibrate L.I. against manifest failure of subsystem
- Often may use an early-version subsystem and/or prior-generation full system
- Often does NOT require final hardware, complete system, overall tests

Thus L.I. calibration can precede eventual test
of final subsystem and final total system

Earlier calibration 2 (backup slide)

Thus Leading Indicator eases need to test until manifest failure

If and when this subsystem is revised, Leading Indicator and Calibration may be easy to reuse, or at least easy to rerun

In some cases, a subsystem(s) will:

- will be completed, finalized and available ahead of the overall system
- will enable early testing for reliability, lifetime & leading indicator calibration

Earlier calibration 3 (backup slide)

In many cases, when overall system eventually is completed, finalized and available:

- There will NOT be significant change in this subsystem or in calibration of indicator versus duration
- There MAY be change in the load or stress that exercises this subsystem

Therefore:

- Re-use prior calibration of leading indicator versus duration,
- But may change duration versus operating time

Useful implications of Leading Indicator 3

Some challenges

- Available test population is too few
- Available test time is too short
- Time reduction (“acceleration”) by stress exaggeration is too constrained to for ALT
- Test results and engineering response are too late

Are mitigated by Leading Indicator (L.I.)

- Calibrate L.I. before final testing
- L.I. enables life test to prognosticated failure
- (L.I. & Exaggerated Stress) => Stronger reduction in test time
- L.I. provides richer feedback

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=> prognostication, time-elective and unit-selective

5) Conclusions

Acknowledge & differentiate

This work started with Motivation and Vision (Slides 1 & 2)
then later learned about prior technologies, esp. MCSA

Previously mech. engrs., maintenance engrs., and ORNL had:

- created and developed VSA and MCSA
- created and developed conditional maintenance for mechanical and electro-mechanical systems

By contrast, to combine a Leading Indicator with ALT and HALT is new

Some Generalizations 1

Similar analysis works in various mathematical contexts

- External periodic excitation & Fourier analysis
- Pulse mode excitation & Laplace analysis
- External random excitation & Autocorrelation analysis

Similar indicators work in various physical contexts

- Self-driven signal: Ultrasonic emission indicates stress cracking
- System-driven signal: VSA
- Probe-driven signal: Ultrasonic microscope indicates solid-state fatigue
- Engineered signal: Stator current monitor in MCSA

Some generalizations 2

This presentation described VSA and MCSA
for mechanical & electro-mech rotary system

Beyond this, we know other wideband Leading Indicators

for other mechanisms for WF^3,

but these are not yet ready to present:

PWB Flexing, Cracking, De-adhesion

Pwr. Converters

Organic Elect. Pkgs.

and more

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    (Present xor skip depending on timing)

5) Conclusions

Smarter maintenance with a Leading Indicator 1

During normal operation: Measure & interpret Leading Indicator (L.I.)

Prognosticate: For each individual unit during real time operation, use L.I. to predict individual duration (time) until future failure

Conditional Maintenance :

- Some units are “vulnerable”: prognosticated to fail in near future
- Service ONLY vulnerable units
- For non-vulnerable units, do not service now

Smarter maintenance with a Leading Indicator 2

Time-elective advantages:

- Generous fore-warning
- Maintenance may be scheduled conveniently

Unit-selective advantages:

- Maintenance is based on specific measurements rather than averages and generalizations
- Maintenance is **not** unconditional on at all units
- Maintenance is **aimed** at units with most wear and fatigue
- Reduces maintenance expenses

System advantages with a Leading Indicator 1

Leading Indicator, prognostication & conditional maintenance enable higher reliability for total system

- compared to system-wide uniform pre-scheduled maintenance

Nevertheless these reduce maintenance costs

- Incurs less labor, less disruption, fewer spare parts

System advantages with a Leading Indicator 2

For specified mechanism for WF^3 during specified future interval, this may provides strong assurance of non-failure

- Because of large BW, an indicator can simultaneously monitor several mechanisms for WF^3
- However, this does not preclude failure due to unnoticed WF^3 mechanisms or failure during later intervals

Also this provides richer feedback for product iteration

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Conclusions 1

Wide-band indicators allow use of spectrum analysis to separate modes

Leading indicators are defined as measurements that correlate with future events, especially future failures

VSA = Vibration Spectrum Analysis for mech. rotary sys.

MCSA = Motor Current Spectrum Analysis for electro-mech rotary sys.

These are

- Real-time indicators for wear and fatigue
- Leading Indicators for future failure
- Often quite informative, compatible, economical, useful

Conclusions 2

During reliability & life tests, use a Leading Indicator to reduce ("accelerate") test time

- Distinct from exaggerated stress to reduce test time
- These two methods can be used individually
- Even better, use both simultaneously (Pat.Pending)
- This can provide especially large reduction in test time

During operation, use a leading indicator for real-time monitoring of individual units. This enables prognostication

- => better maintenance
- => better system reliability

Conclusions 3

Our later work moves beyond
mechanical and electro-mechanical systems

Analogous techniques are known and useful for power electronics, analog signal electronics, digital signal electronics, and more

We are interested in cooperation

- on life test & prognostication
- for diverse applications
- with diverse colleagues

Please contact us!

Short Bibliography

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