Use of Tach from Vibration to Estimate Bearing Spall Length

Eric Bechhoefer[1], Omri Matania[2], and Jacob Bortman[3]

[1]*GPMS International, Inc, Waterbury, VT, USA*
eric@gpms-vt.com

[2,3]*Ben-Gurion University of the Negev, Isreal*
omrimatania@gmail.com
jacbort@bgu.ac.il

ABSTRACT

Vibration analysis is often used for bearing fault diagnostics. Envelope analysis or other cyclo-stationary processes can capture a fault feature or condition indicator that is correlated to the spall length. However, no study has defined a process for estimating spall length on real-world data. The problem is that the spall length is a time-domain property of the signal. This paper generates a synthetic tachometer signal from the fault itself. It is synchronous to the rolling element exit from the spall, allowing for a time-domain representation of waveform using the time synchronous average. From this, an estimate of the length of the bearing fault can be determined.

1. HEALTH AND USAGE MONITORING SYSTEM OBJECTIVES

One of the objectives of a Health and Usage Monitoring System (HUMS) is to identify degrading drivetrain components, such as rolling element bearings. Rolling element bearing failures form one of rotating equipment's most critical failure modes. Even though vibration analysis has been successfully used for bearing fault detection and diagnostics for years, it typically does not estimate the spall length of the bearing. Some studies have used simulation or notched bearing faults on a test stand to estimate spall length, but few methods have been used to estimate spall length in real-world systems.

An estimate of the spall length would provide insight into the degrading reliability of a drivetrain as the fault propagates. This would improve the timeliness of scheduling a maintenance action. In this paper, the time domain features associated with the rolling element (RE) entry and exit into the spall can be used to estimate the spall length.

The RE–spall interaction generates an impact event in the time domain. These features are typically not visible due to the superposition of other various signal sources (gear mesh, shaft modes) within the gearbox. While a bearing signature may have a peak-to-peak value of 0.3gs for a fault, gear mesh could be 10x this value. One signal separation method in the time/angular domain is the time-synchronous average (TSA). However, the TSA is ineffective in extracting these features associated with a bearing because there is typically no tachometer on the bearing cage. The bearing elements are asynchronous to the shaft they support because of the RE non-Hertzian contact with the inner and outer races.

Eps (1991) observed acceleration of the RE associated with the RE passage into and out of the spall. This consisted of a step response for the RE entering the spall and an impulse response for the RE when exiting the spall. The step response (entry into the spall) had less frequency content than the impulse response. The impulse response of RE on the exit of the spall is broadband. The impact generates a high-frequency, cyclo-stationary response, as was reported by Antonni (2009).

Building on Eps, Kogan et al. (2017), in "A new model for spall-rolling-element interaction," developed a simulation model of the interaction of the RE entry and exit from the spall. This suggests that using acceleration data, it would be possible to estimate the spall length as a time domain feature. The length of the spall would be the difference in time from the entry and exit into the spall. This time difference is then multiplied by the shaft rate and the circumference of the race (inner or outer) to give an estimate of the spall length.

From the bearing's equation of motion, the fault frequency is:

$$f_{ir} = {}^{N}\!/_{2}\, f_{shaft}\left(1 + {}^{D_{RE}}\!/_{D_p}\, cos(\beta)\right) \tag{1}$$

$$f_{or} = {}^{N}\!/_{2}\, f_{shaft}\left(1 - {}^{D_{RE}}\!/_{D_p}\, cos(\beta)\right) \tag{2}$$

$$f_{cage} = {}^{1}\!/_{2} f_{shaft}\left(1 + {}^{D_{RE}}\!/_{D_p} cos(\beta)\right) \quad (3)$$

Here, N is the number of rolling elements, D_{RE} is the rolling element diameter, D_P is the bearing pitch diameter, β is the contact angle, f_{shaft} is the shaft rate, and f_{ir}, f_{or}, and f_{cage} are the inner race, outer race, and cage rates. By rearranging terms:

$$f_{ir} = N \times (f_{shaft} - f_{cage}) \text{ and } f_{or} = N \times f_{cage} \quad (4)$$

If both the shaft and cage rates are known, the fault frequency for the inner and outer races can be found. While the shaft rate is usually known, instrumenting the cage with a tachometer sensor is impractical, except in the laboratory.

Bonnardot demonstrated the use a gearbox's accelerometer signal to generate a TSA's tachometer signal. This is usually done with a signal associated with a gear mesh. However, Siegel et al. (2012) used this technique to extract the fault frequencies associated with a bearing spall and used this to calculate the magnitude envelope energy. In "Estimating the Fault Size using Vibration Analysis," Wang et al. used the "Tach from Vibration" processing to generate a tach, then used this tach signal with the envelope squared signal and the TSA to generate a time domain representation of the RE element features. This work was done on a test stand, not with a naturally occurring fault in a gearbox. Additionally, the determination of fault length was not easily observed.

In this paper, the spall length is easily detected and calculated using the absolute value of the Hilbert transform of the acceleration data.

2. TACH FROM VIBRATION AND THE TIME SYNCHRONOUS AVERAGE

Bonnardot (2005) describes a method of using an acceleration signal of a gearbox to perform the TSA. The acceleration data is bandpass filtered around a gear mesh frequency; then, by taking the Hilbert transform to estimate phase, the phase is used to estimate zero-crossing time (ZCT). The phase data is calculated from the argument (arctangent) of the ratio of the imaginary value to the real value at each time index, i. Due to the nature of using the FIR (Finite Impulse Response) bandpass filter, spectral leakage reduces the SNR of the signal of interest. This paper uses an ideal bandpass to create an analytic signal in one functional procedure.

The pseudo-code to recover a tachometer signal from vibration (TfV) is:

- Define the sample rate = sr. The number of data points of vibration data, n = sr * the acquisition length in seconds (example: n = 6103.5 * 6 seconds, or 36621), then:
- Calculate the next larger radix-2 length for the FFT.
  - *nRadix* = 2^ceil(log2(n)) = 65536

Note: The signal of interest is derived from the envelop analysis, and it has been lowpass filtered and decimated, resulting in an effective sample rate of 6103.5.

- Calculate the low and high bandwidth index (*bwlow*, *bwhigh*), which are centered on the bearing fault feature. This would typically be +/- 2 percent of the fault feature frequency.
- Given the shaft rate of, say, 30.07 Hz and the fault feature rate of 9.28, the low and high frequencies bandpass limits are 273.49 to 284.64 Hz.
- Take the zero-padded FFT of the vibration data.
- Zero the FFT from zero to *bwlow*, and from *bwhigh* to *nRadix*

This indexing occurs in the frequency domain. Hence, in this example, the low index is floor(273.49/(6103.5 (the sample rate) x 65536, the length of the signal) or 2936, while the high index would be 3057. Hence, the Fourier transform only had frequency content from index 2936 to 3057, which contains only the inner race-bearing fault data.

- Take the inverse FFT, which generates the analytic signal.
- Calculate the unwrapped argument of the signal from 1 to n as a time series.
- Normalize the time series of radians by the fault feature ratio of the bearing fault (assuming 1st harmonics)
- Interpolate the number of indexes for every 2π radians. Each 2π becomes one zero cross-index.
- Normalized to tachometer zero crossing times by sr. This converts the zero-cross index to time.

2.1. Review of the TSA

Braun (1975) described the TSA analysis, which was perhaps first implemented for gearbox analysis in Stewart (R.M Stewart went on to develop perhaps the first HUMS). The time waveform signal to be averaged, *x(t)*, is digitized at a sample rate of *nT*, giving a waveform *x(nT)*, with an averaged period of *mT*, such that:

$$y(nT) = {}^{1}\!/_{N} \sum_{r=0}^{N-1} x(nT - rmT) \quad (5)$$

This is a linear filtering operation where it can be shown that the discrete transfer function is:

$$H(z) = {}^{Y(z)}\!/_{X(z)} = {}^{1}\!/_{N}\, {}^{1 - z^{-mN}}\!/_{1 - z^{-m}} \quad (6)$$

This is a comb filter, where the filter response is based on the number of averages, *N*.

This suggests that if the instantaneous frequency of, say, a gear mesh is somewhat different than the measured tachometer signal (due to jitter or some gear dynamic phenomenology), the gear mesh signal can become attenuated by the TSA.

Practically speaking, the TSA is a simple algorithm. The TSA resamples the vibration associated with a shaft or gear in the spatial domain, such that the vibration associated with each shaft order in the Fourier domain represents one frequency bin. For example, in a system in which the shaft rate is such that for a given vibration sample rate, the acquisition system, on average, collects 800 samples per revolution, the TSA would resample the 800 samples to 1024 data points (1024 is the next highest radix-2 value from 800). When applying the TSA to the Envelope, the order is relative to the bearing fault frequency (eq 1, 2).

The TSA has two contending issues in its application. First, as it is an average, the desired feature's SNR improves with 1/sqrt (revolutions). That is, the process gained by acquiring one second of data with a bearing fault rate of 273.5 is 12.2 dB (the test dataset uses a 30 Hz shaft rate, with an inner race fault rate of 9.28, e.g., about 273Hz). Consequently, if six seconds of data are acquired, the process gain would be 16.07 dB. However, the TSA, which can be modeled as a DC, FIR filter, is very sensitive to timing/jitter error. In Figure 1, the attenuation 3dB loss in signal from timing error for one second of data (in this example) is 0.45%. For the 1638 revs associated with six seconds of data, 3dB attenuation is just 0.07% error. The TSA needs an accurate zero-cross time.

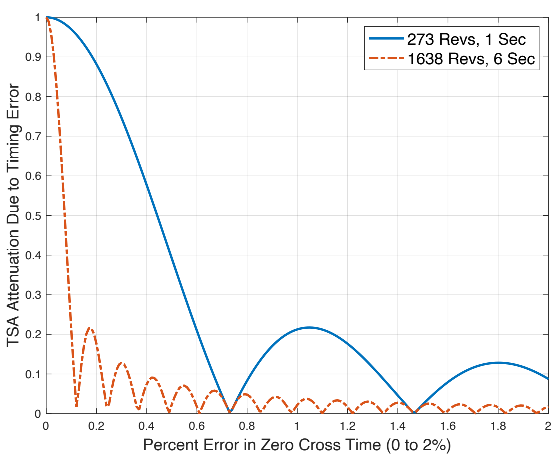

Figure 1 TSA Attenuation Due to Tach Error

3. THE TEST DATASET: 2.1 MW WIND TURBINE

This data was from an inner race fault on a 2.1MW wind turbine. The data was collected once per day on a propagating fault, with the bearing being pulled from service after 50 days of monitoring. This is a complex, three-stage, epicyclic gearbox with an output shaft rate of approximately 30 Hz and an inner rate of 9.28 the shaft rate.

The fault feature's ZCT measures the time between RE exiting the inner race spall. One TSA "revolution" is the inner race circumference divided by the number of rolling elements. The inner race diameter was 152mm and consisted of 29 RE; one TSA REV length is 16.5mm.

As presented by Wang, a correction factor is needed to model the entrance and exit distance of the RE into the spall. This factor (x) is a function of the ball diameter D_{RE} and the depth of the spall δ:

$$x = \sqrt{D_{RE}\delta + \delta^2} \tag{7}$$

Given the fault frequency of approximately 280 Hz and a sample rate of 97656 samples per second (*sps)*, the length of the TSA is 512, as per:

$$length = 2\text{\^{}}ceil(log_2\left({}^{sps}/_{freq}\right)) \tag{8}$$

From eq. 6 above, each TSA index is 16.5mm/512 or 0.032mm. If the start to end of the spall in the time domain is 130 points, then the spall length would be 130 x 0.032, or 4.16 mm.

3.1. High-Speed Bearing Inner Race Fault

The envelope analysis was performed on the raw, time-domain data over 50 days to identify the inner race fault feature.

This was done by taking the Hilbert transform of the raw signal, bandpass filtering the signal between 9 and 12 kHz, taking the envelope, and decimating the signal by a factor of 16. As the original sample rate was 97656, the decimated envelope's same rate is now 6103.5 (see TfV pseudo-code).

The envelop window was selected using Timoshenko's (1940) equation for the natural frequencies of a shell. Timoshenko teaches that for a ring with uniform mass, the exact shape of the mode of vibration consists of a curve, which is a sinusoid on the developed circumference of the ring.

The natural frequencies are then:

$$\omega_s = n(n^2-1)/\sqrt{n^2+1} \quad \sqrt{EI/\mu R^4} \qquad \text{(eq. 9)}$$

Where:

- μ is the mass per unit length,
- EI is the bending stiffness (Young modulus x Inertia)
- R is the radius.

Taking measurements from the bearing for diameters of the inner and outer race, the width of the bearing, density of steel, and the natural frequencies for the second through first four modes are: 3.8 kHz, 10.7 kHz, and 20.5 kHz. The 10.7 kHz frequency was chosen because the 3.8 kHz can be confounded by gear mesh harmonics, while the 20.5 kHz was above the bandwidth of the sensor bracket. The 1.5 kHz "width" was selected to capture the bandwidth of the potential fault frequency.

The envelope "window" is then 10.5 +/- 1.5 kHz or 9 to 12kHz. This corresponded well with observed broadband noise in the spectrum, a characteristic of the bearings resonance due to the RE exiting from the spall. The decimation was performed to the enveloped signal after low-pass filtering. It is bandwidth limited to 3 Hz. The resulting envelope signal bandwidth is only 3kHz, compared to the nearly 50 kHz of the original signal. The decimation reduces the original 600,000 data points to 36600 with an effective sample rate of 6103.5 sps. As the gearbox high-speed shaft had a tachometer, it is possible to compare this tach signal with the TfV signal (Figure 2).

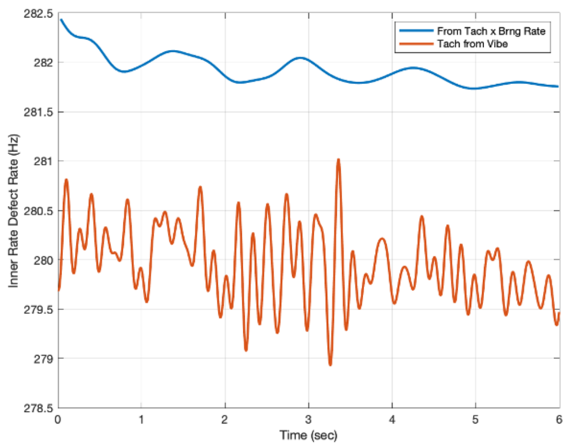

Figure 2 Drivetrain Tach vs. TfV Derived Tach

Note that the TfV rate is approximately 0.7% slower than the rate calculated from the high-speed shaft rate. This is to be expected due to the RE's non-Hertzian contact with the inner race, which is often seen at 0.5 to 1.0%.

In comparing the envelop spectrum vs. the TSA spectrum, we see that the TSA spectrum has a process gain of 2dB (Figure 3). This is one advantage of the TSA, as it results in process gain, improving the original signal's SNR.

3.2. Validation and Interpretation of Simulation Data

What exactly would the TSA envelope look like? Kogan et al., as noted, developed a simulation capability to generate a time domain signal representative of a RE entering and exiting a spall. The simulation data allows for the generation of high fidelity, with an effective same rate and 100,000 sps. The bandwidth is effectively Nyquist, as there is no transfer function or low pass filtering that would occur in a real-world example where brackets and sensor mounting, in effect, act as a low or bandpass filters.

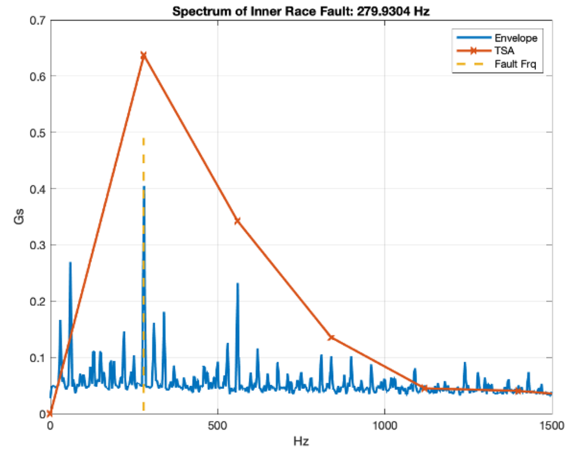

Figure 3 TSA of Enveloped gave a Process Gain of 2dB over the Envelop Analysis Alone

Figure (4) plots the simulated time domain bearing fault signal against two envelope representations generated from the TfV processing. In the raw signal, it is clear that at time 0.004s, the RE is entering the spall, as exiting at time 0.007s. This represents a 5mm spall on bearing supporting a 20 Hz shaft with the “Env TSA TfV 5th Harm” uses the fifth harmonic for the target frequency of the TfV, while the “Env TSA, TfV 1st Harm” uses the first harmonic for the TfV. The fault frequency is 88.2 Hz, so the resolution in time, using the fifth harmonic, is 441 Hz. The resulting higher bandwidth of the envelope TSA using the 5th harmonic has more details and better resolution in time over the 1st harmonic

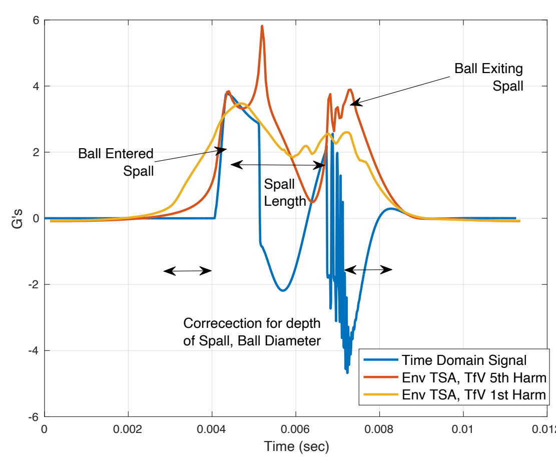

Figure 4 Simulated Bearing Fault Data Processed Using the TfV

From this, it is seen that the TSA and resulting waveform are sensitive to errors/jitter in the ZCT, as calculated from TfV. The higher the resolution in time, the more detail/accuracy in the resulting TSA

3.3. TfV Result for the Wind Turbine Bearing Fault

One raw acquisition file was captured per day. The TSA was calculated from the envelope of the raw signal, as seen in the surface plot in Figure 5.

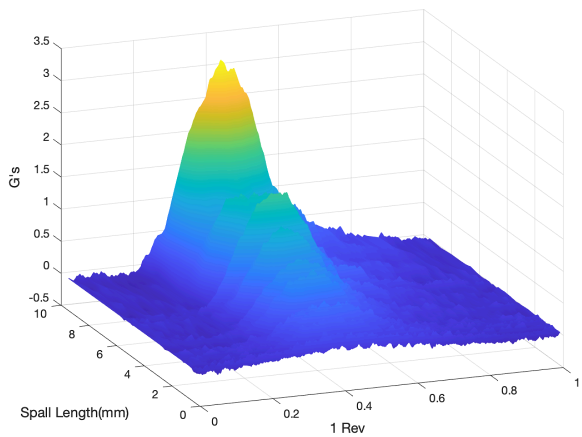

Figure 5 TSA of Envelope of an Inner Race Fault Propagating Over a 50-Day Period

The envelope of the TSA results in the loss of some details, such as the signal's high-frequency resonance. However, the entry and exit points of the spall are detected. Using eq 7 to correct the ball diameter, an acceptable estimate of spall length can be calculated. For example, on day 49, the spall length is estimated to be 9 mm (Figure 6).

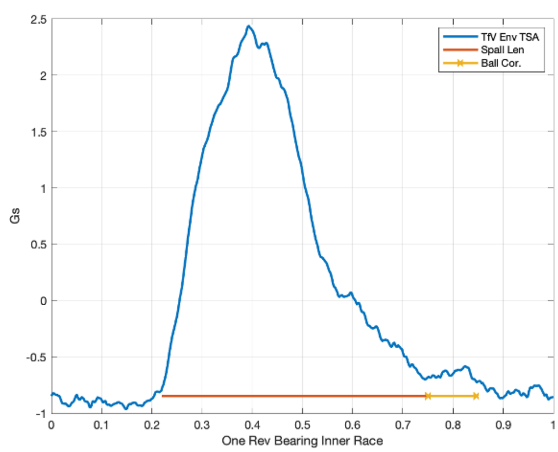

Figure 6 Day 49 Time Domain Representation of an Inner Rate Fault

As noted, this estimated damage length is calculated from the entry to the exit point of the spall. Note that the length of the spall at the end of the trail was approximately 12mm, which matched well with the TfV estimate (Figure 7).

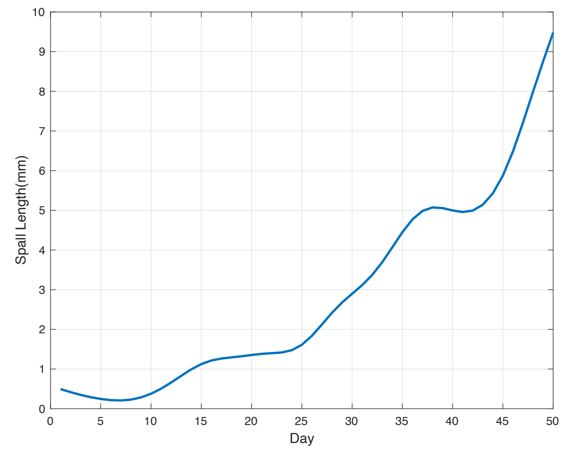

Figure 7 TfV Estimate of Spall Length

3.4. Discussion

Many different analyses were tested. For example, the TSA of the raw data itself gave poor results. As the TSA is very sensitive to ZCT errors due to jitter, no actual features were observed in the real-world data (although they were present in the simulated data). It was observed that using higher harmonics reduces the ZCT errors (in both real and simulated data), improving the resolution in time and the resulting TSA. However, there is a tradeoff in performance because the higher harmonics of the fault features tend to have lower SNR. Again, the ZCT error is a function of SNR. The process of taking the envelope (with the Hilbert transform) has the effect of reducing the bandwidth of the signal, making the TSA less sensitive to ZCT errors.

Given that the length of the spall could be estimated, it would be interesting to see how that length correlates to, say, the inner race envelope energy. That and two other condition indicators (CIs) were tested. A CI based on the envelope TSA RMS and a third CI based on the Envelope TSA peak-to-peak were captured. These were normalized to 1 by dividing by their max values (Figure 8).

The correlation between the time and frequency CIs suggests that spall length and traditional envelope energy CI values are also well correlated. A lack of correlation would indicate a gross error in our understanding of trending bearing faults. The high correlation spall length with the envelope energy condition indicators confirms what most condition monitoring practitioners already know: a trending envelop energy indicates a propagating fault.

This process has some limitations. For example, this technique was tested on an RR M250C47 turboshaft engine. The turbine's shaft rate is 536 Hz, and the bearing fault rate is 7.11, giving a fault frequency of 3810 Hz for the TSA. With a sample rate of 100 kHz, the TSA length is 32 points. It is unlikely that 32 points give enough resolution in time to detect the bearing fault.

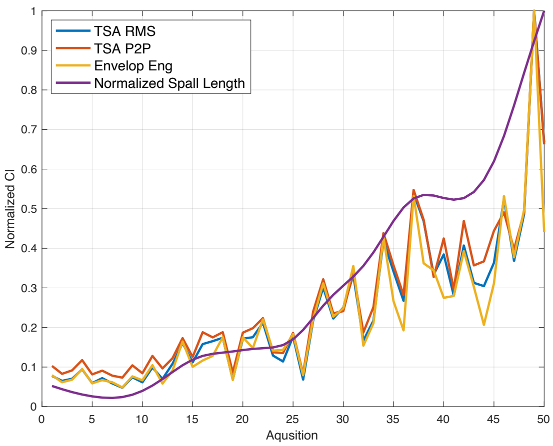

Figure 8 Normalized CIs ad Spall Length vs. Day

4. CONCLUSION

Fundamental to condition monitoring is the ability to detect and quantify the damage of a component. The ability to tie physical damage with a given signal is a powerful tool that can facilitate changing a maintenance paradigm, namely from inspection intervals to on-condition. In some sense, the high correlation between an estimated length of a bearing spall and envelope energy is expected. Even knowing the physical length of a spall does not change condition monitoring – it just changes the nature of thresholding. At what length of a spall should the bearing be replaced?

This paper demonstrates a process of estimating the spall length of a damaged bearing. The spall length was derived from the envelope of the TSA, where the zero cross data was calculated from the fault feature itself. This was done using a "tach from vibration" processing of the bearing envelope. This process was verified using simulation data, which was validated on a propagating, real-world inner race fault from a wind turbine gearbox. It is further shown that one revolution of the TSA is the circumference of the bearing between two rolling elements. From the effective sample rate, it is then possible to determine the length of each index in the TSA waveform, from which the spall length can be seen.

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BIOGRAPHIES

Eric Bechhoefer received his BS in Biology from the University of Michigan, his MS in Operations Research from the Naval Postgraduate School, and a Ph.D. in General Engineering from Kennedy Western University. He is a former Naval Aviator who has worked extensively on condition-based maintenance, rotor track and balance, vibration analysis of rotating machinery, and fault detection in electronic systems. Dr. Bechhoefer is a Fellow of the Prognostics Health Management Society, a Fellow of the Society for Machinery Fault Prevention Technology, and a senior member of the IEEE Reliability Society. Additionally, Dr Bechhoefer is also a member of the SAE committee covering Integrated Vehicle Health Management, and a member of the MSG-3, Rotorcraft Maintenance Programs Industry Group.

Omri Matania is currently a Ph.D. candidate in BGU-PHM LAB in the department of mechanical engineering in Ben-Gurion University of the Negev, under the supervision of Prof. Jacob Bortman. Omri Matania is a Talpiot graduate and served nine years in IDF in several roles including algorithm section leader. He completed with honors his bachelor's degree in mathematics and physics in the Hebrew University of Jerusalem and completed his master's degree with honors in mechanical engineering in Ben-Gurion University of the Negev.

Jacob Bortman is currently a full Professor in the Department of Mechanical Engineering and the Head of the PHM Lab at Ben- Gurion University of the Negev. Retired from the Israeli Air Force as Brigadier General after 30 years of service with the last position of the Head of Material Directorate. Chairman and member of several boards: Director of Business Development of Scoutcam Ltd, Chairman of the board of directors, Selfly Ltd., Board member of Augmentum Ltd., Board member of Harel Finance Holdings Ltd., Chairman of the board of directors, Ilumigyn Ltd. Member of the committee for "The National Initiative for Secured Intelligent Systems to Empower the National Security and Techno-Scientific Resilience: A National Strategy for Israel". Editorial Board member of: “Journal of Mechanical Science and Technology Advances (Springer, Quarterly issue)”. Member of: BINDT - The British Institute of Non-Destructive Testing, Head of the Israeli Organization for PHM, IACMM - Israel Association for Comp. Methods in Mechanics, ISIG - Israel Structural Integrity Group, ESIS - European Structural Integrity Society. Received the Israel National Defense prize for leading with IAI strategic development program, Outstanding lecturer in BGU, The Israeli Prime Minister National Prize for Excellency and Quality in the Public Service - First place in Israel. Over 80 refereed articles in scientific journals and in international conferences.