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Architecture for a Low Cost, Light Weight HUMS for Commercial Helicopters

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Abstract

Health and Usage Monitoring Systems (HUMS) are vibration-based equipment that measures the health of mission-critical components. HUMS provides maintainers and operators with information that allows early detection of impending failures, ensuring timely corrective action. This results in improved safety and aircraft availability. HUMS provides other maintenance support tools like rotor track and balance, automated flight manual exceedance detection, and flight data monitoring.

While safety is always a concern, commercial aviation/helicopter operators balance the cost of HUMS with enhanced safety and improved operational availability. HUMS is not mandated by regulation in all parts of the world, and commercial exposure to HUMS is limited. Part of the reason for the limited deployment of HUMS is the system cost, weight, complexity of analysis, false alarm rate, and, in general, the lack of automation/level of experience needed by smaller operations to run a HUMS program.

This paper aims to propose an architecture for a low-cost, lightweight HUMS specifically designed for commercial operators. This architecture uses a Tach-from-Vibe (TfV) process to provide a tachometer signal to other HUMS sensors. This allows for less HUMS-installed hardware and fewer aircraft interfaces. Less hardware reduces the HUMS cost and system weight, while fewer aircraft interfaces reduce the cost and time needed for the HUMS installation. This makes HUMS for Part 27 more attractive as it improves the business case for HUMS for commercial operators.

Keywords: smart sensor, TSA, Tach-from-Vibe.

Introduction

HUMS provides maintainers and operators with information that allows early detection of impending failures, ensuring timely corrective action. This results in improved safety and aircraft availability. HUMS also provides other maintenance and operational support capabilities, such as rotor track and balance, automated flight manual exceedance detection, and flight data monitoring.

While safety is paramount, commercial aviation/helicopter operators balance the cost of HUMS with enhanced safety and improved operational availability. HUMS is not mandated by regulation in all parts of the world, although HUMS is standard for Part 29, transport category aircraft supporting offshore operations.

Part 29 aircraft with a maximum weight greater than 20,000 pounds and 10 or more passenger seats are category A. Aircraft with 20,000 pounds or less and nine or fewer passenger seats are category B. Both categories are large aircraft, where the cost and weight of HUMS are a small percentage of the total cost and weight. Normal category rotorcraft is known as Part 27, with a maximum weight of 7,000 pounds or less and nine or fewer passenger seats.

Most commercial operators fly Part 27 aircraft, which are sensitive to the cost and weight of HUMS. As noted, while HUMS improves safety and operational availability, the business case or return on investment is harder for commercial operators flying Part 27 to make with an expensive and heavy HUMS designed for larger aircraft. For many operators, an acceptable installed weight for a Part 27 aircraft is under 10 lbs. and a cost of less than 1% of the aircraft's value.

TfV provides a tachometer signal to other HUMS sensors. This allows for less HUMS-installed hardware and fewer aircraft interfaces. Less hardware reduces the HUMS cost and system weight, while fewer aircraft interfaces reduce the cost and time needed for the HUMS installation. This makes HUMS for Part 27 more attractive as it improves the business case for HUMS for commercial operators.

Vibration Processing and the Need for a Tachometer Signal

In vibration diagnostics, the Fast Fourier Transform (FFT) is often used to determine the magnitude of a component's vibration (such as shafts, gears, or bearings), which can indicate wear and failure. However, many features associated with rotating component faults are not sinusoidal and are challenging to detect with the FFT. In these cases, an analysis based on the time domain can detect faults earlier.

The FFT, by orthogonalizing a time domain time signal, allows sinusoidal features of rotating equipment to be quantified. While vibration in the time domain is the superposition of all sources, in the frequency domain, the spectrum measures the sinusoidal energy associated with a specific rotating component. However, impact type of signals, such as a breathing crack in a gear, a gear scuff impact, or other non-sinusoidal signals from a rolling element in a bearing exiting a spall, are not well detected by the FFT.

Another assumption of the FFT is that the signal is stationary. The engine controller's finite bandwidth violates this assumption in helicopters. As loads vary over time due to aircraft maneuvers/pilot inputs, the engine controller attempts to maintain an engine output speed of 100%, but there is always variation in the engine output shaft rate due to the change in power needed to meet the aircraft maneuvers.

The ability to detect non-sinusoidal and time-varying signals is important for successful HUMS for fault detection. A powerful technique to orthogonalize (e.g., separate a feature of a specific rotating component) that is not based on the FFT and to correct for a variation in the shaft rate over time is the time synchronous average (TSA). The TSA is an algorithm well suited for HUMS in detecting damaged gears and allows more precise measurement of periodic signatures.

Review of the TSA

Analysis of the TSA was well described by Braun [1] and perhaps first implemented for gearbox analysis in ([2], R.M Stewart went on to develop the first HUMS).

The TSA resamples the vibration associated with a shaft or gear in the spatial domain, such that the vibration associated with each shaft order (harmonic) 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). If the shaft slowed down, then in one revolution, it may sample 810 data points, which again would be resampled to 1024 data points. In this way, the TSA corrects the shaft rate variation.

The TSA has two features to consider in this application. First, as the TSA is an average, the desired feature's SNR improves with 1/sqrt (revolutions). Second, the TSA can be described as a DC FIR filter and is very sensitive to timing/jitter errors. For example, the attenuation 3dB loss in signal from timing error for one second of data 30 Hz is 4.1%. Then, any signal less than 28.77 Hz or greater than 31.23 Hz would have more than 50% of its signal attenuated. This also applies to the shaft rate harmonics. The second harmonic with signal content less than 58.77 or greater than 61.23 Hz would also be attenuated by at least 50%. For the six seconds of data, the 3dB loss is 0.68%, less than 29.8Hz, or greater than 30.2 Hz. This means that an accurate zero cross time (ZCT) is needed and that the accuracy of the ZCT increases with acquisition time. In the case of the six-second acquisition, if the error in the ZCT jitter is greater than 0.68%, 50% of the signal will be lost.

Traditionally, the TSA requires an external tachometer to provide a key-phasor to the shaft under analysis. This key-phasor is the time of a target crossing the tachometer sensor. In some cases, this may be:

a) The received reflection of a retroreflective sensor to a reflective tape as a target or
b) The change in voltage resulted from the changing flux due to the passing of a ferrous target and a variable reluctance sensor.

With a known ratio of the tachometer to the shaft under analysis, zero crossing times can be calculated, which allows the synchronous signals to be measured while the asynchronous signals are filtered. As the TSA [4] is operated on for different shaft and gear analyses that call the FFT, it is typical for the length of the TSA to be a radix-2 number. Many common vibration analyses (Residual or Difference Analysis, Narrowband analysis [2, 3]) use the FFT to ideally filter the signal or perform a Hilbert transform of the signal (for Amplitude and Frequency Analysis), which supports the desire for a Radix-2 length TSA.

Tach-from-Vibe TSA
Bonnardot [4] describes a method of using a gearbox's acceleration signal to perform the TSA. The concept centers on bandpass filtering the signal around a gear mesh, taking the Hilbert transform to estimate phase, and using the change in phase over time to estimate the ZCT. Note that an idealized bandwidth filter is used, which improves the performance of the analysis.

Define the Sample rate = *sr*. The number of data points of vibration data, n = *sr* x acquisition length in seconds, then:

- Calculate the next larger radix-2 length for the FFT. nRadix = 2^ceil(log2(n))
- Calculate the low and high bandwidth index (*bwlow*, *bwhigh*), which are centered on a known shaft or gear mesh. The narrower the bandwidth of the filter, the less chance there is for the analysis to be corrupted by other signal sources. However, a bandwidth that is too narrow will not be responsive to changes in component RPM or error in measuring the components RPM. Typically, a bandwidth of +/- 2 percent is used. If the signal were a 17-tooth pinion on an input shaft with a 99.94 Hz rate, the *bwlow* and *bwhigh* would be, respectively 1663 and 1731Hz.
- Take the zero-padded FFT of the vibration data. That is, add zeros to fill the remainder of the radix-2 array with zero values.
- Zero the FFT from zero to *bwlow* and from *bwhigh* to *nRadix*. This is an ideal filtering process, then take the inverse FFT to create the analytic signal
- Calculate the unwrapped argument of the signal from 1 to the end of the data, *n*.

- If the analysis is on a gear mesh, normalize the time series of radians by the number of teeth on the gear.
- As this is a time-domain signal based on the sample rate, it is necessary to interpolate for the array index (which is every 2π radians).
- Normalized to tachometer zero crossing times by dividing by the zero cross interpolated index by *sr* to generate an array of zero-cross times.

Global Tach-from-Vibration

A notional HUMS for a light helicopter is shown in Figure 1. The system consists of an Onboard Control Unit (OBCU), which provides power and control for the bused smart sensors. The OBCU interfaces with the aircraft via analog and/or ARINC429 interfaces. The parameter data can include engine torque, compressor RPM (Ng), drivetrain RPM (Np), airspeed, pressure altitude, yaw rate, roll, and heading. These parameters are used to determine when an operation begins, when the operation ends, if there was a flight manual exceedance, and when to perform an acquisition. When the aircraft is in a regime where it is appropriate to acquire vibration data, the OBCU sends configuration data to the sensors. Configuration data includes information about what components the sensors will analyze. The HUMS also has antennas for GPS and other wired/wireless interfaces for downloading analysis data.

The configuration consists of shaft identifiers and the ratio from the shafts to a tachometer. If the shaft has a gear(s), the configuration has the gear identifier, the number of teeth on the gear, and other analysis input parameters, such as the bandwidth of the gear analysis. Similarly, if there is a bearing with the shaft, configuration for the bearing analysis is also needed. For a bearing, the configuration consists of the envelope bandwidth, the resonance frequency of the bearing, the length of the spectrum, and the bearing fault feature rate. The fault features include the cage, ball, inner race, and out race rate. When these rates are multiplied by the shaft rate, the fault frequencies can be calculated.

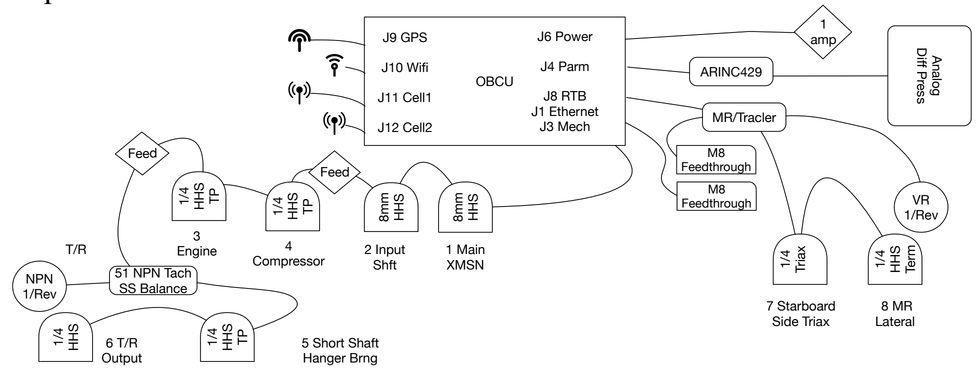

Figure 1 Notional HUMS for a Light Helicopter

In the notional system, the drivetrain monitoring starts with sensor ID 1, which is on a data bus. This bus is powered by the OBCU from port J3 (the Mech bus). Sensor 1 main transmission. Sensor 2 monitors the input shaft while Sensors 3 and 4 the engine turbine and compressor sections, respectively. As the engine compartment is separated by a firewall, connections are made through a flameproof feedthrough (e.g., "Feed"). A 1/Rev optical sensor is used to balance the tail rotor for a key phasor. Sensor 5 monitors the tail rotor drive shaft (e.g., here called a Short Shaft Hanger Bearing), while sensor 6 monitors the Tail rotor gearbox.

The main rotor data bus (for rotor track and balance, RTB, J8) has two sensors. Sensor 7 measures the rotor mast's lateral vibration, while sensor 8 measures the cockpit's fore/aft and vertical vibration.

Nominally, this type of architecture would require four tachometers: the two 1/Rev tachometers for balancing the tail rotor and main rotor, a tachometer for the drivetrain (which includes the turbine section), and a tachometer for the compressor/accessory section of the engine. The compressor/accessories, such as the starter/generator and fuel pump, are asynchronous with the turbine. Tach-from-Vibe (TfV) allows the local smart sensor to calculate the zero-cross time for a tachometer signal on a shaft it monitors. However, low signal-to-noise can develop a poor tachometer signal. In this case, it would be advantageous for a sensor with a good signal-to-noise and relatively low sample rate to broadcast its calculated tachometer signal. A low sample rate means that the computation of the TfV will be faster.

The operational concept of TfV systems is that the OBCU records parameter data and uses this data to determine an appropriate regime for performing an acquisition. The OBCU sends configuration data, including sample rate and acquisition length, to the sensors on the data bus. For a set of sensors on the drivetrain data bus, the TfV sensor collects zero-cross data and then broadcasts the zero-cross time to all sensors on the data bus. Each sensor then uses its' configuration (ratio to the tachometer, etc.), vibration data, and tachometer signal to perform the TSA or resampling analysis to calculate the conditions indicators (CIs) associated with each component the sensors monitor.

Consideration for Selecting an Appropriate Sensor for TfV.

Performance considerations must be considered to ensure performance on the Global TfV.

- Acceleration is proportional to the shaft rate squared. That is, higher-speed shafts have much higher energy features that can be used for TfV.
- Gear mesh signals generated more acceleration than its association shaft, reducing TfV error.
- The time to calculate the TfV signal is proportional to the length of the vibration signal length as Ω is proportional to N x Log2(N).
- Generally, any given shaft should have 30+ revolutions in the TSA.
- ZCT timing error can be reduced by performing the TfV on a higher-speed shaft and using the ratio from the TfV tach signal to reduce error. That is, say the timing error is 1% when TfV is performed at 1.7kHz (gear mesh on a 17 tooth pinion on a 100 Hz shaft), then the error is reduced by 17 if the TSA is performed on the 100 Hz shaft.

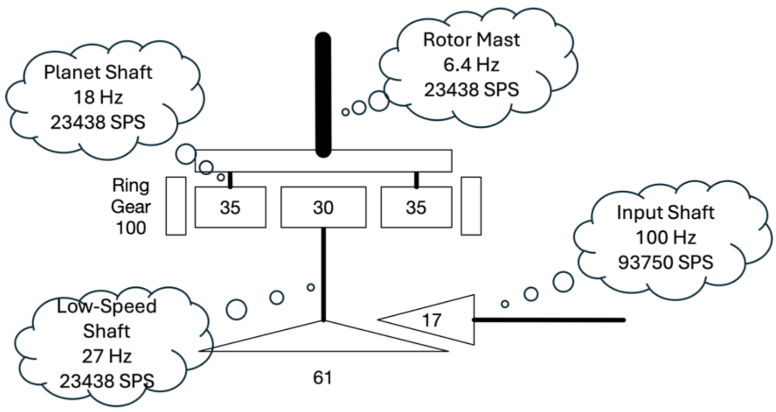

Figure 2 Notional Gearbox using Global Tach-from-Vibration Processing.

Since the lowest speed shaft (in this notional gearbox) is the mast rotor at 6.4 Hz, the minimum acquisition time for Sensor 1 (XMSN) is 30/6.4, or five seconds. The sample rate for the Sensor 1 is 23438. However, the highest measured acceleration will be from the gear mesh on the input shaft (17-tooth) pinion or the low-speed shaft bevel gear (61-tooth), which is approximately 1.7 kHz. The input shaft and pinion are analyzed by sensor 2 because of their mounting location to capture radial acceleration.

Given the sample rate of 93750 for sensor 2, five seconds of data would be 468750 data points. The following radix-2 number for the TfV to operate on would be 2^19, or 524288 data points. If TfV is performed using data from Sensor 1, with a sample rate of 23438, or 117190 data points. The next largest radix-2 value is 2^17 or 131072. Given the FFT's order of operation, it would take 4.5x longer for Sensor 2 to calculate the TfV vs. Sensor 1. If the processing time is, say, 15 seconds for Sensor 1, then Sensor 2 will take over a minute to calculate the TfV. The longer processing time can impact the overall system performance by taking longer to process.

A good configuration would be to set Sensor 1 (XMSN) to perform the TfV using the frequency of 1.7kHz on the input pinion. The TfV algorithm is configured to use only every 17th data point so that the ZCT represents a tachometer signal from the input shaft. Then, the configured ratios to the shafts monitored by Sensor 1 would be:

- Low-Speed Shaft Ratio from TfV Tach: 17/61 (the input pinion/bevel gear) or 0.2786885.
- The ratio to the mast is 1/(1+100/30) x the Low-Speed shaft ratio. As this is an epicyclic gearbox, the ratio from the mast to the Low-speed shaft is 1 + the ring gear/sun gear), or 4.33333. However, since the mast is driven by the input shaft through the low-speed shaft, the cumulative final ratio is 1/4.3333 x 17/61 or 0.064312736.
- Planet Shaft Ratio from TfV would be the mast ratio, 0.064312736 x the ring gear/planet gear, or 0.064312736 x 100/35 = 0.18375067. In a similarly ay, the ratio for the tachometer from the TfV to any other shaft under analysis can be derived.

As the compressor is asynchronous to the drivetrain/input shaft rate, it will perform its own TfV. The compressor (sensor 4) often operates at 30,000 to 50,000 RPM (depending on engine size), and TfV can be implemented on the compressor's accessory drive pinion. As the shaft rate is often greater than 800 Hz, one second of data at 93750 samples per second (sps) is ideal. The number of sample points is less than radix 2^17, so processing time is relatively quick (similar to the time needed for Sensor 1).

Conclusion

Without regulatory demand for HUMS, the operator's application of the technology is based on the operator's perception of the ROI of an installed system. This decision is significantly impacted by the cost of the system, the installation time, and the weight. Introduction of global TfV into a data bus, smart sensor architecture allows for removal of tachometer interfaces, brackets, and cabling, reducing cost, weight, and installation time by perhaps 20%, without impacting performance. The reduction in parts/interfaces also makes HUMS more reliable. Hopefully, the reduced cost and the perception of an increased ROI will make HUMS more attractive to Part 27 aircraft operators.

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