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Gearbox Predictive Maintenance Using Load-Normalized Envelope Spectra

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Abstract

This disclosure describes a predictive maintenance system for gearboxes that overcomes the limitations of vibration alarms sensitive to load variations. Conventional absolute-level alarms frequently trigger false positives or are deactivated due to normal operational duty cycles. The presented system utilizes load-normalized envelope spectra to establish a dynamic baseline. By continuously adapting to instantaneous load conditions, the system monitors specific frequency bands associated with gearbox component wear, enabling the detection of incipient faults. Baselines are iteratively refined from operational data without requiring a priori "known-good" machine states, allowing for robust fault detection and alarm generation that persists across changing operational duties.

1. Technical Field

[0001] The technical field relates to condition monitoring and predictive maintenance for industrial machinery, specifically focusing on rotary power transmission equipment such as gearboxes. It involves the analysis of operational data, particularly vibration signals, to detect incipient faults and predict component degradation.

2. Technical Context

[0002] Industrial machinery often operates under dynamic load conditions, where the instantaneous mechanical load on components can vary significantly over time. For gearboxes, these load variations directly influence the amplitude of vibration signals generated during normal operation. Traditional vibration-based condition monitoring systems typically rely on fixed alarm thresholds derived from absolute vibration levels. These thresholds are established assuming a relatively constant operational state or a "known-good" baseline. When the machine's operational duty changes, for instance, from light load to heavy load, the baseline vibration amplitude shifts. This often leads to false alarms being triggered under normal, higher-load operating conditions, or conversely, a reduction in sensitivity to actual faults during lower-load operation. In many industrial environments, such false alarms become a nuisance, leading operators to desensitize or entirely disable the monitoring system, thereby negating its predictive capabilities. The problem addressed is the need for a vibration monitoring system that can robustly detect gearbox faults across a wide range of operational loads, without generating false alarms due to normal duty changes and without requiring a pre-established "known-good" baseline.

3. System Overview

[0003] The disclosed system provides a method for predictive maintenance of gearboxes by analyzing load-normalized envelope spectra of vibration signals. As shown in FIG. 1, a vibration sensor (10) and a load sensor (12) continuously acquire data from the gearbox. These raw signals are processed by a data acquisition unit (14) and then a processor unit (16). The processor unit (16) performs signal conditioning, envelope demodulation, spectral analysis, and load normalization. It then compares the resulting load-normalized envelope spectra against a dynamically established baseline to identify deviations indicative of faults. Historical data, including load and vibration characteristics, are stored in a data storage unit (18) to support baseline generation and refinement. Alerts and operational insights are presented via a user interface (20). This approach allows the system to distinguish between vibration changes caused by varying operational loads and those resulting from actual mechanical degradation, enabling robust fault detection that survives duty changes.

4. Components

[0004] The system comprises several key components:

[0005]

- **Vibration Sensor (10)**: Typically an accelerometer, mounted on the gearbox casing to detect mechanical vibrations. The sensor (10) converts mechanical vibrations into an electrical signal. It is selected to have a suitable frequency response range, often extending to 10 kHz or higher, to capture high-frequency components associated with bearing and gear meshing impacts.
- **Load Sensor (12)**: Measures the instantaneous operational load on the gearbox. This can be a torque sensor on the input or output shaft, a power sensor measuring motor electrical power consumption, or a pressure sensor in a hydraulic drive system. The sensor (12) provides a continuous or quasi-continuous signal proportional to the mechanical stress on the gearbox components.
- **Data Acquisition Unit (14)**: This unit digitizes the analog signals from the vibration sensor (10) and load sensor (12). It includes analog-to-digital converters (ADCs), anti-aliasing filters, and potentially signal amplifiers. The sampling rate for vibration data typically ranges from 20 kHz to 50 kHz to capture high-frequency components, while the load signal may be sampled at a lower rate, for example, 100 Hz to 1 kHz.
- **Processor Unit (16)**: A computational module, which may include a digital signal processor (DSP) or a general-purpose central processing unit (CPU). It executes the algorithms for signal processing, envelope demodulation, spectral analysis, load normalization, baseline generation, and anomaly detection.
- **Data Storage (18)**: A non-volatile memory or database system for archiving raw and processed data. This includes historical vibration spectra, load profiles, calculated baselines, and detected anomalies. The stored data is critical for long-term trend analysis and for refining the baseline model.
- **User Interface (20)**: A display and input system for operators and maintenance personnel. It presents current machine status, trend plots, alarm notifications, and diagnostic information. It allows for configuration of monitoring parameters and acknowledgment of alerts.

[0006] The gearbox itself, shown in FIG. 2, typically consists of an input shaft (30), supported by input bearings (32), which drives an input gear (34). This input gear (34) meshes with an output gear (36) mounted on an output shaft (40), which is in turn supported by output bearings (38).

5. Operation

[0007] The system's operation involves continuous data acquisition, signal processing, baseline establishment, load normalization, and anomaly detection.

[0008] Upon system start-up, the vibration sensor (10) and load sensor (12) begin acquiring data. The data acquisition unit (14) converts these analog signals into digital form. The digitized vibration signal is typically high-pass filtered to remove low-frequency machine unbalance and misalignment components, focusing on frequencies associated with bearing and gear faults. The filtered signal undergoes envelope demodulation. This involves rectifying the signal and applying a low-pass filter to extract the amplitude variations (envelope) of the high-frequency components. A Fast Fourier Transform (FFT) is then applied to the envelope signal to generate an envelope spectrum. This spectrum reveals characteristic fault frequencies for gears (e.g., gear mesh frequencies, sidebands) and bearings (e.g., ball pass frequencies, cage frequencies), which are often masked by other vibrations in the raw spectrum.

[0009] Concurrently, the load signal from the load sensor (12) is acquired. This load value is used to normalize the envelope spectrum. For each spectral band of interest, the amplitude is adjusted based on the instantaneous load. A common normalization approach involves dividing the spectral amplitude by a power function of the load, or by using a regression model that correlates spectral amplitudes with load values. This process creates a "load-normalized envelope spectrum."

[0010] Baseline establishment occurs dynamically. Initially, without a "known-good" period, the system collects load-normalized envelope spectra over a specified operational period, for example, 24 to 72 hours, covering various load conditions. The processor unit (16) then calculates a statistical representation of these spectra, such as the median or average amplitude within defined frequency bands, to form an initial baseline. This baseline is continuously refined using an adaptive algorithm, for instance, by calculating a moving average or exponential moving average of the load-normalized spectra, but only incorporating data points that are within a certain statistical distance (e.g., two standard deviations) from the current baseline. This prevents anomalous data from corrupting the baseline.

[0011] During steady running, the system continuously generates load-normalized envelope spectra and compares them against the dynamically updated baseline. Specific frequency bands, corresponding to known gearbox fault frequencies (e.g., bearing outer race fault frequency, gear tooth meshing frequency harmonics, sidebands around these frequencies), are monitored. An alarm is triggered if the amplitude in any monitored band of the current load-normalized envelope spectrum exceeds the baseline by a predefined threshold, for example, 6 dB or 12 dB. The load normalization ensures that these thresholds are robust against changes in operational duty.

[0012] On fault or interruption, such as a sudden increase in vibration or a complete machine stoppage, the system responds. If a fault is detected, an alert is sent via the user interface (20), potentially including the specific frequency band affected, the magnitude of the deviation, and a timestamp. If the machine stops, data acquisition may pause or switch to a diagnostic mode. Upon restart, the system resumes its monitoring and baseline refinement process. The adaptive baseline mechanism ensures that even after prolonged periods of shutdown or significant changes in operational profile, the system can re-establish a reliable baseline for continued robust monitoring.

6. Example Embodiments

[0013] **Embodiment 1** This embodiment utilizes a single-axis accelerometer (10) for vibration sensing and a motor current transducer (12) as the load sensor. The data acquisition unit (14) samples the accelerometer at 25.6 kHz and the motor current at 1 kHz. The processor unit (16) applies a 5 kHz high-pass filter to the vibration signal before envelope demodulation, followed by an FFT to generate an envelope spectrum up to 10 kHz. Load normalization is performed by dividing the amplitude in each spectral bin by the square of the instantaneous motor current, assuming a proportional relationship between current and mechanical load. The baseline is established as the 90th percentile of load-normalized amplitudes collected over the preceding 72 hours, with data points exceeding 3 standard deviations from the current baseline being excluded from refinement. Alarms are set to trigger if any monitored band amplitude exceeds the baseline by 8 dB for more than 5 consecutive spectral measurements.

[0014] **Embodiment 2** In this configuration, a tri-axial accelerometer (10) is employed, providing vibration data in three orthogonal directions. The load sensor (12) is an inline torque transducer on the gearbox output shaft. The data acquisition unit (14) samples each accelerometer axis at 51.2 kHz and the torque signal at 500 Hz. The processor unit (16) applies envelope demodulation to the vector sum of the three axial vibration signals to generate a composite envelope spectrum. Load normalization is performed using a multi-variate regression model, where historical load-normalized spectral amplitudes are regressed against the instantaneous torque and speed values. This model dynamically adjusts the expected spectral amplitude based on both load and speed. The baseline is calculated as the rolling average of the load-normalized spectra over the last 100 hours of operation, with an outlier rejection algorithm that discards any data point more than 1.5 times the interquartile range from the median before averaging. Alerts are generated if a monitored frequency band amplitude consistently exceeds a threshold corresponding to a 95% confidence interval above the current baseline.

[0015] **Embodiment 3** This embodiment focuses on a gearbox in a variable-speed application. The vibration sensor (10) is a high-sensitivity accelerometer. The load sensor (12) is a direct power sensor, measuring shaft power. The data acquisition unit (14) incorporates a variable sampling rate for the vibration signal, adjusting it proportionally to the gearbox's input speed to maintain a constant number of samples per revolution. This technique, known as order tracking, ensures that spectral lines corresponding to rotating components remain fixed in the order domain, simplifying analysis across speed variations. Load normalization is then applied to these order-tracked envelope spectra, specifically by normalizing amplitude per order band using the measured shaft power. The baseline for each order band is established using a non-parametric method, such as kernel density estimation, over a collection of 500 recently acquired load-normalized order spectra. An alarm is raised if a new order spectrum falls outside the 99th percentile contour of the established baseline distribution for any critical order band.

7. Alternative Configurations

[0016] Several alternative configurations can be implemented. The load sensor (12) could be an encoder measuring motor or shaft speed combined with an estimate of load derived from process parameters, such as fluid flow rate in a pump application or material feed rate in a conveyor system. The envelope demodulation technique could be substituted with alternative methods such as Hilbert transform or synchronous average resampling. Instead of a single vibration sensor (10), an array of multiple accelerometers could be used to provide more spatially resolved vibration data, allowing for source localization of faults. The baseline generation algorithm could incorporate machine learning models, such as autoencoders or Gaussian Mixture Models, to learn complex normal operating patterns across different load conditions, enabling the detection of more subtle anomalies. The alarm mechanism could be configured to trigger not only on amplitude excursions but also on changes in the statistical distribution of the spectral content within a given band over time, such as an increase in kurtosis or crest factor.

8. Parameter Variations

Parameter	Range	Effect of Moving Towards Lower End	Effect of Moving Towards Higher End
Vibration Sensor Frequency Range	500 Hz to 20 kHz	May miss high-frequency bearing/gear impacts	Provides more detailed high-frequency information, higher data volume
Vibration Sampling Rate	10 kHz to 100 kHz	Risk of aliasing for high-frequency components	Improved frequency resolution, higher data storage requirements
Load Signal Update Rate	1 Hz to 1 kHz	Less precise load normalization for rapidly changing loads	More accurate load adaptation, increased processing overhead
Baseline Averaging Window	12 hours to 30 days	Rapid adaptation to new operating conditions, potentially less stable	Slower adaptation, more stable baseline, less sensitive to short-term changes
Alarm Threshold (dB)	3 dB to 15 dB	Increased sensitivity, higher risk of false positives	Reduced sensitivity, lower risk of false positives, potential for missed faults
Envelope Filter Bandwidth	1 kHz to 5 kHz	May miss some modulation frequencies, less detail	Captures broader modulation effects, more noisy spectrum
Load Normalization Exponent	0.5 to 3.0 (for power law)	Less aggressive normalization, may under-compensate for load changes	More aggressive normalization, may over-compensate for load changes

9. Additional Implementations

[0018] The core principles of load-normalized envelope spectra can be extended beyond gearboxes to other rotating machinery with varying loads, such as large electric motors, pumps, and compressors. For systems operating in highly variable speed environments, the load normalization can be combined with order tracking to normalize spectral amplitudes across both speed and load variations simultaneously. The system can be integrated into broader industrial control systems, allowing for automated responses to detected faults, such as initiating a controlled shutdown or scheduling maintenance tasks. Furthermore, the historical data stored in the data storage unit (18) can be utilized for advanced diagnostics, including fault progression modeling and remaining useful life (RUL) estimation, by trending the growth rates of normalized fault signatures over extended periods. The system's baseline learning capability could be enhanced with online unsupervised machine learning algorithms to automatically identify new, previously uncharacterized operating modes and establish distinct baselines for each, improving robustness in complex operational scenarios.

10. Figures

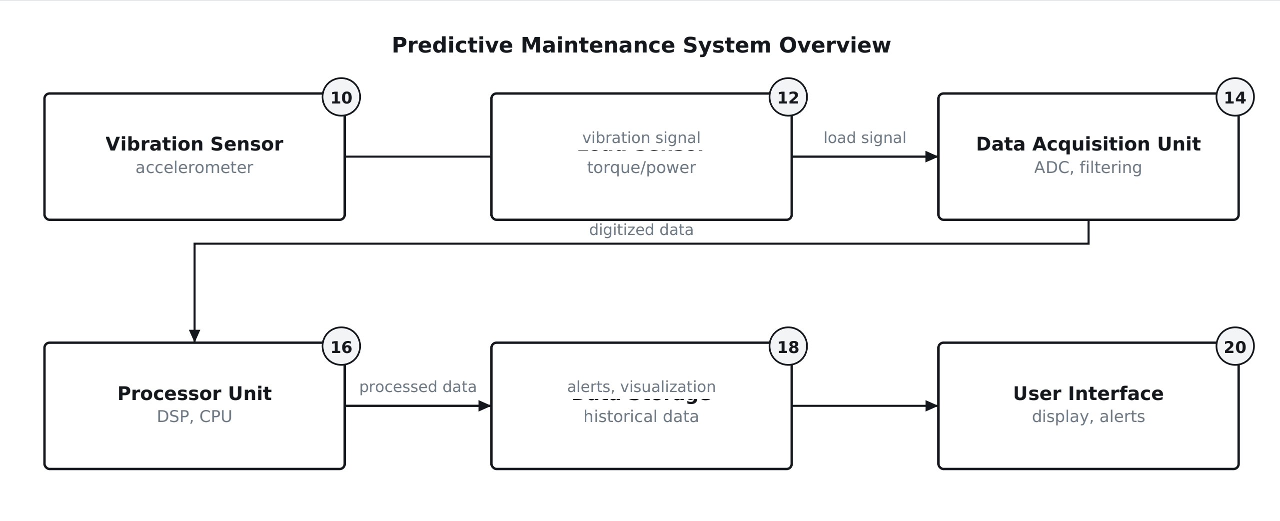

FIG. 1 Overall architecture for a load-normalized predictive maintenance system. PNG

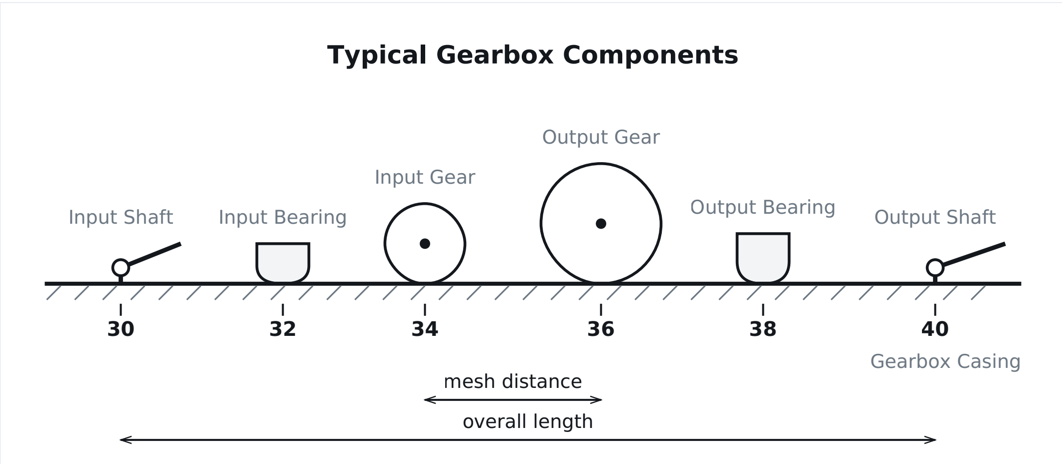

FIG. 2 An example configuration of internal gearbox components subject to monitoring. PNG

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