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Early diagnostic of concurrent gear degradation processes progressing under time-varying loads

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ABSTRACT

This study develops a gear diagnostic procedure for the detection of multi- and concurrent degradation processes evolving under time-varying loads. Instead of a conventional comparison between a descriptor and an alarm level, this procedure bases its detection strategy on a descriptor evolution tracking; a lasting descriptor increase denotes the presence of ongoing degradation mechanisms. The procedure works from time domain residual signals prepared in the frequency domain, and accepts any gear conditions as reference signature. To extract the load fluctuation repercussions, the procedure integrates a scaling factor. The investigation first examines a simplification assuming a linear connection between the load and the dynamic response amplitudes. However, while generally valuable, the precision losses associated with large load variations may mask the contribution of tiny flaws. To better reflect the real non-linear relation, the paper reformulates the scaling factor; a power law with an exponent value of 0.85 produces noticeable improvements of the load effect extraction. To reduce the consequences of remaining oscillations, the procedure also includes a filtering phase. During the validation program, a synthetic wear progression assuming a commensurate relation between the wear depth and friction assured controlled evolutions of the surface degradation influence, whereas the fillet crack growth remained entirely determined by the operation conditions. Globally, the tested conditions attest that the final strategy provides accurate monitoring of coexisting isolated damages and general surface deterioration, and that its tracking-detection capacities are unaffected by severe time variations of external loads. The procedure promptly detects the presence of evolving abnormal phenomena. The tests show that the descriptor curve shapes virtually describe the constant wear progression superimposed on the crack length evolution. At the tooth fracture, the mean values of the residual signal evince strong perturbations, while after this episode, the monitoring curves continue signaling the ongoing wear process.

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1. Introduction and literature survey

The dynamic response of a healthy gear transmission depends on the transmission structure, together with its operating conditions: speed, load and lubricant properties. Moreover, since the system degradation eventually influences the original response, dynamic signature monitoring should represent an easy fault detection avenue. In practice, however, the degradation contribution to the global behavior often remains hardly detectable, particularly during the early stages of damage progression. Therefore, the literature offers a rich collection of papers developing or evaluating fault indicators and detection methods.

The survey papers [1–4] describe the more popular monitoring approaches. While the majority exhibit good overall reaction capacities, most of the common indicators present reaction levels that are a function of the damage type. Some parameters were indeed designed to detect isolated damages, whereas others target general surface degradation [5,6]. Globally, almost all of them produce predictions based on information extracted from vibration signals obtained after time synchronous averaging [7]. They also ignore the effects of load variations. They thus consider that any fluctuation of the vibration signal should originate from a deterioration evolution. This intrinsic assumption may obviously lead to false positive detection errors.

Wang investigated the load variation problem in Ref. [7]. The author examined some advanced techniques developed with the objective of increasing the detection accuracy under variable load conditions. He evaluates and compares the wavelet analysis, the resonance demodulation and the autoregressive modeling methods, and concludes that because of the minimum prior knowledge required, the autoregressive approach is potentially the best technique for on-board diagnostic systems. Later, Wang et al. [8] introduced a new metric based on the amplitude of wavelet transform to detect early fault progression under varying loads. They showed that even with no real integration of the load fluctuations, the proposed parameter is virtually able to remove their influence on residual signals. At about the same time, Bartelmus and his coauthors published a series of articles [9–11] on diagnostics of gearboxes operating under time-variable conditions. They demonstrated that the response of a gearbox to load variations depends on its condition [9]. They also specifically stressed [10] that a reliable diagnostic strategy must truly account for the external load. The diagnostic procedure they proposed evaluates the slope changes of a linear regression fitted on the dynamic response of a gearbox submitted to variable operating conditions; the detection results from a direct comparison with an equivalent healthy gearbox functioning under the same condition range. The procedure presents some similarities with the approach proposed by Cempel et al. [12], where the analysed feature is rescaled to a standard load condition.

In a recent publication [13], we presented a simple and effective detection strategy for gear tooth fillet crack (TFC) propagation. Instead of considering descriptor threshold values, this monitoring approach analyses the descriptor response evolution. The procedure first removes a reference signature from the gear set dynamic response. The reference signal may be measured on the intact gear set or under any damaged conditions. For the studied cases, the procedure was shown to be efficient for early crack growth recognition. The present paper extents the application range of the procedure to the detection of multi- and concurrent degradation processes progressing under time-varying loads. In addition to local TFC, the enhanced version should handle general surface alterations.

Section 2 reviews the important elements of the TFC monitoring method of Ref. [13], and develops the concurrent degradation process/time-varying load monitoring procedure. The final approach is applied to numerical faulty signatures established from the numerical model developed in [14], and expanded in [13], to integrate the TFC propagation. Hence, Section 3 begins by briefly describing the model, and then adds the ability to deal with altered tooth flanks. Finally, the last section illustrates the detection capacity of the procedure in presence of evolving interactions between the dynamic response, growing cracks and surface wear evolution in gear sets operating under periodic, pseudo-random or monotonic-increase load variations.

2. Monitoring procedure

2.1. Original procedure

Fault detection methods are based on the premise that gear degradation increases the dynamic response content. Hence, Stewart [15] suggested preparing a concentrated fault signature through the elimination of the tooth meshing component and associated harmonics from the time average signal to form a characteristic residual vibration signal (RS). Subsequent research works demonstrated that RS evidence the defect contribution. To eliminate the components not related to the fault progression more efficiently, recent publications have made use of a simple time signal subtraction. For example, Wu et al.'s [16] approach includes the subtraction of a reference signal collected for the intact gear set from the time response signal measured on the damaged system. Alternatively, Hong et al. [17] introduced a synthetic estimation constructed from the vibrational characteristics of the investigated transmission to replace the reference signal. While the procedure put forward in [17] includes a dynamic time warping to align the signals, the other techniques developed in the literature require a precise alignment of the data based on a physical reference point. In industrial environments, this constraint gives rise to practical problems, and is therefore rarely implemented [17]. On the other hand, the approach we developed in [13] avoids the required time synchronism, and simply establishes the RS in the frequency domain.