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Compression methods for mechanical vibration signals: Application to the plane engines

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ABSTRACT

A novel approach for the compression of mechanical vibration signals is presented in this paper. The method relies on a simple and flexible decomposition into a large number of subbands, implemented by an orthogonal transform. Compression is achieved by a uniform adaptive quantization of each subband. The method is tested on a large number of real vibration signals issued by plane engines. High compression ratios can be achieved, while keeping a good quality of the reconstructed signal. It is also shown that compression has little impact on the detection of some commonly encountered defects of the plane engine.

1. Introduction

Vibration signals provide useful information for the diagnosis of rotating machineries and they represent a key prerequisite of mechanical health monitoring systems. The goal of health monitoring systems is to perform off-line defect detection in order to anticipate damage and maintenance. Defects that should be detected are mechanical defaults such as damaged bearings (spalling or brinelling of the races and the rolling elements), damaged gears (scuffing of the teeth), coupling between aero and mechanical abnormal behavior like fan flutter, fleeting events like a shock caused by a small FOD (Foreign Object Damage, small birds ingestion for instance) or rubbing between a rotor and a stator. Impending failures (few minutes) are not in the scope of health monitoring. The scope of health monitoring is to detect damages few flights before failure, but it happens that the early symptom of a future failure shall be detected during a single flight (this is the case of fleeting and non-repetitive events). Such systems require, in general, a significant amount of data to learn the features that are associated with faulty behavior of the engine, as well as with its normal functioning. Furthermore, the high sampling frequency of the vibration signals (for most engines applications, 2 accelerometers with a bandwidth up to 20 kHz), as well as the long time intervals required to perform a full acquisition (*i.e.* corresponding to a particular stage of the flight, for instance an engine shut-down that lasts approximately 2 min, at the end of the flight, or cruise that lasts few hours), leads to

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a huge amount of data which needs to be stored and transmitted. Thus, compression becomes a mandatory component of a health monitoring system and required compression rates into the range of 10–100.

Within this framework, the main challenge we deal with is to define a compression algorithm which is capable of achieving a high compression ratio (*CR*), while keeping a reasonable reconstruction quality, in terms of reconstruction signal to noise ratio (RSNR) or mean square error (MSE). Besides the aforementioned performance criteria, we aim to limit the impact of compression on the signature of some particular potential faults of the engine. Nevertheless, since in such an application we often deal with complexity constraints (*e.g.* embedded systems, real-time monitoring), one important objective is to keep compression algorithms at a reasonable level of complexity.

All these specific constraints motivated our research efforts, which aimed to define a new compression approach for mechanical vibration signals. The proposed algorithm meets the aforementioned objectives, by exploiting the particular characteristics of the mechanical vibration signal.

Whereas the generic field of data compression is extensively treated in the literature, the number of works dedicated to the specific topic of vibration signals compression is rather limited. The most popular approach relies on transform based methods, mostly using various wavelet decompositions such as in [1–3]. The affinity for wavelets comes from two directions: their suitability for the compression of signals with non-stationary characteristics and their extensive use in feature extraction for fault diagnosis purposes [3–6]. However, in Ref. [3], the author recalls that wavelet transform (WT) shows a significant gain over the harmonic approaches—discrete cosine transform (DCT) and discrete Fourier transform (DFT)—only for vibration signals with strong non-stationary characteristics.

The second category of methods is represented by predictive coding [7,8]. In general, various adaptive differential pulse coded modulation (ADPCM) schemes are adopted. However, these papers mostly propose basic approaches, and the reported results rely on a limited set of experiments.

In the category of more specific approaches, we can mention [9], where the signal is transformed into an image and then compressed in the domain of a lifting-scheme WT, or the use of empirical mode decomposition (EMD) [10], which, due to its redundancy, is better suited for analysis than for compression.

It should be noted that most of the aforementioned papers focus mainly on signal analysis and feature extraction, compression being only marginally considered. As it has already been noticed, vibration signal processing relies usually on the use of some transformations/decompositions (WT, EMD). In this way, the signal is decomposed into several subbands, where the features of interest can be easily identified. It is well known, on the other hand, that subband coding (SBC) is one of the classical approaches in the data compression field [11]. In the case of mechanical vibration signals, a widely considered model is based on a sum of harmonics [12], which are related to the speed of the rotating machinery. These frequency components can be easily highlighted by a subband decomposition and effective compression can be achieved by an adaptive quantization of the subbands. Surprisingly, although it seems particularly suitable to vibration signal compression and analysis, classical subband decomposition was never considered for this subject, to the best of the authors' knowledge.

In this paper, we propose a new compression method for mechanical vibration signals. This method is referred to as subband adaptive quantization (SAQ). SAQ can be viewed as an alternative approach to the classical SBC, based on the filter banks [13]. It is well adapted to vibration signals properties of an aircraft engine environment: the frequency content is the superposition of a non-uniform colored noise (due to the combustion chamber, and structural frames and mounts eigenmodes) and many integer harmonics of the fluctuating rotating speeds of the shafts (unbalances, misalignments, blade passing frequencies and gearmesh frequencies). During a flight, the rotating speed of each shaft is almost constant around few hundreds of Hertz during cruise with small fluctuations of few Hertz. The main shafts are not mechanically coupled; their rotating speeds are the result of the aerodynamic balance between compressors and turbines for a throttle set by the pilot. From flight to flight, those rotating speeds may vary by more than a dozen Hertz because of the contextual environment changes between two different flights (external ambient temperature change, for instance). In order to take into account those variations of the rotating speeds, a sampling rate of a dozen Hertz is sufficient for the acquisition of those parameters. SAQ of the vibrations for this application is therefore well adapted, because it allows simple and flexible subband decomposition on a large number of narrow-band signals, using suitable orthogonal transforms. Each subband is uniformly quantized on a number of bits which are adaptively allocated using an energetic criterion. The use of a uniform quantization, combined with an adaptive bit distribution, preserves system simplicity and allows high compression ratios to be obtained with a reasonable amount of distortion. This method is applied to a large number of real vibration signals, issued by plane engines in various working regimes and health statuses. Compression performance, evaluated from the reconstruction quality perspective, is compared with several existing approaches. It shows that SAQ is better suited to the vibration signals than the other methods. We also study the impact of SAQ-based compression on the detection of two of the most common defects of the engine: rolling elements fatigue and rotor–stator rubbing. We show that these defects remain detectable even when a strong compression has been applied to the signal.

In Section 2, we explain how subband decomposition can be implemented using an orthogonal transform. The choice of the appropriate transform is investigated in Section 3. In Section 4, we introduce the principles of SAQ. Compression is tested on a large dataset of vibration signals, the results being presented in Section 5. Compression impact on the fault detection of two particular defects of the engine is investigated in Section 6, whereas the last section is dedicated to concluding remarks.