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Non-intrusive rattle noise detection in non-stationary conditions by an angle/time cyclostationary approach

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ABSTRACT

This work proposes an original non-intrusive approach to detect and quantify rattle noise in automotive gearboxes operating under non-stationary conditions by means of vibration or instantaneous angular speed measurements. Rattle noise is produced by vibro impacts between teeth of unloaded gears excited by the engine acyclism. It appears during acceleration or deceleration phases and its detection requires the analysis of non-stationary signals. In order to take advantage of the repetitive nature of the impacts, an angle/time cyclostationary approach is introduced. Rattle noise is thus characterized through the angle/time duality: the cyclic frequency expressed in events per revolution is directly linked to the periodicity of the impacts while their frequency content is expressed in Hertz. The proposed detection method uses an order/frequency spectral coherence and may be applied either on vibration signals or instantaneous angular speed signals. For validation purposes, a specific instrumentation of a gearbox is set up. The relative speed of the unloaded meshing gears is observed by means of optical encoders to directly detect the instants of impact which then serve as a basis for validation of the non-intrusive detection method proposed in this paper.

1. Introduction

At low speed, noise generated by cars is principally caused by parts of the powertrain. In particular, reduction of engine noise emissions has increased the emergence of noise sources which were previously masked. On the other hand, downsized new engines generate more low frequency acyclic excitations into the vehicle. In automotive vocabulary, the term "rattle" refers to an impact-induced phenomenon which can occur when there is a relative motion between two components with loss of contact [1]. The interest of this paper is focused on rattle noise which can suddenly appear in gearboxes [2]. In manual gearboxes, the pinions are constantly meshed together. For each gear pair, one driving pinion is fixed to its shaft while the loose gear is free to rotate. When a gear ratio is engaged, the corresponding loose gear is temporarily fixed to its shaft while the other ones stay free to rotate. Because of the engine acyclism transmitted to the primary shaft of the gearbox, the loose gears vibrate through their backlashes and some impacts can occur between teeth of unloaded gears. The transmission of the shocks to the housing of the gearbox generates rattle noise. Rattle noise is of primary interest in NVH

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(Noise, Vibration and Harshness), not because it damages the gears but because it produces an acoustic nuisance which is a recurrent problem for car manufacturers.

Among signal processing methods, the kurtosis-based family is classically used to characterize the impulsiveness of a signal. Spectral kurtosis, band kurtosis and kurtogram are the most used techniques deriving from the kurtosis, defined as the ratio between the fourth central moment and the squared second central moment. For the detection of generic rattle noise defined by impact-induced phenomena, impulsive criteria such as kurtosis based methods seem suitable [3,4]. These references deal with generic rattle noise for which the engine rotation speed is not a direct control parameter of the system. On the contrary, the interest of the present study is focused on gearbox rattle noise directly linked to the engine acyclism.

Different approaches have been proposed to model gearbox rattle noise. Some authors investigate phenomenological approaches [5,6] while others build global models [7,8]. The experimental analysis of rattle noise requires test benches able to reproduce engine acyclism by means of a universal joint for example [9]. Many studies are focused on idle gear noise (gearbox on neutral) and use electro-dynamic translation exciters [10,11]. Kadmiri et al. [6] exploit a dedicated test bench replicating excitations from an automotive powertrain. They use two optical encoders in order to measure the Instantaneous Angular Speed (IAS) of driving and loose gears under stationary operating conditions. Several methods can be employed to obtain the IAS: the elapsed time method uses a high frequency clock while the ADC (Analog to Digital Conversion)-based method exploits the analog encoder signal [12]. Some recent works analyse the IAS measurement errors such as the geometric error, the filtering effect due to elapsed time measurement or the counting error [13,14]. From these results IAS can be considered as a good and precise way to reach dynamic behaviour of gears when rattle noise occurs. According to the level of the influencing parameters (level of acyclism, drag torque, pinion inertia, etc.), different situations can be distinguished: single-sided impacts, double-sided impacts or irregular impacts [7].

The state of the art illustrates the difficulty to predict with accuracy rattle noise level before the conception phase. This phenomenon indeed depends on many physical parameters and especially on damping which is difficult to model in this type of systems [15]. The occurrence and the level of rattle noise depend on speed/load operating points which are then difficult to predict. Moreover rattle noise appears principally during acceleration and deceleration phases and its detection during operation thus requires the analysis of non-stationary signals. Consequently, in the present practice, the occurrence and the level of rattle noise are usually judged by in situ listenings of trained auditors.

In order to help more efficient evaluations the aim of this paper is then to construct a method to detect and quantify rattle noise from measurements under non-stationary operating conditions. The method has to be non-intrusive in order to be industrially adaptable without requiring modifications on gearboxes. In this work the interest is focused on "periodic" cases which seem to be the least severe in terms of sound intensity [7] and then require more advanced signal processing methods. In particular, in a four-cylinder four-stroke combustion engine the acyclism is principally composed of the second harmonic of the rotation speed (denoted H_2) and periodic rattle is thus generally composed of four impacts per revolution of the primary shaft: one impact on the active flank and one on the reverse flank of the gear per period H_2.

Rotating machines such as gearboxes produce signals exhibiting cyclostationary properties when operating under stationary or quasi-stationary conditions [16,17]. The occurrence and the level of rattle noise depending on operating conditions and in particular on the rotation speed, the interest in our work is focused on tests in run up conditions classically used to scan the NVH behaviour of gearboxes. The assumption of cyclostationarity has thus to be replaced by the so called assumption of "cyclo-non-stationarity" which is a recent field of research [18–20]. In this context, the order-frequency distribution proposed by D'Elia et al. in reference [18] is particularly well suited to the analysis of rattle noise: the "cyclic frequency" expressed in events per revolution (epr) is directly linked to the periodicity of the impacts while the spectral content of these impacts are linked to the "spectral frequency" expressed in Hertz. A formal framework to this approach is given in reference [21] which introduces the "angle/time cyclostationary" class of signals. Some useful results for rattle noise detection are recalled in this paper. For rotating machine diagnostics, cyclostationary tools are generally applied on vibration or acoustic signals. Their application is however not limited to signals of this nature and can for example be applied on signals issued from angular encoders. In this work the angle/time cyclostationary tools will be applied both on vibration and IAS signals.

The organization of the paper is as follows. The angle-time cyclostationary approach is first presented. It enables the detection of rattle noise with an order-frequency distribution which requires the measurement of IAS with an optical encoder. The test bench and the gearbox instrumentation used in this study are then presented. For validation purposes, a specific instrumentation is used with optical encoders that intrusively measure the relative speed between the driving and the loose gears. These measurements will serve as a reference in order to validate the new non-intrusive detection method proposed in the last section. An order/frequency spectral coherence is eventually estimated on vibration and IAS signals to detect and quantify rattle noise occurrence by observing the evolution of the frequency content of a given cyclic order. A comparison is also made with the Spectral Kurtosis which more closely follows the traditional approach for rattle noise detection.

2. Angle/time cyclostationarity

The cyclostationarity assumption is now widely used to analyse vibration signals of rotating machines [16,22]. This section will show the interest of maintaining an angle/time duality to analyse such signals in non-stationary conditions.