GEAR FAULT DIAGNOSIS AND INDUSTRIAL APPLICATIONS

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Summary

This paper introduces the concept of a gear profile, which is the polar representation of the time synchronous averaged vibration signal computed on the rotation period of a pinion. A gear profile provides an attractive visual representation of the meshing efforts on the individual teeth for each of the gears present in a gearbox. It is mostly useful for the detection of local tooth faults (cracks, pitting) or shaft eccentricity faults. Its computation however presents some pitfalls as some parameters need to be selected with care: choice of the mesh harmonic to demodulate, filter bandwidth, signal duration for the time averaging. We propose some practical rules on how to select them. The amplitude and frequency modulation functions of the profile can then be computed, and the amount of the modulation may be quantified by some parameters. We also present a case where the electrical currant measurement can be very helpful for gear fault diagnosis. The technique is illustrated on a few industrial cases.

Key words: gear profile, time synchronous averaging, local tooth faults.

INTRODUCTION

Time Synchronous Averaging (TSA) is a well adopted signal processing technique which enables periodic waveforms to be extracted from noisy signals [1]. It is particularly suited for the vibration analysis of mechanical systems such as gearboxes, as it enables the vibration of a single gear to be separated from the vibration of the complete system. This technique usually requires the measurement of a trigger signal, typically delivered by a one pulse per revolution tachometer. In case that a speed measurement is not available a technique has been proposed in order to perform angular resampling without the need of a speed sensor, when the machine is submitted to limited speed fluctuations [2, 3]. This technique is based on the speed estimation from one mesh harmonic.

TSA is mostly useful for the detection of local faults (tooth cracks, pitting) or distributed faults (eccentricity). This technique however requires the adjustment of a few parameters: choice of the mesh harmonic to demodulate, filter bandwidth, signal duration for the time averaging . In section I we present the methodology and propose some practical rules on how to select the parameters. In section II the technique is illustrated on a few industrial cases for gear diagnosis.

1. METHODOLOGY

The TSA signal of the vibration signal x(t), assumed to be zero-mean, is defined as

$$TSA(t) = E[\ x(t)\ ] \qquad (1)$$

It is estimated by angular resampling and averaging of the vibration signal over the rotation period of the gear of interest. The number of averaging should be high enough in order to ensure convergence of the TSA; however speed fluctuations should remain relatively limited for the speed estimation method used in [3]. The signal duration is here automatically adjusted, and the TSA convergence is assessed by observing the decrease of the energy of the TSA vs. the number of averaging. The good convergence can also be quantified by Stewart's method [4]. If the energy does not converge to a stable value then the number of averaging is either too low or the signal principal part is not deterministic but rather random periodic, i.e. *cyclostationary*. This may then be highlighted by 2^{nd} order tools such as the instantaneous variance or Time Synchronous Variance (TSV) [5]:

$$TSV(t) = E[\ |x(t) - TSA(t)|^2\ ] \qquad (2)$$

where x(t) - TSA(t) is also called the residual signal. The TSV is more appealing when the underlying cyclic phenomena are not exactly periodic but exhibit some jitter, due for instance to random slips as it is the case for bearings [5]. Gear signal however are assumed to be rather periodic, but the TSV may still be useful to analyze in case of incipient tooth faults (pitting) which will at first excite the higher frequencies.

It is also possible to compute some indicators of cyclostationarity at 1^{st} and 2^{nd} order, corresponding respectively to the TSA and the TSV, which may be valuable in order to quantify and trend the observed phenomena [6]:

$$ICS1 = \frac{\sigma^2[TSA]}{\sigma^2[x]} \quad \text{and}$$

$$ICS2 = \frac{\sigma^2[TSV]}{DC[TSV]^2} \tag{3}$$

where σ stands for the standard deviation and DC[.] for the mean value.

The estimated TSA in (1) can then be bandpass filtered around the mesh fundamental frequency or one of its harmonic, and then Hilbert transformed in order to compute the modulation functions. Since the TSA signal is deterministic we propose to select the mesh harmonic with the highest amplitude, which may not always be the fundamental component depending on the measurement transmission path. The filter bandwidth, i.e. the number of sidebands *Ns* to include in the bandpass filter must be high enough so as to keep a good resolution but must not to include some spurious components related to nearby mesh harmonics. We choose a number of *Ns=10* sidebands. This is practically sufficient, however *Ns* must not exceed half the mesh order, i.e. half the number of teeth of the gear.

The filtered TSA signal can then be represented in a polar way over the rotation period of the gear. This so-called *gear profile* provides a visualization of the variation of the meshing pressure on the individual teeth of the gear, useful for the diagnosis. The Amplitude and Frequency Modulation Functions (AMF, FMF) can also be represented in a polar way.

Lastly, the modulation of the AMF can be quantified by the following modulation rates:

$$TMAeff = \frac{AMFeff \times \sqrt{2}}{DC[AMF]} \quad \text{and}$$

$$TMApp = \frac{AMFpp/2}{DC[AMF]} \tag{4}$$

representing the RMS and peak-to-peak amplitude modulation rates respectively. Definitions are equivalent for the FMF.

2. APPLICATIONS

2.1 Kaplan Hydraulik Turbine

This first application deals with a Kaplan hydraulic turbine equipped with a multiplication gearbox with ratio 180/24=7,5. The GCD (Geatest Common Divisor) between tooth numbers is 12 here. The turbine is operating at full load (1,6MW). TSA was performed on the vibration signal measured at bearing 3 in vertical direction (Fig. 1). Fig. 2 shows a good convergence of the TSA energy after about 100 period averaging. The TSA of the 24 tooth gear, represented on Fig. 3, exhibits a few peaks, which can also be seen on the FMA & FMF profiles of the mesh fundamental component (Fig. 4). On Fig. 3 is also represented the instantaneous standard deviation, i.e. the squared root of the TSV. The indicators of cyclostationarity (3) are also computed. Note a relatively low value of the ICS2, indicating that the cyclic phenomena are mainly periodic deterministic.

Note also the rather high values of the modulation rates (*TMAeff* =54%, *TMFeff*=13%). This seems to indicate a relatively poor condition of the gears. Indeed after visual inspection the client observed some “*surface wear on the teeth due to relatively deep pitting*”. Measurements performed the following year showed a little evolution (*TMAeff* =59%, *TMFeff*=33%) which needs to be observed.

Note that the TSA seems to be composed of two identical patterns on Fig. 3, which actually corresponds to the common sub-period of the gears, due to the GCD=12. This is due to the presence of 1/12 sub-harmonics of the mesh frequency in the signal spectrum, indicating the presence of tooth wear families. The computation of the gear profiles was not really necessary for the diagnosis here but allowed to confirm visually the relatively poor condition of the gears.

2.2. Unrolling machine

This second application deals with an unrolling machine used in the aluminum industry. The rolls are driven trough a reduction gearbox with ratio 30/48 (GCD=6). For measurement in March 2010, the TSA of the 30 tooth pinion was computed (Fig. 5) as well as the corresponding gear profiles for second mesh harmonic, since this component appears to have much higher level than fundamental in this case. The AMF profile on Fig. 6 shows high eccentricity (*TMAeff*=93%), which indicates a meshing pressure concentrated on one part of the gear pinion only. Machine inspection revealed some relatively high degree of bearing clearance and a misalignment with the driving motor, however no fault on the gears. Another measurement was then performed in October after maintenance actions. The new profiles (Fig. 7-8) show drastic changes (*TMAeff*=37%). Also observe the changes in the indicators ICS1 & ICS2 (Fig. 5 & 7).

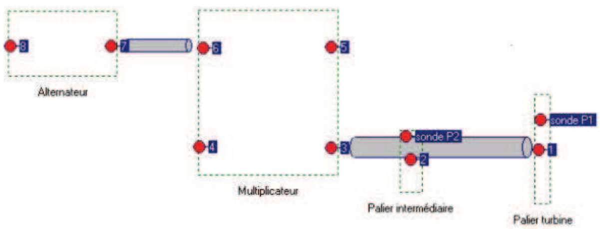

Fig. 1. Schematic of the hydraulic turbine; multiplication ratio is 180/24

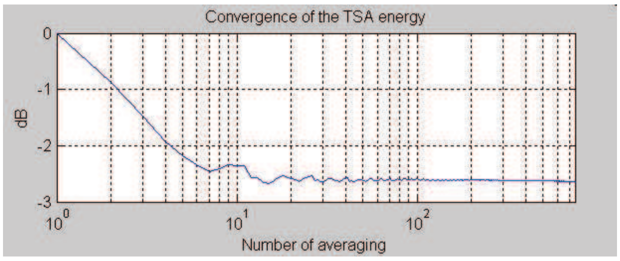

Fig. 2. Convergence of the TSA energy versus the number of averaging for the 24 tooth pinion

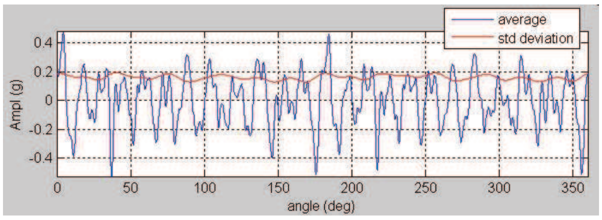

Fig. 3. TSA of the 24 tooth pinion (ICS1=54%, ICS2=4%)

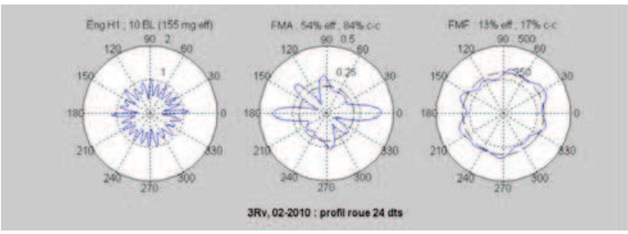

Fig. 4. Gear profile and modulation functions of the mesh first component

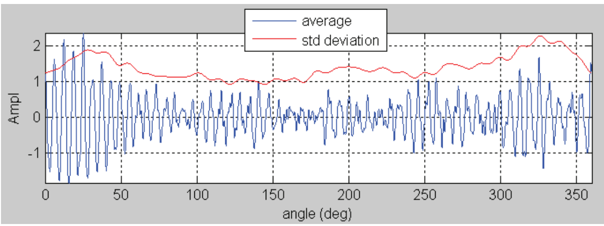

Fig. 5. TSA of the 30 tooth pinion (ICS1=16%, ICS2=24%)

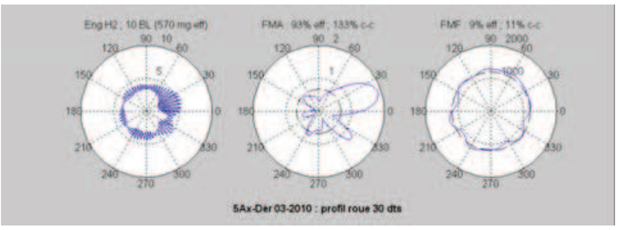

Fig. 6. Gear profile and modulation functions of the mesh 2nd harmonic

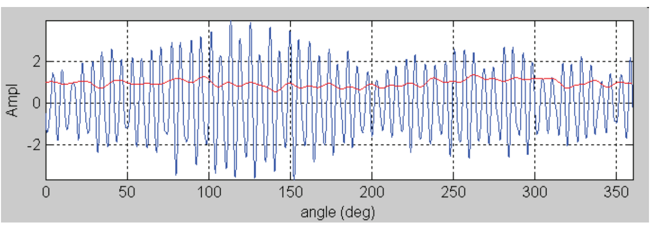

Fig. 7. TSA of the 30 tooth pinion after maintenance (ICS1=72%, ICS2=10%)

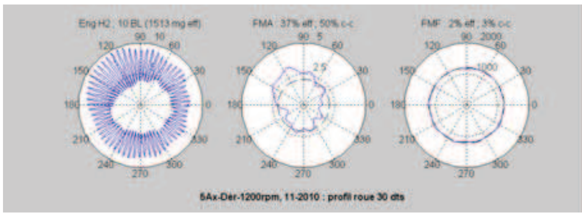

Fig. 8. New gear profile and modulation functions of the mesh 2nd harmonic

2.2. Gear tooth fault diagnosis of drying rolls

This last application deals with the diagnosis of local gear faults of drying rolls in a paper making machine, by means of the electrical current. Currant analysis is a very useful tool for the diagnosis of faults inducing torque or speed fluctuations [7]. It ideally compliments vibration analysis without being intrusive. In this case the operator observed abnormal variations of the current absorbed by the AC motor driving a drying roll section. The variations were apparently random, as it appears in the measurement signal (Fig. 9). The AMF of the current fundamental component was computed and averaged synchronously with the rotation period of the rolls (about 1.6sec). The AMF profile shows 4 main peaks (Fig. 10), which may indicate local tooth faults on the main geared roll. Indeed when dismantling the gear the operator literally observed '*several falling teeth*'.

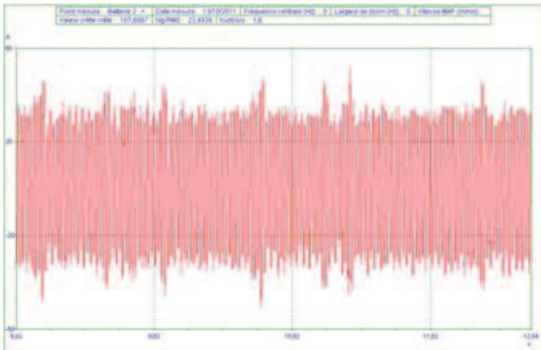

Fig. 9. Electrical current signal of the driving motor

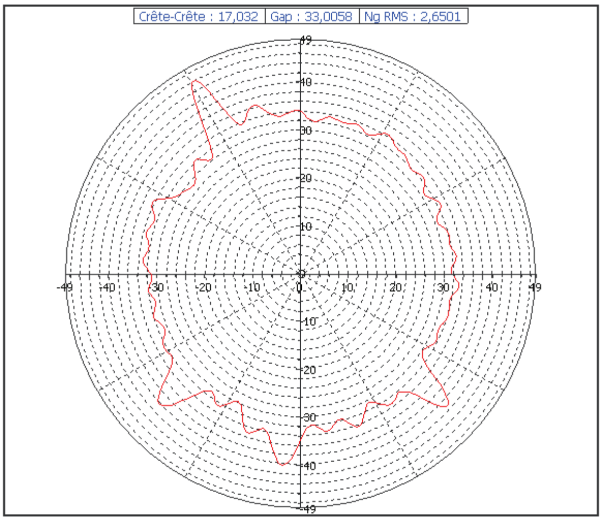

Fig. 10. AMF profile averaged over the rotation period of the geared roll (TMAeff=11%, TMApp=26%)

3. CONCLUSIONS

In this paper, we have shown on a few examples that gear profiles obtained from the classical TSA can bring an interesting added value for gear diagnosis. Care must be taken however as they do not provide the full diagnosis but must come in addition to traditional spectrum analysis (relative amplitudes of mesh harmonic, presence of sub-harmonics, coincidence frequency, level of sidebands…). Gear profiles can be useful in order to visualize the fault (local tooth faults, eccentricity) when a problem is first suspected. More research and experience is needed in order to interpret the different parameters (modulation rates, indicators of cyclostationarity) and to relate them to the severity of the fault.

Acknowledgements

DYNAE gratefully acknowledges its customers, especially: *Usine d'Electricité de Metz (UEM), CONSTELLIUM* and *Papeteries du Rhin.*

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