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Effect of Load on Vibrations of a Railway Gearbox

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Abstract

Condition monitoring of a railway gearbox installed on a metro vehicle is described. The peculiarities of the application, which led to a sort of “bouncing” of the whole gearbox when running in coasting at high speed, are such that extensive failures of the cage of a taper roller bearing were observed and related to the abnormal accelerations measured on the casing. The complexity of the signals led to the need to use numerical indicators more sophisticated than levels or energy. A proper combination of different indicators was checked during tests in different conditions and verified through the application of the procedure to signals from regular service. A combination of energy and kurtosis was found to give the best results in terms of reliability of detection.

Keywords: gearbox, vibrations, railway, metro, condition monitoring, kurtosis, failure, bearings.

1 Introduction

A companion paper [1] discusses in detail the failures that affected a gearbox for metro applications and the measures taken to fix the problem. A fundamental part of the activity was the development of a criterion to establish when measured accelerations, in terms of shocks and vibrations, are acceptable or potentially dangerous.

Scope of this paper is therefore to identify a numerical indicator that is readily applicable to vibrations measured on the structural part of the gearbox. The methodology was developed after the modifications described in [1] which appeared to be successful to avoid the aforementioned failures and seems quite simple and effective. In order to compare the results with “normal” operating conditions of the same gearbox, the methodology was applied back to the measurements taken during previous test campaigns, confirming its validity.

The paper starts with a brief description of the mechanical transmission and of the observed failures, focussing then on the signal peculiarities and the processing strategy. Results are compared to other cases and critically analysed.

2 Description of the mechanical transmission and service

Although the reader is referred to [1] for all the details, a brief description is necessary here to introduce the problem. A conventional metro vehicle (12 t/axle) is equipped with bogies on which two electric motors with opposite shafts are paired and elastically supported. Each motor drives a torsionally rigid splined joint which in turn drives a two-stage gearbox mounted on the axle and suspended by a reaction rod at an end arm (Figure 1).

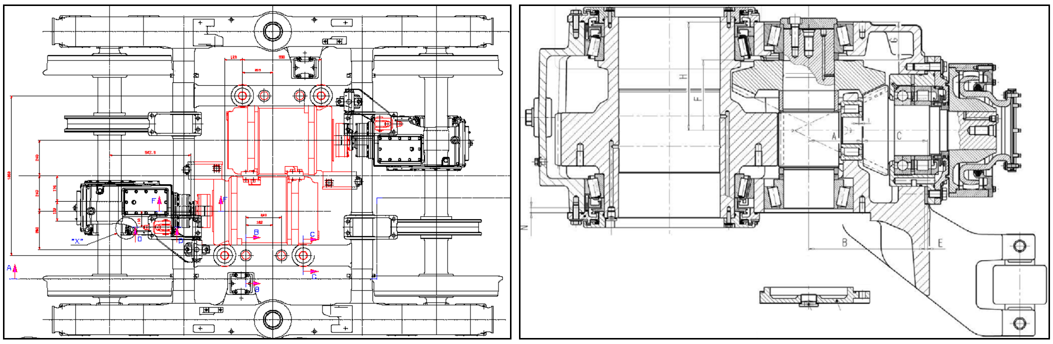

Figure 1: Left: top view of a motor bogie. Electric motor cases are mechanically coupled and elastically suspended to the bogie frame. Right: cross-section of a gearboxes where input shaft, the two reduction stages and the reaction rod attachment can be easily identified.

During service, the transmission is often operated idle (*coasting* condition) for long distances at the maximum operating speed (80 km/h). This feature is believed to be the reason for failures of the cage of one of the two taper bearings of the intermediate gearbox shaft. For this reason, several attempts were made to modify the driveline behaviour during coasting avoiding the appearance of very high "shocks" in the measured vibrations of the gearbox [1]. The last modification introduced, i.e. the application of a braking torque by using a modified braking system from a motorbike, proved to be capable to modify the behaviour of the gearbox and is discussed in this paper (Figure 2).

Vibrations proved to be able to shake the whole gearbox and in some cases were also observable on the axleboxes. The choice of a measuring point was long debated and at the end it was decided to instrument permanently the reaction rod attachment with a 100 mV/g IEPE accelerometer (Figure 3). Although this limits to ±50 g the end-of-scale (the measuring chain having a maximum input voltage of ±5 V), this choice proved to be effective on gearboxes in "good" conditions while damaged gearboxes, i.e. those with deteriorated cage, often pass ±100 g. This situation, observed in a large number of cases, is nevertheless not considered here as the main goal of the activity is to *avoid* the appearance of defects that lead to the increase of acceleration levels.

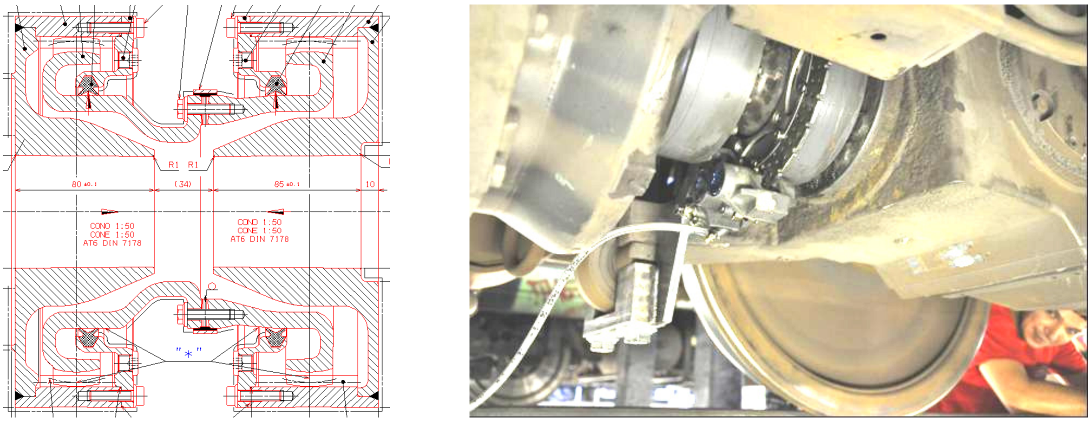

Figure 2: Torsionally rigid joint (left) and application of the experimental braking system (right).

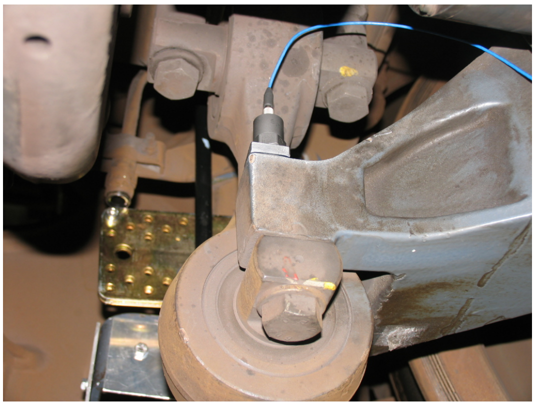

Figure 3: Measuring accelerometer bonded onto the reaction rod attachment.

Reasons for choosing this measurement location are that it is situated in a bulk structural point (less prone to be affected by local modes) and it is well protected during tests. This measurement gives information of the rigid rotation of the gearbox around the axle.

3 Acceleration signal features

Gear meshing induces vibrations in all gearbox casings. Railway gearboxes are rather different from automotive ones, as long as a train is normally bidirectional. Noise from cars in forward and reverse gears is definitely different, and for the gearbox considered here, including a helical bevel gear as the input stage very similar to the differential gear in road vehicles, different meshing conditions in the two directions should be considered absolutely normal.

As a result, loaded driveline generates “continuous” vibrations in the gearbox case which contain meshing frequencies of the two reduction stages; on the contrary, unloaded (idling or coasting) driveline should result in “almost no vibrations” condition. Unfortunately gears always require a certain teeth play as they cannot work preloaded. This play, together with elasticity and high rotary inertia of the motor-joint-pinion group, leads to self-excited oscillations during which the play is alternatively recovered in either direction. The first part of the driveline therefore “bounces” on the existing play alternatively touching the pinion with the mating flanks of the teeth of the bevel wheel.

Except for a specific case that is described in the companion paper and that incidentally misled for some time the troubleshooting activity, these bounces are not regular and happen as apparently “random” spikes with high acceleration levels, sometimes much higher than normal accelerations during torque transmission. These spikes are a consequence of the high shocks that generate abnormal stresses in all the elements – gears, shafts, bearings – leading to the failure of a cage.

It is important to underline that traction or braking torques may produce high vibration levels that are nevertheless relatively well tolerated by the gearbox. As long as loads are constant, in fact, lubrication conditions may be considered as stationary and effectively separating metallic parts; when the load is continuously reversing, hydrodynamic lubrication does not establish leading to potential damages in bearings and gears.

4 Experimental campaign and data collection

4.1 Description of the tests

Two gearboxes, belonging to motor axles #7 and #8 of a train, were monitored with the accelerometers mounted as described above. Sampling frequency was set to 10240 Hz, largely sufficient to detect all tooth meshing frequencies. Gearbox #7 was retrofitted with the braking system while gearbox #8 can be considered the reference one. In order to avoid any passive torque effect from the aerodynamic part of the motor (self-cooling fan), the air inlet grid was covered with a panel. Tests were done in a depot on a dedicated test track up to 60 km/h. For evident thermal reasons, moreover being the tests conducted between with an external temperature of approximately 36 °C during August 2012, the inverter driving the motors was therefore switched off all of the time. A summary of the test runs is shown in Table 1.

As an example, the results from run 10 are shown in Figure 4, where:

- The upper subplot shows the current speed [km/h] and the position of the driving handle (signal high = traction or braking, signal low = "coasting"). Remind that this has limited meaning as the inverter was constantly OFF;
- The mid subplot shows the vertical acceleration [g] recorded on the gearbox where brake disc is applied (motor axle #7). The red trace is the pressure [bar] reached in the braking system;
- The lower subplot shows the vertical acceleration [g] recorded on the gearbox taken as a reference (without brake disc, motor axle #8). Although it is meaningless for this gearbox, the brake calliper signal is reported for synchronization and clarity.

Run	Direction	Max Speed	Conditions
1	Eastbound ➔	65 km/h	Free runs
2	🡐 Westbound	48 km/h	
3	Eastbound ➔	60 km/h	
4	🡐 Westbound	42 km/h	
5	🡐 Westbound	60 km/h	
6	🡐 Westbound	60 km/h	Application of braking
7	Eastbound ➔	60 km/h	
8	🡐 Westbound	56 km/h	
9	Eastbound ➔	36 km/h	
10	🡐 Westbound	56 km/h	

Table 1: Test runs with the braking experimental set on motor axle #7. The first five runs are "free" (pure coasting), while during the remaining runs mechanical braking is applied only to axle #7.

4.2 General observations from "Free runs"

Not all runs are equally good due to speed and configuration limitations. The comparison is better made between runs 1 and 3 (same direction, same maximum speed of 60 km/h) to observe the repeatability and between runs 3 and 5 (opposite direction, same maximum speed of 60 km/h) to see the influence of running direction.

A frame of 5 s is taken at the maximum speed as this exacerbates the behaviour of the (driven) gearboxes, from which emerged clearly that gearbox #7 is heavily contaminated by a wheel flat (the signal is dominated by a very regular pattern that is proportional to speed) while gearbox #8 shows the usual irregular set of randomly spaced spikes and should be considered as one exhibiting the "standard" behaviour (Figure 5).

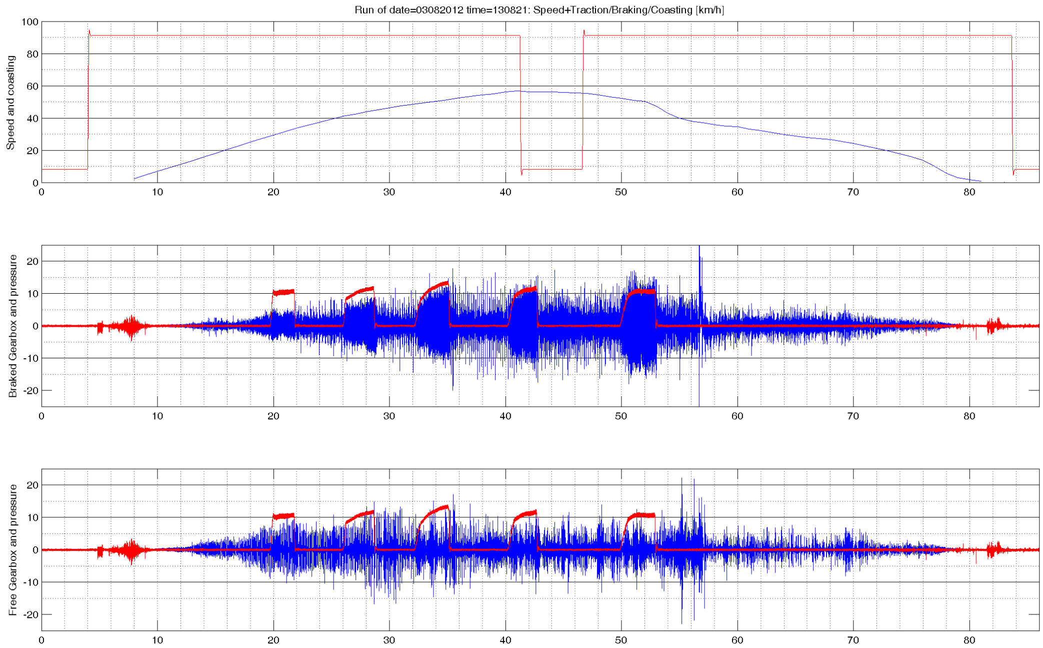

Figure 4: Plot of the Westbound run 10. The application of some braking is visible.

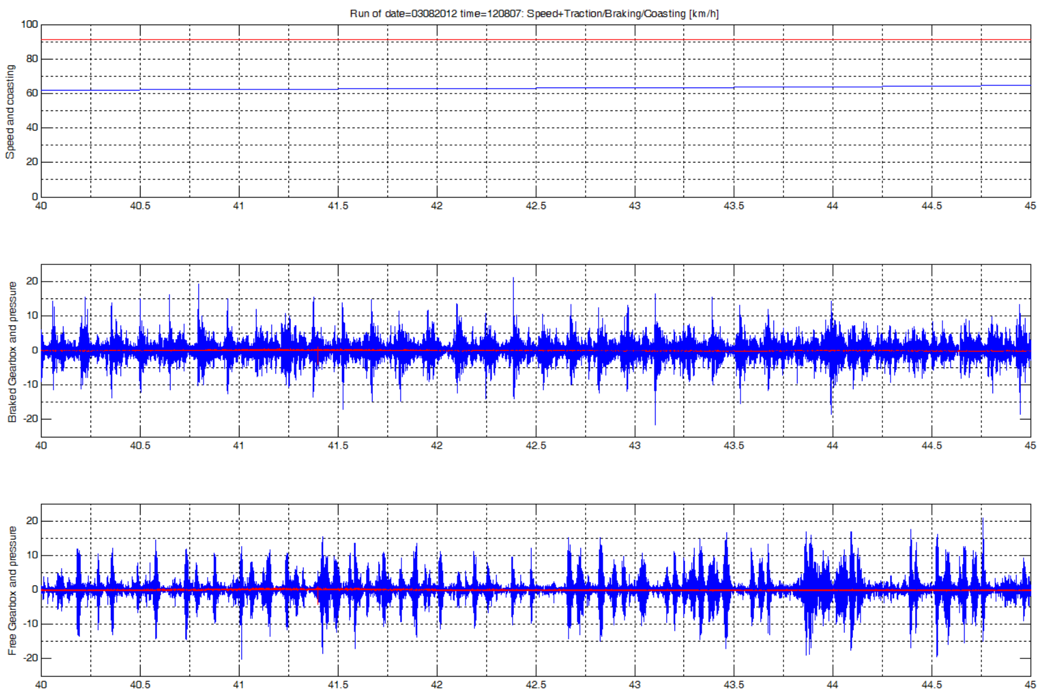

Figure 5: Five seconds of Run 1 (Eastbound) at 60 km/h. The effect of a wheel flat on gearbox #7 is evident, while gearbox #8 vibrates with randomly spaced spikes.

4.3 General observations from “Braked runs”

As expected, the behaviour of the “reference” gearbox (motor axle #8) is not influenced by the effect of the braking on motor axle #7. The best Westbound runs resulted to be run 8 and run 10 since they contain braking at low and high speed. As long as they resulted absolutely repeatable, only run 10 will be shown in the following.

Figure 6 shows the evident modification of the shape of the signal of motor axle #7 when mechanical braking is applied. The shape of the signal changes from free run (spikes from wheel flat) to braked run (apparently smoother signal). The envelope of vibration signal during braking copies the trend of the pressure in the brake calliper. A close-up in the speed range 40÷60 km/h highlights both the influence of the wheel flat and of the braking on the signal from motor axle #7.

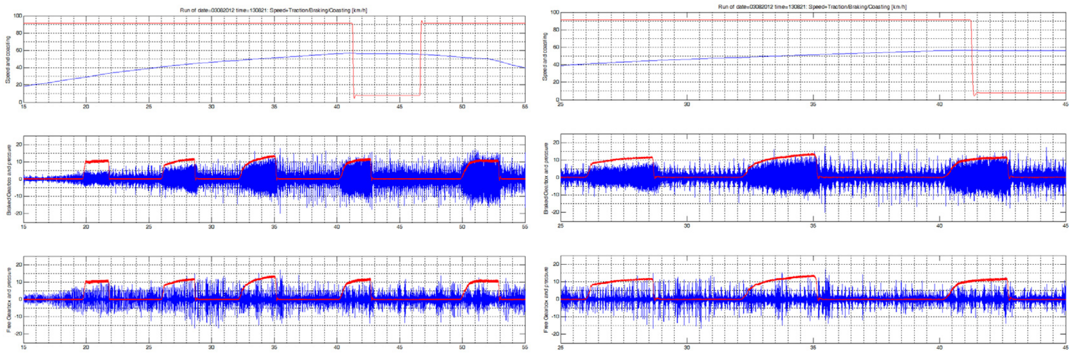

Figure 6: Left: the more significant part of run 10 (Westbound, 56 km/h). Right: close-up in the speed range 40÷60 km/h.

Eastbound runs exhibit at higher speeds a behaviour similar to Westbound runs. Run 9 is the only one which contains braking at lower speeds (Figure 7). A close-up on the two brakings at 20 km/h and 32 km/h shows that the regular pattern arising from the effect of the wheel flat is not clearly visible yet, and that the motor axle #7 shows the typical “randomly spaced spikes” accelerations of the “standard” gearboxes. During braking the amplitude of the signal is much higher and also the energy will be very likely higher. The effect on a wheelset without wheel flats should look like this at all speeds. The small fluctuations in the pressure signals are due to the inevitable out-of-plane resulting mounting error of the brake disc.

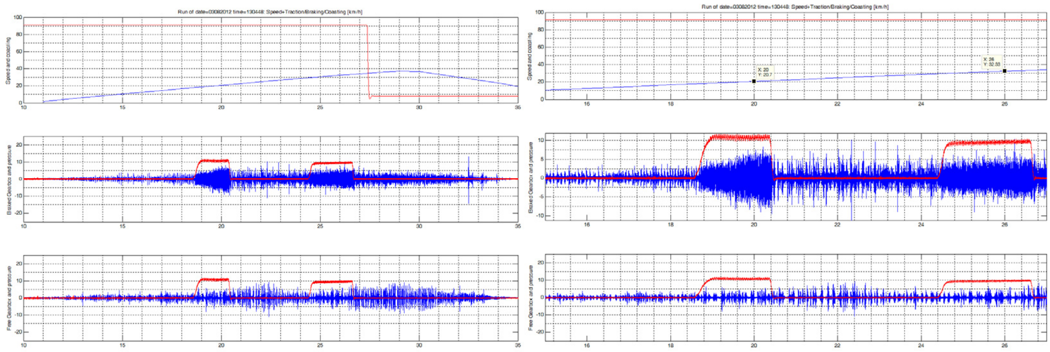

Figure 7: Left: run 9 (Eastbound, 36 km/h). Right: close-up on the two braking.

4.4 Conclusions from available data

It can be concluded from this first analysis that:

- The gearbox that was selected to install the brake disc is mounted on a wheelset that has a wheel flat. This prevents the analysis at higher speeds, where the signal is strongly contaminated by the “bumps” coming from the wheel flat;
- At low speed both gearboxes have the same “standard” behaviour, although for the comparison “standard” gearbox a limited dependency from the direction seems to be present (to be investigated in more detail);
- During braking the vertical acceleration measured on the body (reaction rod attachment) of the braked gearbox changes dramatically. This suggested a more thorough analysis of the signals to identify whether the influence of braking can be positive or negative;
- The amplitude of the “continuous” signal during braking seems related to the pressure existing in the brake calliper.

5 Signal processing description

5.1 Introduction

The evidence that signals change during braking led to the identification of a strategy to evaluate whether the vibration is more conservative or, on the opposite, introduces more stresses in the gears.

To such goal, the following signal processing methodology was adopted:

- The signal is first split in 0.5 s slices (= 5120 samples). This size is small enough to appreciate braking phases (which last a few seconds) and large enough to filter out any local feature that lasts, roughly speaking, a few milliseconds;

- The RMS (root mean square) of each zero-average slice value is evaluated as the second statistical central moment, by using the `std` Matlab function which returns the variance of the signal;
- The kurtosis value of each slice is evaluated as the fourth statistical central moment, by using the `kurtosis` Matlab function which.

The kurtosis is the measure of the "peakedness" or "spikyness" of the probability distribution of a real-valued random variable [2]. For the purpose of this work, kurtosis is a measure of how many samples are distant from the average of the (squared) signal. These samples are dominant in a "spiky" signal with low standard deviation [3], as in the case of the "standard gearbox" considered in this paper, where bearings are in good conditions.

It is important to underline that, being a central moment normalized by the fourth power of the standard deviation, kurtosis results to be dimensionless and unaffected by signal amplitude, i.e. describing only the shape of the signal in terms of spikyness.

The values of the normalized kurtosis for some typical signals are [2]:

- 50% high / 50 % low square wave[1]: k=1
- sine wave: k=1.5
- random signal with uniform distribution: k=1.83
- random signal with normal (Gaussian) distribution: k=3

5.2 Signal processing procedure applied to free and braked runs

The use of energy and kurtosis functions applied to a representative "free run" is shown in Figure 8. For wheelset #7, with a wheel flat, the energy increases linearly with speed (the number of spikes in the 0.5 s time frame is directly proportional to the speed) and the kurtosis is »3. For wheelset #8, which is not defective, the energy signal does not follow closely the speed signal, meaning that it is due to other mechanisms (plays inside the gearbox) while kurtosis remains high.

[1] As long as the fourth power of the signal is considered, after removing the average the signal is constant and the standard deviation raised to the fourth power is identical to the kurtosis.

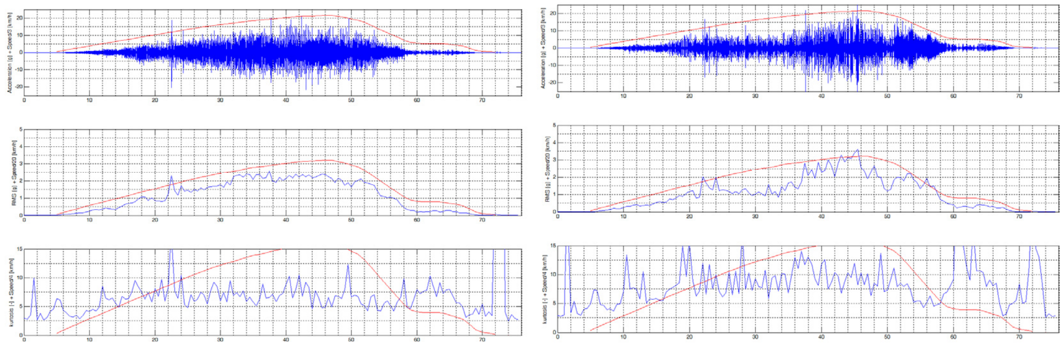

Figure 8: Vertical acceleration, RMS and kurtosis for run 1 (Eastbound, 60 km/h). Left: gearbox on motor axle #7 (with wheel flat). Right: gearbox on motor axle #8 (without wheel flat).

As long as the maximum interest is deserved to the conditions found during “braked runs”, in this paragraph several runs are shown. In all the runs (Figure 9, Figure 10 and Figure 11, with pressure indicated in green) an increase in the energy somewhat proportional to pressure is observed during braking while kurtosis decreases sensibly and consistently.

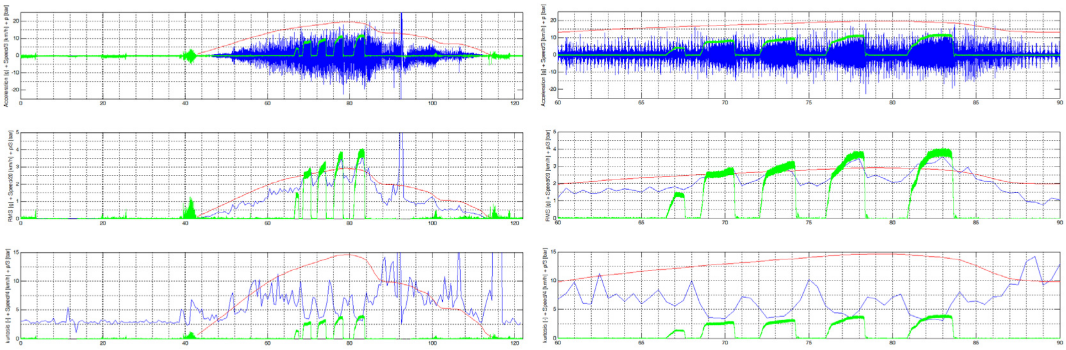

Figure 9: Left: vertical acceleration, RMS and kurtosis for run 6 (Westbound, 60 km/h). Right: close-up on the braking section.

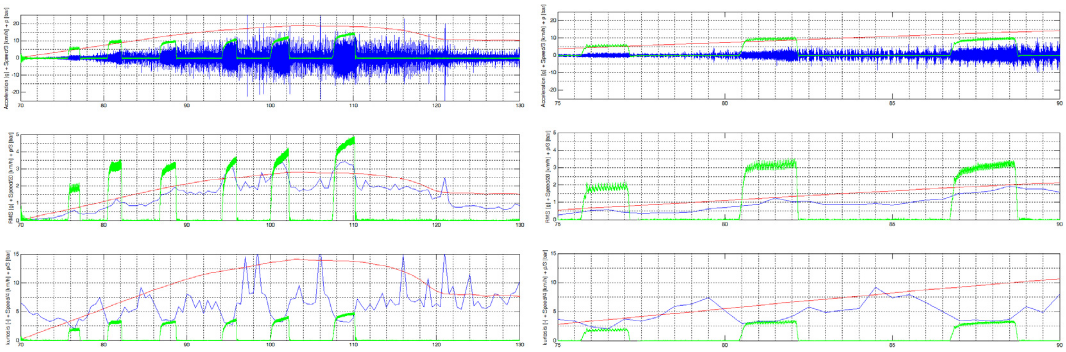

Figure 10: Left: vertical acceleration, RMS and kurtosis for run 8 (Westbound, 56 km/h towards) with braking also at low speed. Right: close-up on the braking part.

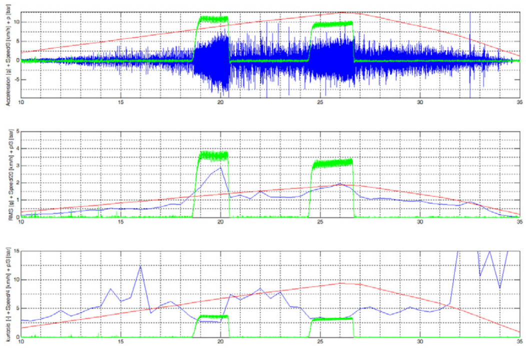

Figure 11: Vertical acceleration, RMS and kurtosis for run 9 (Eastobound,36 km/h towards) with only some braking at low speed.

The following considerations can be drawn:

- For freely rotating gearboxes, vibration energy is poorly correlated to speed. Energy remains almost constant above a certain speed, meaning that once this “threshold” is reached, the gearbox goes on shaking with quasi-random spikes almost regardless of speed;
- On the contrary, where the input is tightly related to speed, such as in the case of the damaged wheelset (presence of a wheel flat), energy is strongly correlated to speed. This condition should be avoided as much as possible in any test campaigns as it can be misleading;
- Kurtosis is consistently >5 and in some cases (see Figure 8) is >7.5 for most of the time, indicating that the presence of spikes in the signal of the “reference” gearbox on motor axle #8 is dominant and extremely serious;
- The application of braking to the gearbox on motor axle #7 generates higher vibration levels than can be clearly seen by the energy even if the signal is disturbed by the spikes coming from the wheel flat;
- At the same time, the kurtosis value falls down, during braking, at values ≈ 3, and in same cased even down to ≈ 2.5, indicating that the vibration signal is extremely regular and repeatable.

5.3 Validation of the signal processing procedure

The use of a complex indicator such as the kurtosis needs to be justified not only by the results obtained in a very special case, i.e. the mechanical braking of a gearbox with the inverter switched off, but also by the results obtained in a “standard” case. Data from a previous campaign (January 2012) where measurements were taken during normal operation conditions have been re-analysed. In these records the inverter was alternatively switched ON and OFF. The ultimate goal of this re-analysis is to show that the signal measured during traction/braking is similar (in kurtosis terms) to the signal measured during the application of “joint braking”.

Figure 12 shows the application of RMS and kurtosis function to the recorded signal with inverter OFF. In order to compare time histories of comparable duration, Figure 13 shows a close-up of 50 s of the same signal where speed is close to 80 km/h. A further 2 s zoom shows the usual series of spikes.

Table 2 summarizes the numerical values obtained by processing the signals. As already observed above, RMS value largely depends on speed, while kurtosis is much less dependent from speed. It is evident how kurtosis with meshing teeth is much less than with inverter OFF.

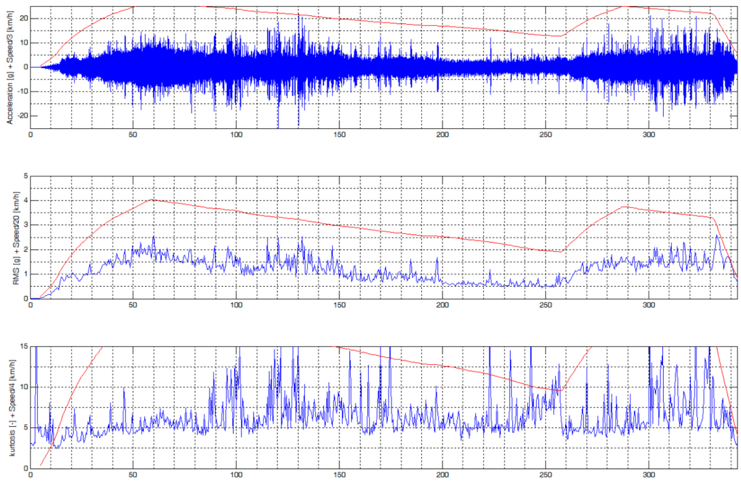

Figure 12: Test run with inverter OFF (acceleration, RMS and kurtosis). Red line indicates speed.

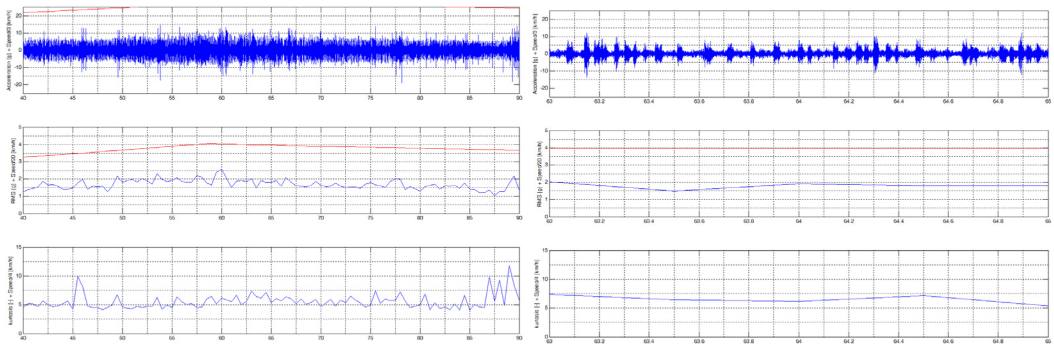

Figure 13: Test run with inverter OFF. Close-up during 50 s (left) and 2 s (right) at top speed.

Figure 14 shows the application of RMS and kurtosis function to the recorded signal with inverter ON and to a short 5 s zoom during acceleration when gears are meshing firmly.

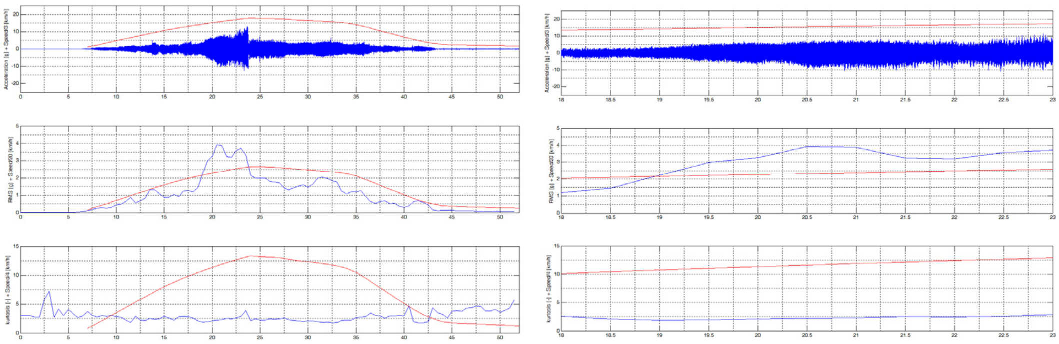

Figure 14: Test run with inverter ON. Full run (left) and close-up on 5 s (right) during acceleration.

INVERTER CONDITION	PEAK	RMS	Kurtosis
OFF	± 10 g "empty" signal	0.5÷2 g	5÷7.5
ON	± 10 g "full" signal	1÷4 g	≈ 2.5

Table 2: RMS and kurtosis with inverter switched OFF and ON

6 Conclusions and further developments

Experimental tests done by using a disc brake mounted on the front flange of the joint of a gearbox gave promising results. The application of a tangential force on the disc surface introduced a lateral force and a braking torque which forced the gears to firmly interact also during coasting leading to the following important modifications in the vibration signals coming from the gearbox:

- During braking, vibration level increases (in terms of energy or RMS) with respect to the coasting phases;
- Nevertheless, the vibration signal looks more "constant" and less "spiky". This is numerically confirmed by the application of the kurtosis function which testifies that the signals are more regular. This implies that gear meshing and all the forces in the drive chain are more regular;
- This could possibly have a beneficial effect on the cage of the taper bearing of the intermediate shaft of the gearbox. It is widely accepted that kinematic chains work better when (even slightly) loaded.

Briefly speaking, keeping a certain load on the motor shaft removes the spikes and makes the gearbox working in “standard” conditions. The application of the function *kurtosis* to signals from previous test campaigns gave consistent results. It appears confirmed that this statistical indicator may usefully complement other kind of analyses to identify whether recorded signals are “spiky” or “smooth”. The use of kurtosis will be extended to future test campaigns and will be regularly used and to assess the working conditions of gearboxes in service.

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