A real time algorithm for monitoring the gearbox reliability test

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Abstract – The aim of this paper is to illustrate a new method for monitoring a gearbox during the reliability test (or duration test). In particular it is illustrated the tune-up of an algorithm for monitoring this test in order to stop it if an unexpected event occurs. In the first part it is explained the reliability test, why and how it is performed on a gearbox. In the second part it is showed the selection of the best points for the measurement and the equipment used for the assessment. In the third part it is presented the algorithm for improving the reliability test. We have settled the algorithm in order to stop the test if the gearbox will be damaged for any reason. By using this algorithm, we can early detect a gear crack, having so the advantage both of providing the integrity of the gearbox and the possibility of inspecting it.

Key-Words: - Gearbox, Fourier Analysis, Pitting, Side Bands.

1 Introduction

Measurement and analysis of vibration, in order to monitor the working condition of industrial equipments during their life, had a great development during the last 30 years. The vibration analysis is now employed in many fields: from steel factories to petrochemical ones, from mechanical industries to the aviation and aerospace applications.

The measurement of vibrations performed on a generic equipment during its working process contains many information on the working condition. Generally, the set-up development or inner mechanical adjustment show a characteristic vibrational pattern; a significative changing of this pattern should reveal the presence of some anomalies in the dynamical system [1,2].

The theoretical basis of the algorithm, subject of this paper, is based on the knowledge that the vibrational signal obtained by the accelerometer processed by means of the spectral analysis is the most efficient technique for monitoring car gearbox; in fact, by monitoring the spectrum signal, we analyze the time evolution of characteristic frequencies of the gearbox components. With such as technique it is possible to detect the anomalies. In fact, every gearbox has a characteristic frequency spectrum but the presence of defects may change this inner spectrum in several ones depending on the type of defect itself [3,4].

It is well known that before the production and commercialization of a new designed gearbox it is necessary to assess many reliability tests. One of these concerns the gearbox with the duration test.

2 Duration test assessment

The duration test is performed after the gearbox passes the check on the lubrication test. Therefore, a running-in for all the gears is planned. During this one, the gear transmission works at low rotation velocity (2000 – 2500 rpm) with low value of torque (roughly the 10% of the maximum torque). When this phase is termed, and after the substitution of the lubricate, the reliability test (duration test) can start.

This test consists of a gearbox running for a huge number of kilometres for all the gears, both in condition of maximum torque and in condition of maximum rotation velocity. The maximum torque and power, and the relative rotation velocity, are set on the basis of the features of engine and gear ones.

Because the test is the same for all the gears, this paper shows the test for one gear only. For that the first gear was chosen.

The rotation velocities are:

- 2500 rpm, condition of maximum torque
- 4000 rpm, condition of maximum power.

The total distance that the gear transmission must realize in first gear is named D_1. The D_1 distance is not realize in one step, but in N steps of equal length $d_1 = D_1/N$. The value chosen for N is 100, so if a gear transmission doesn't show any damage after 100 steps, it means that the 100% of the test is achieved.

As said before, each single step includes two others: the first, in which the gearbox is in the condition of maximum torque, the second one when it is in the condition of maximum power.

The foreseen distances for this two step, named d_{1c} and d_{1p}, are set-up too, so they give the equation $d_{1c} + d_{1p} = D_1$.

In the following we explain how the duration cycle was performed in particular during the last step. First of all, we increase the velocity of primary transmission shaft with the aim of arriving to the value which corresponds to the maximum torque; when the primary transmission shaft reached this velocity, we gradually applied the torque, until the foreseen maximum value is obtained.

The gear transmission, in first gear, runs the foreseen d_{1c} km in conditions of maximum torque, after that the torque is reduced to the 10% of its maximum; the velocity increased for getting the maximum power and subsequently the torque was applied to rise the value corresponding to the maximum power. In this condition of maximum power the gear transmission runs the foreseen d_{1p} kilometres.

When this distance is covered, the step of "rest and lubrication" illustrated before, is done in sixth gear. The purpose of this step is to cold the lubricant and, at the same time, to lubricate all the components of the gear transmission. At the end of this step, another cycle starts composed of maximum torque and maximum power following the same procedure said above. A gear transmission that doesn't show any imperfection is such to pass all the N steps planned.

In tab.1, schematically are presented the distance used for performing the test:

Gear	Planned total distance	To repeat N times		Total
First	D_1	Distance in Max Torque	Distance in Max Power	D_1
		d_{1c}/N	d_{1p}/N	

Table 1 – Planned distances during the duration test

3 Experimental apparatus

Let's give a view on the gearbox under study. The gearbox is composed of 3 shafts and 6 gears. This gearbox has the advantage to take-up less space with respect to the other ones designed with two shafts of equal size as the actual illustrated in the present paper. This is an advantage, in fact, the engine compartment has more space for other accessories (*i.e.*, air conditioner, hydraulic power steering, etc.). The small dimensions of gearbox give us one more advantage for obtaining a greater lock of the wheels by necessity.

The scheme of the gearbox is reported in the Fig.1.

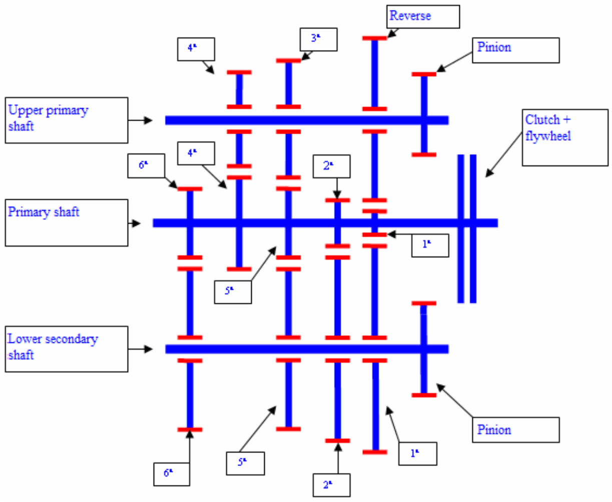

Fig.1 – Gearbox overview

In the first step four piezoelectric accelerometers were employed for supervising the reliability test. In particular we studied gearbox vibration with 3 tri-axial and 1 uniaxial accelerometers.

A huge number of sensors involve to spend much time to set-up the gearbox and also a lot of data to store, to analyze and to process in real time.

In Fig. 2 we see the location of two tri-axial accelerometers.

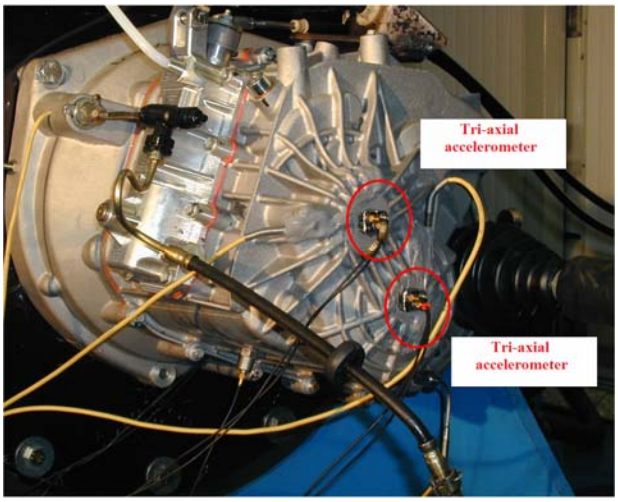

Fig.2 – Two tri-axial accelerometer location

The Fig. 3 illustrates the third tri-axial accelerometer located inside the gearbox near the bearing.

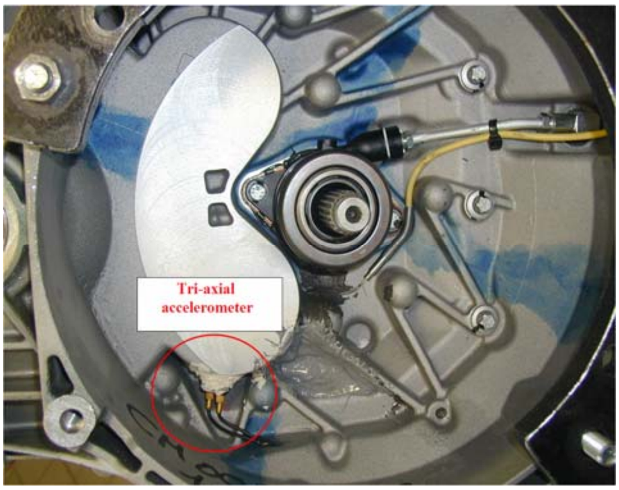

Fig. 3 – The third tri-axial accelerometer location

In Fig. 4 it is showed the uniaxial accelerometer located under the gearbox.

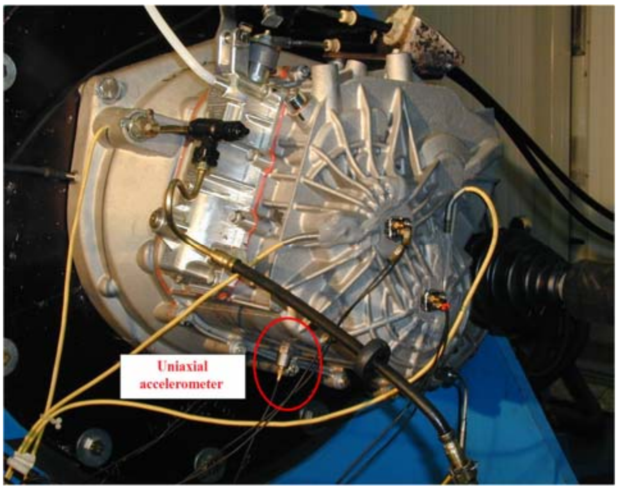

Fig. 4 – Uniaxial accelerometer location

The new algorithm of monitoring offers the important advantage of saving the time to set up a gear transmission on which performing the reliability test. In fact the proposed algorithm utilizes only the signal derived from the uniaxial piezoelectric accelerometer, positioned outside the gearbox (see Fig.5)

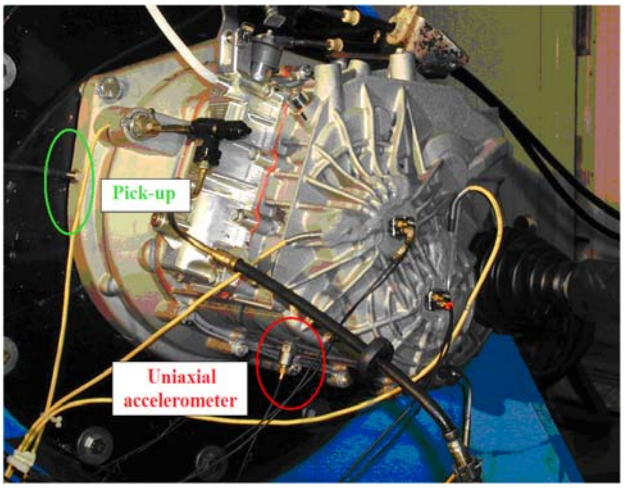

Fig.5 – Uniaxial piezoelectric accelerometer positioned on the external part of the gearbox and Pick-Up located on the flywheel

We verified that using only one accelerometer, opportunely positioned, it is enough to get all the essential information.
Another important sensor used is the Pick-Up for the measurement of the number of revolutions. It is positioned on the flywheel (see Fig. 5).
Note that tests are always performed at the same temperature. The value is roughly 70° C (*i.e.*, the working temperature of the gearbox). For monitoring this parameter, a thermocouple was used as illustrated in Fig. 6

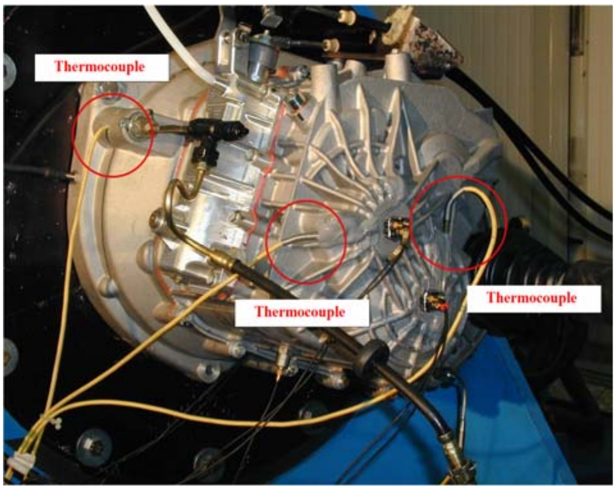

Fig. 6 – Thermocouple locations

4 Vibration monitoring

In this section it is showed the use of the Fourier Analysis of the accelerometer signal, trough the order base instead of frequency base [5,6].
In this work the concept of order has an important role.

4.1 – The concept of order

For a generic pair of gearwheels we define three typical main frequencies: two rotation frequencies and the frequency of geared [7-9].
Taking as reference the rotation of the gear drive, it is possible to introduce the concept of order. The order represents the number of events occurring in one revolution of the drive gear.
If we indicate with Z_1 and Z_2 the number of teeth of drive and driven gear, the rotation speed of the driven gear will be connected to the drive gear's speed through the transmission ratio Z_2/Z_1, and then, for each revolution of the drive gear, the driven gear will do Z_2/Z_1 revolutions. In conclusion, the rotation of the driven gear represents an order Z_2/Z_1 if compared to the rotation of the drive gear.
The mesh frequency, instead, is defined as the frequency generated by the contact of a pair of teeth. If Z_1 is the number of teeth of the drive gear, in one round of the gear it will be checked Z_1 meshes. The mesh, therefore, represents an order of Z_1 with respect to the rotation of the drive gear.
The order can be expressed as

$$order = \frac{n \cdot rpm}{60} \qquad (1)$$

where *rpm* is the rotational speed in revolutions per minute and *n* is the number of events per round.
The positive consequence of using the order base instead of the frequency base is due to record the same event positioned on the graphic always in the same position nevertheless the changing of both the rpm and frequency.
This concept has a key role during the construction of the target spectrum. The use of order base is explained in the algorithm below.

4.2 – Monitoring algorithm

The algorithm of monitoring, object of this work, consists of 5 step:

STEP 1: For each test cycle, both for the value of maximum torque and for the value of maximum power, we calculate, for each gear, the spectrum of the accelerometer signal. This is averaged on the all duration of the whole cycle (it is used an order base as explained above).

STEP 2: We acquire the first five test cycle for each gear, where five is a value according to the case history on which it is done the Reverse Engineering.

STEP 3: We go on by calculating the limit curve, that we indicate later as the target spectrum. It measures the maximum envelope of spectra for the first five test cycles.

STEP 4: We proceed by calculating the integral of the examined spectrum, called later Area_ref (the area of the Current Spectrum, that is the area of the spectrum of the current signal will be called Area_cur).

STEP 5: For each test cycle (after the fifth) and at intervals of 1 second we proceed as following

- calculation of the spectrum of the current accelerometer signal;
- calculation of the area under to the current spectrum (Area_cur).

The key point of the algorithm is to calculate the index $\Delta A_{\%}$, as follows

$$\Delta A_{\%} = 100 \cdot \left(\frac{Area\_cur - Area\_ref}{Area\_ref} \right) \qquad (2)$$

This is an overall index and it is monitored in real time.
Operating with standard conditions, during a test-run, because the current area of the spectrum doesn't change, the index has a value close to 0%. If during the trial the area spectrum increases it is recorded by the index $\Delta A_{\%}$. If the index increases over the threshold value, set at 20%, we must stop the duration test.
Hereby, schematically, are showed the actions following the fifth STEP (Fig. 7).

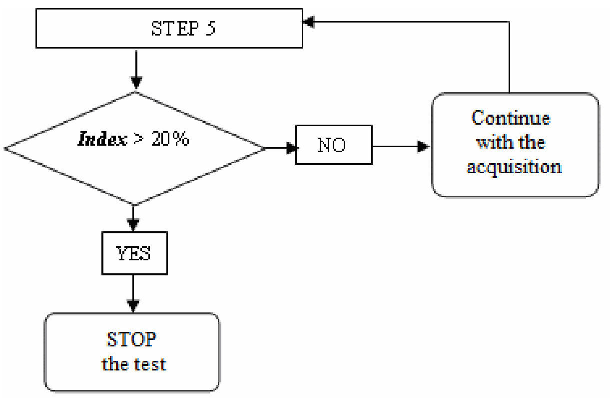

Fig.7 – Flow-chart of STEP 5: how the algorithm stops the test

In the Fig.7 we simply indicate with *Index* the proposed $\Delta A_{\%}$.
As it is showed, the algorithm was designed in order to monitor a wide rage of frequencies, as well as signals which are independent from the complexity of the gear transmission. So it is very

simple to employ. Moreover it requests a few time to find the information by giving an important support for studying the problems occurring in the gear transmission under study.

5 Experimental verification

Several tests were performed giving us positive responses. The graphical representation of the results explain with more details the use of monitoring the duration test of a gear transmission.

In the following pages it will be illustrate how the algorithm works step by step.

First of all it is calculated the target spectrum as explained in the previous section (Fig. 8)

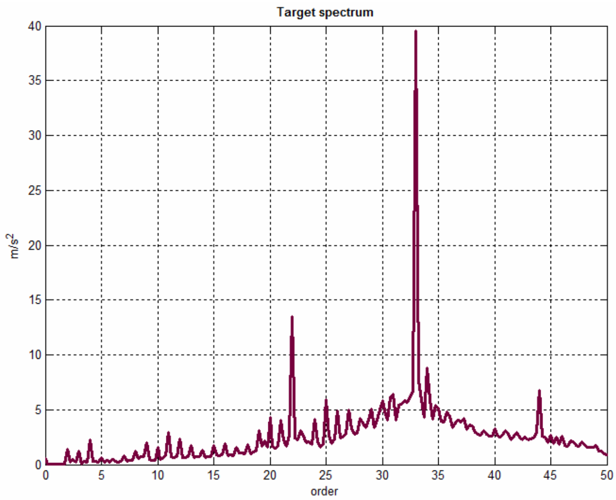

Fig.8 – Target spectrum

The next step involves the calculation of the area (Area_ref) within the target curve (Fig. 9).

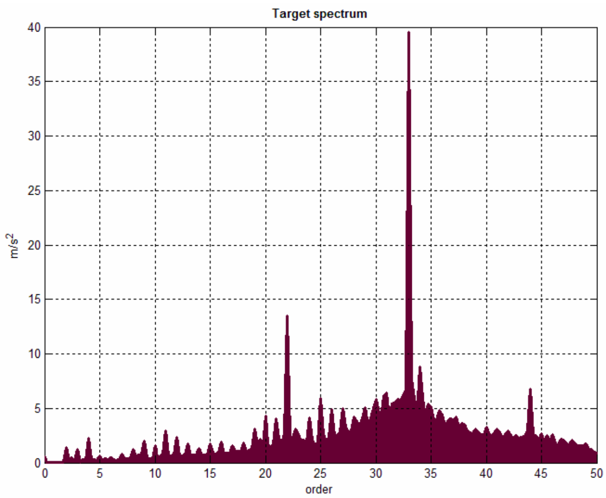

Fig.9 – Area_ref: area within the target curve

Starting from the sixth cycle, the further step is the real time calculation of the spectrum of the actual signal. Using the spectrum of the on-line signal and the target one it is possible to calculate the index for monitoring the duration test.

Below are reported the results obtained for several cycles of reliability test. Before the 16th cycle the index doesn't show any type of damage. At the 16th cycle of test the index exceeds the target, indicating the presence of some irregularities. So when, at the instant 125, the index exceeds the target the test was stopped.

First of all we show the result for the 6th cycle test, that is the first cycle following the calculation of the target spectrum.

Hereby as exemplification two diagrams comparing the actual spectra with reference to the target one are reported in Figs. 10-11.

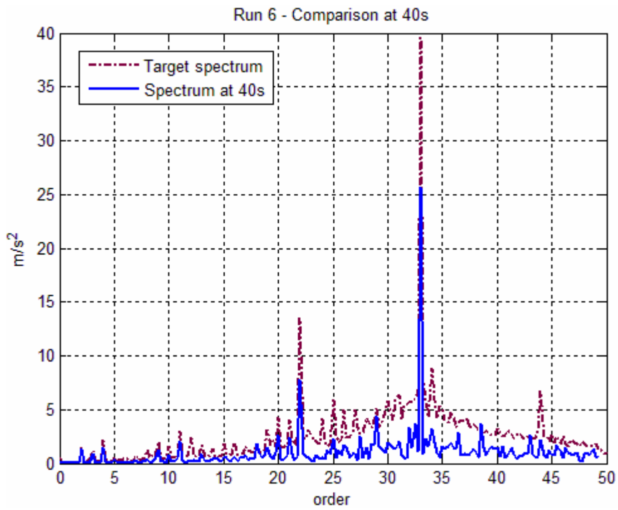

Fig.10 – Run 6, comparison at 40s

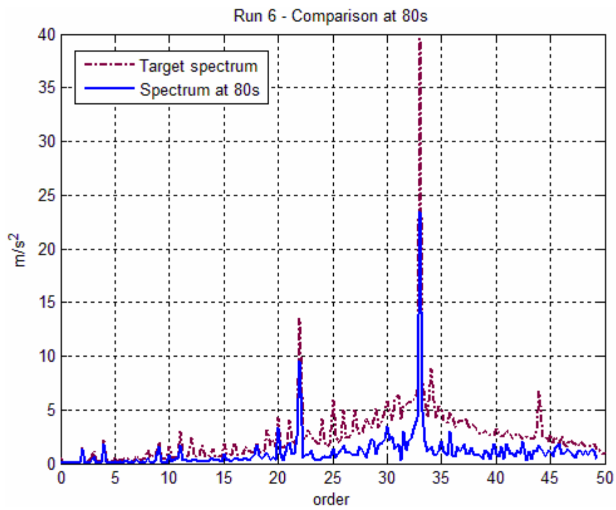

Fig.11 – Run 6, comparison at 80s

It is clear that the actual spectrum has lower energy content. This is pointed out by the monitoring the index introduced before (Fig. 12).

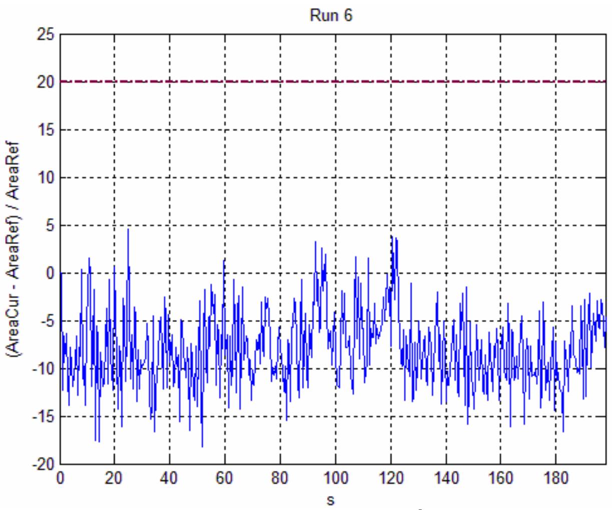

Fig.12 – Monitoring for the 6th cycle test

Through this picture we can be sure that the area of the actual spectrum is less than 20% of the area of target.
Now let's consider the 7th cycle test.

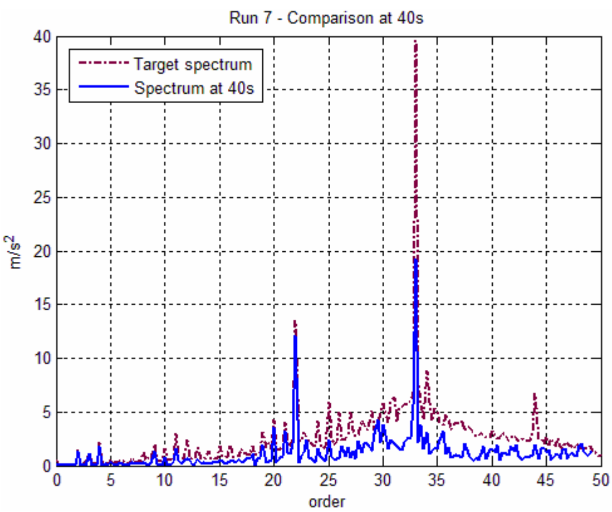

Fig.13 - Run 7, comparison at 40s

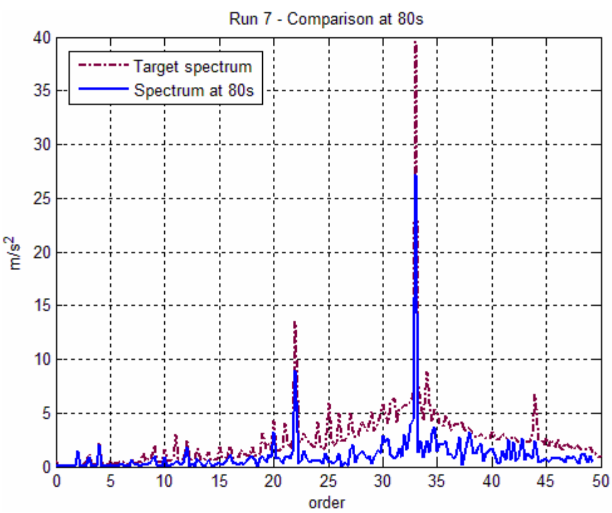

Fig.14 - Run 7, comparison at 80s

Figs. 13-14 show two instants of the 7th cycle test with reference to the target one. The current spectrum has always a lower energy content. This concept is clear for all the instants of the run-test as it is illustrated in Fig.15.

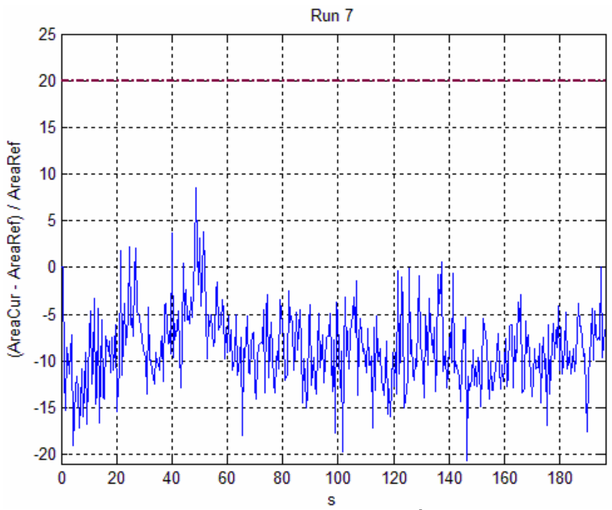

Fig.15 - Monitoring for the 7th cycle test

Same considerations can be done for the next cycles test (before the 16th) in which the index of monitoring doesn't exceed the 20% of the target. Now we proceed go to illustrate the results obtained at the 15th cycle test.

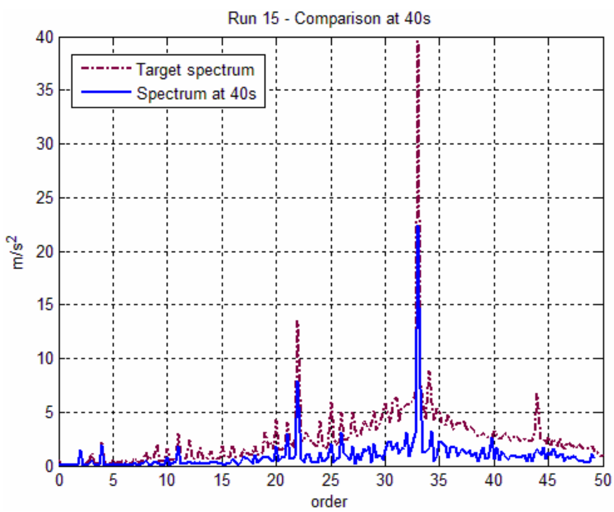

Fig. 16 - Run 15, comparison at 40s

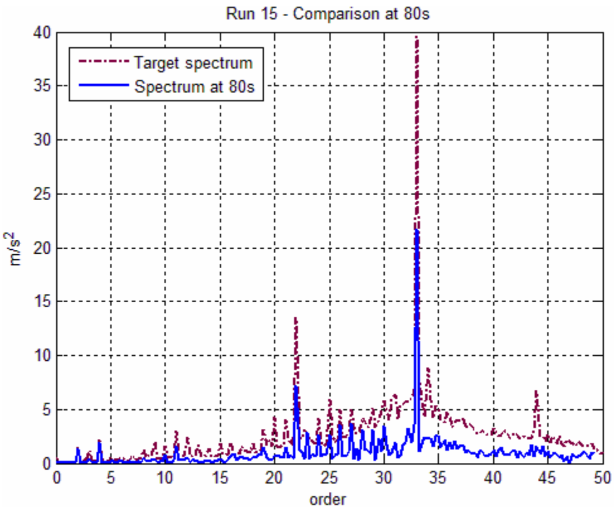

Fig. 17 - Run 15, comparison at 80s

Figs.16-17 show, at the 15th cycle of reliability test, a comparison between the target and the actual spectrum.

In Fig. 18 it is quite evident that the index of monitoring doesn't exceed the 20% of target. Based on the last consideration the reliability test can continue.

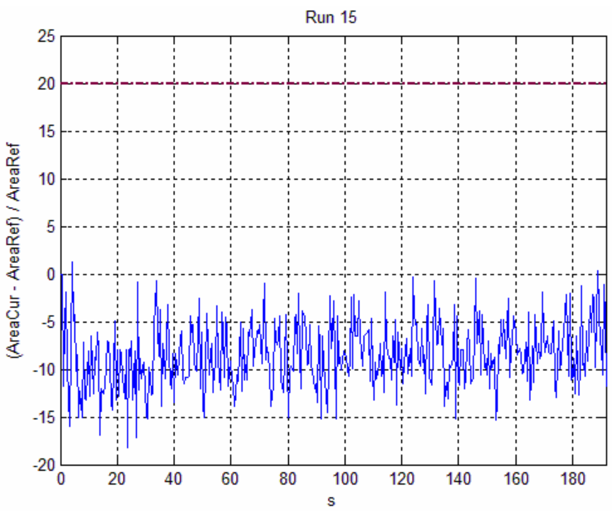

Fig. 18 - Monitoring for the 15th cycle test

Now, as previously remarked, let's give a look at the 16th RUN where an unexpected event occurs. It shows the index exceeding the threshold and consequentially the test was stopped.

After that occurrence, the gearbox was opened and a damaged gear was observed. In the diagram below it is showed some instant of this 16th cycle test, and it is illustrated, how, after the 125th second the index exceeds the 20% of target. This is clear from the diagram reported below when the actual area exceeds the target one.

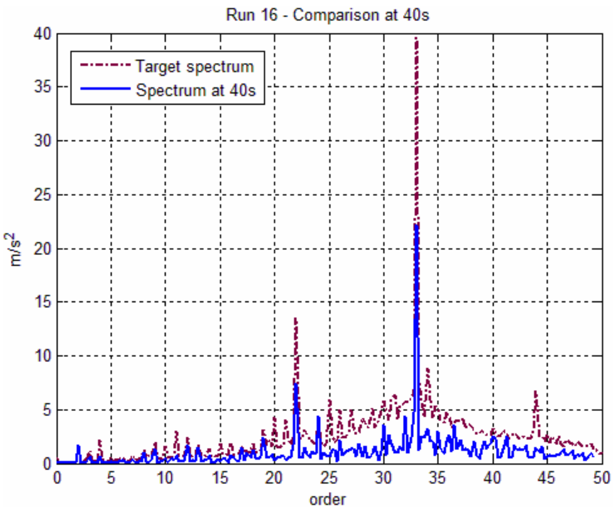

Fig. 19 - Run 16, comparison at 40s

In Fig. 19 it is illustrated a comparison between the actual spectrum and the target one, at 40s. Observing the diagram and by using the index proposed, we say that gearbox works correctly and the test can go on.

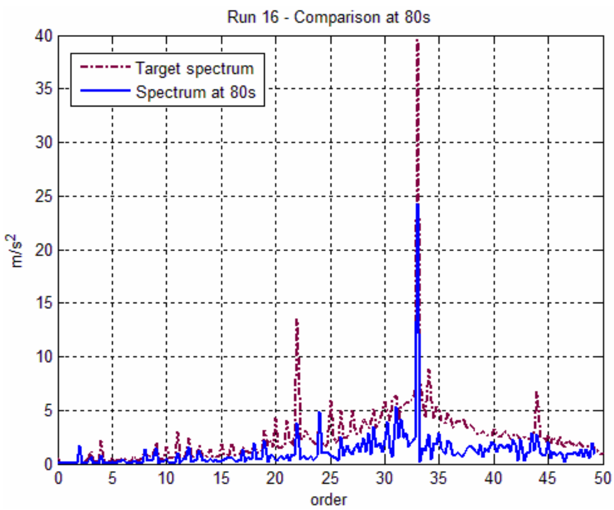

Fig.20 - Run 16, comparison at 80s

Another comparison is illustrated in Fig.20. It's clear that the energy content of the actual spectrum is lower than the target spectrum. The monitoring index is reported below.

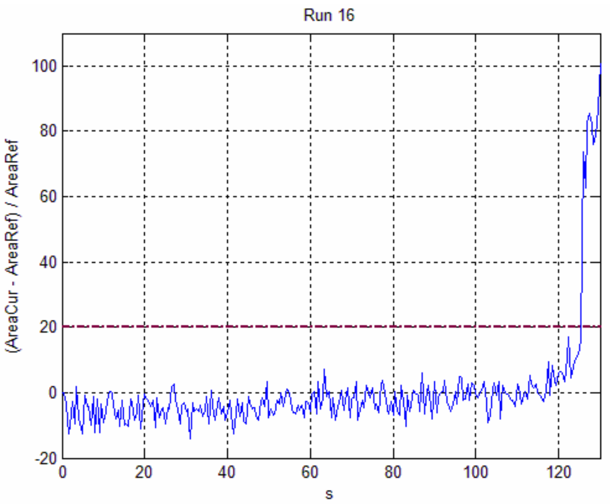

Fig.21 – Monitoring for 16th cycle test

The diagram illustrated in Fig.21 shows the behaviour of the monitoring index during the 16th cycle test. The index exceeds the target at the 125s. Then, starting from this moment there are the conditions to stop the reliability test in order to open the gearbox and inspecting it. The inspection is very important for eventually to modify the gearbox design. Aim of this study is to find out the probable reason generating anomalies in the gearbox.

In Figs. 22-23 there are reported two instants, after the 125s. Clearly the area of the actual spectrum exceeds the area of the target spectrum: in particular there is a variation greater than 20%.

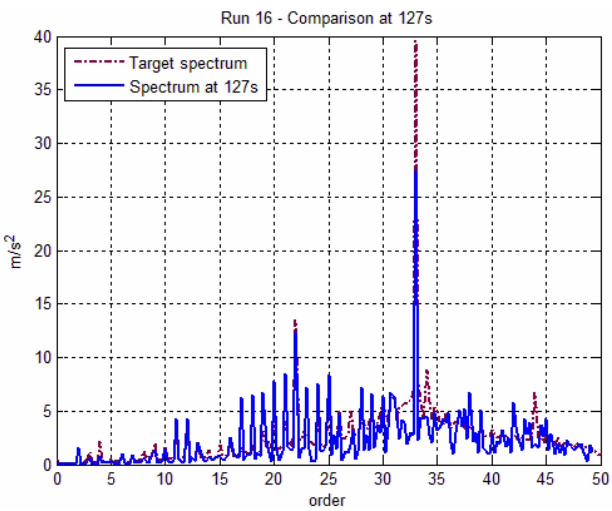

Fig.22 – Comparison at 127s

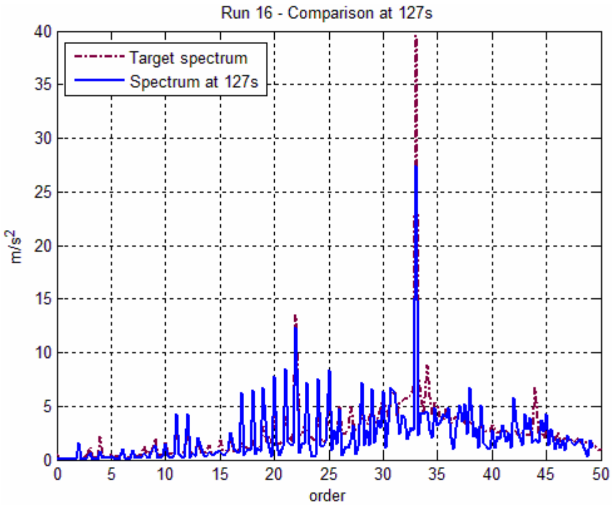

Fig.23 – Comparison at 128s

It is clear that the energy of the last spectrum is increased.

Fig.24 clearly illustrates that starting from the 125th second the index shows some irregularities. For that reason the test must be stopped as soon as possible.

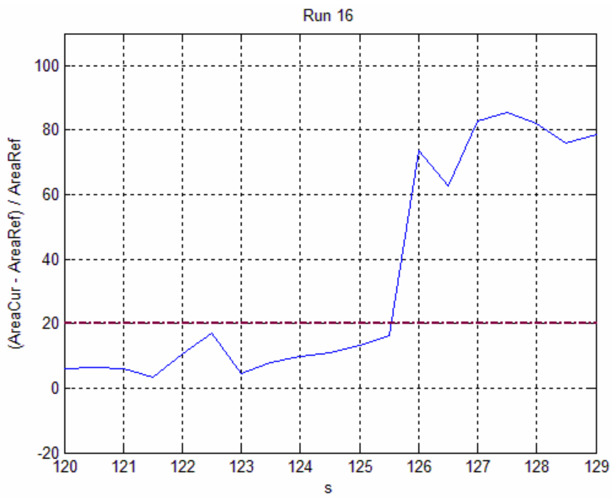

Fig.24 – The final instants of the reliability test (close-up)

In the laboratory several tests were performed on the same gear transmission system. The occurrence of warning conditions showed a tooth of gear damaged as illustrated in the picture below.

Fig.25 – Teeth condition following the first gear crack

It's important to remark that the reliability test, integrated with the technique of monitoring proposed, can be stopped before the occurrence of gear damage. If more gears are damaged, it's very difficult to understand which are the causes that have generated the first crack. For that reason, it's very important to apply a technique of monitoring in order to stop early the reliability test, if an unexpected event occurs.
As said before there are many advantages to stop earlier this test, mainly to review the design of the gearbox.

6 Conclusions

An effective algorithm for monitoring the reliability test of a gearbox is very important. It gives the possibility to check the gearbox before the occurrence of a destructive damage (*e.g.*, gear crack).
If during a duration test, a gearbox, goes out of order, we will lose the possibility of checking the effects that the test causes on the gears of a car transmission [10].
If the test is stopped as illustrated before, there is a chance to check a gear crack or the phenomenon generally called "*pitting*".
These problems cannot be underestimated because only through the detection of them, it is possible to go back to the causes that led to the breaking of the gear transmission.
It should be underlined that a duration test, executed without any kind of monitoring, doesn't allow early alarm. For that reason there isn't possibility of a reconstruction of the reasons causing the damage [11]. Let's think about, first of all, what can happen for a wrong design of the gearbox. Let's think about a tooth that "*breaks away*" from the gear transmission and then it goes in recycling in the gearbox. It can cause several damages and clearly the breaking of more gears. In this case it will be difficult to examine the cause of damage.
The method proposed in the present paper allows the on-line detection of the gearbox damage. It is applied to the duration test and it is based on accelerometer signal processing performed through the application of the order concept.
The algorithm is very sensitive, in fact it is able to capture early any kind of dynamical damage occurs to the gears.
Its reliability is also tested directly by applying it to a real car-gearbox assessed for a test-run.
Finally, we want to remark that the performance is effective and the equipment employed was composed of one accelerometer and one pick-up only.
Further investigations will be conducted in the next future for implementing the algorithm with more effective indexes belonging to, for instance, the wavelet and chaos theory [12-14].

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