The Gear Whine Noise

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Abstract – The Gear Whine Noise (GWN), as well as the gear rattle noise, is one of the main vibro-acoustic phenomena of gearbox. For that reason GWN represents an important problem to solve or to reduce or to "manage" at least in an appropriate way. Running conditions of the gear-box were reproduced in this paper by means of an nnovative test-bed, which allows to perform the test without using the engine.
This means that no occurrence of noise and vibration due to the engine were introduced into the system. From this point of view we say that the present study was performed in optical Noise, Vibration and Harshness.

Key-Words: - vibro-acoustic emission, gearbox, gear whine noise, signal processing, automotive, driving comfort.

1 Introduction

Since 1990, a statistical study showed that the sources of dissatisfaction, before and after buying the vehicle, also affect the appearance of the vibro-acoustic comfort inside the car. In the past, this factor was almost always overshadowed with reference, for example, to performance as fuel economy, safety and price.
In addition, the increasing competition between car manufacturers led, nowadays, a significant reduction of level of noise due to the engine, for example by adopting new design solutions and / or absorbing and damping materials.

A car, in fact, from a vibro-acoustic point of view can be defined as a "complex system", consisting of "primary sources of excitation” which directly generate vibration and noise, and of "passive elements” which transmit acoustic energy and vibration between the sources and the passenger compartment.
Continuing advances, in the automotive industry in recent years, lead the manufacturers of automobiles to develop more and more advanced products both from technical and quality point of view.
In addition, consumer needs, aligned with the highest standards nowadays achieved, prevent manufacturers to make vehicles of poor quality [1].
This is the reason the major car manufacturers devote significant resources to the Noise, Vibration and Harshness (NVH) which deals with noise and car vibration also the driving comfort [2].
This article reports the results of several tests, carried out in optical gear whine noise for evaluating the difference between the vibro-acoustic emission of two gearboxes of the same type, one, in particular, showing a micro-geometrical error located on the base of tooth characterized by lack of material due to a slight drift of the production process. All tests were carried out in the fourth gear [3].

2 The gear whine noise

The Gear Whine Noise (GWN), as well as the gear rattle noise, is one of the main vibro-acoustic phenomena of gearbox [4].
The GWN is an acoustic problem, which can be quite fastidious if it is present within the car, because of the presence of values of frequency and acoustic levels of pressure relatively high.
Usually, the acoustic noise, ranging between 50 and 90 dB (A), occurs at meshing frequency.
Because the acoustic pressure, due to GWN, is not necessarily proportional to the engine speed the unexpected noise and therefore the undesirable acoustic phenomena due to the power system could be high in any engine running condition [4].
For that reason GWN represents an important problem to solve or to reduce or to "manage" at least in an appropriate way [5].
Many factors influence the vibro-acoustic emissions; mainly they are [6-9]:

- Transmission error
- Variation of meshing stiffness
- Dynamical forces of meshing
- Friction forces

- Detention of air and lubricant between the teeth.

3 Technical specifications

The gearbox used for assessing the vibro-acoustic test is designed for medium-powered car and allows the transmission of 350 Nm as maximum torque [10].
The model under study has 3 axles and 6 speeds (Fig.1).

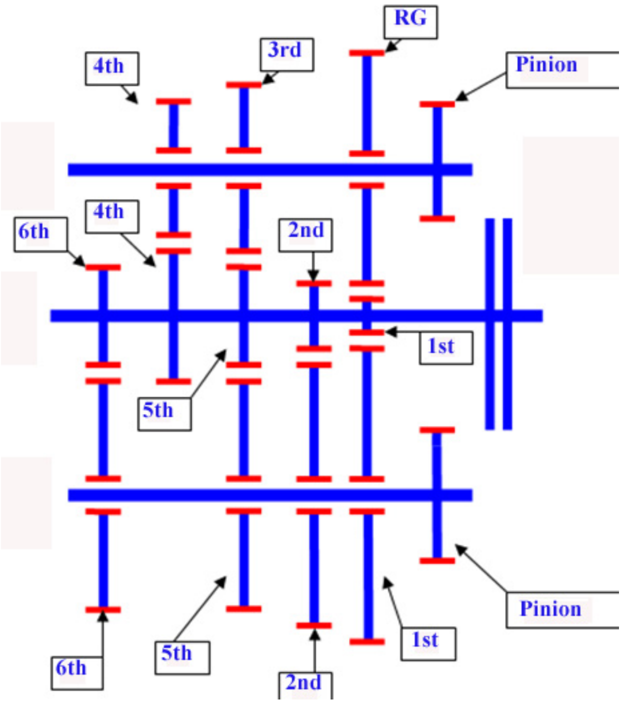

Fig.1 – Schematic model of the gearbox

Two gearboxes of the same type were tested.
They were made following the same manufacturing process.
One of the aforesaid gear-box belongs to a lot which showed abnormal micro geometrical parameters due to the drift of the production process: minimal lack of material localized at the base of tooth [11].
For that reason the flank of teeth interested by the lack of material is not convolved during the contact of the teeth: it does not involve any meshing problem [12-14].
This area, in fact, detected by means of a micrometer at the base of the tooth is localized below the meshing profile [15].
In the Fig.2 is showed a tooth without error (a) and one with error (b).

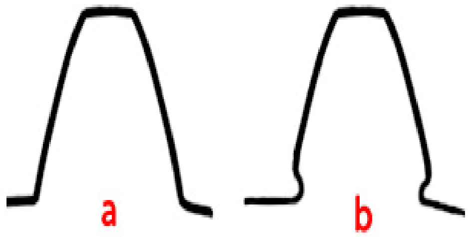

Fig.2 – Example of teeth profile: a) without and b) with geometrical error

4 Test bed

The “running conditions” of the gearbox were reproduced by means of an innovative test-bed, which allows to perform the test without the use of the engine.
This means that no occurrence related to the noise and vibration transmission due to the engine were introduced.
From this point of view we say that the present study on the gearbox was performed in optical NVH.
Therefore, this potentiality allows a detailed study of the phenomenon, in particular, the analysis of the frequency range responsible of unpleasant perceptions for the passengers of the car.
This means that we can simulate on the primary of gearbox, besides the average speed of the engine, even the periodic components due to the forces of combustion and inertia.
The main shaft of the gearbox is put into rotation by an electric motor connected in series through a flexible coupling to a torsional hydraulic pulsator; two semi-axes are braked by means of two additional electrical brakes.
The test bed is installed in a semi-anechoic room, in which electrical motors are acoustically shielded and the floor is covered with soundproofing material in such a way that the tested gearboxes show only acoustic signals.
For the acquisition of this kind of signal the following sensors were employed:

- 1 ferromagnetic pickup, used for the acquisition of the instantaneous rotation speed of the flywheel. It was screwed into a threaded hole drilled in the bell of the gearbox at the flywheel;

- 1 thermocouple, used for monitoring the temperature inside the gearbox; it was positioned directly in contact with lubricating oil;

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- 1 single-axis accelerometer used for vibration measurement; it was positioned at the bottom of the gearbox;

- 3 microphones were used for the acoustic detection. They were arranged in a semicircle near the gearbox far away one meter from it.

The Fig.3 below illustrates the position of microphones.

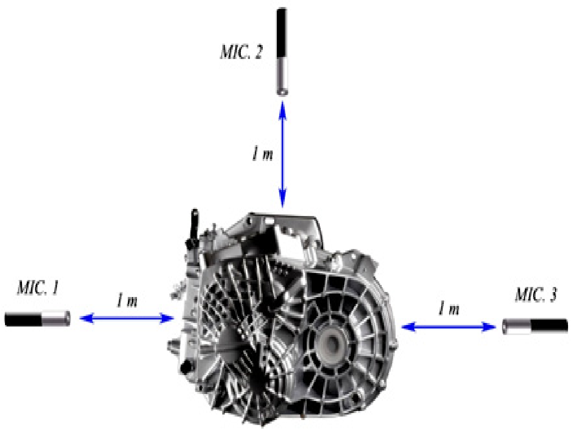

Fig.3 - Position of microphones

5 Assessment

5.1 The set-up of assessment

One of the main points of the present study is to ensure the repeatability of test.
For that reason it is fundamental to maintain a constant temperature of the lubricant.
Both gearboxes were tested as the following protocol:

- Slow acceleration in the fourth gear from 1000 to 4000 rpm in one minute with a constant torque applied to the primary ranging from 30 to 300 Nm, increasing of 30 Nm for each ramp;

- Steady speed in the fourth gear at 1000, 2000, 3000, 4000 rpm with torque applied to the primary, ranging from 30 to 300 Nm.

5.2 Noise path

The table illustrates the block diagram (Table1) showing the path through which the sound of gears, due to meshing gears, spreads out.

The meshing noise is caused by the action of not conjugates gears (*i.e.*, the profiles of the teeth do not conjugate perfectly) and it results in dynamic forces on the teeth, which can generate vibrations of the wheels and shaft.

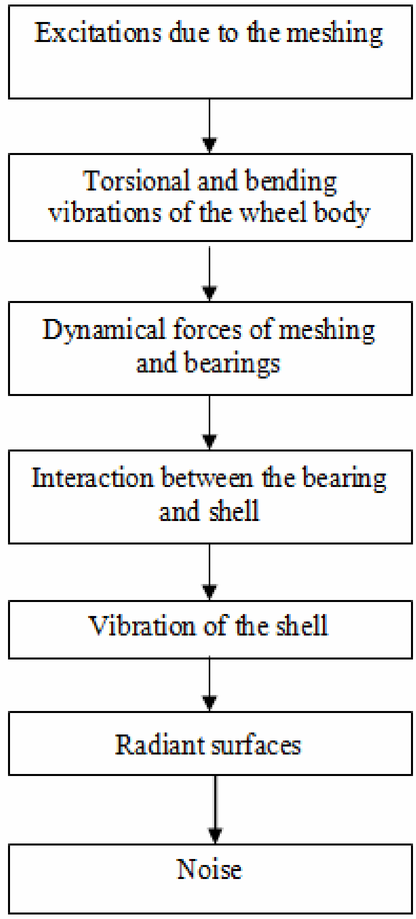

Table 1 - Noise path from the source to the external environment

The dynamical actions during the meshing are transmitted through the bearings to the walls of the shell, and from there, through structural vibrations or sound waves radiated to the rest of the vehicle.
It should be noted that usually the walls of the gearbox is a poor conductor for acoustic waves, so only a fraction of airborne noise generated within the gearbox spreads outside the structure: the most significant part of the noise is transmitted through the structural way to the rest of the vehicle through the joints of the powertrain to the chassis.
The resulting vibrations of the walls of the gearbox ensure that they behave like real "speaker" radiating noise directly.

6 Results

6.1 The colour map diagram

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A detailed data-base was prepared including weather the acoustic signals acquired by means of the microphone and the vibrational signals acquired by means of accelerometer as well as the tachometer signals.
The aforesaid data-base was processed to extract the “order” of main interest for evaluating the Gear Whine phenomenon and in particular for extracting, from each gear, the meshing order.
It is visualized through detailed Colour-Map diagrams.
Such a diagram shows on the abscissa the speed of engine expressed as revolutions per minutes (rpm) and on the ordinates the torque applied to the main shaft (Nm).
On the third axis, the colour scale represents the values of the acoustic levels of pressure detected (dB (A)).
By observing the colour map we can understand which are the areas where the noise riches the highest value; in particular the areas in red show the highest values while the lowest noise levels are pointed out in blue colour.

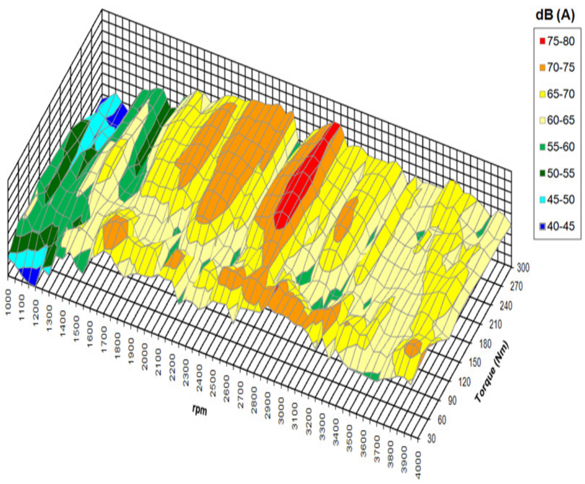

Fig.4 - Gearbox without geometrical errors - 4th gear, Acoustic pressure dB (A) vs rpm and torque

The results of test performed on the gearbox without geometrical error is shown in the Fig.4, while the results obtained from the gearbox with geometrical error is illustrated in the Fig.5.
By comparing the two diagrams it is possible to evaluate the acoustic pressure level showed by two gearboxes with reference to the speed and torque applied to the primary.
In particular, for low values of speed, both gearboxes show quite the same results; the acoustic emission shows an increasing trend directly proportional to the speed reached by the gearboxes.
We note that the maximum value of 70 dB (A) was close to 2000 rpm.
When we operate at low range of revolutions (1000÷2000 rpm) most relevant critical issues for both gearboxes highlight.

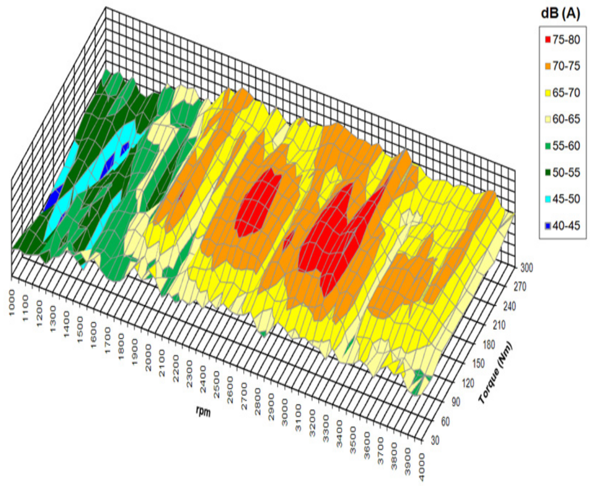

Fig.5 - Gearbox with geometrical errors - 4th gear, Acoustic pressure dB (A) vs rpm and torque

In particular the gearbox with geometrical error is noisier. In fact it has two critical areas of interest, 2400÷2600 rpm and 2900÷3200 rpm.
The gearbox without geometrical error reaches critical level of noise only in one narrower range 2600÷2750 rpm.
Both gearboxes show the acoustic pressure level close to 80 dB (A).
Finally, from 3000 to 4000 rpm the gearbox with geometrical error shows higher values of acoustic pressure level, very close to 70 dB (A) if compared to the gearbox without error.
By analyzing the results of test we can say that the diagrams referred to the gearbox with geometrical error appear shifted, due to the different bending response of teeth to external forces.
The noise caused by the phenomenon of gear whine, in fact, is directly related to the variation due to the error of transmission, mainly because of the meshing stiffness.
Because of the decrease of cross section, due to lack of material at the base, the teeth are less rigid and therefore more flexible to the external stress.
Therefore, this feature allows achieving, on the gearbox with geometrical error, the point of optimal functioning with torque values smaller than those needed to gearbox without error.
The results also show that the gearbox with geometrical error focuses in the normal area of functioning (*i.e.*, the fourth gear) the highest levels of noise.
On the contrary the gearbox without error in the same area (especially for torque values from 90 to

150 Nm and for all the range of rotation) is particularly noiseless, limiting the maximum noise in smaller areas and with higher torque values.
The motor installed on the car is a 1600 cc four-cylinder engine powered by diesel, which delivers a maximum torque of 290 Nm at 1500 rpm and a maximum power of 78 kW at 4000 rpm.
By overlaying the characteristic curve of that engine to color map it is possible to identify the best operating conditions of the power train (Fig.6 and Fig.7).
The car employed for the present study is another variable to take into account to define the actual areas of operation of the power train.
By using the reference equation as a path of the vehicle, we can define, with reference to the gear under control, the minimum and maximum speed of normal range where has to operate the engine.
The positions of the accelerator can, therefore, allow the use of the gear-box throughout the total area pre-determined.
By using the values of the characteristic curve of the engine and vehicle data, the acoustic levels found on the car were defined on the color map.
In advance, the data allow us to confirm that the gearbox with geometrical error may have critical importance for the application on the car.

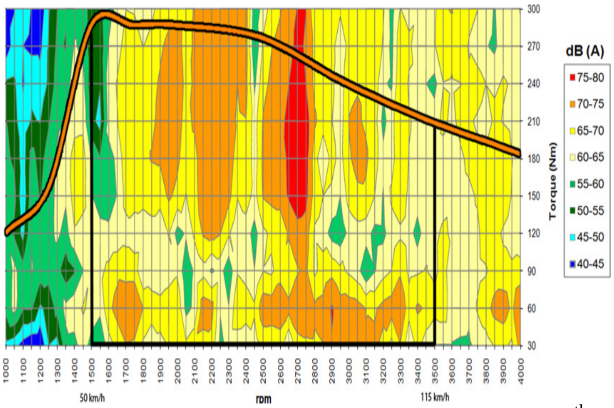

Fig. 6- Gearbox without geometrical errors - 4th gear, Acoustic pressure dB (A) vs rpm

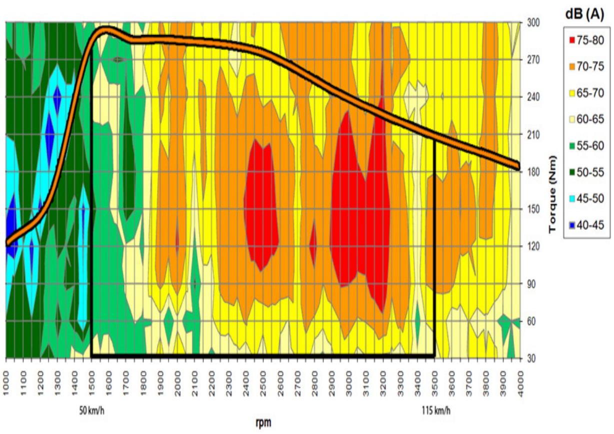

Fig.7 - Gearbox with geometrical errors - 4th gear, Acoustic pressure dB (A) vs rpm

The results are also checked within the car by applying the rule provided for the tests
Below are the diagrams obtained by the microphone located within the car and with the acceleration at full load.
The diagrams of the acoustic level, found within the car for the ramp at full load, show that both the gear-boxes show quite similar acoustical response, although the tips of the noise levels are located at different conditions (2000 rpm for the gear-box without error, 3000 rpm for the one with errors) (Fig.8 and Fig.9).

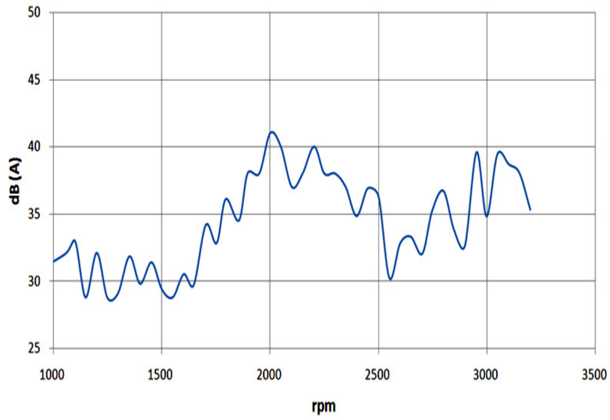

Fig.8 – Acoustic response within the car: gearbox without error

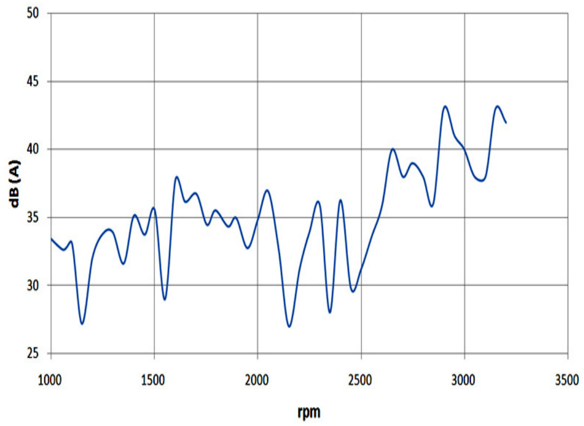

Fig.9 - Acoustic response within the car: gearbox with error

The values obtained by means of measurements performed within the car show that the gear-box with error has higher noise level, especially in the medium - high speed and low torque, where the difference of acoustic pressure level reaches 10 dB (A).
The slow ramp, however, performed with partial throttle in order to get more time to maneuver, detects high noise level for the gear-box with error.

8 Discussion

For low values of speed, the tested gear-boxes are rather aligned and they show that the acoustic emission follows an upward trend, directly proportional to the number of turns, reaching on both gear-boxes, maximum values of 70 dB (A) nearly to 2000 rpm.
Such an operating mode will highlight the most critical issues relevant for both gear-boxes.
In particular, the gear-box with geometrical errors is noisier because it has two critical areas at 2400÷2600 rpm and 2900÷3200 rpm.
Vice versa the gear-box without errors reached critical levels of noise only in one narrower range: 2600÷2750 rpm.
In these areas the acoustic pressure levels reached by the gear-boxes were of about 80 dB (A).
From 3000 to 4000 rpm the gear-box with errors shows on average higher values of about 10 dB (A) with reference to the gear-box without errors.
As already mentioned in the previous paragraph, in fact, because of the direct correlation between the bending of tooth, the transmission error and the vibro-acoustic emissions, it is possible to optimize the noise levels in only a very narrow range of the applied torque.
The data analyses shows that, both in terms of noise and vibration, minimal emissions due to the gear-box without errors are obtained for a value of torque about 120 Nm for all engine speeds.
The gear-box with errors, however, has low acoustic emissions for torque value ranging from 30 to 60 Nm.
In particular, we observe a shift of the optimal operating point to lower values of torque.
In conclusion, the mechanical properties of teeth with errors determine the location of the vibro-acoustic values in the colormap of the operating point.

9 Conclusions

This paper reports the results of several tests, performed in optical Gear Whine Noise, for evaluating the difference of the vibro-acoustic emission of two gearboxes of the same type.
The customer, in fact, seems to be particularly aware about the vibro-acoustic emission of the vehicle [1].
In particular, the gearbox showing a micro geometrical error on the flank of the tooth, characterized by lack of material located at the base of the tooth, was made during a slight drift of the working process.
All the tests were carried out in the fourth gear.
With reference to the number of revolutions of the primary shaft, the gearboxes tested show a very different acoustic behaviour.
It highlights in particular that the gearbox with geometrical errors is characterized by higher acoustic level in almost all engine speed.
The colour maps of data acquired during the test-bed provide a complete map of all possible operating conditions of the gearbox tested.
Within the car, however, the operating points are limited by the type of engine coupled to the gearbox and by the dynamic parameters of the vehicle.
Such a kind of study is in progress.

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