Assessment of Vibration Susceptibility of Electronic Equipment in Formula One Cars

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Abstract. The total noise level in racing car environment is very high, in fact the engine can reach 20000 rpm (revolutions per minute) and the vehicle structure is very stiff. Upper-grade levels in terms of shock, vibration and temperatures need a careful understanding of damage mechanism, which will be active in this environment. This paper presents an experimental vibration diagnostic methodology implemented on Ferrari racing car model 248F1.

I. Introduction

Electronic systems used in automotive field are particularly susceptible to the environmental factors, such as temperature variations, vibrations and corrosion [1]. Vibrations are always present in motor vehicles. The main vibration sources include the engine, the gearbox, the power-train and suspension system. The electronic devices of the vehicle are subject to vibrations during the manufacturing process, the shipment and the operating lifecycle. Usually manufacturing does not cause problems but should not be ignored [2]. The effects of shipment vibrations are normally controlled by suitable protective packaging, such as plastic foam. The operating vibrations can be divided in three main disturbance classes: sinusoidal vibrations, random vibrations and mechanical shocks [3]. Each kind of disturbance phenomena can be investigated in operating conditions by an appropriate analysis method and each vehicle electronic component has a different resistance to vibrations.

Despite of automotive standards, in car racing applications, the vibration robustness of the on board electronic equipment cannot be assessed by testing the prototypes only. Precisely, F1 car vibration profile is influenced by vehicle dynamic arrangements and, during a championship, Ferrari Team can have 72 different setups: 18 tracks * 2 drivers * 2 sessions (qualification and race). All vibration measurements are logged and processed to have an exhaustive monitoring during the whole lifecycle of each component. Every time it's necessary to have a reliability report for each critical electronic device and decide if/where/how is opportune to re-mount the component in next race event. Another important difference between standard automotive and F1 in terms of electronic equipment is the working range; in fact, for standard cars is convenient to use long life components where for F1 car is fundamental to use top performance components. Moreover, despite of standard automotive, in racing applications the equipment can work out of the range specified by manufacturer.

The aim of this paper is to describe the approach to the vibration monitoring of electronic equipment adopted on F1 cars. The next Section introduces the vibration monitoring in F1 context, while the third Section summarises the analysis methods.

II. Vibration monitoring in F1 context

The peculiarity of vibration monitoring in F1 field consist of no static boundary conditions, in fact each race/test session has a specific car set up. For this reason the component assembling can be considered permanently as prototypal. Vibration monitoring method implemented for the 248F1 vehicle simultaneously provide availability check and improvement of electronic devices. In fact, vibration measurement results are compared both with previous similar ones and with operating range specifications in the component datasheet. If a performance decrease is detected higher than a specified safety level, the component must be replaced. More precisely, this alert permits to investigate the malfunctioning, to try different improvement solutions, and to install a more robust version of the component. Each component can be used for the next race session only if it is reliable in terms of both historical measurements and datasheet ranges. In some cases, it's possible to remount the same component by improving the vibration protection (dimensioning and positioning of absorbers, assembling techniques, housing redesign, fixing calibration). Each change needs a new vibration characterization of the component. This third alternative is typical when the damage level is low but the measurement results are near to device critical values. Ferrari Quality Assurance Department and Research & Development Department are continuously involved into same dedicated process, described schematically in Fig. 1.

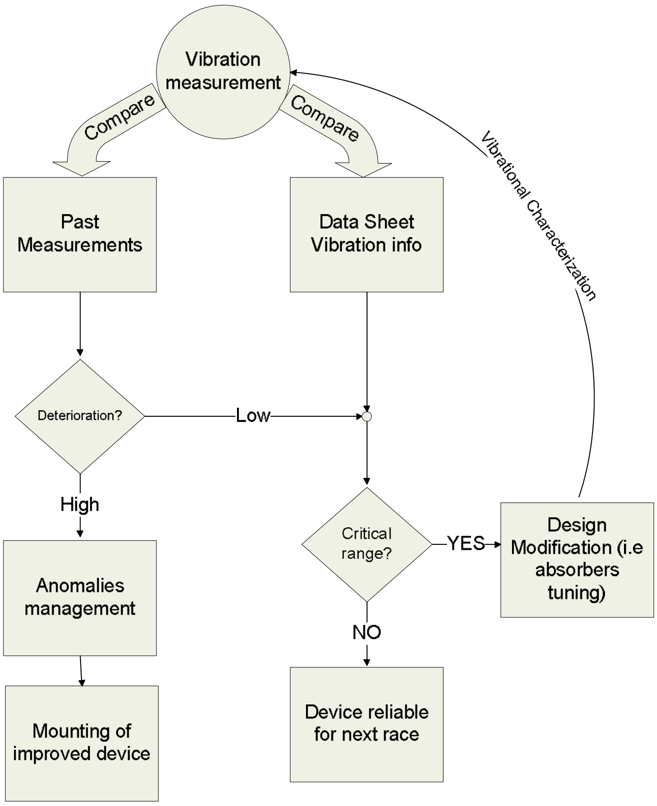

Fig. 1. Scheme of continuous vibration monitoring and protection.

Although the mentioned vibration monitoring approach is unique, there are three measurement environments: the shaker, the engine test bench, and the car. Clearly, vibration measurement executed directly on the car is the most suitable way to monitor the performance/reliability trend of component. However, the total time dedicated to track sessions is not sufficient to have a complete data logging. For this reason, it's necessary to simulate the vehicle running conditions by means of the shaker or the engine test bench. Racing vibration management need to consider three significant characteristics:

- *Assembly:* It's important to find a low-noise location on car and to plan a valid installation modality, cooperating with chassis designers. Moreover, a good housing material and an opportune fixing system, reduce some risks, like the damages coming from cabling break off.
- *Isolation:* A vibration isolator works as a mechanical filter and so it's useful to modify opportunely the natural damping of electronic equipment under test. The efficiency of a vibration isolator varies with the frequency and on the natural frequency of isolation system [4]. For this reason each car setup needs of a specific isolator characterization. To this aim elastomeric isolators which consist of neourethane or Thermo Plastic Rubber (TPR) vulcanize-bonded to steel component have been used. They can be stressed in compression,

tension, shear or a combination of these. The isolators could be in contact with gasoline, hydraulic oil, engine oil and solvents but neourethane absorbers didn't change their physical/chemical properties. At resonance, when the system dissipates the same amount of energy per radian that it stores, it is said to be critically damped. The damping performance of these passive devices can decrease rapidly, therefore, the most of absorbers is replaced with new ones after each race session.

- *Improvement*: Thanks to "electronic vibration map" generated by previously mentioned method (Fig.1), co-design suppliers can receive some useful suggestions to increase the quality of their products. The stress caused to on board electronic equipment from vibrations on F1 cars is like no other ground vehicle. Vibration analysis results are precious to solve old component anomalies and to support the continuous improvement of the on board electronics.

III. Analysis methods

Ideally, the vibration data processing should be done in real time, but the number of acquisition channels is so high that only the most critical channels, in terms of race strategy, are processed in real time, where the other ones are considered in post processing. It can be distinguished two groups of analysis domains: time and frequency, both of them can be implemented in real-time or in post processing, due to the available computational power.

The time domain analysis consists in calculating the Root Mean Square value to estimate the component stress level and the Peak-to-Peak value to estimate the component shock level. Typically, both the metrics are calculated on two engine revolutions corresponding to 720° or one combustion cycle at minimum regime [5].

The frequency domain analysis involves four approaches: the engine order analysis, the fast Fourier transform, the Campbell graphs and Power Spectral Density [6].

As reported above, the main vibration excitation of electronic systems comes from engine and vehicle. Solicitations coming from the vehicle come usually from low frequency (10 Hz to 50 Hz) phenomena, such as kerbs, braking and corners. Those low-frequency excitations rarely affect electronic devices in a significant way.

Excitation coming from the engine during standard revolution (all cylinders work) is pseudo-periodical, strictly linked to engine orders (frequencies that are a multiple of the rotation frequency N or of the combustion frequency N/2) and gives a response that has a pseudo-discrete Fourier spectrum at a given rotation speed. Figure 2 shows an engine order plot of 248F1 eight-cylinder at 14400 rpm.

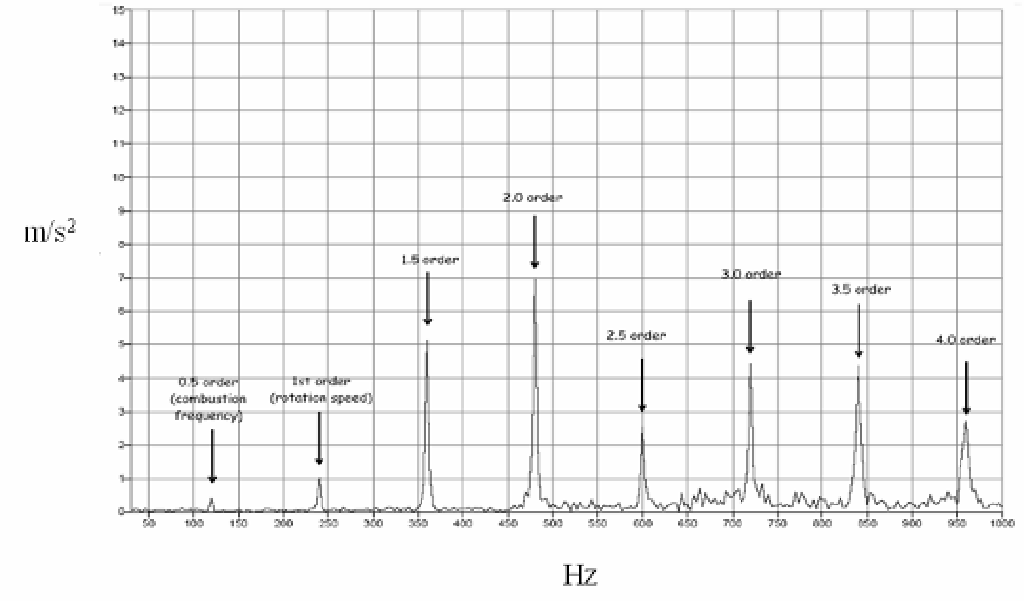

Fig. 2. Example of engine order plot for the Ferrari 248F1 engine.

The relationship between the excited frequencies and the engine rotation speed is:

$$f[Hz] = \frac{Q \cdot N[rpm]}{60[s]} \qquad (1)$$

where Q is the engine order. The second order is the most significant in eight-cylinder F1 engines due to the presence of imbalanced lateral forces. Thanks to (1) it's possible to calculate the most relevant frequency range: 400 Hz - 667 Hz (12000 rpm to 20000 rpm).

A particular attention is focused on frequencies excited at higher engine speeds, clearly the most used in F1 races.

An order tracking analysis over an engine revolution ramp usually completely describes this kind of pseudo-periodic signal. The resonance frequencies are easily recognized because, at different engine speeds, each order reaches a local maximum (Fig.3a). As shown in Fig.3b, the same resonance can be excited by several engine orders at different engine speeds. In normal operating, the engine excites pseudo harmonic orders which are multiples of combustion cycle or multiples of half motor cycle. These orders include about 95% of the engine energy and so, using order analysis it's possible to investigate the excitation modes with low computational costs.

FFT-based approaches, in general, permit to consider 100% of the engine energy but the computational cost is higher and so it's no optimal to use them in real-time analysis.

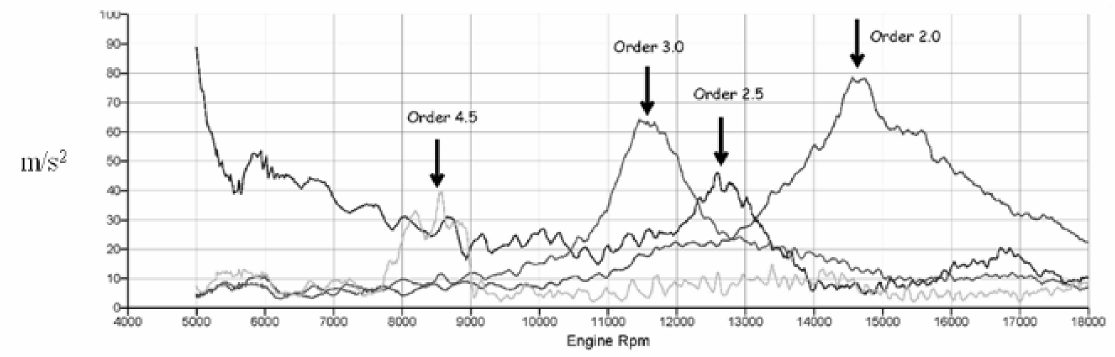

Fig. 3a. Order analysis of an acceleration signal during RPM ramp – local max.

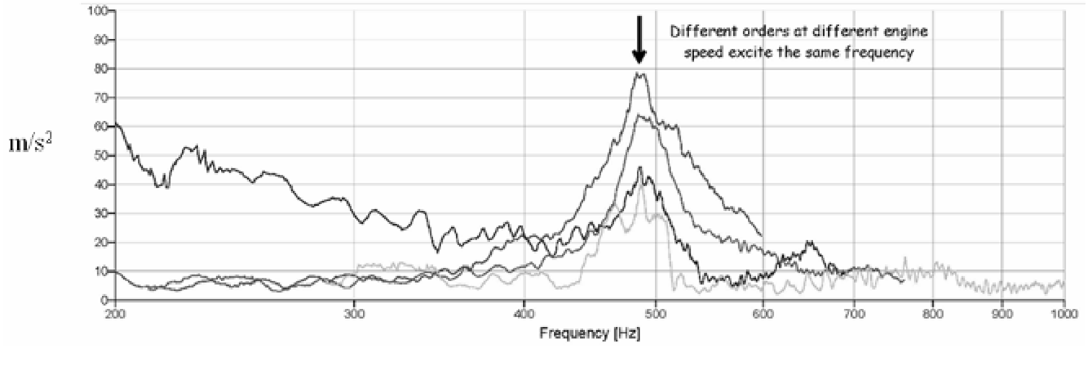

Fig. 3b. Order analysis of an acceleration signal during RPM ramp – resonances.

However, when signals are of a random or apparently random nature, FFT-based approaches can give much more information.

In fact, when the cylinder cut technique (a technique of torque reduction for traction control purposes) is used, the excitation is pseudo-random, more similar to a white noise or to a broadband signal. In this case, an FFT, a Campbell [7] or a time-frequency analysis, without the order representation, can give a better description of the phenomenon (Fig. 4).

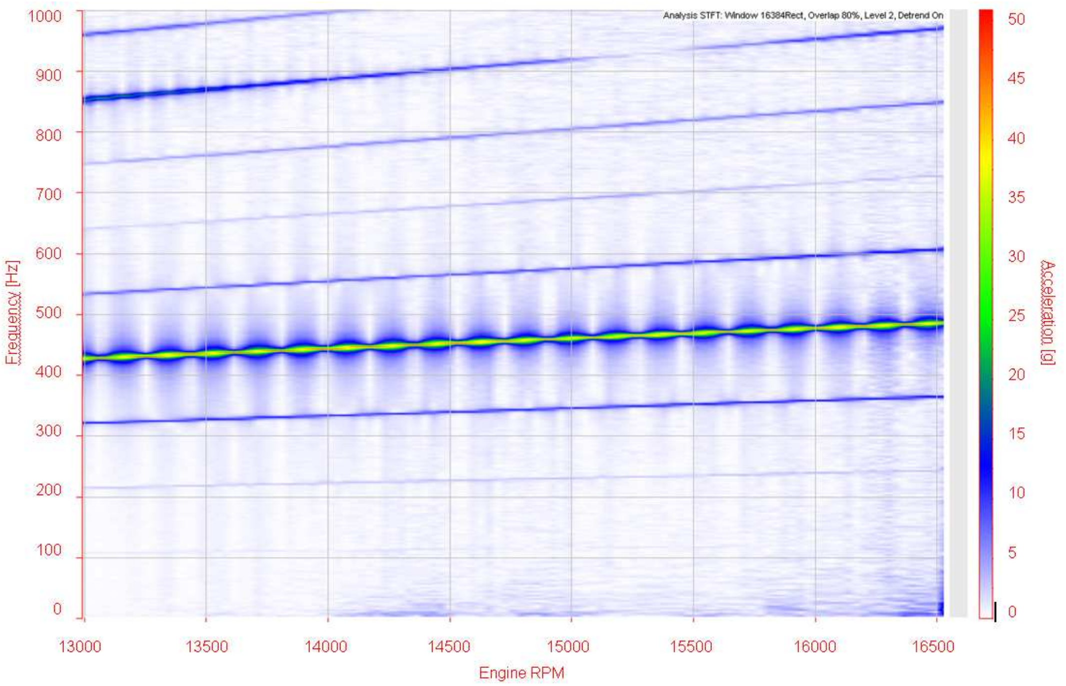

Fig. 4. Campbell analysis of an acceleration signal during RPM ramp.

In Fig.5 a time domain and frequency domain representation of the acquired vibration signal is reported showing, in the second column, some frequencies that are not a multiple of N and neither multiple of N/2 due to the traction control system. The source of signals is the Ferrari 248F1 engine.

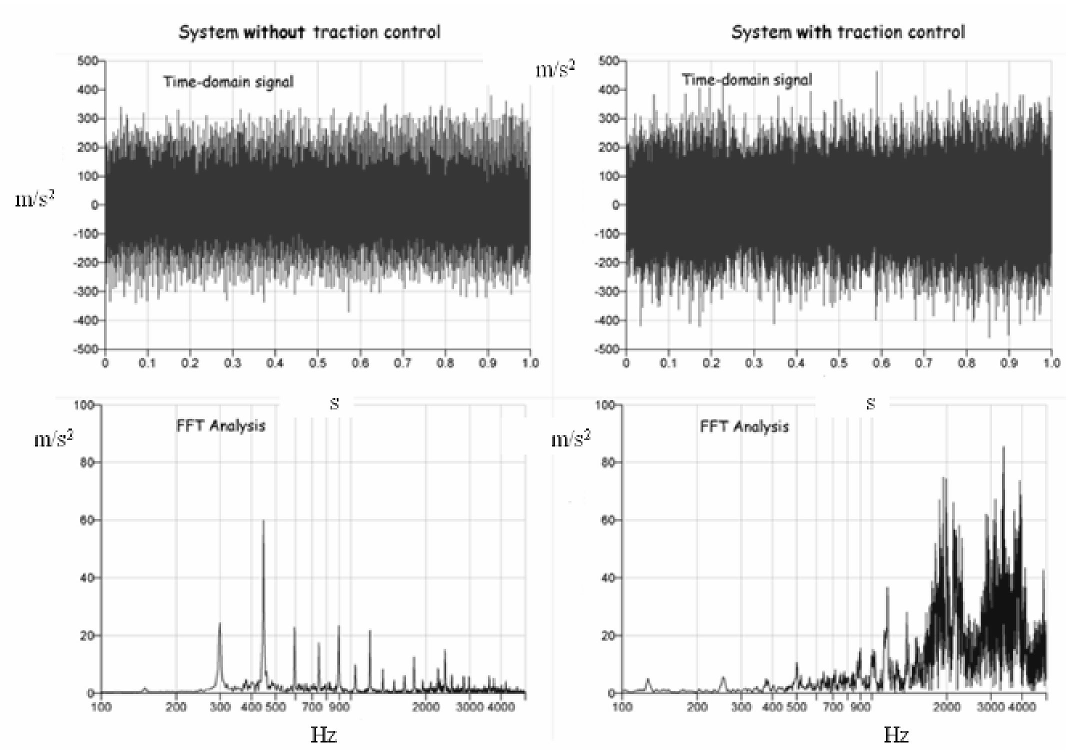

Fig. 5. Time history and FFT with/without traction control of Ferrari 248F1 engine.

Random vibration can be thought of as containing excitation at all frequencies within the specified frequency band but no excitation at any specific single frequency. A plot of the acceleration density for each component frequency versus frequency gives a curve of g^2/Hz over the frequency spectrum of interest. This curve is known as Power Spectral Density (PSD) curve. PSD is useful if data do not contain any purely oscillatory signals, like vibration signals. PSD returns at which frequency ranges the variations are strong and could be quite useful for further analysis.

IV. Conclusions

The methodology described in the article is oriented to identify/monitor a map of electronic equipment failures due to vibrations and shocks. Some of sub-tasks are: to monitor vibration levels during tests, to choose best material/shape for dampers. Maximum advantages of reducing noise and vibration at the source can be realized by careful planning, thoughtful design, and proper choice of materials and structures specifically engineered for the task. To obtain the best results is fundamental a dedicated measurement method, structured for F1 electronics but flexible to work with rapid dynamic car changes and under different race conditions. Next steps of this project will be focused on preventing mechanical stresses of on board equipment during an important development process: assembly/localization design of critical electronic devices.

Acknowledgements

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