Vibrations Measurements of Formula One Car Electronic Devices

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Abstract. F1 car is a very critical system in terms of temperature, shock and vibrations. For this reason, usually, automotive standards are no adequate for motor-sport electronic applications. Further peculiarity of F1 automobiles is the periodic change of vehicle dynamic setting. Vibration monitoring techniques are being used by F1 teams mainly to spot mechanical imbalances and, consequently, to define a car's set up. In the competitive race context, also it is mandatory to improve the electronic components reliability, to optimize their maintenance time, to control the quality of their manufacturing and to take into account their noise and vibration pollution. This paper presents an experimental vibration measurement system implemented on Ferrari racing car model 248F1.

I. Introduction

The components which predominantly suffer the vibrations during F1 races are: the connectors, the transducers, the Electronic Control Units (ECU), the voltage regulators and the steering wheel. It's well known that vibration of contact interfaces is the main cause of contact degradation by the so called fretting corrosion phenomena [1]. Contact resistance is of great importance to the reliability of electrical contacts, and is related to surface degradation and certain failure modes. The electrical interfaces, therefore, affect heavily the overall system reliability and the failure of one of them could have potentially catastrophic consequences. Among the transducers on a F1 car the Linear Variable Differential Transformer (LVDT) ones are used to measure the displacement of clutch plates, gear drums and brake callipers. These displacement transducers are located in the most critical areas of car in terms of vibration and their anomalies may have performance relevant effects.
ECUs mounted on F1 vehicles need of reinforced housing and certified solders; the packaging process is a major source of stress for such devices, due to differences of the thermal/mechanical coefficients of sub-components (silicon chip, adhesive, interposer, mold cap, solder ball etc) [2].
The voltage regulator controls the power supply voltage mean-value through the modulation of the current flowing in the alternator rotor winding; the electrical stresses are produced by a failure of other device causing over voltages. The control loop of voltage regulator must be carefully designed to produce the desired trade-off between stability and speed of response.
F1 steering wheel is a complex electronic device that allows the driver to control a vast amount of car-settings. Various lightweight materials are used for its production: carbon fibre and rubber with aluminium, titanium, steel and plastic. Despite the myriad of materials, buttons, switches and parts that make up each completed steering wheel, the weight of the finished unit, as fitted to the car, is just 1.3 kg.
Despite of standard automotive, in racing applications the devices can work out of the range specified by manufacturer.
The aim of this paper is to present the racing vibrations measurement procedures carried out to test vehicle electronic devices during the whole device lifecycle. Next sections will describe the motorsport vibrations diagnostics. The presented procedure involves three test benches and a virtual instrument to carry out the time/frequency analysis of the vibration signals.
The paper describes the implemented test benches, the virtual instrument controlling the tests and the measurements that can be obtained (section II), the application of the test procedure to the steering wheel case, tested on bench and on car (section III).

II. Test benches

The purpose of a vibration test is to determine if the item being tested is likely to survive the vibration environment in which it will work. The reproduction of in service conditions of each component is possible thanks to an electrodynamics vibrator. The simplest form of mechanical vibration to consider is that based on a linear theory. This means that displacement, velocity and acceleration satisfy a proportional relationship to each other and to the mechanical stiffness of the system [3]. Each device under test has been assumed to have three degrees of freedom.

Vibration test procedure implemented for Ferrari 248F1 electronic systems involves three frequency characterizations, respectively, on vibration table, on engine test bench and on car. Transfer functions generated by these steps are compared with similar plots stored in previous race sessions to detect potential performance decreases.

The shaker test bench consists of:

1. A shaker system (Fig. 1) made by Unholtz-Dickie, model TA115SA-40 (frequency range from 10 Hz to 3 kHz for maximum item weight of 0.5 kg).

Fig. 1 Shaker system Unholtz-Dickie, model TA115SA-40.

2. A piezoelectric triaxial accelerometer by Brϋel & Kjǽr, type 4326A-001: due to mechanical dimensions and stiffness involved, the needed sensor should have a constant amplitude response up to a minimum of 5 kHz, together with a compact design and a low weight (component design involves three piezoelectric elements and three masses arranged in a triangular configuration around a triangular centre post. The ring pre-stresses the piezoelectric elements to give a high degree of linearity. The charge is collected between the housing and the clamping ring. The housing material is titanium [4]).
3. A laser Doppler vibrometer made by Polytec, model OFV525/5000. It includes an high speed sensor head and the vibrometer controller, they allow measurements that cover vibration displacements from sub-nanometre to several centimetres [5]. It is mounted on front the object surface under test.
4. An acquisition system made by Onosokki, model PS5000. It can involve three modules: amplifier (distortion 0.1% THD or less), integrator (direct integration or single integration or double integration) and filter (low pass, high pass and through with noise level 500 μVrms DC to 100 kHz) [6].

The engine test bench consists of:

1. An engine test bench made by Borghi & Saveri, model FE1020ST (four rotors eddy current dynamometer); it works with a simulation program specially developed by Ferrari and AVL. Thanks to this program, engines and drive-trains come fully and precisely tuned for individual track peculiarities. All racetrack factors are simulated, including road grip on a wide variety of surfaces on straights and in curves and on wet and dry tracks. The simulation accounts for wind resistance, tire resilience, cornering capacity and other influences. The program automatically tunes the torque level for the race engines.

2. A piezoelectric triaxial accelerometer made by Brϋel & Kjǽr, type 4326A-001.
3. A laser Doppler vibrometer made by Polytec, model OFV525/5000.
4. An acquisition system made by Onosokki, model PS5000.

The on-board test bench consists of:
1. A piezoelectric triaxial accelerometer made by Brϋel & Kjǽr, type 4326A-001
2. A dedicated acquisition system for car tests with hardware made by National Instruments (model NI PXI 4472, 24 bit, 102.4 kSa/s, 8 channels [7]) and with a software developed in LabVIEW. It permits the integration among signals with different sampling frequency. Although vibration acquisitions have not the same bandwidth, they are synchronized with all others car measurements collected in several telemetry channels. A part of mentioned software screenshot is represented in Fig. 2.

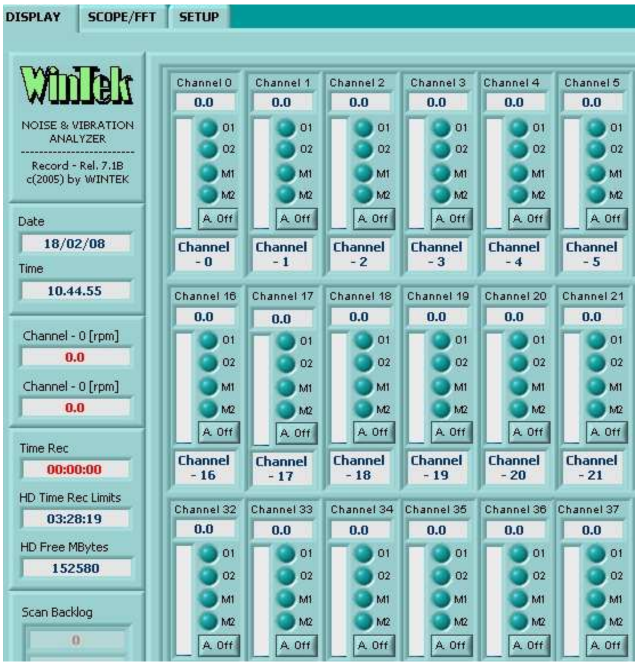

Fig. 2. Graphical User Interface for on car vibration acquisition.

Practical experience reveals that in several cases is not simple to mount the accelerometers on the object of vibration measurements. In these cases, traditional sensors are replaced by optical equipment [8,9]. When the object oscillates and there is optical visibility of the object's surface, nearly always one can form an optical image of contrast part of the object [10]. Other non-contact techniques which allow vibration measurements are the acoustic methods; due to the Doppler effect, the reflected sound wave is frequency modulated by the surface vibration velocity [11]. In a Doppler sensor, two beams intersect at an angle φ on the moving surface where they form a pattern of equally spaced bright and dark fringes. Light scattered from a material moving through this fringe pattern experiences an intensity modulation with a frequency proportional to the speed of the material. Lambda sensor (used for stoichiometric measurement) is one of device optically characterized in terms of vibrations. Fig. 3 represents the logical flow of vibration measurement system: a transducer (typically an accelerometer) converts vibration energy in terms of an electrical value (typically of charge per unit of acceleration, [$pC/m/s^2$]); an appropriate amplifier (typically a charge amplifier) returns a proportional and linearized voltage signal (mV), [12]; the acquisition system produces a digitalized version of measurement (sampling and quantization); the processing system involves a virtual instrument (VI), to process the measurement information, and a logger, to store the vibration data.

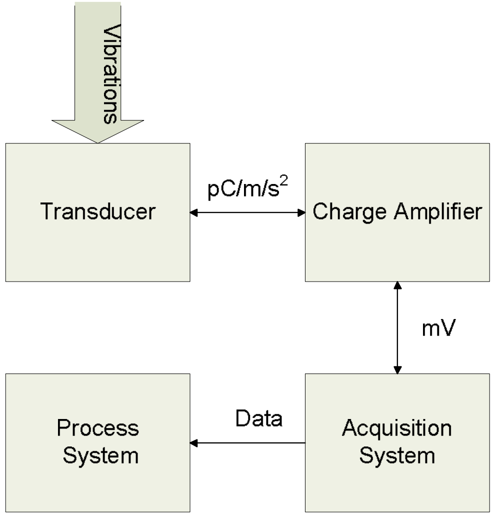

Fig. 3. Block scheme of vibration measurement system

A VI has been developed in Visual C++ language to carry out the vibration signal analysis in the time and frequency domains. A first test using swept sine over the frequency range of interest is essential. This will enable any relative motion of components, or flexing of PCBs, to be examined [13]. Following this initial examination the test can be carried out at a fixed frequency (e.g. a fixed motor speed, or a frequency causing a severe resonance).

III. A significant case study: the steering wheel

The sources of steering wheel vibrations include the engine, the wheels and the tires, as well as the road surface. This results in various vibration patterns transmitted to the steering wheel through the steering shaft. The perceived intensity of hand-transmitted vibration is dependent on the vibration frequency and the frequency-dependence of subjective estimates may depend on the magnitude of vibration [14].

This section focuses on the reliability tests of the steering wheel considering the results of on-car test vibrations measurements both in time domain and in frequency domain. Because of safety problems, it was not possible to measure vibrations directly on the front side of the steering wheel. Therefore it was preferred to locate the accelerometers behind the steering wheel (Fig. 4). Two triaxial accelerometers were mounted respectively on steering wheel rigid section (it measures the source of vibrations from the vehicle) and on steering wheel electronics. Electronics section is mounted using absorbers, therefore vibrations from base are correctly damped (the overall vibrational stress on Z-axis on the steering wheel electronics is less than the base value).

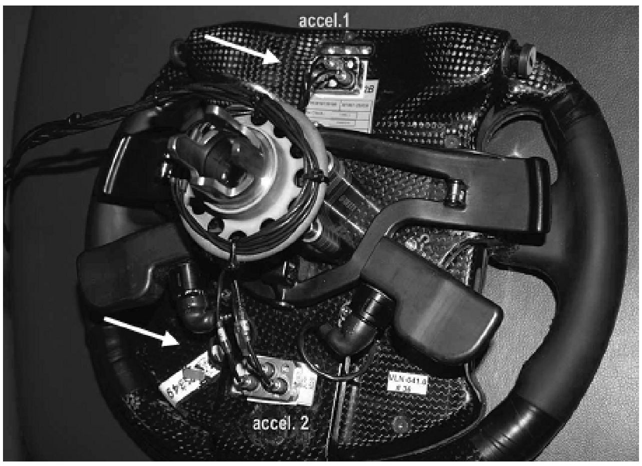

Fig. 4. Accelerometers positioning on steering wheel.

Fig.5 represents the acceleration values obtained from each sensor calculated averaging on three laps (Monza Track); it clarifies the efficacy of absorbers. The accuracy of mentioned measurements is 0.01 m/s^2 because it is the best trade off between sampling resolution of acquisition system (1.2μV) and accelerator accuracy ($10mV/m/s^2$), considering the voltage range (20V) and the physical range (200 m/s^2).

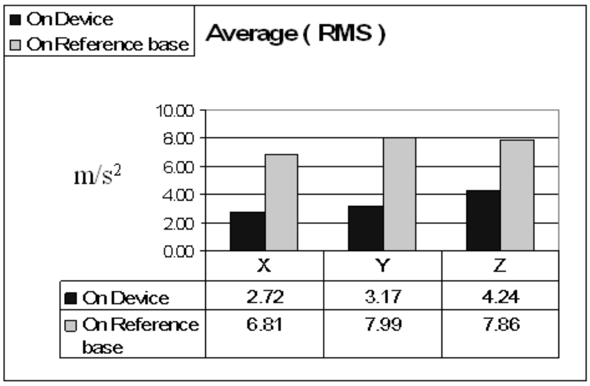

Fig. 5. Time domain vibration on steering wheel base and electronics.

Vibration behavior is greatly modified by vehicle state conditions in terms of PSD. Below are reported two plots which focus on kerbs riding and straight-line running. The GT cars specification for PSD vibrational testing for all the electronic devices which are mounted on the chassis is used as reference (black dashed line). It's evident that this automotive standard is not appropriate for racing applications. As show the thin lines in Fig. 6, during straight line running the PSD is concentred on high frequencies area. Vice versa when the car is on a kerb the PSD distribution is located on lower frequencies (Fig. 7). In order to match both high frequency vibrations from engine and low frequency shocks from kerbs riding, it is opportune to perform on-bench vibration test cycling between two different PSDs. Marked lines represent the interpolation of max points of measured PSD (thin lines) and it is the input function of shaker.

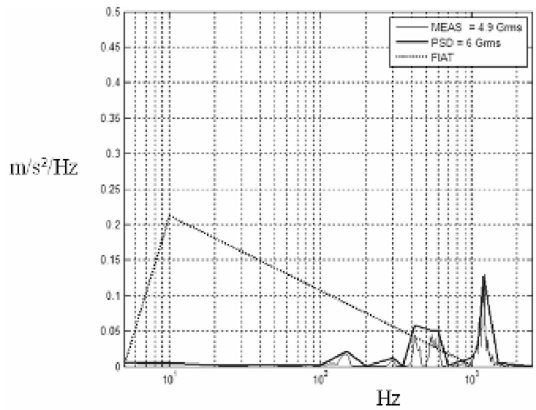

Fig. 6. PSD vibration test on straight line running.

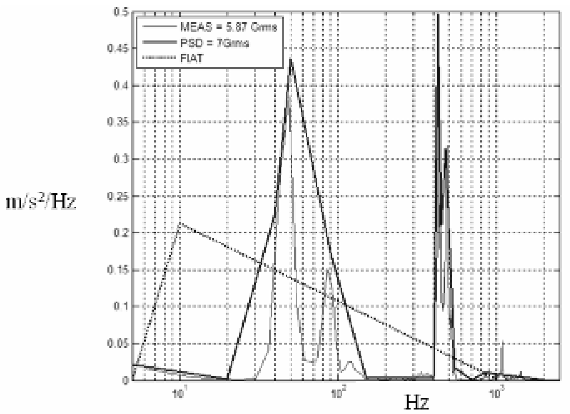

Fig. 7. PSD vibration test on kerbs.

Adopting automotive standard it's possible to consider only a part of real racing stress; to mount on F1 car a steering wheel only automotive approved could involve a risk. It's fundamental to repeat periodically these on-car measurements to use the real vibrational asset as input of simulation bench test. In this way it is possible to validate accurately in laboratory the robustness of steering wheel.

IV. Conclusions

The paper describes a practical vibration monitoring procedure for electronic equipment in racing context. Three test benches are mentioned to show all data acquisition systems implemented for Ferrari 248F1.The collected vibration data are useful to several goals: mechanical stress study, shock characterization, resonance analysis, damping efficiency, noise source investigation, reliability tests and some feedback to suppliers in the continuous improvement process. The proposed approach not only guarantees the component functionality but it is useful to continuous improvement of device design/assembling. Moreover, in the considered case study, the efficacy of absorbers on the steering wheel can be assessed too by measuring how much they reduce the effects of vibrations on the wheel.

Acknowledgements

The authors would like to express their gratitude to Stefano Lovera and Prof. Pasquale Daponte for their valuable suggestions on this paper.

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