Development of a distributed electronic system for low-cost heavy-duty engine test bench

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***Abstract* – Test benches are important tools for the optimization and diagnosis of internal combustion engines. This paper presents the work done to develop a low-cost tech bench for heavy-duty engines, which uses an electromagnetic brake, to apply load to the engine, and a distributed electronic system for control and data acquisition. Signal noise contamination in test benches represents a problematic aspect of the engine testing. Moreover, a distributed control and monitoring electronic systems, allied with a Controller Area Network (CAN) communication bus for signal transmission, was used to mitigate and ultimately immunize signals from noise sources such as electric or electromagnetic fields. Overall, a heavy-duty test bench aiming the engines diagnostics was obtained, where all control and data acquisition is performed via an USB serial port, interfacing with two CAN bus networks, in a complete distributed control system.**

Keywords –engine test bench; distributed system; heavy-duty engine; signal noise immunity

I. INTRODUCTION

Medium and heavy-duty test benches, or engine dynamometers, usually employ complex water brakes (hydrodynamic dynamometers), hydraulic brakes, Eddy current brakes or alternating current motors to apply a full spectrum of loads to the engines on test [1]. All those brake types are quite expensive and require complex auxiliary and control systems. Well-known companies such as AVL, Horiba, KST, and others provide industrial solutions for heavy-duty engine test benches. While those commercial systems enable a precise testing and represent high endurance test benches, their high pricing representing more than an hundred thousand euros only for the dynamometer installation, without considering the cost of the auxiliary systems and fuel consumption measurement are not practicable for a low-cost testbench solution, whose main goal is to perform a short set of test points to validate the engine functionality, rather than to perform its optimization.

Two different architectures can be considered when developing a control and monitoring system: centralized and distributed system. A centralized system represents a system in where most inputs and outputs are linked to one main controller, normally a computer fitted with a digital acquisition board. In those systems, long connecting cables to the main controller are required due to the high dispersion of peripherals (sensors and actuators). Signal degradation represents the main disadvantage of a long cabled centralized system. Signal degradation can occur, e.g., from a sensor to the measurement unit due to noise contamination. Engine test facilities can have high cable lengths, with up to 15m when using a centralized control system [2], and reaching 30m or more in some cases. Engine test benches are, by implication of their component parts and their low power measurement and control signals, extremely vulnerable to signal degradation caused by multiple sources of noise contamination, as depicted in Fig. 1.

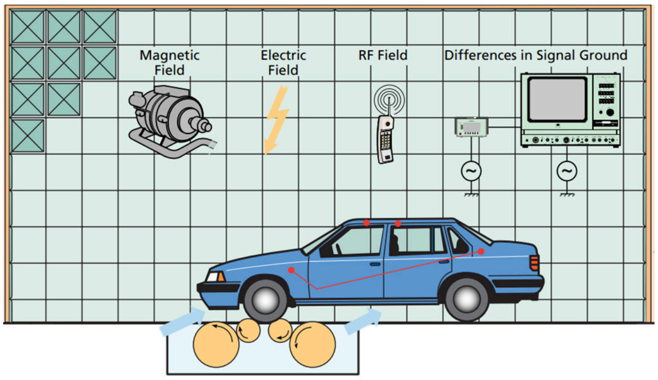

Fig. 1 - Noise sources in a Dynamometer Test Bench, adapted from [3]

Engine test benches usually use Eddy current dynamometers to impose a braking torque to the engine. This braking torque is produced by the rotation of the dynamometer's rotor in the presence of an electromagnetic field (EMF), generally generated by a direct current flowing through coils inside the dynamometer. The generated EMF represents a strong source of noise contamination by electromagnetic induction [4]. Measurement or control cables nearby the dynamometer will then have their signals distorted, inducing erroneous measurements or commands in the system.

Other sources of noise and errors are the vibrations associated to test benches and the high temperatures of most of its parts.

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In order to address this problem, a distributed architecture focuses on distributing the control and monitoring devices closer to the I/O peripherals, being the communication between components performed using one, or more, digital communication bus. For example, in sensors all processing, calibration and analog to digital conversion are performed with electronic systems embedded to the sensors or added as close as possible near the sensors.

Even if introducing some complexity and cost to the system parts, distributed systems present the advantage of drastically reducing the analog cable length. Even the overall cable length is reduced and components installation is quite simplified, since most components share the same digital bus. Moreover, when compared to a centralized system, decentralized systems are also more flexible relatively to the expansion and addition of new components and come with a smaller overall cost (cheaper interfaces to the computer systems).

Although reducing the chance of noise contamination of signals, distributed systems doesn't eliminate noise *per se*.,

In fact, in an engine test cell, the coexistence of different noise frequency sources generates a typical problem in data acquisition and process control due to difficulty to have a clear signal given the variety of equipment interferences like high voltage intermittent circuits, diverse magnetic fields and intrusive signal circuits with diverse grounds. To minimize these interferences, some typical solutions are implemented, like using mean values of big data obtained, or use filters, or lose a lot of time and resources to separate all electric circuits, these options normally causes signal degradation and loss of test information.

These problems are typical for analog signal, reason why automotive manufacturers decided to use digital communication in their vehicle's circuits, commonly with CAN structure. The use of CAN bus communication brings the noise level close to nullity. By using differential data transmission (CANH and CANL complementary signals) and due to coupled electrical interference, result of the twisting of the signal cable wires, noise interference immunity is achieved, as depicted in Fig. 2 [5],[6].

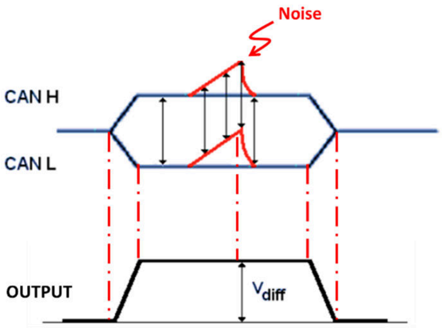


Fig. 2 – Representation of CAN noise immunity

Additionally, CAN transceivers can present a high level of galvanic isolation, enabling the communication between systems with different power supplies and with total electric isolation between them. Using this concept, the proposed methodology intends to demonstrate the advantages of minimizing the analog signals getting a CAN base circuit for all the data acquisition and control testing process. The development of all the components of the control and acquisition systems present the additional advantage of allowing a proper understanding of the systems principal components as well as the information flow. This knowledge leads to a higher confidence of the acquired data and mitigate some problems arising from digital readout [4].

II. DEVELOPED TEST BENCH

The developed test bench presents two fundamental and distinct, but intrinsically complementary, circuits: data acquisition and process control. Fig. 3 illustrates a schematic representation of the developed test bench. It consists of a heavy-duty engine which is linked to a magnetic brake fixed to 4 load cells allowing to measure the engine braking torque. Other sensors and systems were considered to monitor the engine operation condition.

The data monitored by the developed system is obtained either internally, from the variables available within the engine's electronic control unit (ECU) in the J1939 standard, such as engine speed and temperatures, or externally via a peripheral sensorial system. This dedicated sensorial system was added to monitor additional parameters, which otherwise were not available or for redundancy reasons. The external sensorial system allows the measurement of engine variables such as fuel consumption, coolant and oil temperatures and gearbox rotational speed. Additionally, the developed apparatus monitors brake related parameters, such as rotor and coil temperatures, measured by an IR temperature sensor and contact thermocouples, respectively. Engine torque was determined using 4 load cells which are installed as mountings of an Eddy current brake used to impose a counteracting load.

The engine speed and brake/load level conditions are controlled by two developed distributed electronic modules: the ECM (Engine Control Module) and BCM (Brake Control Module), respectively. These modules, together with the ECU and external sensorial system parameters, are centralized by an individual control unit, EDAS V2, through two CAN buses. The central control unit EDAS V2 communicates with a PC, running a dedicated monitoring and control software, through a serial USB communication. This centralized control unit represents an update from the EDAS V1 [7].

The test bench monitoring and control system is completely distributed, with all sensors and control systems (ECM and BCM) communicating through a CAN bus. The heavy-duty engine used in this study is a Scania DC12 series 11.7 L 6-cylinder engine with a maximum torque of 2000 Nm@1000-1300 rpm and maximum power of 230 kW@2300 rpm.

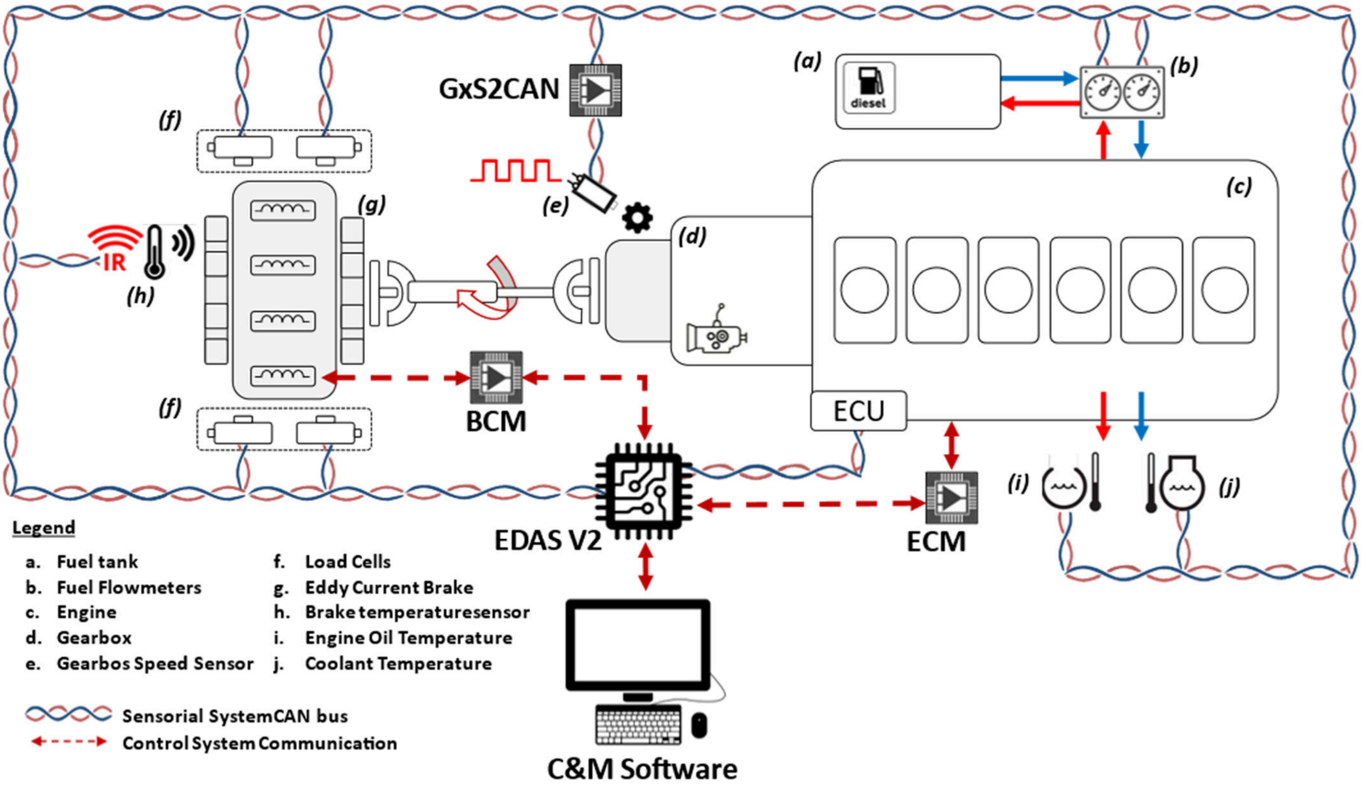


Fig. 3 – Engine Test Bench electronic signal architecture for data acquisition and test control

III. DISTRIBUTED ELECTRONIC SYSTEM

This section presents the main electronic modules developed for the distributed control and monitoring systems of the test bench. A brief description of the modules' functionalities is given, as well as, for the control modules, their iteration and integration within the existing hardware.

A. Electronic Brake Control

This module allows for a discrete control of the dynamometer brake level and, consequently, the load applied to the engine.

The dynamometer presents a discrete control of the applied load, presenting 4 different levels of braking from 25 to 100 % brake capacity, which are obtained by the actuation of 4 contactors that supply direct current (DC) to a pair of coils each, as presented in Fig. 4.

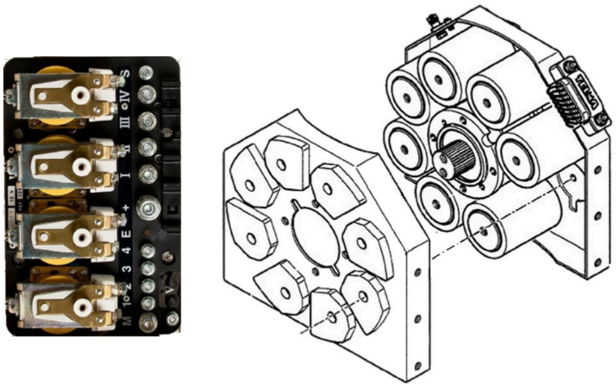


Fig. 4 – (*Left*) Brake level control contactors and (*Right*) exploded view of the dynamometer

Originally controlled by a lever (Fig. 5 - *Left*), which, in turn, sequentially closes the four power contactors/coils of the electromagnetic brake. This control module was developed in order to "replace" the manual actuation mechanism for the brake contactors, allowing a fully automatic control. (Fig. 5 - *Right*) The module uses four eFuses, AUIR3314 from Infineon®, to activate the brake contactors. More than a regular power transistor, they include temperature, over current protection, amongst others features.

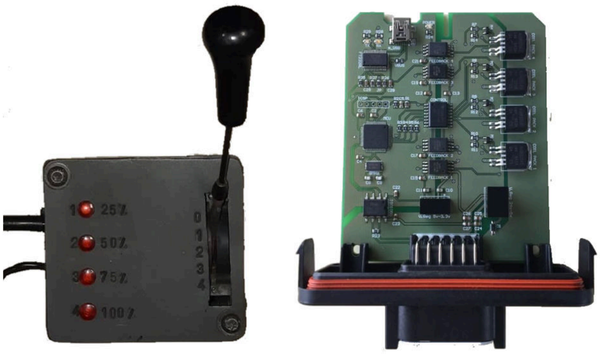


Fig. 5 – (*Left*) Manual brake level control and (*Right*) Developed electronic control module

Although representing an alternative mechanism, the developed system still allows a manual actuation by use of the already existing lever whenever the test technician decides to switch actuation modes.

At the core of the brake control module, a 32bits Microchip® microcontroller, receives a CAN message with a command word, from an external control unit and, in accordance, sets the state of the brake contactors, corresponding to the desired brake level. Additionally, the module presents a feedback functionality, current feedback of the eFuses, that indicates the actuation status of the brake.

Moreover, as shown in Figure 5 (right), the microcontroller, CAN transceiver and other low-level components (3.3 V) were totally electrically isolated from the power voltage (24 V). For that purpose, an isolated voltage convertor, opto-coupled digital isolators and isolated operational amplifiers were used.

Contrarily to the manual actuation mechanism, which actuates the contactors sequentially, the developed module allows for a simultaneous actuation of the contactors, leading to a more direct and precise control of the brake level.

B. *Electronic Speed Control*

The electronic speed control module, shown in Fig. 6 (right), is used to control of the engine rotation speed, via the CAN bus. From factory the existing cruise control system uses and analog line to transmit the state of four buttons ("idle", "down", "up" and "memory"). Working in parallel with the existing cruise control buttons, the developed module generates an analog voltage in accordance with the intended function.

Fig. 6 - (*Left*) Manual engine speed controller and (*Right*) Developed electronic speed control module

The system is built around a CAN microcontroller from Microchip® and an Atmel® microcontroller. Where received CAN messages are converted in voltage levels, in accordance to the desired function. Thus, it is possible to increase and decrease the engine speed as well as memorize a new engine idle regime. The actuation status of the cruise control system is returned by the module through a feedback option, even if the cruise control is activated by the manual commands.

As a safety measure, the electronic cruise control is deactivated by the engine ECU, whenever both manual and electronic systems are actuated simultaneously.

C. *Gearbox Rotational Speed Measurement*

This module receives the digital signal (frequency modulated) from a Hall effect sensor, located at the output shaft of the engine's gearbox (Fig. 7) and calculates the according rotational speed. Given so, the rotational speed is sent via the CAN communication bus to the central control and monitoring unit.

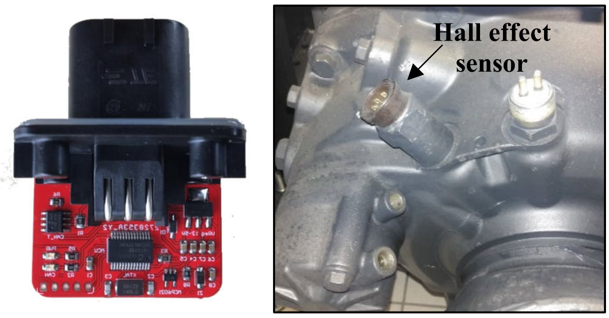
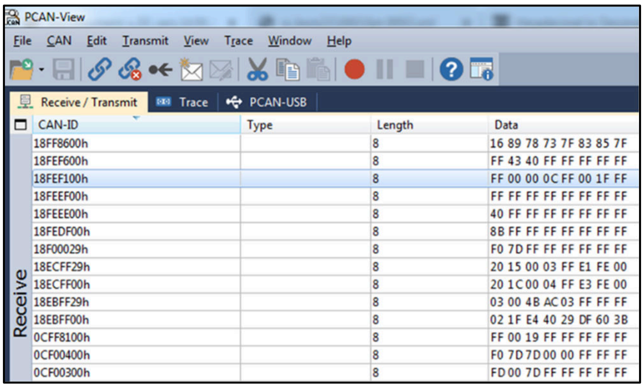


Fig. 7 – (*Left*) Developed analog to CAN gearbox speed converter and (*Right*) Hall effect speed sensor location

IV. COMMUNICATION PROTOCOLS

A. *CAN*

Engine parameters available within the engine ECU were obtained by reverse engineering of the CAN messages broadcasted by the engine ECU. As shown in Fig. 8. The available data in the CAN bus, of the tested heavy-duty engine, was acquired and analyzed using the software PCAN-View®.



CAN-ID	Type	Length	Data
18FF8600h		8	16 89 78 73 7F 83 85 7F
18FEF600h		8	FF 43 40 FF FF FF FF FF
18FEF100h		8	FF 00 00 0C FF 00 1F FF
18FEEF00h		8	FF FF FF FF FF FF FF FF
18FEEE00h		8	40 FF FF FF FF FF FF FF
18FEDF00h		8	8B FF FF FF FF FF FF FF
18F00029h		8	F0 7D FF FF FF FF FF FF
18ECFF29h		8	20 15 00 03 FF E1 FE 00
18ECFF00h		8	20 1C 00 04 FF E3 FE 00
18EBFF29h		8	03 00 4B AC 03 FF FF FF
18EBFF00h		8	02 1F E4 40 29 DF 60 3B
0CFF8100h		8	FF 00 19 FF FF FF FF FF
0CF00400h		8	F0 7D 7D 00 00 FF FF FF
0CF00300h		8	FD 00 7D FF FF FF FF FF

Fig. 8 – Reverse engineering of the available CAN ID's in the engine bus with PCAN-View®

After analysis of the messages present in the engine CAN bus, for a wide range of engine operation, some message ID's presented invariant data bytes, meaning that although present in the communication bus, those variables were not defined for the studied engine. The other ID's, the ones with variable data bytes, were verified to be compliant with the J1939 norm. For example, as shown in Fig. 9, the CAN message with the engine speed of 0 rpm and 600 rpm, present the ID "0x0CF00400" and the data of "0x0000" and "0x12D0", respectively (bytes 4 and 3). By applying the J1939 norm resolution (×0.125) the engine rotation can be found.

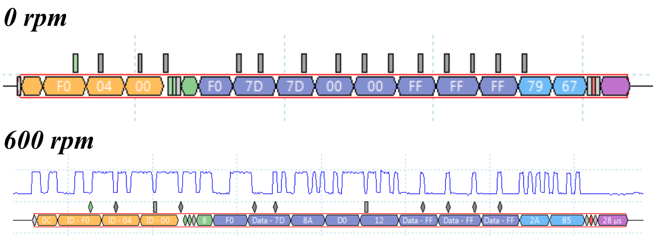


Fig. 9 – CAN message structure of engine speed according to the J1939 norm for 0 and 600 rpm

B. Control and Monitoring Software

A dedicated monitoring and control software was developed in a LabView® environment, communicating with the central unit by serial communication. The software allows the control of the brake level and the engine rotation as well as the definition of automatic test routines. Different routines can be defined by importing text files with a set of point to test (engine rotation and load). Fig. 10 illustrates the software interface for engine control and data acquisition.

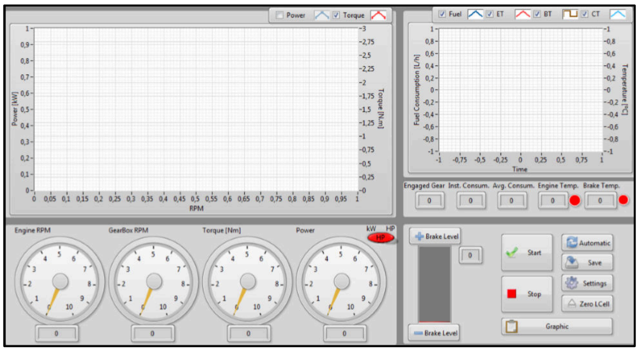


Fig. 10 – Control and acquisition interface in LABVIEW®

Additionally, alert and emergency parameters can be defined, e.g. maximum temperatures and rpm, to automatically stop the test procedure, in case of exceeding one of these parameters during testing.

Parameters from the engine, as well as from the external sensorial system can be monitored and saved to a text file, for future analysis. Fig. 11 represents an alternative interface of the developed monitoring software, aiming the supervision of test bench and its main components.

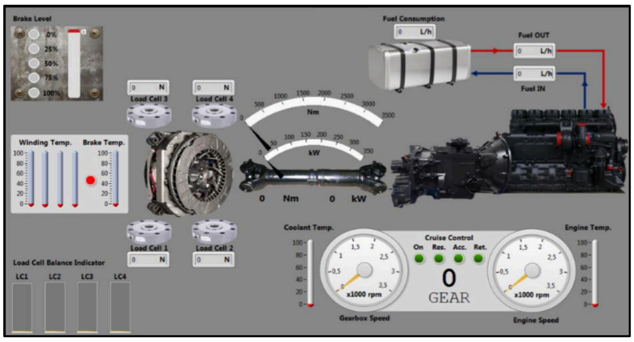


Fig. 11 – Monitoring software interface in LABVIEW®

V. RESULTS

An example of force measurements from the load cells when different braking levels are applied as well as critical acquisition stages and control actions are presented in Fig. 12.

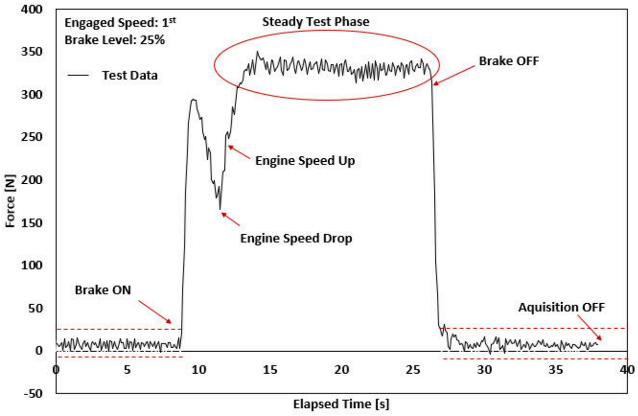


Fig. 12 – Force values as function of time for 25 % brake level

This is the most complex signal obtained, since the signal cumulative interferences are caused by both electrical as mechanical origins. It is possible to verify the high frequency response of the signal to a sudden variation of the force. An evident advantage is the almost complete immunity to electrical noise presented in the signal. It becomes clear that the high frequency oscillations in the signal are motivated to the mechanical vibration of the bench structure due to the engine operation rather than electrical or electromagnetic interference.

In order to validate the engine diagnostic functionality of the developed test bench, the engine was tested with a malfunctioning fuel injector and engine parameters, such as fuel consumption and torque, were compared against the value obtained with the unfaulty engine. Fig. *13* shows the difference in torque measurement with respect to time for faulty and unfaulty engine condition at 1300 rpm.

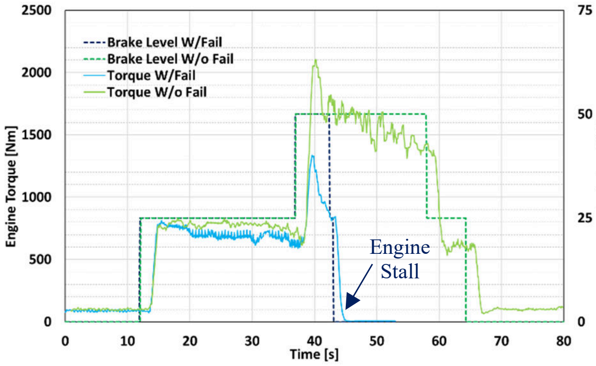


Fig. 13 - Torque measurement for faulty and unfaulty engines

The major indicator of a fault existence is the fact that the faulty engine couldn't withstand the 50 % brake level condition as well as lower torque value at 25 % brake.

For further analysis, a 9-point operating condition matrix was tested with engine speed values of 1000;1300 and 1600 rpm and brake levels of 0; 25 and 50 %. All test points were performed in 3rd gear with a transmission ratio of 1.36. Fig. 14 and Fig. 15 illustrate the obtained results for both engine conditions.

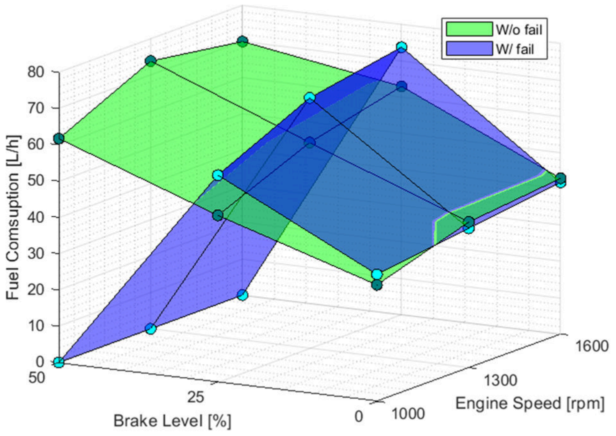


Fig. 14 – Fuel consumption as function of rpm and brake level

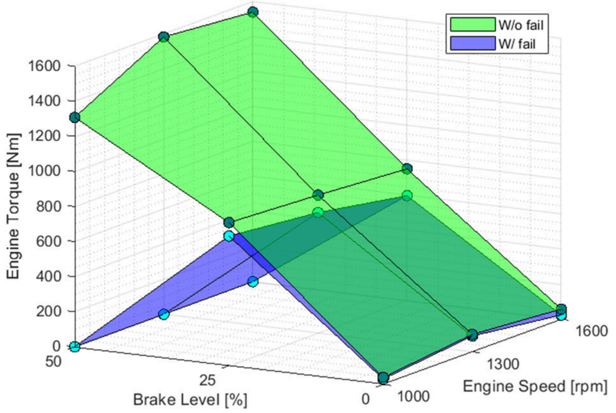


Fig. 15 – Engine torque as function of rpm and brake level

From the obtained results, clear quantifiable differences between a healthy and faulty engine are observed. Comparing the common test points, it is observable that the faulty engine needed a higher engine load to withstand the same operating condition. Consequently, higher fuel consumptions are observed in these conditions when compared to the healthy engine condition, as depicted in Fig. *14*. Additionally, as in Fig. *15*, lower torque values were observed. Parameter differences between faulty and unfaulty engine condition were observed to increase as the counteracting load increases.

VI. CONCLUSIONS

- An electromechanical brake, from a heavy-duty vehicle, proved to be a capable load generator for the development of a low-cost test bench.
- A fully distributed system and a CAN network for data acquisition and control enabled a feasible, less complex, noise immune and cheaper system. To complement the parameters acquired internally from the engine ECU, complementary sensors were selected and ensured an efficient integration and communication with the central control unit.
- Different electronic circuits have also been developed for more efficient and reliable signal processing, ensuring greater immunity to electrical noise.
- The development of an electronic brake control system allowed for a greater automatization of the test procedure and more reliability of the system, as constant feedback of the procedure is received and monitored.
- The estimated cost of the developed test bench rounded ten thousand euros which represent one order of magnitude lower than commercially available test benches.
- The presented low-cost test bench has an undeniable value. Made with vehicle of-the-shelf parts and low-cost electronic devices could be successfully used to test an engine in an acceptable variety of working points. Being an important tool to assess the working condition of combustion engines.
- Application of load conditions to the engine revealed to be an important aspect for engine diagnostic and health condition monitoring as parameter difference tend to be more observable and meaningful as load is applied.

ACKNOWLEDGMENT

The authors acknowledge Diamantino Perpétua & Filhos,Lda for their support throughout the development of the project.

This work has been partially supported by Fundação para a Ciência e a Tecnologia (FCT) under project UID/MULTI/00308/2019.

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