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ENGINE TEST STAND LAYOUT AND POST PROCESSING TOOLS FOR THE DETECTION OF MANY ENGINE PERFORMANCE PARAMETERS

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ABSTRACT

An eddy-current brake, capable of measuring the torque and the power of internal combustion engines at desired rotational speeds, has been fully interfaced with an external NI cDAQ 9178 data logger. Thanks to this system, it is possible to collect and synchronize the data coming from the test stand and from several other sensors equipping the motors under test: a load cell used in a chrono-gravimetric fuel consumption system, many thermocouples, a lambda probe, an exhaust gas analyser. To have a better control of the position of the throttling valve during the trials (hence a higher repeatability), a control system, based on an Arduino board, directly acts on the valve through a servomotor. Then, a series of software tools allows the interfacing of the various devices and the automatic post-processing of the acquired data (filtering of signals, recognition of data corresponding to the single engine speeds, time-averaging). The described testing equipment and the implemented procedures allow investigating, on the whole operating range of a motor (i.e., at different engine speeds and loads), each single performance parameter's value, such as: the torque, the power, the fuel consumption of the motor, the temperature and the composition of the exhausts (up to nine different gases), the temperature of the engine head and of the cylinder block, the combustion quality and many other additional parameters describing the engine performance. This test stand, with the described post processing procedures, will be used in future works to evaluate the performance of traditional and alternative-fuelled internal combustion engines for both agricultural and co-generative applications.

Keywords: engine test stand, agricultural engines, engine performance detection.

INTRODUCTION

GENERAL CONSIDERATIONS AND PROBLEM DESCRIPTION

In recent years, the interest in the evaluation of the performance of internal combustion engines (ICE) has steadily grown not only in the automotive sector but also in the cogeneration sector [1,2] and in the agricultural sector [3–5]. This demand is determined by the increasing restrictions in terms of fuel consumption and emissions, stated by many norms (e.g. TIER for the agricultural sector), and to the interesting opportunity of using alternative fuels, having a global carbon-impact lower than conventional fossil fuels [6, 7]. As a consequence, there has been a continuous evolution in the field of research and experimentation of all the vehicle technical systems involved in the power generation [3] and delivery [8]. Nevertheless, even though simulation tools are more and more used in the development of new engines [9-13], experimental tests are still an essential tool for the design and the performance evaluation of ICEs [14–16] and can be successfully used together with simulations as the necessary validations [17]. The development of modern engines and the evaluation of their performance requires the running of many tests, performed with different control strategies ("speed-controlled" or "accelerative tests") with the aim to acquire the engine performance and the parameters of interest. Only in a second moment, simulations can be performed on the basis of these experimental tests.

STATE OF THE ART

The dynamometer is the typical instrument used to evaluate experimentally the performance of ICEs, in particular their torque and power. Its measurement principle is based on the Newton's third law applied to a rotating system: the dynamometer is able to develop a breaking moment contrasting the torque of the engine connected to it: in steady state, the system "engine-and-dynamometer" rotates at a constant speed so the breaking moment (known because applied by a controlled system, i.e. the dynamometer) is equal and opposite to the motor torque (unknown). A dynamometer is therefore used for the direct measurement of the mechanical moment of a motor and, indirectly, also for the calculation of the power delivered by the same motor.

Dynamometers can be classified into three categories depending on the type of breaking apparatus: mechanical dynamometers/brakes; hydraulic dynamometers/brakes; electric dynamometers/brakes. In mechanical brakes, torque is evaluated by applying and measuring a friction force on the engine crankshaft at the wanted constant rotational speed of the engine. The hydraulic brakes consist of a rotor and a casing anchored to the ground. The rotor is part of a hydraulic pump and it is connected to the shaft of the motor to be tested. The system also embeds a water reservoir that is pumped and recirculated through a set of pipes. An adjustable valve controls the flow of water in the piping, thus generating the load necessary to stabilize the rotational speed to a desired constant value. The engine performance is

ARPN Journal of Engineering and Applied Sciences

evaluated by correlating the hydraulic pressure over the valve and the rotational speed. These brakes show the best capability of variation of the load but require large amount of pressurized liquid to be cooled and they are, therefore, not easy to be managed. Electric brakes are actually the widest used systems to measure engine performances, due to their high precision and sensibility. It is possible to list two main sub-categories of electric brakes: dyno-motor brakes and eddy-current brakes. In Dyno-motor brake systems the tested engine is connected to a dynamo, so they can operate as brakes, thus dissipating the power generated by the engine under test through a proper cooling system, but they also can operate as a DC motor, thus providing the engine with a power coming from an external electric supply to simulate, for example, a inclined road on which the driver uses the engine-brake. Eddy-current (magnetic) brakes dissipate as heat the kinetic energy on a flywheel, made of a conductive material, connected to the engine and rotating near a magnet. The circulation of eddy currents in the metallic flywheel through electromagnetic induction (ruled by the Faraday-Neumann law) dissipates energy into heat due to the electric resistance of the conductive material itself (Joule losses). In these systems, the braking torque is controlled by operating properly on the electric parameters (voltage level, current intensity, frequency). Nowadays, these last typologies of brakes (in particular, the eddy-current brake) are the most used, due to their high accuracy and easiness of control of the braking torque.

Besides power and torque, there are several other parameters that should be measured and taken into account to properly evaluate the performance of ICEs, in particular: the fuel consumption, the air-fuel-ratio (AFR), the flow rate and temperature of the exhausts, the temperature of the main components of the engine, the pollutants' concentration in the exhaust and, if possible, the pressure within the combustion chambers. All these data must be properly acquired and the signal coming from each probe must be post-processed (i.e., conditioned, time-averaged and matched) to get proper and reliable information from the experimental tests.

AIMS OF THE RESEARCH

The aims of the present work are to: i) describe a multi-purpose test bench for the evaluation of the performance of ICEs; ii) describe the probes and the data acquisition system that are used in the bench; iii) report a methodology used for filtering and post-processing the acquired data in order to better evaluate the engine performance parameters.

MATERIALS AND METHODS

ENGINE TEST STAND LAYOUT AND COMPONENTS

The test bench described here is located in the Fluid Machinery Laboratory of the Faculty of Science and Technology of the Free University of Bozen-Bolzano. The system, a "Braker Engine 100/E" by Soft-Engine S.r.l. (Falconara Marittima, Ancona, Italy), is composed by an eddy-current brake powered with a 192V AC voltage and has a maximum power consumption of 2.0 kW. The maximum rotational speed is 5500 rpm and the maximum admissible power is 75 kW. It is controlled by a dedicated hardware which allows performing different type of tests (e.g., controlling the torque or the speed or both these quantities simultaneously) but also sampling data and applying them the numeric corrections based on meteorological-environmental parameters (i.e., temperature, pressure and relative humidity) in accordance with international norms, such as EC, SAE or DIN.

The brake is equipped with a load cell CTL500 by Laumas Elettronica S.r.l (Montechiarugolo, Perugia, Italy), to evaluate the braking torque, and an incremental encoder Minicod T produced by TeleStar S.r.l. (Vaprio D'Agogna, Novara, Italy), to control the rotational speed of the tested engine. The load cell is placed at a distance of 0.235 m from the brake-shaft axis and measures the braking force developed by the dyno and counterbalancing the torque developed by the engine. Torque is evaluated as the multiplication of the measured forced and of the application distance. The characteristics of the probe are reported in Table-1. The load cell has a Wheatstone full-bridge configuration that is properly connected to a data acquisition device that will be described hereinafter.

Table-1. Technical features of the "CTL500" load cell of the test bench.

Quantity	Unit	Value
Rated output	$mV\ V^{-1}$	2 ± 0.1%
Temperature effect on zero	$\%\ °C^{-1}$	0.005
Temperature effect on span	$\%\ °C^{-1}$	0.003
Compensated temperature range	°C	-10 / +50
Operating temperature range	°C	-20 / +70
Creep at nominal load after 4 h	%	0.05
Maximum supply voltage without damage	V	15
Input resistance	Ω	350 ± 5
Output resistance	Ω	350 ± 2
Zero balance	%	± 1
Insulation resistance	MΩ	> 5000
Safe overload (% of full scale)	%	150
Ultimate overload (% full scale)	%	> 300
Deflection at nominal load	mm	0.3

The shaft rotational speed is measured by an incremental encoder with a resolution of 1000 impulses rev^{-1}. A single impulse corresponds to a rotation of 0.36°

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of the shaft, so the angular position is defined by multiplying the counted number of impulses by 0.36°. The difference of two consecutive angular positions multiplied by the sampling frequency allows obtaining the engine rotational speed. With this type of encoder (Figure-1) it is possible to know the shaft angular position and angular variation over the time but also the direction of rotation.

The signals from the load cell and from the encoder are directly acquired by the brake electronic control unit. Nevertheless, in order to collect on a single device all the data coming from the probes originally equipping the test bench (i.e., the two described sensors) and from the many other probes added by the authors, the signals of these two probes are also acquired by an external data acquisition system, working in parallel with the test bench hardware and described hereinafter. This solution allows a better management of the experimental measurements and also facilitates both the post-processing and the synchronization of the data. In fact, the test bench also embeds a set of other sensors that allow having a better evaluation of the performance of the engine. First of all, the fuel consumption of the ICE is evaluated by means of a chrono-gravimetric solution. In particular, a specific off-centre load cell has been used. Among the many types of load cells (i.e., strain gauges, hydraulic or pneumatic, optic fibre and piezo-resistive load cells), load cells using a strain gauge are the most commonly used and this typology of probes is also used in the described bench.

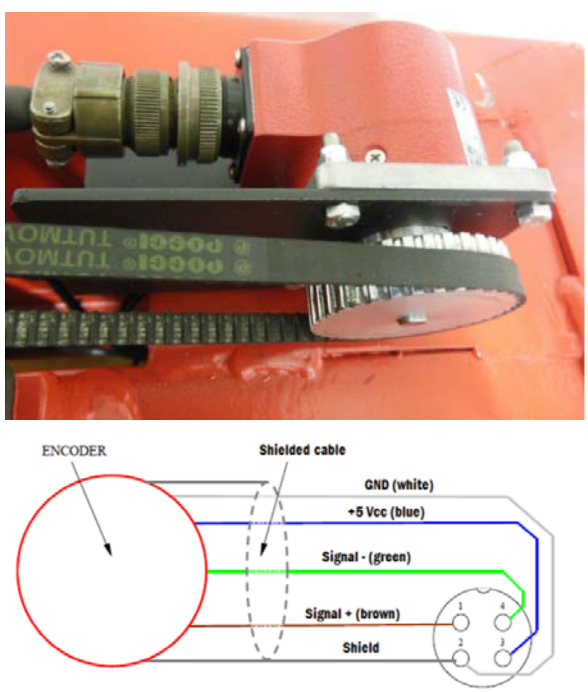

Figure-1. Minicod T encoder and wire connection scheme.

The load cell has a Wheatstone full-bridge configuration that is connected to the data acquisition device. The load cell, a CN/L by N.B.C. Elettronica Group S.r.l. (Delebio, Sondrio, Italy; Table-2), is placed under the fuel tank in a cantilever configuration. The instant fuel consumption is evaluated as loss in weight of the tank over the time (i.e., weight difference between the beginning and the end of the test at a specific rotational speed divided by the time duration of the test).

Table-2. Technical features of the “CN/L” load cell of the fuel tank.

Quantity	Unit	Value
Capacity	kg_f	7.5
Rated output	$mV\ V^{-1}$	2 ± 10%
Platform size	mm, mm	400 × 400
Nominal excitation range	V	5 ÷ 10
Zero balance output	$mV\ V^{-1}$	±0.02
Accuracy class	-	OIML R60

In order to get higher precision measurements, both the two load cells (respectively measuring the torque and the fuel consumption) were calibrated by loading them with different reference weights, so that a calibration curve was obtained for each of the two load cells.

Also the composition and the quality of the exhausts of the engine are monitored and controlled during the tests. A specific discharge duct has been designed in order to embed the additional probes. In particular, a lambda sensor and a gas temperature probe have been fitted in the duct. In Otto engines, in order to evaluate the correct ratio between the intake air and the fuel, it is important to install a proper probe in the exhaust duct to measure the eventual residual oxygen content or the presence of unburnt fuel. The zirconium-dioxide lambda sensor is able to measure the concentration of oxygen in a gas with respect to the ambient concentration. If the combustion was stoichiometric, the O_2 concentration should be zero. In the described bench, a LSU 4.9 lambda sensor (Robert Bosch GmbH, Stuttgart, Germany; Table-3) is connected to a MKL1 Lambda Control Unit, produced by MecTronik (Cerea, Verona, Italy) to condition the signals; also this latter system was interfaced with the data acquisition system. This sensor is placed on the exhaust pipe at 25-cm distance from the motor head in order to grant the correct working temperature (from 600 to 800 °C). When the temperature is not sufficiently high, the LSU 4.9 needs to be heated up; for this reason, heating of the sensor is supplied by a GPS-2303 laboratory DC power supply (GW Instek, New Taipei City, Taiwan).

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ARPN Journal of Engineering and Applied Sciences

Table-3. Technical features of the "LSU 4.9" lambda sensor.

Quantity	Unit	Value/Specification
Nominal voltage	V	8 ÷22
Analogic output	V	0 ÷ 5
Heating system type	-	PWM – Low side (10 A)
Microcontroller	-	Infineon 40 MIBS RISC with DSP
Residual oxygen	%	0 ÷ 20.5
Sensor temperature	°C	650 ÷ 1000

Finally, a set of thermocouples are used to monitor the temperatures of the main significant components or fluids of the engine, which are correlated with the engine performances [4, 18-20]. In particular, the used data acquisition system allows collecting data from up to 12 thermocouples. At present, the test bench is equipped to measure the temperature of the exhaust gases using a specific probe on the exhaust duct, the temperature of the engine head and the temperature of the cylinder block.

With the aim of sampling simultaneously the data of all the aforementioned probes, all sensors are connected to a cDAQ 9178 data logger (National Instruments, Austin, TX, USA). The cDAQ-9178 is an eight-slot Compact DAQ chassis designed for mixed measurement test systems. If it is combined with up to eight NI C-Series I/O modules, it becomes a custom analogue I/O, digital I/O, and counter/timer measurement system. It permits to acquire from the analogue input modules at different rates and runs up to seven I/O tasks simultaneously. The acquisition frequency was set to 10 Hz for the analogue signals, which, for the typology of measured quantities, is the best trade-off between having a sufficient amount of data to follow the transients without losing accuracy and requiring too much memory. The digital signals, namely the signals from the encoder, have a higher frequency, however manageable by the digital input module of the data acquisition system. The configuration of the entire system is illustrated in Figure-2: each sensor is connected to the data logger and this device is connected to a personal computer for the final elaboration and storage of the data.

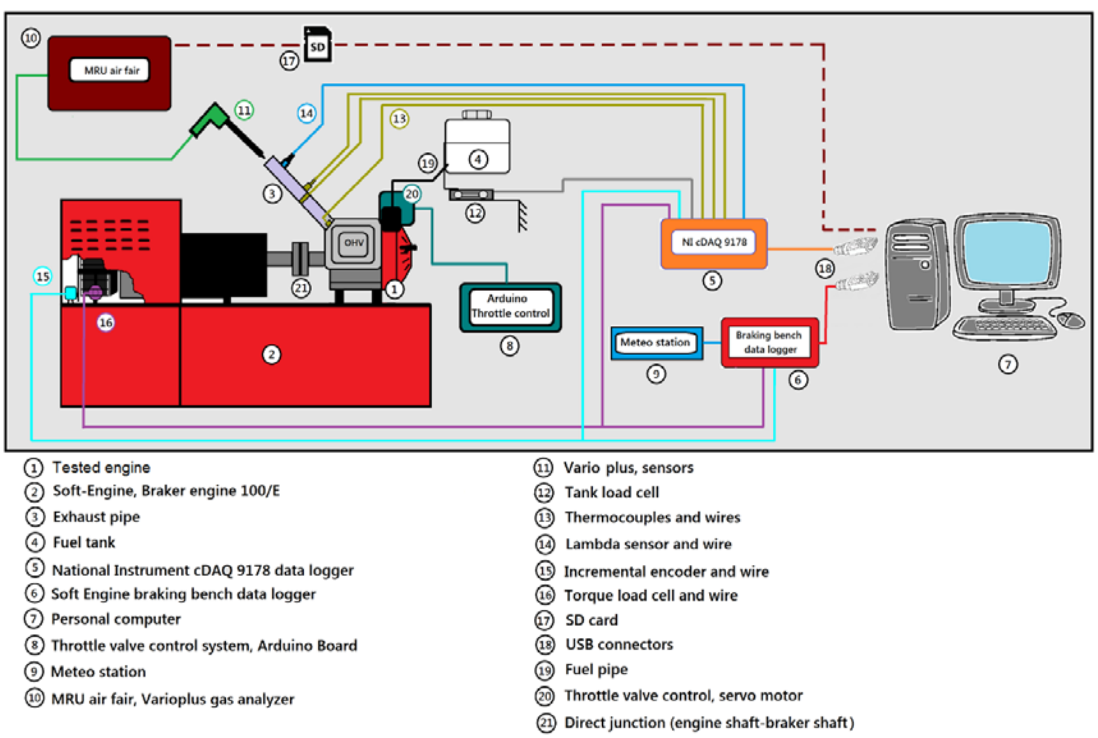

Figure-2. Complete layout of the test bench.

In Otto engines, users control the power supplied by the engine (e.g., the travelling speed for vehicles) by acting on the throttling valve opening in the air intake through a proper interface (pedal or leverage). Therefore, in order to test a motor at different loads and have a better control of the position of the accelerator (thus granting the repeatability of the trials), a control system, directly acting on the throttling valve, was installed on the motor. It is composed by a HS-485HB Deluxe servo motor (Hitec RCD Inc., Poway, CA, USA) connected to the throttling

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ARPN Journal of Engineering and Applied Sciences

valve and controlled by an Arduino UNO Rev.3 board (http://arduino.cc/). The used servo delivers a torque of 6.0 kg_f cm when it is fed with a 6V-DC voltage. The Arduino Uno is a prototyping board based on the ATmega328 microcontroller (Atmel, San Jose, CA, USA) and has 14 digital I/O pins, 6 analogue inputs, a USB connection and a power jack. Since it is not possible to operate directly the throttle valve with the servo motor, a proper linkage was used. Therefore, it was necessary to correlate preliminary the angular position of the servo motor shaft (given as output in the serial monitor of Arduino) with the angular position of the throttle valve by building the relative correlation function.

Finally, the test bench is also equipped with an exhaust gas analyser [16,21]: the Vario plus Industrial (MRU Instruments, Houston, TX, USA). This instrument is able to measure up to nine different gas species (O_2, CO, NO, NO_x, CO_2, NO_2, SO_2, H_2S, HC; Table 4) thanks to two different measurement principles of the internal probes. The first type of probe employs an electrochemical sensor with three electrodes, all in contact with an electrolyte. As a result of an electrochemical reaction, an electric current flows through the external circuit where this signal is amplified and measured. The second type of gas sensors employs an infra-red sensor; it works by measuring the wavelengths absorbed by the gases to identify them. In fact, each substance has its own unique infrared spectrum which makes this type of detection and analysis very accurate in chemical and industrial applications.

Table-4. Measuring ranges of the “Vario plus Industrial” gas analyser.

Chemical specie	Range	Measuring principle
CO_2	0-30%	Infrared
O_2	0-21%	Electrochemical
NO	0-5000 ppm	Electrochemical
NO_2	0-1000 ppm	Electrochemical
NO_x	0-5000 ppm	Electrochemical
SO_2	0-5000 ppm	Electrochemical
HC	0-5% as CH_4	Infrared
H_2S	0-500 ppm	Electrochemical
CO (H_2 compensated)	0-10000 ppm	Electrochemical
CO extra high	0-10%	Infrared

POST PROCESSING SOFTWARE TOOLS

The large amount of data coming from the experimental tests needs to be properly post processed in order to obtain reliable and significant data. These data can be used to optimize the fuel consumption or the performance of the engine, for example in terms of pollutant emissions, to adequately program the engine control unit and, finally, to study an indirect system for remotely monitoring the engine performances over their entire span, based on the measurement of some significant temperatures [3–5]. The processing of these acquisitions requires a considerable amount of time and resources, effectively reducing the opportunity to experiment with new technical solutions. For these reasons, the execution of the tests must be highly automated; the automation system must be able to simultaneously perform the control and test management and the data acquisition. Therefore, a series of tools, written in high-level languages, have been implemented to allow the interfacing of the various devices and measuring instruments and, finally, to make the test efficient, thus reducing the number of required tests. The tests carried out in an automatic mode allow exploiting the potential of the systems, having a great confidence in the quality of the result.

The data coming from all the described instrumentation have been collected in a single spreadsheet and the automatic post processing was performed using Matlab software. The first part of the procedure consists in reading the whole dataset containing the acquired raw data and then filtering the main measurement errors (negative values, high peaks, etc.).

In all the experiments with fixed rotational speeds, the tests are realized into steps of rpms, spaced according to the user’s specifications. The speed is kept constant for a few seconds, depending on the requirements of the test, and then the control system of the brake sets the new rotational speed and tries to make the engine reach the next step by controlling the braking action, till the maximum rpm for the tested motor is reached and the test ends. Each rotational speed of the engine is kept constant for 45 s in the trials, as the fuel consumption is measured with a chrono-gravimetric system (a longer acquisition allows a better evaluation of the flow rate) and the exhaust gases analysis requires a certain time lapse to correctly measure the concentration of pollutants.

Since all the raw data coming from the data acquisition system are collected continuously, a procedure

ARPN Journal of Engineering and Applied Sciences

to recognize and separate the acquired signals corresponding to a single rotational speed has been found. In order to do this, the first derivative of the rotational speed of the test bench is calculated: when the variation of speed is almost zero, the brake is working at constant speed; during the passage from one speed to the other, the first derivative has a non-zero value (Figure-3).

Because of the nature of the experimental analysis and because of the typical slightly unstable signal of some of the probes used in the test bench (in particular, the lambda probe and the load cells), the raw signals were processed in order to remove the high frequency variations of the signals, not corresponding to real physical variations of the measured quantities (filtering). For this reason, a 100-values moving average was applied to all the raw data acquired by the data acquisition system (Figure-4).

Once the data are selected and filtered, it is necessary to extract a single value of the required physical quantity corresponding to a specific rotational speed. For this reason, the values of the filtered data corresponding to fixed rotational speeds were averaged to get single values.

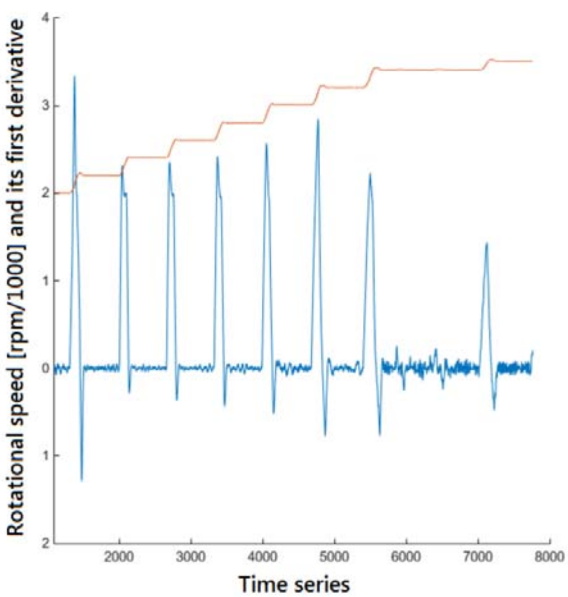

Figure-3. Rotational speed measurement (red curve) and its first derivative (blue curve) for a small scale Otto engine designed for agricultural purposes.

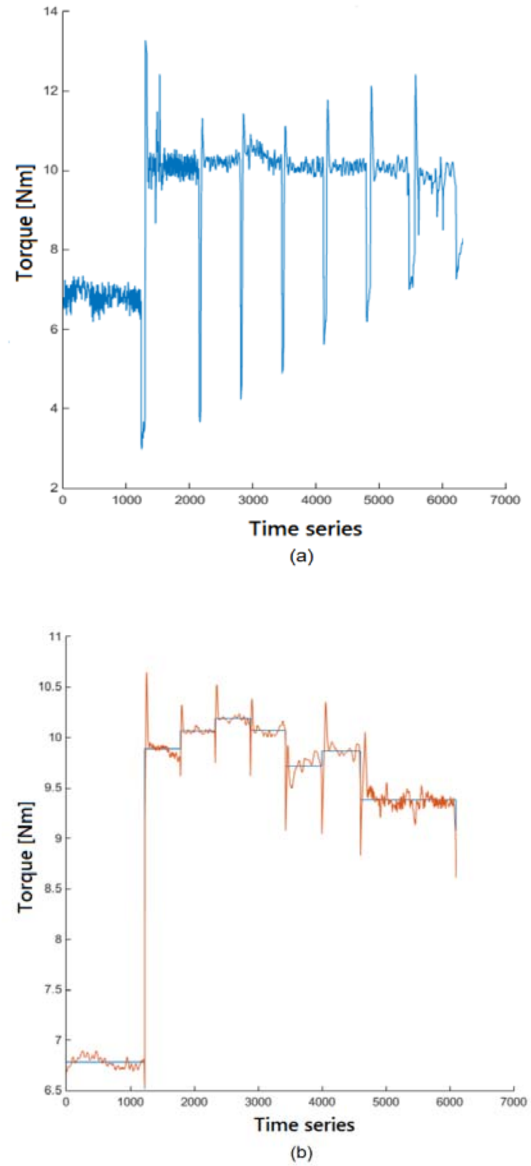

Figure-4. Engine torque before (a) and after (b) the filtering procedure; in this latter figure it is also possible to observe the average values of torque (superimposed in blue) as extracted from the graph.

The calculation of the fuel flow rate has been performed by using a specific procedure, different from the procedure described above, applied to all the other acquired data. After the filtering of the data coming from the load cell of the tank, operated by using a moving average, a linear least-square interpolation was applied to the temporal trend of the tank weight within each time interval corresponding to a constant rotational speed: the angular coefficients of the interpolation lines correspond to the fuel flow rates consumed by the engine at those speeds (Figure-5).

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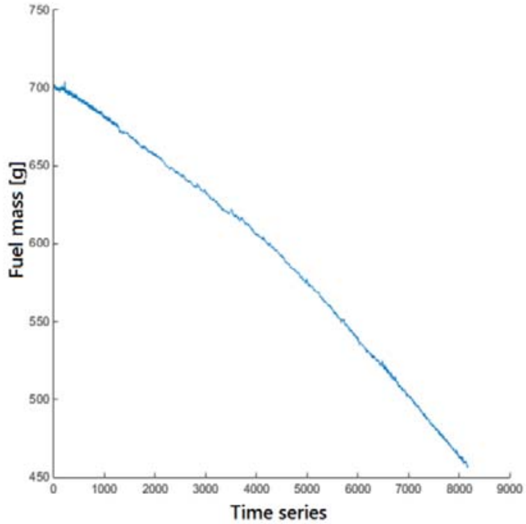
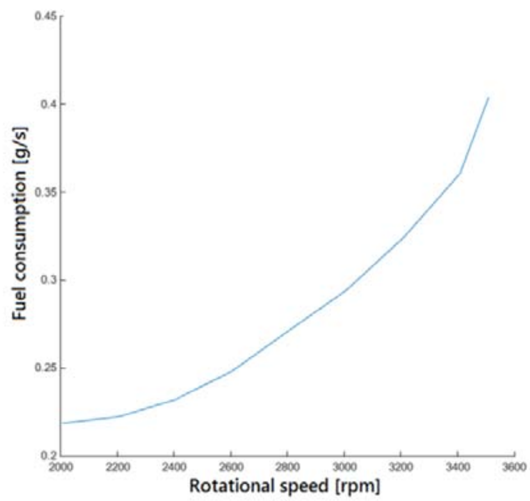


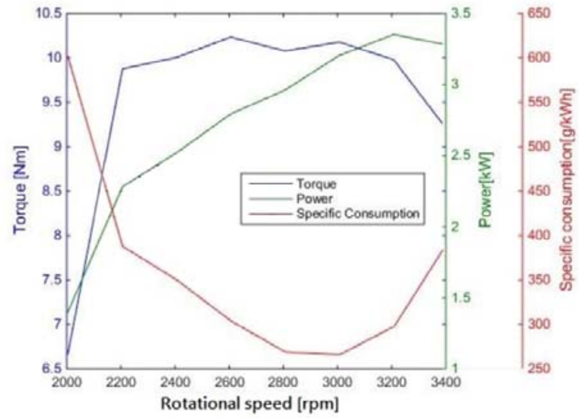
(a)



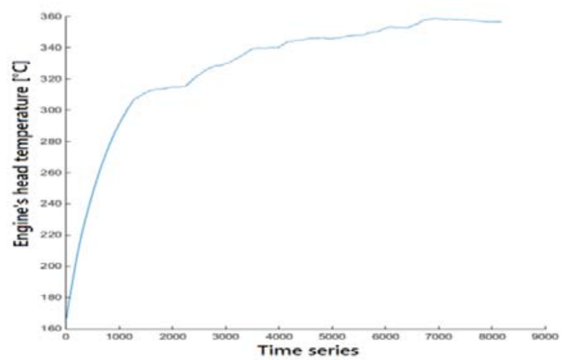
(b)

Figure-5. Fuel tank weight (a) and corresponding fuel consumption (b) as a function of the engine rotational speed (result of the interpolations described in the text).

Finally, by combining the results achieved with the aforementioned procedure using Matlab, it is possible to obtain a series of interesting graphs that describe the engine performance over its operative range (Figure-6): power, brake specific fuel consumption, mean effective pressure, mass flow of air, exhaust mass flow, mechanical efficiency, available thermal power at the exhaust, etc.



(a)



(b)

Figure-6. Characteristic performance curves of an engine as a function of the rotational speed (a) and trend of the engine head temperature during the test (b).

CONCLUSIONS AND FUTURE WORK

This work reports the test bench set-ups used for the evaluation of the performance of internal combustion engines. The probes that are embedded in the system are described here and their working principle is also reported. Regardless of the typology of acquired data, through the use of a series of calculation procedures written in Matlab language, it is possible to separate, filter and analyse the data coming from the described probes. The procedure has proven to be reliable and robust and allows obtaining also a series of additional parameters describing the engine performance.

The described testing procedure allows investigating both a single parameter's value, and also the whole operating performance of an engine. The use of this smart application allows investigating the entire acquisitions with reduced post processing time.

This test stand with the described post processing procedure will be used in the future works of the authors to evaluate the performance of traditional and alternative-fuelled ICEs for both agricultural and co-generative applications.

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