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Vibration analysis to estimate turbocharger speed fluctuation in diesel engines

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Abstract

The optimum management of the engine system has a crucial role in order to achieve high efficiency and reduced pollutant emissions. Advanced methods have been proposed, in which several types of sensors are used to directly/indirectly sense the combustion and to provide a feedback signal to optimize the engine management.

In turbocharged engines, it has been demonstrated that a relationship exists between the rotational speed of the turbocharger and the thermo-fluid dynamic condition of the gases at the exhaust valve opening. Such a relation allows to establish a link between the engine operating conditions in terms of speed, load and injection settings and the turbocharger speed.

A research activity was performed aimed at developing a methodology in which the signal from an accelerometer mounted on the compressor housing was used to extract information about the turbocharger speed value. The activity was organized in two subsequent steps, each one focused on one specific objective:

- estimation of the mean turbocharger rotational speed
- evaluation of the turbocharger speed fluctuations.

Tests were performed on a small displacement two-cylinder diesel engine mainly used in urban vehicles that was equipped with a turbocharger. The results obtained during the first step of activity demonstrated the opportunity of further investigations in order to compute the turbocharger speed fluctuation from the accelerometer signal processing. This paper is devoted to present the results of the second step of the research activity, with the final aim of realizing a non intrusive control of combustion process, in which the variation of combustion development as regards nominal condition is detected via the estimation of the turbocharger speed.

Keywords: Diesel engine; turbocharger; accelerometer; engine vibration;

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1. Introduction

Growing concern on pollutant emissions in atmosphere and demanding legislation on exhaust emissions from internal combustion engines have led the research activities to focus on the development of monitoring and controlling algorithms able to ensure the optimal management of the engine system in its real operating condition.

Different approaches have been proposed to deal with the continuous monitoring of the engine parameters in order to guarantee the combustion effectiveness in terms of performance/emissions and to maintain the nominal operating conditions in spite of variation of fuel properties, engine aging and degradation of components.

Many research works have demonstrated that in turbocharged engines, a relationship exists between the rotational speed of the turbocharger and the thermo-fluid dynamic condition of the gases at the exhaust valve opening.

[1] presents a numerical model to predict the exhaust pressure pulses from instantaneous turbocharger speed measurements. Vichi et al. [2] performed a numerical investigation on the turbocharger behavior as consequence of a variation of the engine operating condition; the authors confirmed that a direct link exists between the average turbocharger speed and the engine torque. [3] shows the results of an investigation on the effect of a variation of the injection characteristics on the instantaneous turbocharger speed.

The relation between engine operative condition and turbocharger behaviour allows to establish a link between the engine operating conditions in terms of speed, load and injection settings and the turbocharger speed.

Advanced methods have been presented to monitor the turbocharger condition via several types of sensors in which via direct/indirect measurements.

Turbocharger seed sensors may be installed in a hole obtained in the compressor housing, with a small gap between the probe and the compressor wheel. Great potential is offered by the employment of non-direct measurements, such as engine noise emissions and vibration, due to the advantages in terms of installation constraints, cost, durability and reliability.

Acoustic emission associated with the blade passage was used by [4] to estimate the turbocharger speed in order to improve the engine output torque under full load conditions. [5] presents the results of an investigation in which sound measurements are used for the diagnosis of turbocharger operational instabilities. A vibration analysis was performed by Crescenzo et al. [6]; a standard knock sensor compatible with on-board application was used with the aim of obtaining an estimation of the turbocharger speed. [7] is devoted to present a methodology for determining the instantaneous turbocharger rotational speed through the vibration of the turbocharger compressor. [8] proposes a method to track the fundamental frequency of a small turbocharger from vibration measurements.

Research activities were performed by the authors aimed at developing a methodology in which the signal from an accelerometer mounted on the compressor housing is used to extract information about the turbocharger speed value. Preliminary tests were devoted to select the optimal position of the sensor, by comparing the mean turbocharger rotational speed via a passive eddy current sensor (mounted on the compressor housing) to the estimation via the compressor vibration measurement [9]. The activity was then organized in subsequent steps, each one focused on one specific objective:

- estimation of the mean turbocharger rotational speed
- evaluation of the turbocharger speed fluctuations.

Experimentation was performed on a small displacement two-cylinder diesel engine mainly used in urban vehicles that was equipped with a turbocharger. The results obtained during the first step of activity demonstrated the opportunity of further investigations in order to compute the turbocharger speed fluctuation from the accelerometer signal processing [9]. This paper is devoted to present the results of the second step of the research activity; turbocharger speed fluctuations have been evaluated via the accelerometer signal acquired during tests in which different values of speed and load were imposed on the engine. The final aim of the research is to set up a non intrusive control of combustion process, in which the variation of combustion development as regards nominal condition is detected via the estimation of the turbocharger speed.

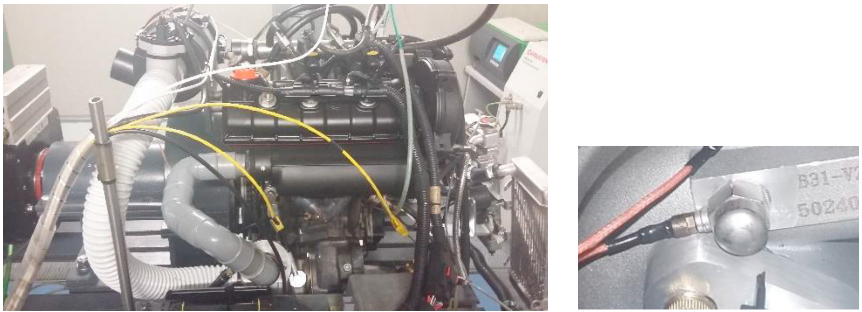
2. Engine test rig and experimental conditions

The experimentation was performed on a water-cooled two cylinder, common-rail diesel engine (LWD 442CRS, manufactured by KOHLER), whose characteristics are summarized in Table 1. It is a light and compact engine that has a leading role in micro-cars in urban areas. The engine is manufactured in naturally aspirated configuration; its intake and exhaust systems were modified in order to equip the engine with a turbocharger (IHI RMB31); the engine geometrical compression ratio was not modified [10].

Table 1. LDW442CRS engine specifications.

cylinders	2
displaced volume	440 cc
stroke	60.6 mm
compression ratio	20:1
maximum power	8.7 kW @4400 rpm
maximum torque	21 Nm @2000 rpm
injection system	common rail

The engine was installed in the test bed of the Engineering Department at Roma Tre University. It was connected to an asynchronous motor (Siemens 1PH7, nominal torque 360 Nm, power 70 kW) and was instrumented in order to fully characterize the engine operative conditions (Figure 1 shows the complete engine setup).



a

b

Fig. 1. (a) engine test bench; (b) accelerometer on the compressor housing.

The engine instrumentation includes the torque sensor HBM T12 (it is a strain gauge transducer with an optical encoder), the angular sensor for monitoring the engine speed AVL 364C. AVL Fuel Balance 733 was used for fuel consumption measurement. An accelerometer (Endevco 7240C) was used for vibration measurements: it is a mono-axial piezoelectric transducer whose sensitivity is 3 pC/g and resonance frequency 90 kHz. Its signal was conditioned via B&K Nexus device. The accelerometer was mounted with a threaded pin on the compressor housing. Aimed at obtaining a measurement of the turbocharger rotational speed, a passive eddy current sensor (Jaquet Hermes 5.1 DSE0805.01) was installed into the compressor cover, with a small gap between the probe and the compressor wheel. The sensor detects passing blades and generates two output signals: an analog signal proportional to the turbocharger rotational speed and a digital square wave signal (0-5 Volt) characterized by a rising transition in correspondence of a compressor rotation. The analog signal was used as a turbocharger reference speed mean value. The digital signal was used to investigate the speed fluctuations due to pulsating flows.

Additional instruments were installed to measure the in-cylinder pressure (piezoelectric probe AVL GU13P), the instantaneous pressure along the intake (piezoresistive transducers Kistler 4007BS5F) and exhaust systems (piezoelectric water cooled transducers AVL QC43D).

National Instruments data acquisition devices were used to simultaneously acquire all signals; a custom program was developed by the authors to manage the data monitoring and acquisition [11]. The sampling frequency was varied based on the engine speed value, thus to ensure a fixed crank angle resolution of all signals.

Before starting the experiments, the engine was warmed up until it had reached nominally stationary conditions. For all test cases, the inlet air temperature and humidity were about 23°C and 45%, respectively. The engine was tested in several steady-state operating points. In particular, measurements were taken at engine speeds from 3600 to 4400 rpm with a step of 400 rpm, and at three different loads corresponding to 60, 80 and 100% of the maximum torque output. The measuring range was selected based on the results of a previous experimentation [12] taking into account the aim of guaranteeing a wide variation of turbine speed values able to test the developed methodology.

During tests, ECU managed the injection strategy, thus to set a two-pulse injection mode for all engine operation range. During pre-injection, a fixed amount of 1 mm^3/str of fuel was delivered. Main injection was set in order to guarantee the imposed value of load.

For each tested engine operating condition, 25 engine cycles were acquired; an algorithm was developed to elaborate the data in order to compute the average signals thus to attenuate the engine cyclic irregularities.

3. Results

Based on the results provided by a preliminary previous experimentation, the optimal position for the accelerometer on the compressor housing was established. It allows to obtain a reliable estimation of the mean velocity of the turbocharger as demonstrated by the computation of the errors between the direct measurement provided by the passive current sensor and the computed value via the accelerometer signal processing [9].

The first part of this section is devoted to present data related to the crank angle evolution of the acquired signal; some results related to the computation of the mean turbocharger speed during steady-state and transient tests are shown.

In the second part, some representative results related to the instantaneous turbocharger velocity are presented.

Figure 2 shows the pressure trace in one of the cylinders overlapped to the pressure acquired in the intake manifold (the transducer was installed in one of the short duct connecting the plenum with one cylinder) and the exhaust system (the transducer was installed just upstream of the turbine, close to the two-branch junction connecting the cylinders with the exhaust). These pressure traces characterize the engine behavior: the operative point of the turbocharger depends on the exhaust pressure upstream of the turbine inlet that in turn is related to the combustion process and the injection setting. The compressor behavior is linked to the pressure in the intake manifold that affects the air trapped into the cylinders.

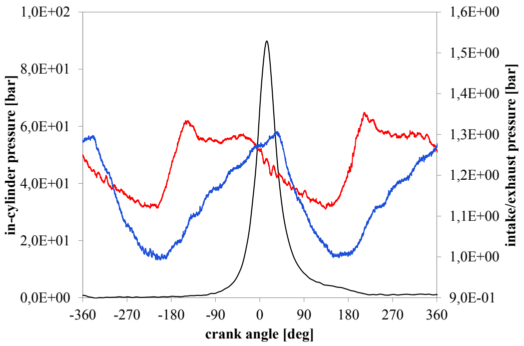


Fig. 2. In cylinder pressure ——, intake pressure ——, exhaust pressure —— at 4000 rpm - 100%.

Figures 3 and 4 show the effect of the operative condition of the engine on the compressor housing vibration; in Figure 3, the comparison between the accelerometer traces related to a variation of the engine speed (100% load) is presented. The plot of Figure 4 shows the traces related to a variation of the load condition imposed on the engine (4400 rpm). In both plots, the exhaust pressure signals are depicted to highlight the exhaust condition at the turbine inlet.

The exhaust valve opens at 58 crank angle degrees BBDC, a compression pressure perturbation propagates towards the turbine and it is responsible for its acceleration. The acquired signals demonstrate the sensitivity of the accelerometers mounted on the compressor housing to the unsteady phenomena in the exhaust.

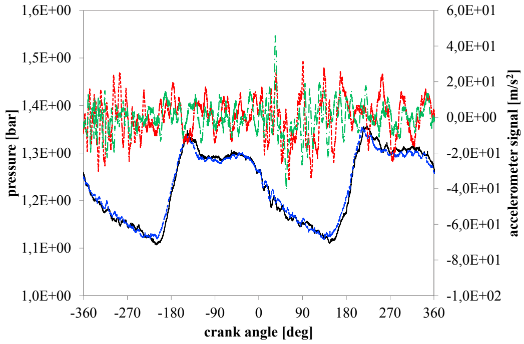


Fig. 3. Exhaust pressure at 100% load: 4400 rpm ——, 4000 rpm – – ; accelerometer signal at 100% load: 4400 rpm ----, 4000 rpm — · · .

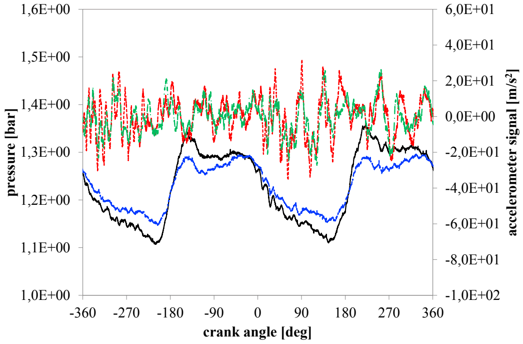


Fig. 4. Exhaust pressure at 4400 rpm: 100% load ——, 60% load – – ·; accelerometer signal at 4400 rpm: 100% load ----, 60% load — · .

Time-frequency processing of the acquired vibration signals was performed and spectrograms were computed. The input signal was divided in sections by using Hamming windows with 50% of overlap between contiguous segments of data. The Short-Time Fourier Transform of each segment was thus computed. Figure 5 shows the spectrogram obtained with the signal related to the engine condition 4000 rpm, full load. At this engine operative condition, the turbocharger velocity measured by the passive eddy current sensor is 122700 rpm, that corresponds to 2045 Hz as frequency and at 16360 Hz as blade frequency, according to:

$$f_b = n * s/60 \quad [\mathrm{Hz}]$$

where n is the number of compressor blades, s is the shaft speed.

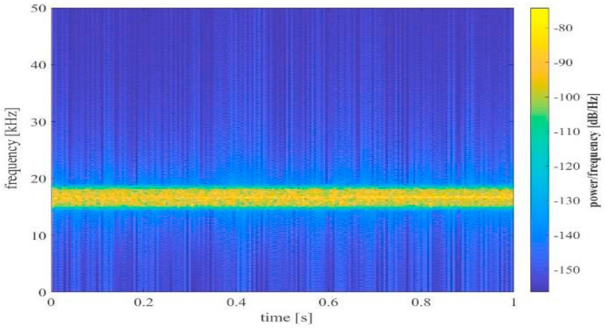


Fig. 5. Accelerometer spectrogram at 4000 rpm - 100% load.

The yellow line corresponding to the compressor blade frequency is evident in the plot. Spectrograms were computed for the signals in the complete engine operative field and for each engine condition, the blade frequency was evaluated. In order to estimate the accuracy of the vibration based estimations, the signal from the eddy current sensor mounted on the compressor housing was used as reference value to compute the relative error. Figure 6 presents the obtained values. The diagram highlights the high accuracy of the estimations for all the investigated engine conditions, thus demonstrating the ability of the accelerometer to accurately estimate the mean value of the turbocharger speed during steady-stare tests.

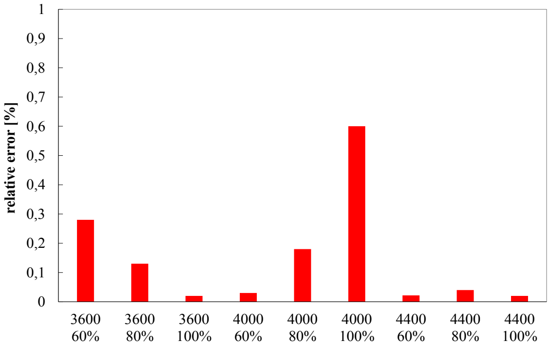


Fig. 6. Relative errors of the blade frequency estimations via the accelerometer.

In order to evaluate the ability of the methodology to be applied to the data acquired during engine unsteady operation, some transient tests have been performed. Load condition was maintained at a constant value, while engine speed was varied from 3600 to 4400 rpm (test 1); engine speed was maintained at a constant value (4000 rpm) and a variation of load from 50% to 100% was imposed (test 2). Following figures show the obtained results; each figure is divided in two plots: the one on the top presents the spectrogram of the vibration signal, the yellow line corresponds to the evolution of the compressor blade frequency; the one on the bottom shows the reference signal obtained by the intrusive transducer.

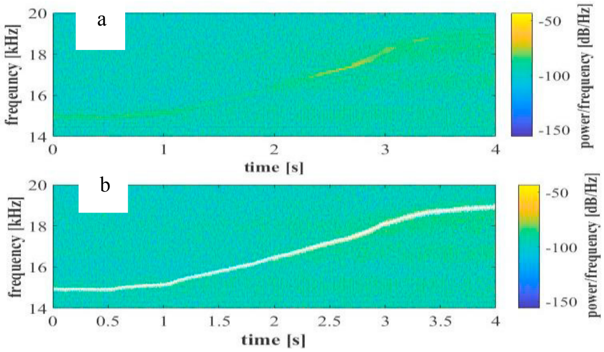


Fig. 7. (a) accelerometer spectrogram; (b) reference signal by the eddy current sensor (test 1)

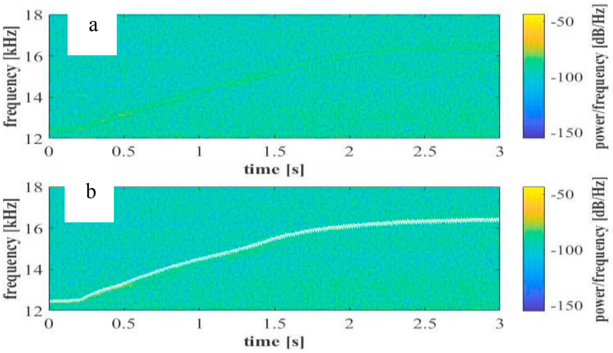


Fig. 8. (a) accelerometer spectrogram; (b) reference signal by the eddy current sensor (test 2)

As stated in the introduction, the aim of this work was to estimate not only the mean speed of the turbocharger but also its fluctuations, with the final objective of using such estimation as feedback signal to optimize the engine operation. For this reason, the acquired data have been further processed to obtain information about the instantaneous value of the turbocharger speed caused by the pulsating flow in the exhaust. In the processing, the signals have been filtered by using a frequency band of amplitude ±0.6% the value corresponding to the mean value of the turbocharger velocity (such a window amplitude was selected since it proved to be effective for all tested conditions).

The obtained data allowed to evaluate the amplitude and the pulsation of the fluctuating component of the turbocharger speed. Figures 9 and 10 present the data related to a fixed value of engine speed (4000 rpm) and two different load conditions (100% and 60%, respectively). In the plots, the comparison between the estimated instantaneous turbocharger oscillation via the accelerometer trace and the reference signal provided by the eddy current sensor is shown (the digital data acquired from the eddy current sensor were processed in matlab environment to obtain the instantaneous component of the velocity). The traces highlight that the signal from the accelerometer is not affected by cylinder-by-cylinder inhomogeneity; at this stage the objective of the methodology was to allow the detection of variations in turbocharger speed signal to perform a control of the engine cycle caused i.e. by different properties of the fuel.

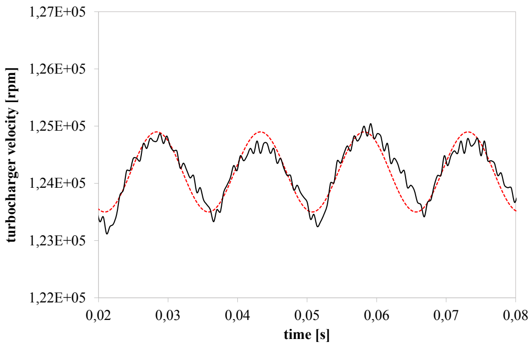


Fig. 9. Turbocharger speed velocity at 4000 rpm - 100% load via the eddy current sensor ——, the accelerometer - - - .

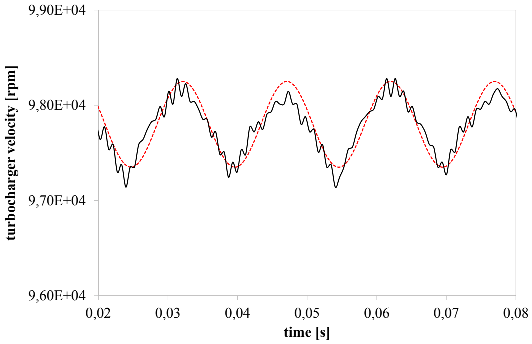


Fig. 10. Turbocharger speed velocity at 4000 rpm - 60% load via the eddy current sensor ——, the accelerometer - - - .

The relative errors of the estimation were computed in all tested engine operative conditions and are reported in the following plot. The values, always less than 0.1%, demonstrate the accuracy of the computations.

4. Concluding remarks

The paper presents a methodology in which the vibration from an accelerometer placed on the compressor housing of a turbocharged diesel engine is processed to estimate the turbocharger rotational speed in terms of its mean and instantaneous components.

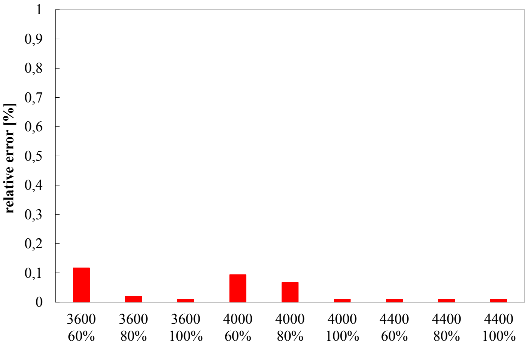


Fig. 11. Relative errors of the turbocharger speed fluctuation estimated via the accelerometer.

Experimentation was performed on a small displacement two-cylinder diesel engine mainly used in urban vehicles, that was equipped with a small turbocharger. The analysis of the acquired signals was divided in two subsequent steps. During the first one, the processing of the data was devoted to estimate the mean value of the turbocharger rotational speed. The obtained results demonstrated the opportunity of further investigations in order to compute the turbocharger speed fluctuation from the accelerometer signal processing. During the second step of the activity, starting from the estimated mean velocity, the turbocharger speed fluctuations were computed. The calculation of the errors between the direct measurements provided by an eddy current sensor mounted on the compressor and the estimated values proved the accuracy of the methodology in all tested engine operative conditions. This result suggests further activity that will be devoted to apply the methodology to other engine architectures and to implement an algorithm in which the accelerometer signal is used as feedback for the real-time control of the engine parameters to ensure a proper combustion in terms of efficiency and pollutant emissions.

References

[1] Macián, V., Luján, J. M., Bermúdez, V., and Guardiola, C. (2004) "Exhaust pressure pulsation observation from turbocharger instantaneous speed measurement." *Measurement Science and Technology* 15.6 (2004):1185-1194.

[2] Vichi, G., Stiaccini, I., Bellissima, A., Minamino R., Ferrari, L., and Ferrara, G. (2014) "Numerical Investigation of the Relationship between Engine Performance and Turbocharger Speed of a Four Stroke Diesel Engine. " *SAE Technical Paper* 2014-32-0126.

[3] Vichi, G., Stiaccini, I., Becciani, M., Ferrara, G., Ferrari, L., Bellissima, L., and Minamino, R. (2015) "Detection of Cylinder-to-Cylinder Injection Variation in a Four-Stroke Diesel Engine by Monitoring the Turbocharger Speed." *SAE Technical Paper* 2015-32-0761.

[4] Cavina, N., De Cesare, M., Ravaioli, V., Ponti F., and Covassin, F. (2014) "Full Load Performance Optimization Based on Turbocharger Speed Evaluation via Acoustic Sensing." *ASME 2014 Internal Combustion Engine Division Fall Technical Conference Volume 2: Instrumentation, Controls, and Hybrids; Numerical Simulation; Engine Design and Mechanical Development*.

[5] Aretakis, N., Mathioudakis, K., Kefalakis, M., and Papailiou, K. (2004) "Turbocharger Unstable Operation Diagnosis Using Vibroacoustic Measurements." *Transactions of the ASME* 126 (2004): 840-847.

[6] Crescenzo, D., Olsson, V., Arco Sola, J., Wu, H., Cronhjort, A., Lycke, E., Leufven, O., and Stenlaas, O. (2016) "Turbocharger Speed Estimation via Vibration Analysis." *SAE Technical Paper* 2016-01-0632.

[7] Ponti, F., Ravaioli, V., and De Cesare M. (2014) "Estimation Methodology for Automotive Turbochargers Speed Fluctuations due to Pulsating Flows". *J. Eng. Gas Turbines Power* 137.12 (2014).

[8] Pedersen, T., Herlufsen, H., and Hansen, H. (2005) "Order Tracking in Vibro-acoustic Measurements: A Novel Approach Eliminating the Tacho Probe." *SAE Technical Paper* 2005-01-2266.

[9] Chiatti, G., Chiavola, O., Conti, E., and Recco, E. (2017) "Automotive turbocharger speed estimation via vibration analysis for combustion optimization." *Int. J. Mech. Eng. and Technology* 8.10 (2017): 153-163.

[10] Chiatti, G., Chiavola, O., and Recco, E. (2017) "Combustion Monitoring trough Vibrational Data in a Turbocharged City Car Engine." *Int. J. Mech. Eng. and Technology* 8.3 (2017): 197-208.

[11] Chiatti, G., Chiavola, O., and Recco, E. (2014) "Analysis of the Relationship between Noise Emission and In-Cylinder Pressure in a Small Displacement Diesel Engine." *SAE Technical Paper* 2014-01-1364.

[12] Chiatti, G., Chiavola, O., and Recco, E. (2017) "Turbocharging a small displacement diesel engine for urban vehicles." *Int. J. Mech. Eng. and Technology* 8.7 (2017): 1916-1928.