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Turbocharger speed estimation via vibration measurements for combustion sensing

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Abstract

Monitoring of engine operating condition is essential to comply with severe limitations of harmful exhaust emissions and fuel consumption. Several strategies have been proposed, in which different types of sensors are used for the direct/indirect combustion sensing and to provide a feedback signal to optimize the process.
It has been demonstrated that in a turbocharged engine 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.
This work presents a methodology devoted to extract from an accelerometer signal, the mean turbocharger rotational speed 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.

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Keywords: Diesel engine, turbocharger, accelerometer, engine vibration

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1. Introduction

Over the next years, target emissions from ICE will become tighter around the world; reducing harmful exhaust emissions coming from ICE is achievable only via optimized combustion engines. The trade-off between fuel consumption and NOx emissions and between NOx and particulate emissions is becoming more and more critical. In this scenario, the optimum management of the engine system has a crucial role in order to achieve high engine efficiency and reduced pollutant emissions. Advanced methods have been proposed in which the engine management

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is performed by means of several types of sensors able to directly/indirectly sense the combustion and to provide a feedback signal to optimize the process.

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.

Vichi et al. [1] performed numerical and experimental activity with the aim of detecting a variation in the injection characteristics as regards the nominal operating condition via the instantaneous turbocharger speed monitoring.

Methodologies based on acoustic and vibration sensors have been developed to extract information about the turbocharger operating conditions from non-intrusive measurements.

Aretakis et al. [2] performed an experimental activity in which accelerometers mounted on the compressor casing and microphones placed in the vicinity of it are used to establish whether the compressor operates in the stable part of its performance characteristic or in the presence of unstable operation phenomena.

Cavina et al. [3] presented a method to evaluate the turbocharger rotational speed via an acoustic sensor with the aim of developing turbocharger control strategies.

Ponti et al. [4] developed a methodology for determining the instantaneous turbocharger rotational speed through the processing of an accelerometer signal mounted on the turbocharger compressor. Crescenzo et al. [5] presented a methodology designed to obtain the turbocharger rotational speed via vibration analysis in a heavy duty diesel engine.

Pederson et al. [6] proposed a method to track the fundamental frequency of a small turbocharger from the measured vibration signal.

Previous works of the authors [7, 8] have been devoted to the development of a methodology for combustion sensing via the analysis of the signal from an accelerometer mounted on one stud of the engine block. A relationship was established between the combustion progress (in terms of indicators such as SOC and MFB50) and the accelerometer trace, whose processing allowed to extract the vibration components mainly related to the combustion event.

In this work, the same sensor is used to monitor the turbocharger vibration with the aim of extracting from the accelerometer signal, the mean turbocharger rotational speed with the final objective 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.

A small two-cylinder diesel engine mainly used in urban vehicles was equipped with a turbocharger and an accelerometer was mounted on the compressor housing. Experimental tests were devoted to compare the mean turbocharger rotational speed evaluated by means of a passive eddy current sensor to the value obtained by processing the compressor vibration signal. The effect of a variation of combustion development on the turbocharger speed was analyzed in order to investigate the possible use of the accelerometer output as feedback signal for improving the engine control functions.

Nomenclature

BBDC	before bottom dead centre
BTDC	before top dead centre
MFB50	crank angle degree for 50% of mass fraction burned
SOC	start of combustion
SOI_{main}	start of main injection

2. Experimental set up

The investigation was carried out on a Lombardini LWD 442 CRS engine. The engine is manufactured in naturally aspired configuration. Its intake and exhaust systems were modified in order to equip the engine with the IHI RMB31 turbocharger. The turbocharger consists of a compressor wheel with 8 blades and a turbine wheel with 8 blades. The engine geometrical compression ratio was not modified. The main engine specifications are listed in Table 1.

The engine is equipped with an electronically controlled common rail injection system. The injection strategy consisted of two injections per cycle, pre and main.

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

In order to monitor the combustion development, a glow plug adaptor was used and AVL GH13P piezoelectric pressure transducer was installed. It has a measuring range that goes from 0 to 250 bar, and it has a sensitivity of 15,4 pC/bar. Pressure transducers were used in different positions along the intake (piezoresistive transducers Kistler BS5F) and the exhaust (piezoelectric transducers AVL QC43D) systems. Temperature of exhaust gas was measured by K type thermocouples.

Accelerometers Endevco 7240C were used to investigate the turbocharger vibration. They are mono-axial piezoelectric transducers with sensitivity equal to 3 pC/g; the resonance frequency is 90 kHz.

Accelerometers were firmly mounted on the compressor housing by means of a threaded pin. Two different mounting positions were tested in order to investigate the vibration of the compressor housing in radial and axial directions. Another accelerometer was mounted on one stud of the engine block (the sensors positions are shown in Figure 2) and was used as reference signal for combustion sensing, according to previous research activity by the authors [7, 8]. The vibration signals were conditioned by means of the B&K Nexus device (amplifier and low pass filter at 22.4 kHz).

Fig. 1. Engine test bench.

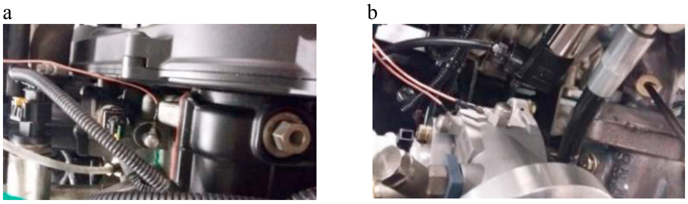

Fig. 2. (a) accelerometer installation on the engine block; (b) accelerometers mounting positions on the compressor.

Aimed at obtaining a measurement of the turbocharger rotational speed, a passive eddy current sensor (Jaquet Hermes 5.1 DSE0805.01) was installed in a hole obtained in the compressor housing, with a small gap between the probe and the compressor wheel. The sensor outputs are an analog signal that is proportional to the turbocharger rotational speed and a digital 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.

An optical shaft encoder (AVL364C) was used for engine speed measurements.

All signals were acquired by NI boards type 6110 and 6533 by means of a custom software developed by the authors in LabVIEW environment [9].

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. According to [6], the acquisition time was established in order to guarantee a resolution in frequency of 1 Hz.

2. Results and discussion

The experimental activity was organized in two phases; each one was aimed at:

- implementing a turbocharger speed evaluation methodology based on the accelerometer signal processing;
- changing the injection settings in order to modify the combustion development and then the turbocharger speed.

Figure 1 presents the crank angle evolution of the pressure in one of the cylinders, 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 signals characterize the engine behavior: the turbocharger operative point is linked to the exhaust pressure upstream of the turbine that in turn depends on 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.

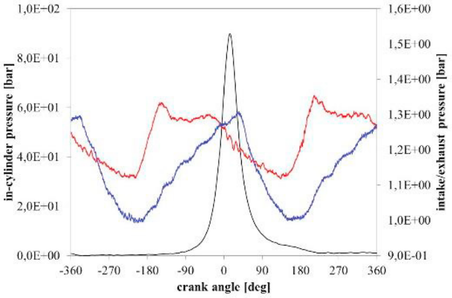

Fig. 3. In cylinder pressure ▬, intake pressure ▬, exhaust pressure ▬ at 4000 rpm - 100%.

Aimed at correlating the engine block vibration signal with the combustion event, some tests have been performed under fired and motored conditions. The comparison between signals acquired during these tests allowed to highlight in the accelerometer trace the combustion related components. Figure 4 shows the engine block vibration signal related to full load and motored conditions at 4000 rpm as engine speed. In order to point out the combustion event, the difference between in-cylinder pressure obtained under fired and motored conditions is also plotted.

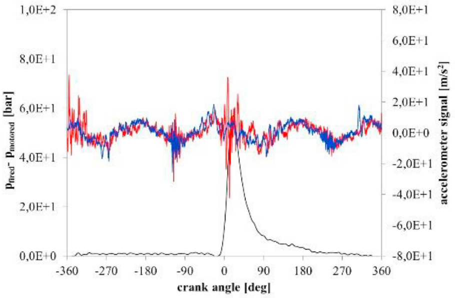

Fig. 4. Difference between in cylinder pressure at 4000 rpm during fired (100% load) and motored tests ▬, accelerometer signal at 100% load ▬ , accelerometer signal in motored condition ▬.

The high frequency components caused by the rapid pressure increase due to the initial phases of combustion process are highlighted. The plot shows that the accelerometer sensor is affected by the combustion event in both cylinders.

Following figures present the data acquired from the accelerometer transducers placed on the compressor housing. In Figure 5, the accelerometer signals in radial direction and in axial direction are displayed (engine condition 4000 rpm – full load). The traces are overlapped to the crank angle evolution of the pressure in the intake and exhaust systems, since the conditions in these systems represent the excitation forces for the turbocharger.

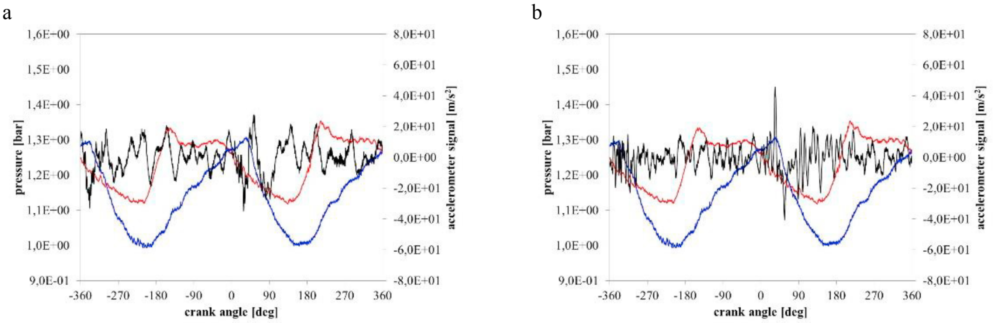

Fig. 5. (a) intake pressure —, exhaust pressure —, accelerometer in radial direction on the compressor housing —; (b) intake pressure —, exhaust pressure —, accelerometer in axial direction on the compressor housing — (4000 rpm - 100% load).

The trends highlight the effect of pressure development in the intake and exhaust systems on the compressor vibration traces. Both positions present high frequency oscillations characterized by significant amplitude in correspondence of the intake valve opening (at 10 crank angle degrees BTDC); the pressure wave propagates along the intake manifold, reaches the compressor and let the turbine begin to accelerate. At the exhaust valve opening (at 58 crank angle degrees BBDC), the compression pressure perturbation propagating towards the turbine is responsible for its acceleration. The acquired signals demonstrate the sensitivity of the accelerometers mounted on the compressor housing to such unsteady phenomena.

Figures 6 and 7 show the effect of the variation of the engine speed and load condition on the radial and axial vibrations of the compressor (the reference signals are those related to the condition 4000 rpm – 100% load).

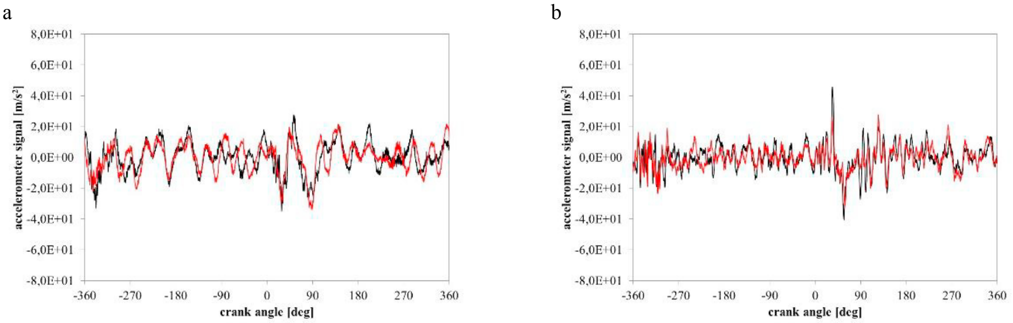

Fig. 6.(a) accelerometer in radial direction on the compressor housing at 100% load — and at 80% load — (4000 rpm); (b) accelerometer in axial direction on the compressor housing at 100% load — and at 80% load — (4000 rpm).

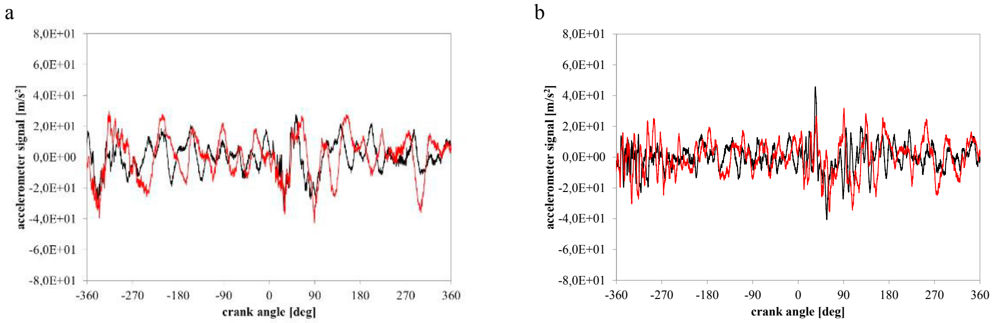

Fig. 7.(a) accelerometer in radial direction on the compressor housing at 4000 rpm — and at 4400 rpm — (100% load); (b) accelerometer in axial direction on the compressor housing at 4000 rpm — and at 4400 rpm — (100% load).

Following Figures 8, 9 and 10 present the spectral content of the compressor housing vibration in radial and axial directions.

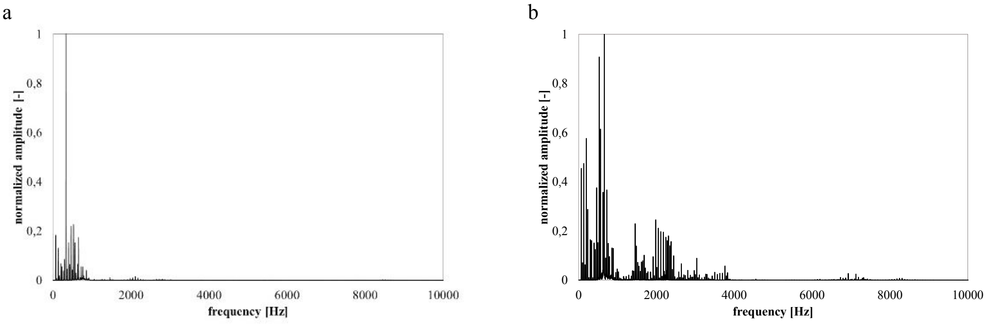

Fig. 8. (a) radially mounted accelerometer spectrum; (b)axially mounted accelerometer spectrum (4000 - 100%).

Since the engine was running in stationary conditions, it was characterized by a periodic behavior; then in all the spectra of the engine working variables the firing frequency and its harmonics appear. Both spectra shows a higher frequency content in the frequency range lower than 1 kHz.

In addition, the axially mounted accelerometer signal exhibits high energy peaks in the frequency range around 2 kHz. According to [5], the frequency corresponding to the turbocharger rotational speed and the blade passing frequency should be visible. It is defined as the product between the rotational speed (expressed in terms of revolutions per second) and the number of compressor blades. The turbocharger rotational speed at 4000 rpm, full load condition measured by the passive eddy current sensor was 122700 rpm, that corresponds to 2045 Hz. Such a frequency is evident in the axially mounted accelerometer, while it is characterized by low energy content in the spectrum of the radially mounted accelerometer. The same features were observed in the signals acquired for the others tested engine operative conditions and for this reason, the accelerometer axially mounted on the compressor housing was selected as the best mounting position.

The detection of the turbocharging rotational frequency from the accelerometer spectrum is very difficult through the analysis of the complete spectrum and then it was decided to apply a proper band-pass filter to the signal, that allows to isolate the frequency band in which such a line is located, according to [4]. The choice of the filter was performed by means of the reference frequency given by the passive eddy current sensor. The bandwidth was defined by setting a margin of ±10% of the estimated frequency [5].

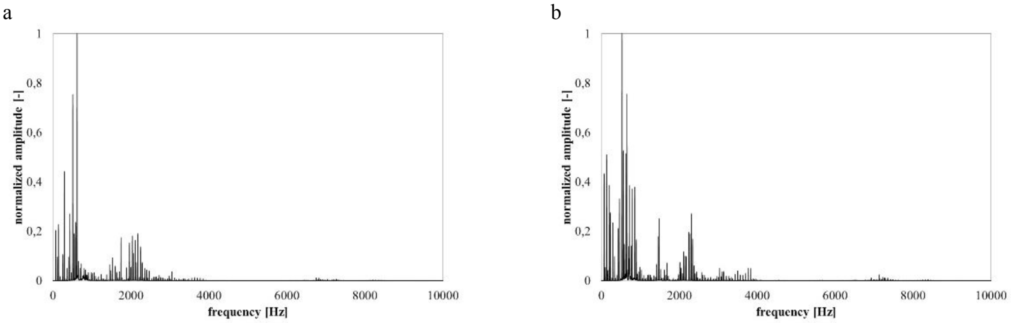

Fig. 9. (a) axially mounted accelerometer spectrum at 4400 rpm – 100% load; (b) axially mounted accelerometer spectrum at 4000 rpm - 80% load.

Figure 10 shows the frequency spectrum obtained by applying the band-pass filter to the acquired accelerometer signal; the frequency corresponding to the mean turbocharger rotational speed corresponds to the highest peak.

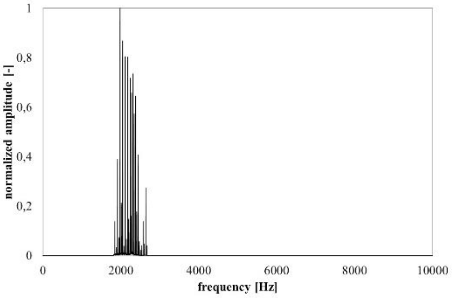

Fig. 10. Filtered axially mounted accelerometer spectrum (4000 rpm - 100%).

The analysis was performed for all tested engine conditions and the error characterizing the estimation of the turbocharger speed as regards the reference speed signal was computed. In Table 2, the relative errors of the estimations are reported.

Table 2. Relative errors of the estimations.

Engine speed [rpm]	60% load	80% load	100% load
3600	0,042	0,009	0,011
4000	0,008	0,037	0,041
4400	0,010	0,004	0,023

Aimed at using the accelerometer signal to detect a variation in the turbocharger rotational speed caused by a variation of the combustion process, the injection settings were modified (Table 3). A delay of SOI_{main} was imposed, without changing the amount of delivered fuel (test a); the injection timings and the total amount of injected fuel were maintained unchanged but a variation of the fuel delivered in the pre and main injections was imposed (test b). In Figure 11, the crank angle evolutions of axially mounted accelerometer acquired during tests a, test b are compared to that one obtained with standard injection setting.

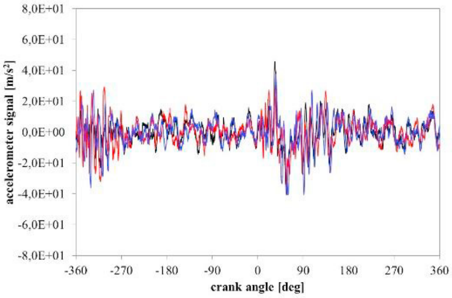

Fig. 11. Accelerometer in axial direction on the compressor housing at 4000 rpm – 100% load: standard injection —, test a —, test b —.

In order to isolate the frequency band in which the peak corresponding to the mean turbocharger speed was located, the vibration traces have been band-pass filtered by using the reference frequency given by the passive eddy current sensor in standard injection setting, with a margin of ±10%. In the last line of Table 3, the relative errors of the estimations for test a and b are shown.

The turbocharger rotational speed estimations evaluated by processing the accelerometer signals were affected by a relative error always less than 0,042.

Table 3. Injection setting and relative errors of the estimations.

	Standard injection	Test a	Test b
P_{rail}	805 bar	805 bar	805 bar
SOI_{pre}	27,7 cad BTDC	27,7 cad BTDC	27,7 cad BTDC
SOI_{main}	15,2 cad BTDC	10,2 cad BTDC	15,2 cad BTDC
Q_{pre}	1 mm^3/str	1 mm^3/str	2 mm^3/str
Q_{main}	14,4 mm^3/str	14,4 mm^3/str	13,4 mm^3/str
relative error	0,041	0,017	0,023

4. Concluding remarks

The work presents a methodology used to monitor the turbocharger vibration with the aim of extracting from the accelerometer signal the mean turbocharger rotational speed.

Tests were performed on a small displacement two-cylinder diesel engine mainly used in urban vehicles that was equipped with a turbocharger. Accelerometers were installed on the compressor housing; the frequency domain analysis of the signals allowed to select the axially mounted sensor as the best mounting position able to sense the turbocharger rotational speed.

Aimed at exploring the possible employment of the vibration as feedback signal for improving the engine control functions, a variation of the injection setting was imposed on the engine in order to modify the combustion development and then the turbocharger speed. The turbocharger rotational speed evaluated by means of a passive eddy current sensor was used a reference data to evaluate the error affecting the estimations of the turbocharger speed via the accelerometer spectral processing.

The results demonstrate the opportunity of further investigations in order to improve the quality of the reference signal and to reduce the error affecting the estimations by optimizing the acquisition process and the processing technique.

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