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Experimental Assessment of a Pressure Wave Charger for Motorcycle Engines

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Abstract

Charging a motorcycle engine is challenging, since requirements of lightness, system simplicity and engine responsiveness are key factors. This paper reports on a preliminary study on a pressure wave compressor, the "Impulse Drum Charger". Performances of a 4-stroke motorcycle engine with and without Drum Charger were compared at the test bench and a pressure analysis in the intake manifold was carried out as well. Results show that this system is able to effectively improve engine power (up to 1.4 kW at 9500 rpm WOT) without an ECU recalibration.

Keywords: SI engine; Motorcycle; Pressure Wave Charger; Impulse Drum Charger.

1. Introduction

Charging intake air of an internal combustion engine is a well-known technique, that allows to increase the density of the working medium before it enters the cylinder. Air compression can be used to increase power density and, depending on design and application, to improve the combustion process, in order to reduce exhaust pollutant emissions, noise emission or fuel consumption [1]. The medium temperature should not raise too much, in order not to adversely affect the high-pressure working cycle: in many applications a charge air cooler is used to decrease

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Nomenclature

CAD	Crank Angle Degree
BTDC	Before Top Dead Center
DOHC	Double OverHead Camshaft
ECU	Engine Control Unit
FLC	Full-Load Curve
IDC(s)	Impulse Drum Charger(s)
MON	Motor Octane Number
PFI	Port Fuel Injection
RON	Research Octane Number
SA	Spark Advance
SI	Spark Ignition
UEGO	Universal Exhaust Gas Oxygen
WOT	Wide Open Throttle

such temperature [2].

Depending on the charging principle, it is possible to distinguish many families of air chargers [1,3]. A first possibility, the supercharging, consists on a mechanical driving of the charger: roots blower, sliding vane, screw compressor, but also reciprocating and centrifugal compressor belong to this group. Another possibility is to use part of the exhaust gas enthalpy to drive the compressor: turbocharging is the most common solution, especially in automotive and heavy/light duty applications. Finally, it is possible to exploit the pressure waves propagating through intake or exhaust ducts after valve opening or closing to obtain an impulsive boost effect (e.g. the Comprex [4]).

Charging a motorbike engine is not easy, due to different kinds of difficulties as reported by Zinner *et al.* [5]. Many attempts were tried in the past, but nowadays only few models (e.g. Kawasaki H2) are equipped with superchargers. As a matter of fact, motorbikes tend to be constructively “simple” and low-weight, with few add-ons. The insertion of a charger should not complicate engine nesting inside the frame, and auxiliary elements like intercooler are disliked. Another key factor is power-to-weight ratio, which is high in motorbike applications: a turbocharger or supercharger insertion can adversely affect this feature. Usually, naturally aspirated engines are characterized by an overabundant max power for motorcycles: charging, in this case, can be attractive to improve low-end torque, something that can be particularly useful in city riding. In these conditions, rideability is of absolute importance: an air charger should guarantee a high responsiveness, and this factor often penalizes turbocharged solution [6], since turbo-lag can be a strong limit. Turbomatching (the coupling between engine and turbocharger [1]) is not easy: benefits could be limited only to a part of engine map. Finally, the cost of the charging system is not low: it could encumber too much on the total engine cost [3]. Just out of curiosity, when a motorbike engine is transferred to a 4-wheel vehicle, many of these limitations become less influent, and charging is possible and desirable, as found in Formula SAE application (Romani *et al.* [7], Wang *et al.* [8]).

Even if charging a motorcycle engine is not easy, as said, interesting solutions can be found. One of these, the Impulse Drum Charger (IDC), by *AlterEgo Hardware*, can be classified as a compressor that exploits exhaust pressure pulses. Externally, it is composed of two shells: inside the lower one there are two cavities, separated by an elastic membrane (Fig. 1). One cavity (the “hot side”) is in communication with the exhaust manifold through a dedicated duct, receiving pressure waves when the exhaust valves open. This pulse is able to deflect the membrane, forcing fresh air in the other cavity (the “cold side”) to exit the IDC with an overpressure (Fig. 2b) through a chamber in the upper shell towards the airbox. When the pulse is over, a bow-spring allows the membrane to return to its rest position: in this moment, thanks to this movement, external fresh air at atmospheric pressure is aspirated in the cold side (Fig. 2a) coming from another chamber, located in the upper shell too, connected to the external environment. Two sets of reed valves separate upper and lower shells, avoiding backflows (boosted air can only go towards the airbox). This behavior occurs once per engine cycle (i.e. 2 crankshaft revolutions). It must be remarked that exhaust gases and fresh air, separated by the elastic membrane, never mix together.

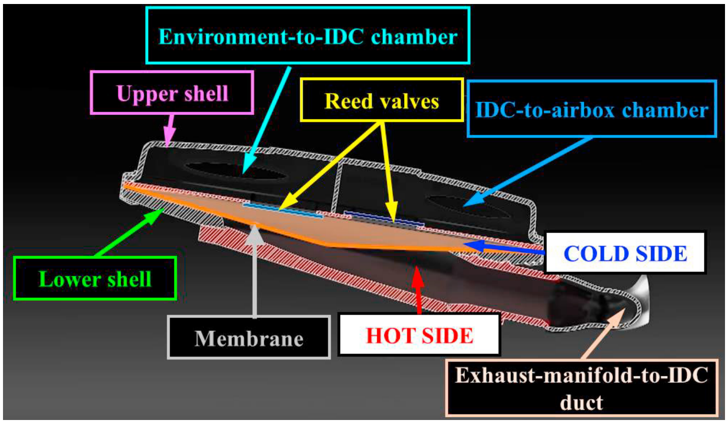

Fig. 1. Schematic of IDC (courtesy of *AlterEgo Hardware*).

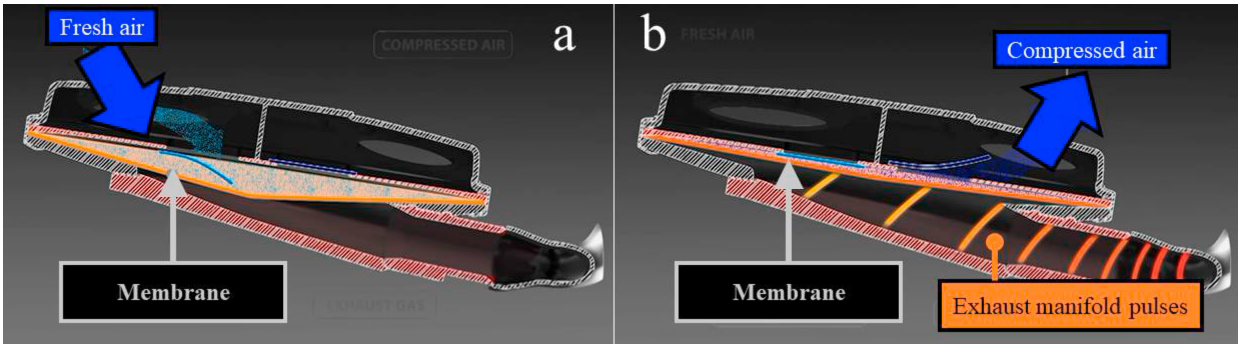

Fig. 2. IDC functioning principle (courtesy of *AlterEgo Hardware*): (a) fresh air suction in the cold side, caused by membrane returning to rest position, (b) air compressed and forced towards plenum, caused by membrane deflection when exhaust pulses arrive.

This work was focused on the first analysis of this new concept charger, in order to assess its behavior and performance. Besides the engine brake power evaluation, an analysis of intake pressure and a detection of possible knocking phenomena were carried out as well.

2. Experimental Setup

2.1. Original Engine

Test were carried out on a KTM RC390 4-stroke engine (year 2015). Table 1 lists the engine specifications.

Table 1. Engine specifications of the tested model (KTM RC390).

Parameters	Value/Description
Bore x Stroke (mm x mm)	89 x 60
Number of cylinders (-)	1
Displacement Volume (cm^3)	373
Compression Ratio (-)	12.6:1
Connecting-Rod Length (mm)	105
Valve System	DOHC 4 valves
Fuel system	PFI, Standard European market gasoline RON 95 MON 85

2.2. Drum Charger coupling and engine modifications

In the tested engine (displacement of 373 cm^3) two IDCs in parallel were necessary. In fact, the ratio between engine displacement and IDC volume is a key factor to obtain sufficient boost. It is necessary to modify both intake and exhaust engine ducts to properly couple IDCs with the engine (Fig. 3a). Concerning the intake, the airbox is modified in order to receive the airflow from the IDCs. Downstream, the remaining intake line parts (throttle valve, intake manifold, intake ports) are the same of original engine. The original exhaust line with one duct from the exhaust manifold to the muffler was also modified (Fig. 3b), adding in parallel two ducts which connect the manifold to the hot side of drum IDCs. Because of the modified layout, it was also necessary to replace the original muffler with a new one supplied by *Egb*.

It must be remarked that the presence of two IDCs makes the analysis much more critical. As a matter of fact, exhaust pipes to left and right IDCs cannot be identical, because of exhaust ducts nesting around the motorcycle frame. Inside the ducts, the measured gas temperatures resulted to be different because of 3-D effects related to exhaust geometry and external air cooling. Consequently, since, as well known, the pulse propagation is strongly affected by medium temperature, the operation of the two IDCs could be not perfectly phased. Many efforts were made in order to minimize this effect, but it was not possible to completely avoid it in this preliminary phase. This should be taken into account during an optimized design phase.

2.3. Test bench and instrumentation

The engine was installed on the test bench and coupled with a Borghi & Saveri FE600-SD eddy-current brake. In addition to the original KTM ECU, an Athena GK-ECUJ5-0010 was used in series to modify both spark advance and PFI energizing time to reach lambda target. Engine was instrumented with temperature sensors located in the engine intake and exhaust pipes, as well as in the cooling and lubrication circuits [9]. In-cylinder pressure was measured by a piezo-electric sensor (Kistler 6052C) flush-installed in the cylinder head, while pressure in the intake manifold (downstream of throttle valve), in the exhaust manifold and in IDC hot side were recorded using piezo-resistive transducers (Kistler 4075A5). Crankshaft angular position was measured by means of an optical encoder (AVL 365). These signals, together with ignition timing from a current clamp, were sampled at 0.1 CAD resolution and acquired by a Kistler KiBox combustion analysis system. For each tested point, 200 consecutive indicated cycles were recorded to have a statistically significant amount of data. Lastly, a UEGO lambda sensor (Horiba MEXA-720) was installed in the exhaust line upstream of muffler.

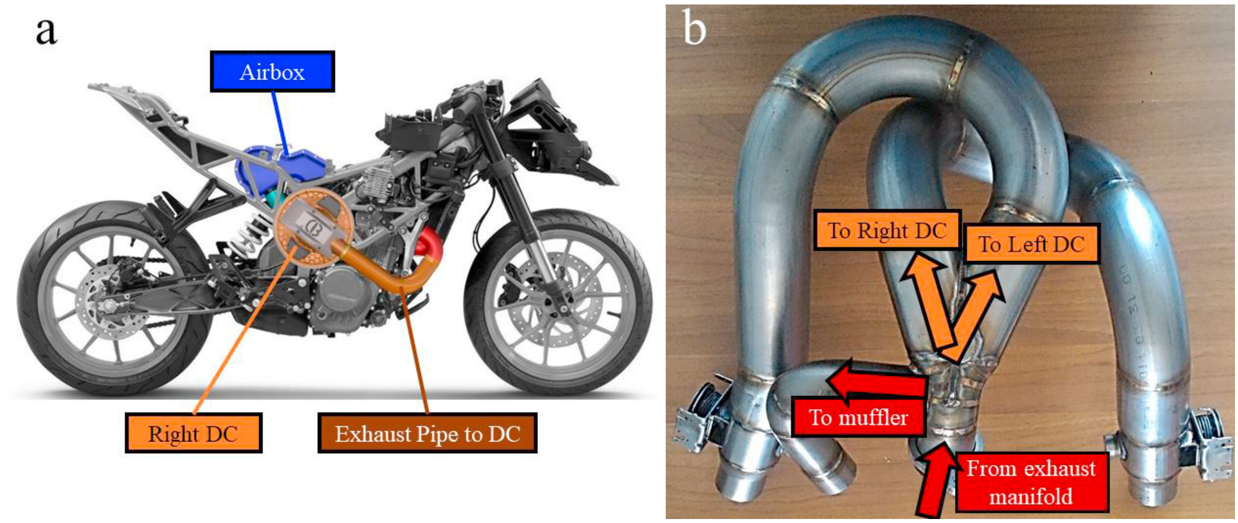

Fig. 3 (a) schematic of IDC installed on a KTM RC390 (courtesy of *AlterEgo Hardware*), (b) new exhaust duct to couple two IDCs with the engine. In the latter, red arrows represent exhaust mass flows while orange arrows represent pressure wave pulses.

3. Test Table

In a first phase of the work, an observation of the pressure trends at the IDCs inlet (exhaust gas pulses, i.e. the driving force) and at the outlet (boost, i.e. the desired effect) was performed in order to understand the main phenomena and the waves phasing.

The main campaign consisted of a comparison among three different layouts: the engine in its original configuration (“Original”), with the muffler to be used with IDCs (“Baseline”) and with the complete Drum Charger setup (“IDC”). Besides the FLC in the original configuration, the modified ones were thoroughly analyzed in three significant engine points: 4500 rpm WOT (representative of low-speed), 7000 rpm WOT (representative of medium-speed and close to original engine max torque point) and 9500 rpm WOT (representative of high speed, max power point). In Table 2 further details about main test campaign can be found.

Since original KTM ECU is not open and its correction algorithms are unknown, in order to avoid that the results were affected by Spark Advance (SA) or relative air-fuel ratio (λ) variations, these two parameters were maintained equal to the Original configuration values by means of the additional Athena system (Table 3).

Table 2. Main test campaign

Layout	Tested points	Performance analysis	Intake Pressure analysis	Knocking analysis
Original	FLC	x	x	x
Baseline (Engine with new muffler)	4500 – 7000 – 9500 rpm WOT	x		
IDC (Engine with new muffler and Drum Chargers)	4500 – 7000 – 9500 rpm WOT	x	x	x

Table 3. ECU fixed parameters

Tested point	Spark advance [CAD BTDC]	Lambda [-]
4500 rpm WOT	31	1.03
7000 rpm WOT	27	0.93
9500 rpm WOT	31.5	0.97

4. Results and Discussion

The pressure trends analysis was carried out at 4500 rpm WOT and 6000 rpm WOT in order to evaluate the effects of the IDCs insertion. Tests were performed by comparing two configurations: the complete system (blue curve in Fig. 4 “IDC on”), and the system with the IDCs disconnected from the airbox (black curve, “IDC off”): in the latter layout, IDCs are connected to the engine exhaust, but not to the airbox, which is free to directly aspirate environmental air. In this manner, engine operates with an identical exhaust configuration, and it is possible to focus the analysis on the boost effect only.

Analyzing the results in Fig. 4 it is possible to observe that, as expected, the exhaust pulse (red curve, near 200 CAD) deflects the membrane producing a subsequent intake pulse delayed by about 60-70 CAD. Obviously, the angular interval between these two pulses is dependent on engine speed: since exhaust valve opening angle is fixed and the wave propagation physical time is almost constant, the crankshaft position in which boost waves reach the engine intake varies with regimes. Consequently, since the air charging effect depends on engine speed, the more precise the synchronization between boost pulse and intake valve opening phase, the higher the engine performance.

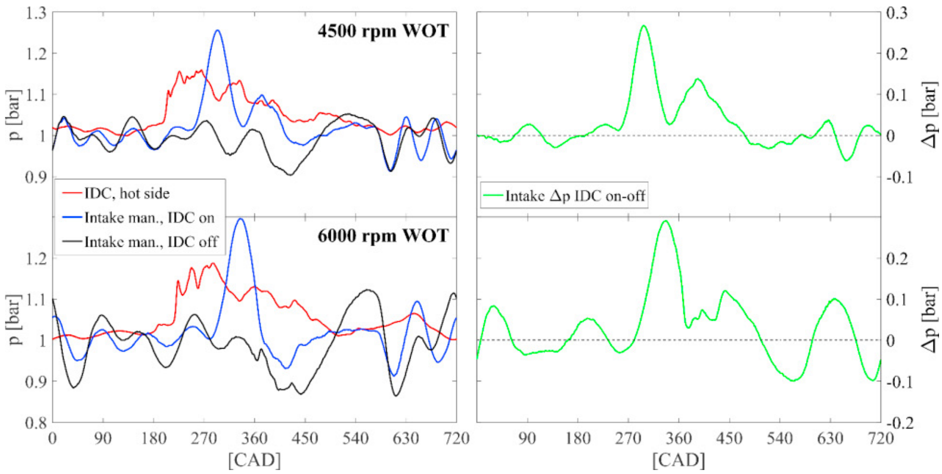

Fig. 4. Pressure characterization versus crank angle at different engine speeds (top: 4500 rpm, bottom: 6000 rpm). Left side: pressure in IDC hot side (red); intake manifold pressure with IDC inserted (blue) or removed (black). Right side: intake manifold pressure difference (green) between IDC inserted and removed. When green curve is negative, the naturally aspirated configuration (IDC off) guarantees in that moment an intake pressure higher than the one with IDCs.

The following performance characterization started with a knocking analysis, since, when charging a SI engine, especially in oversquare (short-stroke) engines such as the tested one, a wide safety margin against knock must be preserved. During the tests, indicating analysis over 200 consecutive cycles with Kistler KiBox allowed us to determine the so-called "k-ratio", an experimental knocking detection index based on a Siemens VDO algorithm [11]. If the threshold of 1.4 is exceeded, it can be stated that knocking begins to occur [12]. In Fig. 5, k-ratio values for Original and IDC configurations are reported. It can be seen that Original configuration is near the threshold (i.e. engine is close to an incipient knock); it is interesting to note that IDC does not change this behavior significantly. In particular, 4500 rpm WOT is the only point where a small increase of k-ratio was found, slightly worsening knock. At 7000 rpm, instead, a small decrease occurs, while no effect was found at 9500 rpm. It must be remarked that all these points were recorded with no changes in SA nor lambda (Table 3).

It is worth saying that engine intake temperature does not rise passing from Original to IDC configuration, owing to the limited overpressure and to the negligible heat transfer between the IDC hot and cold sides.

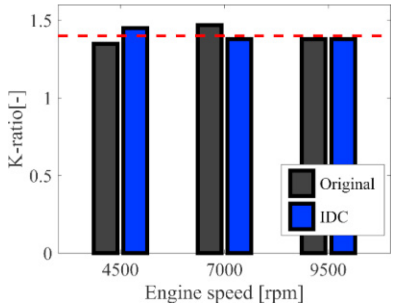

Fig. 5. Calculated k-ratio. Dashed red line represents the 1.4 threshold.

Table 4. Performance comparison for the three tested layouts.

	Corrected Power [kW]		
Tested point	Original	Baseline	IDC
4500 rpm WOT	12.0	11.4	13.8
7000 rpm WOT	23.6	25.2	24.7
9500 rpm WOT	29.7	30.0	31.1

Performances (Fig. 6 and Table 4) were acquired and corrected by taking into account barometric pressure, humidity and room temperature according to SAE J1349 [10]. The most evident effect of IDC is at 4500 rpm: there is a significant power increase if compared to both Original Engine and Baseline (Original: +15.0%, Baseline: +21.1%). The same behavior, with a lower gain, can be found at 9500 rpm (+4.7% and +3.6% respectively). At 7000 rpm, instead, IDC is able to increase power if compared to Original layout (+4.6%) but performs less than Baseline (-2.0%). This can be probably due to effects superimposition: the new muffler has a positive effect at 7000 rpm (in fact, both Baseline and IDC show higher performances than Original), while the pulses from the two IDCs, are probably positioned in a not favorable timing with respect to intake valves opening phase and in-cylinder pressure level. As a matter of fact, by analyzing intake pressure oscillations during an engine cycle and focusing on the angular interval when intake valves are open (Fig. 7), one can see that at 7000 rpm IDC configuration is able to generate a pressure level almost always higher than the Original one. At 9500 rpm, even if in the first phase of intake valve opening (up to 400 CAD) IDC pressure is lower, performance continues to remain better. This can suggest that an air pulse is more effective during the second half of intake stroke, when piston starts to slow down (so, reducing suction effectiveness [2]).

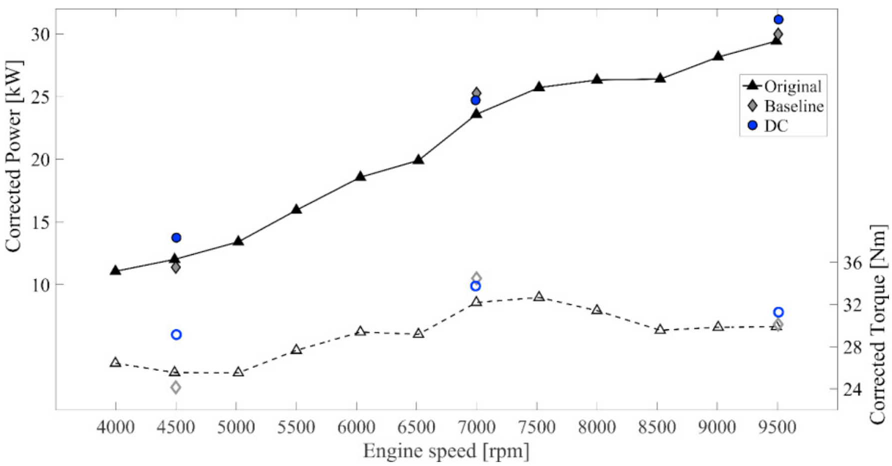

Fig. 6. Corrected performances of the three layouts: power (left) and torque (right) vs engine speed.

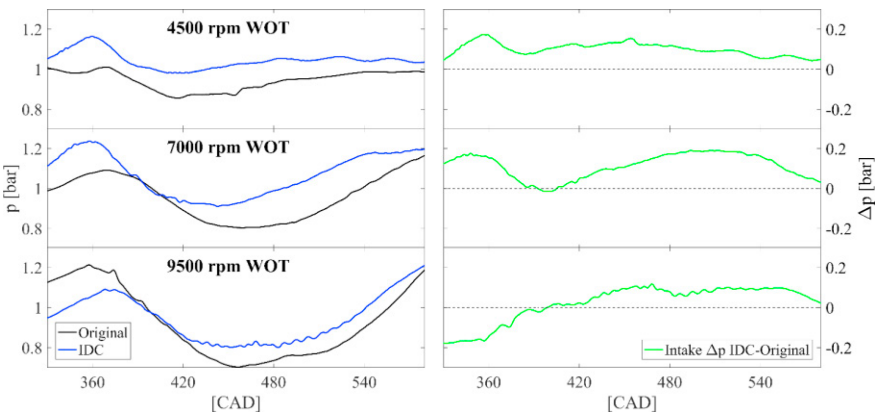

Fig. 7. Intake pressure (absolute bar) during intake valve opening period at different engine speeds (top: 4500 rpm, middle: 7000 rpm, bottom: 9500 rpm). Left side: Original (black) and IDC (blue) values. Right side: difference (green) between IDC and Original. When green curve is negative, Original engine guarantees in that moment an intake pressure higher than the one with IDCs.

4. Conclusions and Future Work

Drum Charger is a compressor designed to exploit the pulses generated by exhaust valve opening. In this work, a first study of the coupling of this system with a 4-stroke motorbike engine (KTM RC 390) was carried out. Knock characterization showed that IDC insertion does not worsen k-ratio significantly. After the performance characterization of the original engine, the differences in terms of brake power were studied with fixed ECU parameters (spark advance and lambda). At low-speed full-load (4500 rpm WOT) and high-speed full-load (9500 rpm WOT) the performances of the engine equipped with IDCs were found to be better than Original engine, with a max power gain of about 1.4 kW. At medium-speed full-load (7000 rpm WOT) the power improvement seems to be mainly due to the muffler, different from the Original one, and not to the boost itself. Pressure analysis confirmed that the IDC insertion allows the intake pressure to rise in any case, but its effect also depends on the proper timing with respect to intake valves opening phase and in-cylinder pressure level.

Future work will be based on a deeper analysis concerning pressure waves. Measurements will be carried out in several points, even inside the Drum Charger. This should allow to better understand the boost generation mechanism and should produce useful data for setup and tuning of CFD models.

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