

Individual Cylinder Air-Fuel Ratio Control for Engines with Unevenly Spaced Firing Order

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ABSTRACT

The most recent European regulations for two- and three-wheelers (Euro 5) are imposing an enhanced combustion control in motorcycle engines to respect tighter emission limits, and Air-Fuel Ratio (AFR) closed-loop control has become a key function of the engine management system also for this type of applications.

In a multi-cylinder engine, typically only one oxygen sensor is installed on each bank, so that the mean AFR of two or more cylinders rather than the single cylinder one is actually controlled. The installation of one sensor per cylinder is normally avoided due to cost, layout and reliability issues. In the last years, several studies were presented to demonstrate the feasibility of an individual AFR controller based on a single sensor. These solutions are based on the mathematical modelling of the engine air path dynamics, or on the frequency analysis of the lambda probe signal.

This work presents a novel approach that has been developed specifically for engines with big-bang (or unevenly spaced) firing order, which is typically adopted in motorcycle applications with either V (all of them) or in-line cylinder configuration. This approach is much simpler if compared to previously published solutions, because it doesn't require a mathematical model of the air path dynamics, it doesn't need high computational resources, and it is reliable and robust up to high engine speeds, which are often reached in motorcycle engines.

The control algorithm was developed, designed and tested in a simulation environment, by means of a 1-D model of a twin-cylinder motorcycle engine, and then real-time implemented and experimentally validated on the vehicle.

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INTRODUCTION

From 2020 two- and three- wheel vehicles will start the transition from Euro 4 to Euro 5 [1]. The new standard will require a new set of on board diagnostics (OBD) to improve combustion control, and to further reduce both fuel consumption and pollutant emissions. One of the most important parameters related to the combustion quality is the Air-Fuel-Ratio of the charge, and through the monitoring of this value by the lambda probe it is possible to employ a closed loop controller able to keep it very close to stoichiometric conditions. Modern motorbike engines are equipped with a three-way catalyst (TWC) that requires a controlled AFR oscillation between rich and lean values alternatively, to maximize pollutant conversion efficiency [2].

One important problem related to AFR control is the possibility to monitor the AFR distribution in a multi-cylinder engine. In fact, the possibility to control the AFR value related to each single cylinder

individually would allow to improve the engine performance while further reducing pollutant emissions [3, 4]. This can also be translated in less strict requirements in the design of injection and air intake system devices, because the control system would compensate possible imperfections that contribute to AFR distribution non-uniformity [5, 6]. The most obvious solution could be to install a lambda sensor on each exhaust runner, but the associated costs make it unfeasible. Therefore, it is important to find the way to build a controller based on the already available sensors on board (such as lambda probe and crankshaft position sensor). Previous studies related to this topic involve complex models of the air path dynamics for calculating gas transport and mixing phenomena, to extract single cylinder AFR values from the lambda sensor signal measured at the catalyst inlet [7, 8, 9, 10, 11]. A possible alternative could be the lambda signal frequency content analysis carried out in real-time, to track engine cycle and round frequencies, and the corresponding cylinder AFR imbalance in terms of amplitude and phase [12, 13, 14].

This work presents the development of an individual cylinder AFR controller for a straight-twin engine with 270° crankshaft interval configuration, equipped with a single oxygen sensor installed at the junction of the two exhaust runners. In this configuration, one cylinder expansion stroke is followed by the other cylinder expansion stroke with a 270° delay, therefore between the firing of the first and second cylinder there is a 270° CA interval, vice versa between the firing of the second one and the first cylinder the interval is equal to 450° CA. This unevenly spaced firing order, also called “big-bang”, is widely adopted in motorbike applications, both for L and V engines (depending on the value of the V angle). This feature of the engine allows building an AFR control system based only on the analysis of the lambda signal waveform, together with the crankshaft position signal information. Therefore, this approach doesn’t require great pre-calibration efforts, nor it doesn’t need exceptional computational resources to be deployed in real time.

The work has been carried out in three main steps. In the first step an engine model was designed in a 1-D environment and it was validated by comparing simulation results with experimental data. The signals produced by the lambda sensors (virtual HEGO and UEGO sensors) have been simulated in several operational points. Starting from the observation of their main characteristics, it has been possible to define an algorithm able to detect an AFR difference between the two cylinders, and to establish in which cylinder the AFR is richer and in which is leaner. In the second step, the algorithm effectiveness has been tested on the real lambda signal experimentally acquired on-board the vehicle. Finally, in the third step a closed-loop control structure has been developed in Simulink, connecting it to the 1-D engine model through a co-simulation approach. Thanks to the co-simulation environment, the best control system configurations were selected, and it was also possible to identify the threshold values needed to recognize the presence of the minimum detectable AFR difference between the cylinders.

EXPERIMENTAL SETUP

The experimental tests were carried out on a motorbike equipped with a straight-twin engine with 270° crankshaft configuration, installed on a roll bench dynamometer. In this configuration, a 270° CA degrees interval occurs between the firing event of one cylinder (in this paper called ‘first’ cylinder) and the firing event of the other one (called ‘second’ cylinder), vice versa a 450° CA degrees interval takes place between the firing of the second and the first cylinder. The corresponding exhaust runners are joined before the TWC inlet. The engine main features are reported in Table 1. The standard AFR control system is based on a HEGO probe, placed in the runners’ junction and it consists of a closed-loop control programmed to force AFR oscillation between rich and lean values (for TWC efficiency).

Table 1. Engine main technical features

Displacement	650 cc
Maximum Torque	60 Nm at 6000 rpm
Maximum Power	45 kW at 7000 rpm

A preliminary experimental campaign had been carried out on the engine test-bench to characterize the main operating parameters. The setup, shown in Figure 1, included a fuel metering system, an eddy current brake to measure BMEP, piezoelectric pressure sensors for each cylinder, an indicating system to measure IMEP and PMEP, and two linear lambda probes, one for each cylinder, installed in the exhaust runners before the junction. Several tests have been done in different operational points, under steady state conditions. The data acquired allowed to validate a 1-D engine model.

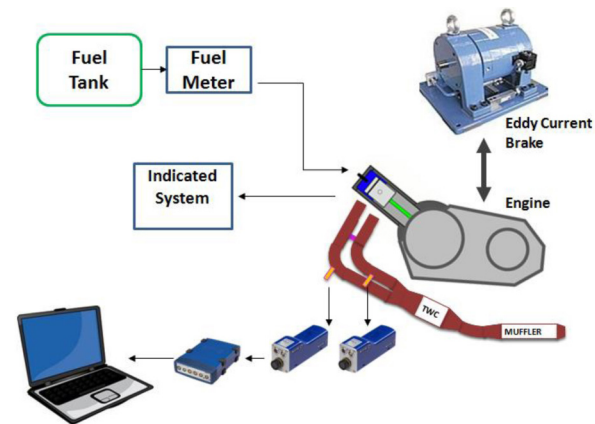


Figure 1. Test bench set-up

A second experimental campaign has then been performed in order to validate the AFR Unbalance Index (UI). This time the tests have been carried out on a high speed chassis dynamometer for motorcycles. The relevant sensors for these tests were both standard on board devices, such as crankshaft position sensor and standard equipment HEGO probe (Figure 2), and external devices, consisting of the two UEGO probes introduced in first step (one of them is shown in Figure 3). A prototype ECU was used, connected to specific instruments able to acquire all relevant signals, and to control all actuation parameters. Some tests have been executed under quasi steady state conditions, or more precisely by keeping engine speed, load, and coolant temperature in a limited range and for a defined time interval. One part of the tests was performed by deactivating the closed loop (average AFR) control system, while other tests were conducted with active closed loop control (including swinging AFR profile related to TWC efficiency optimization). In this way, it was possible to track the AFR signal evolution both under simplified conditions, and during more realistic, and complex, engine operation.

The chassis dyno installation schematic is reported in Figure 4.

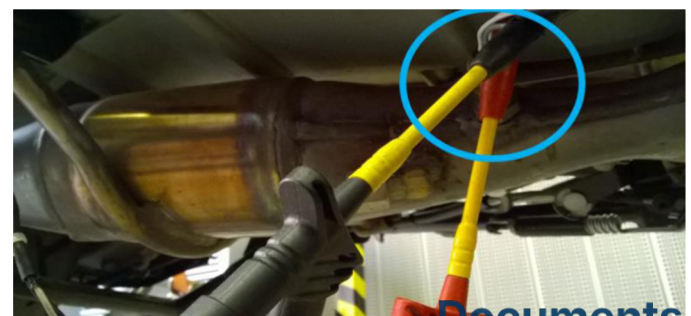


Figure 2. HEGO probe located in runners' junction before TWC



Figure 3. UEGO probe located in the exhaust runner

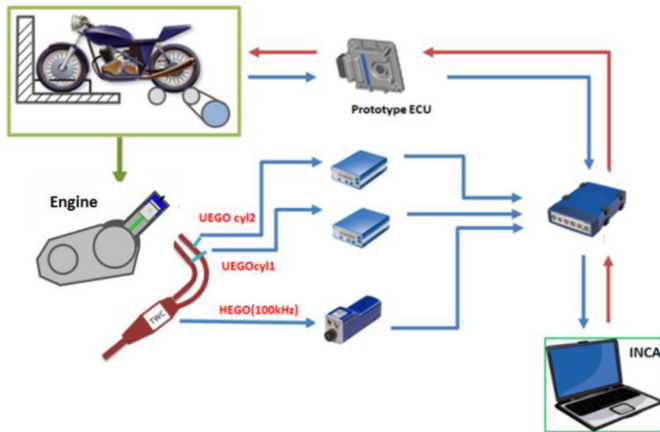


Figure 4. Chassis dyno setup

MODEL DESCRIPTION AND VALIDATION

The development of an AFR closed-loop controller can be effectively supported by a physically-based engine model, in a simulation environment. In this approach, the engine behavior can be reproduced by a virtual model, able to receive environment and actuation parameters as inputs, and to provide response signals as output, reproducing the system physical phenomena. The use of a model allows to study the system behavior over a wide set of operating (and pre-determined) conditions, in a very short time. In this work, the 1-D model has been designed using GT-Power software libraries. As a first step, the entire air system layout was inserted after having identified all geometrical data by measuring all the pipes, junctions and runners characteristics, and by considering technical data provided by manufacturer (valves, engine, throttle), and materials characteristics (roughness, conductivity, ...). A heat transfer model (based on Woschni function) and a combustion heat release model (based on Wiebe function) were also introduced and identified. In order to validate the model, the simulation outputs (AFR, PMEP, IMEP, FMEP) were

compared with experimental data (obtained during the first, preliminary experimental campaign). After an iterative process focused on adapting some parameters such as pipes and valves geometry, and materials roughness, the validation stage was completed and the outputs matched experimental data. Table 2 briefly shows the model prediction capability, by considering as an example the operating conditions corresponding 6000 rpm and full load.

Table 2. Model validation example. Test point: rpm=6000; throttle angle=90°

	Measured	Simulated	% error
BMEP	10.55 bar	10.90 bar	3.32
FMEP	3.80 bar	3.98 bar	4.74
PMEP	-0.71 bar	-0.72 bar	1.41
BH	11.20 kg/h	11.19 kg/h	0.09
Lambda cyl1	0.90	0.89	1.11
Lambda cyl2	0.90	0.89	1.11

Also, a linear lambda sensor has been simulated through a first order low-pass filter:

$$Y(s) = \frac{1}{\tau s + 1} U(s) \quad (1)$$

This approach is suggested in [9] with proposed τ values between 30 ms and 50 ms. By considering the specific sensor dynamics, in this work it was assumed $\tau=30$ ms. Moreover, the HEGO sensor has been simulated by interpolating the linear lambda signal (low-pass filter response) through the 1-D table shown in Figure 5. The table has been identified by using experimental data obtained from the tests, focusing the analysis in the AFR rich area, to better reproduce most part of the engine operating conditions. Figure 6 shows the 1D model structure.

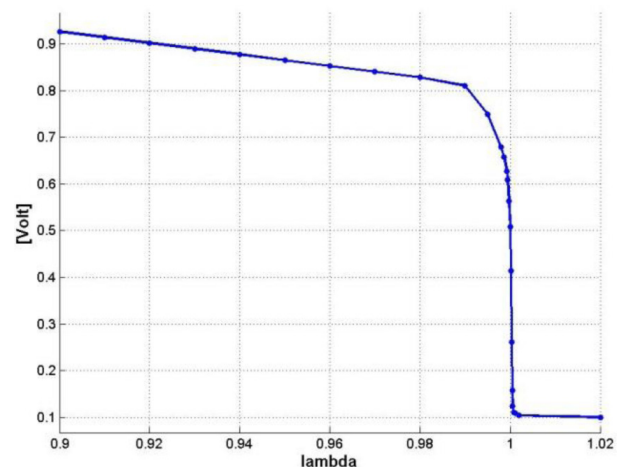


Figure 5. Simulated HEGO response

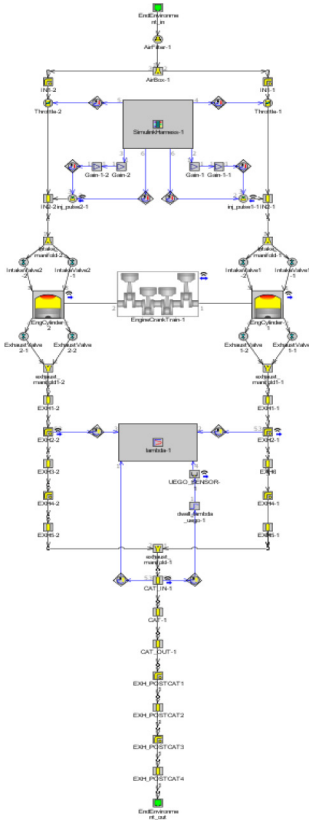


Figure 6. 1-D engine model structure

AFR UNBALANCE INDEX DEFINITION

The 1-D model was then used to generate a simulated lambda signal produced by a virtual lambda sensor located in the junction of the two exhaust runners. Several simulations were executed to analyze the signal behavior due to the presence of an imposed AFR unbalance, while varying its magnitude at different engine operational point. The comparison of the UEGO simulated profiles allowed reaching two important considerations. The first and more evident consideration is that the existence of an AFR unbalance between the cylinders induces a periodic oscillation on the confluence lambda sensor output, whose period is equal to the combustion cycle duration, and furthermore its amplitude is directly proportional to the unbalance magnitude, as it is shown in Figures 7, 8, 9 and 10. The second consideration is that the waveform of the confluence lambda signal is not symmetrical, and it is more similar to a saw-tooth shape whose orientation depends on which way the unbalance between the cylinders was imposed. When the first cylinder is richer than the second cylinder (Figures 9 and 10), the transition from the leanest values to the richest values of the virtual UEGO signal lasts less than half combustion cycle (360 CA deg), and vice versa when the first cylinder is leaner than the second cylinder (Figures 7 and 8), the same transition lasts more than 360 CA deg, as it can clearly be observed by comparing Figure 7 with Figure 9, or Figure 8 with Figure 10. This behavior is determined by the special engine configuration with unevenly spaced combustions, which determine that the exhaust gases coming from the second cylinder reside more time in the exhaust system than the exhaust gases coming from the first cylinder, thus producing the AFR confluence profile shown in magenta (the confluence AFR that would be measured by an ideal UEGO sensor). Since the target of this work

is to develop a controller based on the standard sensors installed onboard the vehicle, even the HEGO response has been modeled and analyzed. It can be noticed that HEGO response reflects, in most cases, the shape of the UEGO response, but its amplitude is altered by the nonlinear dependence of the sensor voltage response versus AFR value, and the resulting waveform is strongly deformed when the AFR value oscillates across stoichiometry, as it happens in the test of Figure 10. However the richest points and leanest points are still located in the same positions presented in the previous signal.

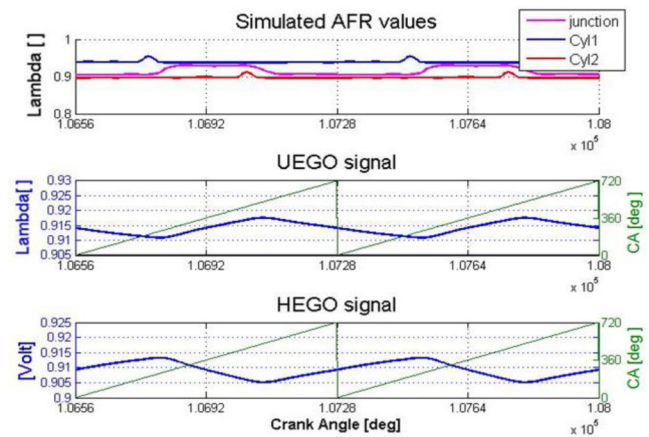


Figure 7. Cylinder 1 5% leaner than cylinder 2 (3000 rpm, full load)

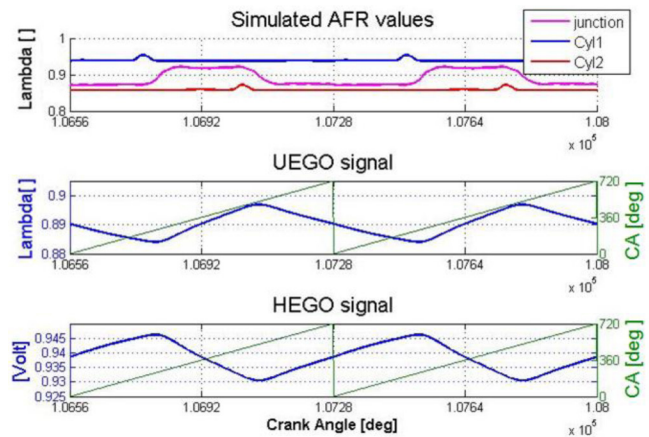


Figure 8. Cylinder 1 10% leaner than cylinder 2 (3000 rpm, full load)

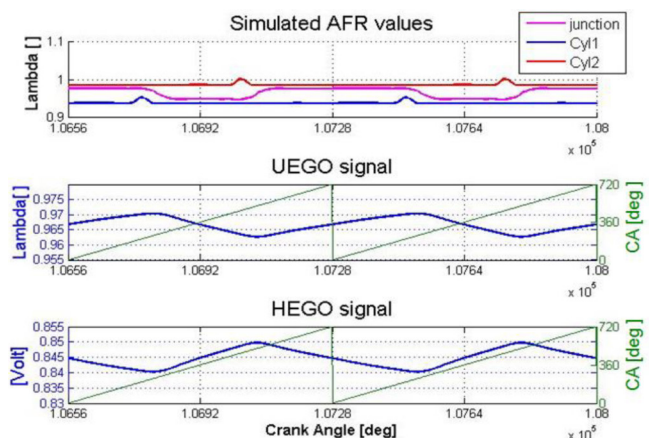


Figure 9. Cylinder 1 5% richer than cylinder 2 (3000 rpm, full load)