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Development of a lumped model for the characterisation of the intake phase in spark-ignition internal combustion engines

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Abstract

The present work aims to develop a control-oriented lumped model to investigate the fluid dynamic behaviour of multi-valve spark-ignition engines (ICEs). Specifically, the attention has been focused on the intake phase and in-cylinder air charge estimation. To this purpose, a spark-ignition engine has been characterised at a flow rig in terms of flow coefficients. The experimental data have been used to define the fluid dynamic behaviour of the different intake system components and to calibrate and validate the proposed model that has been developed in Matlab/Simulink environment. Furthermore, in order to evaluate the capability of the zero-dimensional code and to estimate the instantaneous in-cylinder mass flow in different operating conditions, the numerical data have been compared to the results of a one-dimensional commercial software.
The comparison between numerical and experimental data shows a good agreement. The investigation highlights that the proposed control-oriented lumped model represents a useful and simple tool to evaluate the engine breathability and to define the proper valve timing.

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Keywords: Internal Combustion engine; intake system; lumped model

1. Introduction

The design and the optimisation of highly efficient internal combustion engines (ICEs) require a thorough

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understanding of the different processes that take place within the modern automotive systems [1-2]. Specifically, an accurate knowledge and control of the intake phase and the air fuel mixing is fundamental to respect the more and more severe regulations on the exhaust gas, to improve engine efficiencies, and to reduce fuel consumptions.

To this purpose, several methodologies can be adopted, based both on experimental and numerical approaches [3-5]. Specifically, mathematical models are largely used owing to the possibility to investigate different geometries and operating conditions and to reduce significantly the time and cost of the research [6-8]. The models can be divided in three main groups: zero-dimensional or lumped, one-dimensional, and three-dimensional models [9].

Zero-dimensional codes are based on thermodynamic and phenomenological laws and are characterised by the highest simplicity and lowest computational effort. At the same time, 0D codes guarantee high accuracy due to the possibility to define coupled sub-models able to properly simulate complex systems like the intake apparatus of modern internal combustion engines (ICEs) [6]. For this reason, the development of simple control-oriented numerical tools appears of great interest in order to estimate the instantaneous mass flow rate entering the combustion chamber and to define the proper intake and exhaust valves timing [10-13].

This paper aims at developing a control-oriented lumped model to characterise the dynamic behaviour of the intake process in multi-valve internal combustion engines. A phenomenological code has been proposed considering the continuity and momentum equations.

The main components of the intake system have been modelled adopting the geometric and fluid dynamic characteristics. In particular, an experimental analysis has been performed at the flow rig in order to define the flow coefficient of the intake system. Particular attention has been focused on intake duct, plenum, throttle valve, engine head, and intake and exhaust valves. Furthermore, a comparison with a one-dimensional commercial code has been presented.

2. Numerical model

An unsteady lumped model has been developed in Matlab/Simulink environment in order to characterise the intake system of an innovative variable valve timing (VVT) spark-ignition engine, whose main characteristics are listed in Table 1. The different components of the intake system have been modelled: the manifold, the intake and exhaust ducts, the cylinders, the intake and exhaust valves, the plenum and the throttle valve [13-14]. The zero-dimensional model acquires the valve lifts laws, that are a function of the engine speed and load. The simplified scheme of the engine is shown in Figure 1.

The modelling of the different components has been performed taking into account the inertia phenomena and the mass accumulation capability of the intake system elements [8,12] in order to correctly estimate the fluid dynamic efficiency and, therefore, the overall performance of the engine. In particular, inertial effects are due to the inversion of the driving force (the pressure difference within the component), that may happen during the final part of the intake phase. In addition, each component is able to accumulate mass due to the periodic behaviour of the engine.

To this purpose, two main elements have been defined: the pure "inertial" component (i.e. pipe), characterised by the inertial effects, and the pure "capacity" component (i.e. plenum), capable to accumulate and release mass.

The inertial component is a connecting element between two reservoirs characterised by p_{in} and p_{out} pressure levels.

Table 1: Main engine characteristics

Engine	Four-stroke
Ignition method	Spark-ignition
Compression ratio, r_c	10
Number of cylinders, N_c	2
Number of intake valve per cylinder, $N_{v,i}$	2
Number of exhaust valve per cylinder, $N_{v,e}$	2
Stroke/Bore, L/B	1.068
Intake valve diameter/Bore, D_i/B	0.373
Throttle diameter/Bore, D/B	0.745