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A non-linear quasi-3D model with Flux-Corrected-Transport for engine gas-exchange modelling

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ABSTRACT

Modelling has proven to be an important tool in the design of manifolds and silencers for internal combustion engines. Although simple 1D models are generally sufficiently precise in the case of manifold models, they would usually fail to predict the high frequency behaviour of modern compact manifold designs and, of course, of a complex-shaped silencing system. Complete 3D models are able to account for transversal modes and other non-1D phenomena, but at a high computational cost. A suitable alternative is provided by time-domain non-linear quasi-3D models, whose computational cost is relatively low but still providing an accurate description of the high frequency behaviour of certain elements. In this paper, a quasi-3D model which makes use of a non-linear second order time and space discretization based on finite volumes is presented. As an alternative for avoiding overshoots at discontinuities, a Flux-Corrected Transport technique has been adapted to the quasi-3D method in order to achieve convergence and avoid numerical dispersion. It is shown that the combination of dissipation via damping together with the phoenical form of the anti-diffusion term provides satisfactory results.

1. Introduction

Engine modelling has become in recent years an essential tool in the design of reciprocating internal combustion engines, as it allows reducing considerably the development time and costs. Classical design methodologies are based on prototype manufacturing and trial-and-error tests. Currently, most of those tests have been replaced by numerical computations, so that only the most promising design options are actually tested on engine bench.

For years, 1D gas dynamics codes in the time domain [1] have offered sufficiently good solutions for modelling both engine performance and intake and exhaust noise. The choice of 1D models is justified because in most ducts present in engine intake and exhaust systems it can be assumed that there is only one flow direction. However, for a more demanding level of design, a 1D representation may not be sufficient to describe accurately the flow in certain elements. This is especially important in the case of silencers, where the 1D assumption can only be applied to simple geometries [2] and, even in that case, suitable results can only be obtained for frequencies below the cut-off frequency of higher order modes [3]. In the case of duct junctions [4] it is the existence of complex 3D flow structures what sets the applicability limit for a simple zero-dimensional description [5]. In view of these limitations, the first option would typically be the use of a computational fluid dynamics (CFD) model; however, the application of such a model to a complete intake or exhaust system entails an excessive computational time.

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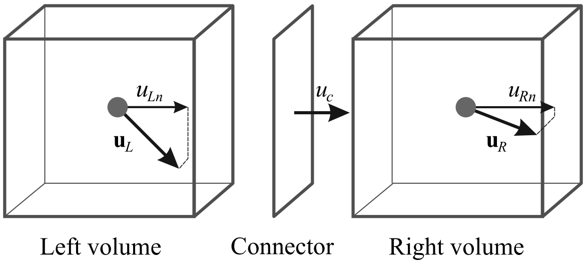

Fig. 1. Basic mesh elements and definition of velocity projections.

A possible solution comes from the use of a 3D model only locally at those parts in which 3D effects are relevant, through the coupling between 1D and 3D models [6]. Such coupling can be done directly in the time domain [7] or by means of time–frequency hybrid schemes [8] in which the element information is obtained from 3D or quasi-3D linear models [9], although the use of hybrid schemes is hampered by their very slow convergence.

An alternative compromise solution is given by quasi-3D models, in which the momentum equation is solved in a simplified way on a staggered mesh [10]. A good quasi-3D model should be able to offer almost as good results as a CFD tool, at least for the particular problem for which it was designed, while reducing greatly the computation time. Such solutions have become standard in commercial codes, and have been successfully applied to silencers with perforated tubes and/or absorbing material, both in the acoustic regime [11] and in real engine conditions [12]. It is well known, however, that such methods are affected by the occurrence of non-physical oscillations, especially in cases where pressure gradients are significant, unless some additional term is included in the momentum equation, be it either an equivalent friction force [10] or a momentum diffusion term [13].

The main objective of this paper is to evaluate the possibility of avoiding such additional terms by means of the use of a Flux Corrected Transport (FCT) methodology [14], which has proven to be a suitable solution to avoid overshoots at discontinuities when the flow equations are solved with finite differences schemes, even in ducts with non-uniform cross-section [15].

The paper is organized as follows: First, in Section 2 the method is described, including the discretization of the equations and the formulation of the FCT method. Then, in Section 3 the stability and convergence of the method are tested on the shock-tube problem and, in Section 4, results of its application to a simple but representative three-dimensional geometry are shown and discussed. Finally, in Section 5 the conclusion of the work is summarized.

2. Description of the method

When trying to determine the reasons why 3D methods need high computational resources and, if possible, to reduce those needs, it is readily concluded that the main problem lies in the momentum equation. Even neglecting any viscosity terms, it is a vector equation and thus a system of three equations has to be solved, in addition to the mass and energy equations, in each cell for each time step. Therefore, this is the aspect addressed when considering a quasi-3D approach, as described in the following.

2.1. Mesh elements

Two types of basic elements are considered that henceforth will be referred to as volumes and connectors. Volumes contain information about scalar magnitudes such as pressure, density or temperature, and of course of the cell volume itself, whereas connectors contain information on vector quantities (flow velocity or momentum), on their own orientation in space also some scale information (the connector area). It is precisely this attribution of the scalar intensive properties to the volumes and of the vector quantities to the connectors what defines the staggered character of the resulting mesh. This character in turn determines the staggered nature of the solution procedure, in which changes in the scalar quantities defined at the volumes are computed from the fluxes at the connectors computed at the previous time step, so that the control volumes associated with the mass and energy equations and those associated with the momentum equation overlap both in space and time [11].

In Fig. 1, two volumes connected by a connector are shown. The volumes are represented by cubes, although they do not actually have any defined shape, in the same way as the connector is simply an area across which the flow passes between the two volumes. In general, a connector always connects two volumes, whereas a volume may be attached to as many connectors as required by the problem.

2.2. Discretization of the basic equations

The starting point of the method is the usual Euler equations for the 3D case. However, in the context of the quasi-3D method the key issue is where and how those equations are solved. Initially, from the initial conditions defined, the mass