

The 3Dcell Approach for the Acoustic Modeling of After-Treatment Devices

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ABSTRACT

In the last decades the continuously tightening limitations on pollutant emissions has led to an extensive adoption of after-treatment devices on the exhaust systems of modern internal combustion engines. While these devices are primarily introduced for reducing and controlling the emissions, they also play an important role influencing the wave motion inside the exhaust system and so affecting the acoustics and the performances of the engine. In this paper a novel approach is proposed for the modeling of two after-treatment devices: the catalyst and the Diesel Particulate Filter. The models are based on a fast quasi-3D approach, named 3Dcell, originally developed by the authors for the acoustic modeling of silencers. This approach allows to model the wave motion by solving the momentum equation along the three directions. The capability of modeling complex shape devices, allowing the description of three-dimensional wave action, makes this tool an interesting solution for studying the acoustic behavior of today's mostly used after-treatment devices. In this work the 3Dcell approach has been extended to the modeling of the catalyst and DPF monolith, in order to combine the capability of predicting the flow distribution in the monolith channels with a lower computational demand than traditional 3D CFD approaches. The developed models have been applied to the simulation of the acoustic behavior of these components, comparing the results to measured data. For completeness sake the results have also been compared to traditional 1D models applied to the acoustic simulation of after-treatment devices.

INTRODUCTION

The fluid dynamic processes occurring inside intake and exhaust systems of I. C. engines are one of the main noise sources in land transport vehicles. Therefore, it is considered by vehicle manufacturers as one of the factors determining the feasibility of a certain vehicle design. With the purpose to mitigate these noise sources, silencers have been traditionally included in the intake and, mostly, in the exhaust systems. For a long time, such silencers have been almost the only elements present along the exhaust system, but this situation has changed significantly in the last decades. The generalized trend in achieving higher and higher levels of engine performances, together with social environmental concerns pushing for the introduction of increasingly severe restrictions to pollutant emissions, have led to the inclusion of different devices in the intake and exhaust systems, whose primary functions are related to emission abatement and performance enhancement. Therefore, the acoustic design of intake and exhaust systems has been affected, since these devices have a direct influence on the internal wave dynamics, and thus on intake and exhaust noise. On the other hand, the fact that those devices have a non-negligible influence on wave propagation, has opened new scenarios regarding the eventual improvement of their attenuation potential. These considerations are also supported by the fact that the actual development trend, both for light and heavy duty vehicles, shows technical solutions in which there is a complete integration of the after-treatment device with the noise abatement system. In parallel, latest tendencies in intake and exhaust system design make extensive use of numerical modeling techniques, both for performance and noise assessment [1,2,3]. Therefore, any attempt to exploit the attenuation potential of any non-silencer elements

requires, in the frame of current design methodologies, that suitable models are available for the prediction of their acoustic behavior. Looking at the actual state of the art, one can conclude that 1D linear and non linear models are the most widespread and used tools, mainly because of their robustness and low computational demand. However, the increasing complexity degree of silencers and after-treatment devices does not play in favour of their adoption. The main reason is that the achievement of good accuracy in the prediction of the acoustic behavior requires a considerable expertise and physical process understanding to the final user. This is usually a limitation and moreover makes difficult to exploit the tool for optimization purposes. An opposite scenario appears relying to the 3D CFD tools available on the market. They are powerful tools, usually provided with easy to use GUI, which allows the user to quickly produce a calculation grid of complex shape devices and perform the simulations. The price that the user has to pay is the computational effort required to perform a complete simulation [4, 5]. A good compromise between predictiveness and computational demand is represented by quasi-3D approaches. They offer the possibility of modeling complex shapes with approximated 3D calculation grids, typically based on 0D volumes suitably connected between each other, on which simplified solvers of the governing equation are applied. The literature offers some example of the capabilities of these tools for the prediction of the noise abatement of complex silencers [6, 7].

LITERATURE SURVEY

Looking at the exhaust systems of common light and heavy duty vehicles, one finds, apart from the usual silencers, the turbocharging device (eventually with its waste-gate valve) and the after-treatment devices. The first solution of after-treatment device to appear on a vehicle was the catalytic converter. Concern about its influence on exhaust noise dates back to the early 1990's [8] and experimental studies on the effect of different catalyst configurations have since then been reported [9, 10]. Regarding the modeling of these devices, there is an abundant literature available, most of which deals with the linear description of wave propagation inside the monolith. Solutions proposed range from finite element formulations incorporating mean flow [11], to analytical [12] and numerical [13] solutions of conveniently reduced equations describing the transversal variation of flow properties. The effect of the cross-section geometry has also been investigated [14], as well as the effect of the existence of an axial temperature gradient [15, 16] and of the wall porosity [17, 18]. Considering the linear analysis not only of the monolith, but of the whole catalytic converter, a transfer matrix formulation, incorporating the details of the flow in the monolith ducts through the definition of a corrected wave number, was presented in [19] and applied later to the study of the relative importance of reactive and dissipative effects [20]. Simple time-domain one-dimensional models for the

whole converter assembly have also been proposed [21]. Regarding the consideration of this acoustic behavior as an additional design criterion, early attempts at the simultaneous optimization of conversion efficiency, flow distribution, total back-pressure and acoustic performance have been reported [22], and also innovative assemblies conceived with the purpose of maximizing exhaust noise suppression [23]. On the other hand, the Diesel particulate filter has recently become the standard solution for particulate emission control in Diesel engines. Problems related with filtration efficiency, thermal aspects and pressure drop are current being investigated, and suitable models addressing those issues have been recently proposed [24]. The acoustics of these devices has been recently analyzed; in particular, wave propagation in the filter unit was first considered in [25], where experimental results together with a 1-D model were presented. The model was then improved taking into consideration the effects of wall porosity and the subsequent interactions between channels [26], with very good results. This model was later used [27] for the analysis of a complex after-treatment device, incorporating a Diesel oxidation catalyst together with the particulate filter, and very good agreement was found when comparing the results with acoustic measurements on the whole unit. In parallel with these developments, first attempts to the overall optimization of Diesel particulate filter design incorporating acoustic performance have also been reported [28], considering the influence of the aspect ratio and of different substrates of the filter. As a summary of the previous considerations, it can be stated that, in general, there is a general awareness of the importance of non-silencer devices for noise control. This results in the search for suitable tools to evaluate their effect on the intake and exhaust wave dynamics, trying to incorporate acoustic considerations as an additional design criterion. Moreover the Diesel after-treatment devices including particulate filters still have a considerable potential to be exploited from the acoustic viewpoint. Thus, the rest of the paper will focus on this type of device.

THE 3DCELL APPROACH

The 3Dcell approach consists in reproducing a 3D geometry as a network of 0D elements, such as volumes, to which characteristic length in the space are assigned [29]. This model was developed and applied to the study of silencing devices by the Internal Combustion Engine Group of Politecnico di Milano. As shown in [Figure 1](#), the 3Dcell framework is defined by means of two fundamental elements, namely cell and connector. The cell element is defined by its volume and by a list of connectors linked to it. The connector element stores information about the connectivity between neighboring cells, and geometrical parameters such as the distance from the adjacent cell centres, the flow area and the direction, with respect to an absolute orientation system, given by the normal to the surface it represents.

The 3Dcell method is based on the formulation of the conservation equations of mass, momentum and energy for unsteady flows in which the gas viscosity, both in the intake and exhaust system, has been neglected. Since its value is very low, this

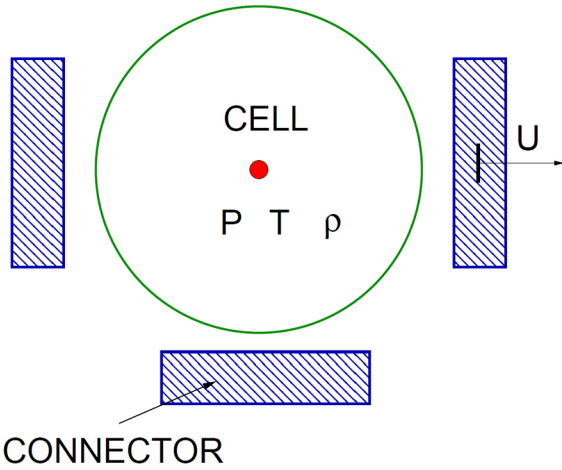


Figure 1. Schematic of the the 3Dcell element: cell and connectors.

approximation is acceptable and allows to considerably simplify the solution procedure, leading to the Euler formulation [30, 31]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \quad (1)$$

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = -\nabla p \quad (2)$$

$$\frac{\partial \rho e_0}{\partial t} + \nabla \cdot (\rho e_0 \mathbf{U}) + \nabla \cdot (p \mathbf{U}) = 0. \quad (3)$$

This system of equations is then closed by the perfect gas equation of state.

The 3Dcell model is based on a pseudo-staggered grid approach, meaning that intensive properties such as pressure, temperature, density, internal energy and other derived quantities are defined over the cell element, while velocity and momentum are defined on the connectors [32, 33]. The continuity and energy conservation equations are solved with respect to the cell element, taking into account the net flux of the conserved variables through all the connectors linked to the cell. According to this type of discretization, the continuity equation can be integrated over the volume and over the time, leading to the following discretized form:

$$\rho^{n+1} = \rho^n + \frac{1}{V} \sum_{c=1}^{N_c} \rho_c^n U_c^n \Delta t, \quad (4)$$

where the subscript c indicates the connector and N_c is the total number of connector linked to the cell. The term U_c indicates the gas velocity at the connector, which is always assumed oriented along the connector direction. Similarly the energy conservation equation can be discretized as follows:

$$(\rho E)^{n+1} = (\rho E)^n + \frac{\Delta t}{V} \sum_{c=1}^{N_c} \rho_c^n E_c^n U_c^n + \frac{\Delta t}{V} \sum_{c=1}^{N_c} p_c^n U_c^n. \quad (5)$$

As can be noted, in this specific case the source term related to the heat exchanged with the walls has not been introduced in the energy equation. In fact the contribution of the convective heat losses is negligible in the case of acoustic simulations of stand alone mufflers at ambient pressure and temperature when small perturbations are imposed as noise source. According to the definition of pseudo-staggered arrangement, to allow the construction of the connector momentum equation, the velocity has been defined also in the centroid of the cell element. The cell velocity is oriented in the space and consequently has three components, as shown in Figure 2. Hence, when the solution of the connector momentum is addressed, the projection of the velocity along the connector normal direction is considered, as shown in Figure 2. This reduces a 3D problem to a 1D problem arbitrarily oriented in space. Therefore, the connector momentum balance will take into account the momentum variation along the connector direction and the resultant of the pressure forces acting on the left and right side of the connector itself [34]:

$$\begin{aligned} (\rho U F)_c^{n+1} &= (\rho U F)_c^n \\ &+ \frac{\Delta t}{\Delta L} [(\rho U_n^2 + p)_L - (\rho U_n^2 + p)_R] F_c \\ &+ M_s, \end{aligned} \quad (6)$$

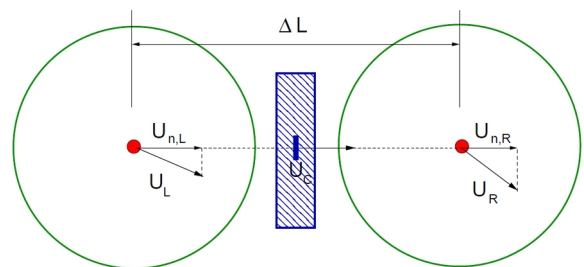


Figure 2. Schematic of the connector element with two neighboring cells.

where ΔL is the characteristic length between the centroid of the two neighboring cells, U_n the projection of cell velocity along the connector normal direction and M_s is a generic source term. This source term can assume different expressions depending on the type of the connector that has to be modeled. Once the connector momentum has been calculated, the cell momentum is determined according to the net momentum flux entering the cell as follows:

$$(\rho \mathbf{UV})_{cell} = \frac{1}{2} \sum_{c=1}^{N_c} (\rho \mathbf{UF}_c \Delta L)_c. \quad (7)$$

In this way, when looping over the connectors linked to a specific cell, only the left or right portion (according to the orientation of the port) of the momentum is accounted. This allows handling clusters of 3Dcell elements in which the mesh spacing is not uniform. Moreover, the summation involves vectorial quantities oriented along the port directions, providing the cell momentum with a direction arbitrarily oriented in the space.

MODELING THE ACOUSTICS OF AFTER-TREATMENT DEVICES

In this section the modeling techniques adopted for the simulation of after-treatment devices will be presented. The two main after-treatment components taken into account are the catalytic converter, being a TWC or a DOC or any other chemically active device based on substrate deposition, and the Diesel Particulate Filter.

CATALYST SUBSTRATE

Monolithic catalyst substrates are honeycomb structures with many small, parallel channels running axially through the part (Fig. 3). The cross-section is typically circular or oval, but sometimes it can be shaped differently depending on specific requirements. Major advantages of monolithic catalyst supports include high geometric surface area (GSA) per unit volume (compactness), large open frontal area (low pressure drop), and low friction resistance. Monolithic catalyst substrates are made of ceramics or metal; the formers usually have square cells, while most metallic substrates have sinusoidal channels. However, other channel cross sections are possible, including triangular, hexagonal, trapezoidal and round, which will not be considered in this work. As long as the substrate is structured, it is possible to find an analytical expression in which the cell density, open frontal area, wall thickness and channel diameter are linked together [35]. From the fluid dynamic point of view, the catalyst is a device which creates a flow resistance in the gas stream, leading to the generation of a pressure drop. This resistance is mainly due to two different contributions: (i) gas-wall friction inside the tiny channels (distributed pressure loss); (ii) sudden

contraction and sudden expansion at the inlet and at the outlet of the monolith respectively (concentrated pressure loss due to vena contracta effects). The 3Dcell model of the catalyst is built taking into account both accuracy and computational demand requirements. This means that the mesh size does not resolve the smallest scale length determined by the thickness of the substrate, avoiding a dramatic increase of computational cells and calculation runtime. Therefore the monolith is discretized as rows of macro-cells having the same mesh size of the fluid cells in the inlet and outlet cones (as shown in Fig. 4). A typical mesh size adopted for this type of simulation is 1cm. Each macro-cell models a group of tiny channels, whose total number is given by the cell frontal area and substrate density. The conservation equations are solved only for a single channel and then extended to all the other channels belonging to the same macro-cell. At the interconnection between the external cell and the catalyst cell the fluxes of mass and energy are multiplied by the number of the channels in the macro-cell.

The mass and energy conservation equations for the solution of the fluid-dynamic field inside the catalytic converter remain unchanged with respect to Eq. 1 and 3. Instead, the momentum equation solved on the connector is modified by the addition of a source term which takes into account the gas-wall friction inside the tiny channels. In particular, the friction term, driven by

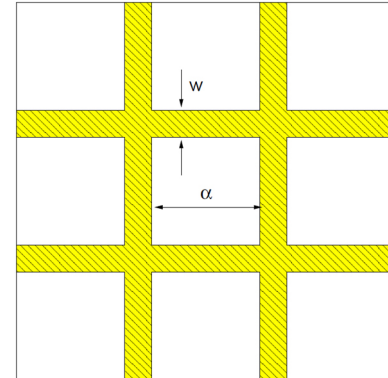


Figure 3. Schematic of the catalyst monolith.

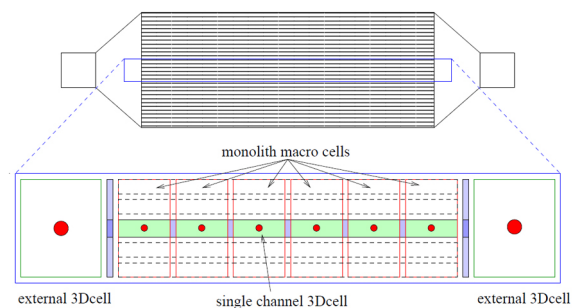


Figure 4. Example of domain decomposition into macro-cells for the modeling of the catalyst substrate.