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A hybrid method of estimating pulsating flow parameters in the space-time domain

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ABSTRACT

This paper presents a method for estimating pulsating flow parameters in partially open pipes, such as pipelines, internal combustion engine inlets, exhaust pipes and piston compressors. The procedure is based on the method of characteristics, and employs a combination of measurements and simulations. An experimental test rig is described, which enables pressure, temperature and mass flow rate to be measured within a defined cross section. The second part of the paper discusses the main assumptions of a simulation algorithm elaborated in the Matlab/Simulink environment. The simulation results are shown as 3D plots in the space-time domain, and compared with proposed models of phenomena relating to wave propagation, boundary conditions, acoustics and fluid mechanics. The simulation results are finally compared with acoustic phenomena, with an emphasis on the identification of resonant frequencies.

1. Introduction

This article introduces a hybrid method for estimating pulsating flow parameters in the space-time domain. Modelling the dynamics of pulsating flows in pipes enables more efficient designs and quieter transport of fluids. Sometimes, modelling the resonance effect can also be useful, e.g. for dynamic charging of engines. The method described here enables four crucial transient flow parameters to be estimated: speed of sound, pressure, temperature and velocity. Initial states and parameters can be measured, but this is not always practical. Our method provides an estimate of intersection parameters based on measurements taken at each end of the relevant pipe. This data is used to specify the boundary conditions. The method is suitable for cases when it is necessary to estimate parameters along a space-time axis.

The proposed method is based on a 1D model of pulsating flows supported by the method of characteristics (MOC) *Palczynski* [1]. MOC is a mathematical technique for solving hyperbolic partial differential equations. The method reduces partial differential equations (PDE) into a family of ordinary equations, enabling a solution to be integrated from initial data. It is a type of finite difference method, which can be either implicit or explicit. *Courant et al.* [2] introduced a first order of accuracy explicit method in 1952, which could be used with the Characteristics form of the hyperbolic type PDE (*Benson* [3]). In 1964, *Benson* [4] proposed a method based on Courant's schemes for simulating internal combustion engines and reciprocating compressors. The proposed method compares well with other first order of accuracy explicit methods and has advantages when dealing with boundary conditions.

In 1952, schemes with second order accuracy were proposed by *Hartee* [5]. In 1960 *Lax and Wendorff* [6] introduced a second order of accuracy explicit method, developed later by *Richtmyer* [7] into a Two Step version. Since the 1980 s and 1990 s, the development of Total Variation Dimensioning (TVD) schemes and Flux Corrected Transport has allowed for the practical use of conservation schemes, such as the two-step Lax Wendorff (LW2) or MacCormack (MC) methods, for intra pipe modelling. The

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combination of TVD and LW2 or MC methods is now a recognized solution for efficient 1D manifold modelling, and is embedded into research (GASDYN) and commercial (GT-POWER) codes. Polish authors have used MOC for the analysis of fluid dynamics (*Jungowski* [8], *Wislocki* [9], *Prosnak* [10], *Puzyrewski* and *Sawicki* [11]) and manifold modelling (*Kordzinski* [12] and *Sobieszczanski* [13]). *Guderlay* [14] formulated a general theory of characteristics, in which variable specific heat capacities were introduced into Riemann invariants. Nowadays, MOC is finding new applications thanks to increases in available computing power and the flexibility of hybrid methods, combining experiment and other software (from 1D to 3D e.g. CFD), as presented by *Montenegro* [15], *Hua Shen* [16], *Galindo* [17,18] and *Bruck* [19]. It has been successfully used for inlet and outlet gas exchange process modelling of internal combustion engines (*Serrano et al.* [20],*Torregrosa et al.* [21], *Chalet* [22] and *Desantes et al.* [23]) and applied graphically by *Benson* [24] and *Winterbone and Pearson* [25]. Building on this research, the proposed method uses experimental data as the initial conditions. Boundary conditions are based on acoustic wave phenomena and the cross-section change coefficient. This makes a clear comparison possible between the model and experimental data taken from references at particular cross sections (in the middle and at the ends of the pipe). The main advantage is the possibility of generating 3D estimates of particular parameters in the space-time domain. This enables very smart and useful representations to be made of experimental-simulation results.

2. Principles of the method of characteristics

Benson's [24] non-dimensional notation was used for first step approximation, where heat transfer and friction in pipes are often omitted (Fig. 1). The flow can be defined as homentropic, and there is no area section change. The two non-dimensional Riemann invariants (α and β) can be defined along the characteristics lines $C^+$and C^- [25]:

$$\alpha = A_i^{n+1} - \frac{\kappa-1}{2} * U_i^{n+1} = A_R^n - \frac{\kappa-1}{2} U_R^n \tag{1}$$

$$\beta = A_i^{n+1} - \frac{\kappa-1}{2} * U_i^{n+1} = A_L^n + \frac{\kappa-1}{2} U_L^n \tag{2}$$

where:

1. L,R,S- nodes at time space domain due to C^+, C^-, C^0characteristics;
2. i-space point;
3. n-natural value at time domain;
4. A-non-dimensional speed of sound $A = \frac{a}{a_{ref}}$;
5. U-non-dimensional velocity $U = \frac{u}{a_{ref}}$;
6. a_{ref} – reference speed of sound.

.

Using MOC, it appears that when all parameters at time step n are known, the Riemann characteristics (Eqs. (1) and (2)) can be calculated. Using this information the next step can be calculated.

For homentropic flow, contraction of the gas between S and the mesh node (i, $n+1$) can be defined:

$$\frac{p_S^n}{(\rho_S^n)^\kappa} = \frac{p_i^{n+1}}{(\rho_i^{n+1})^\kappa} \tag{3}$$

Having found δx_L, δx_R, δx_S (the distance between i node and L, S, R points) the thermodynamic states can be determined at nodes L, R and S using linear interpolation. There should be calculated: ρ_i^{n+1} , u_i^{n+1}, and p_i^{n+1}.

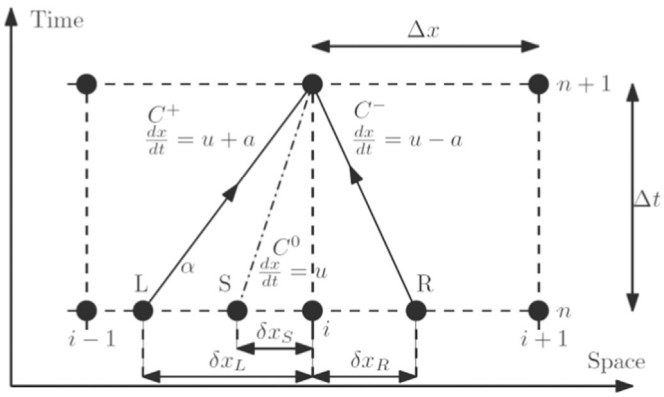

Fig. 1. Method of characteristics on space-time domain [1].