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On the influence of cyclic variability on surface noise contribution analysis of internal combustion engines

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ABSTRACT

Practical mechanical systems often operate with some degree of uncertainty. The uncertainties can result from poorly known or variable parameters, from uncertain inputs or from rapidly changing forcing that can be best described in a stochastic framework. In automotive applications, cylinder pressure variability is one of the uncertain parameters that engineers have to deal with when designing and analyzing internal combustion engines. The characterization of acoustic radiation patterns of internal combustion engines is a challenging task required for the purpose of effective noise reduction. In this paper the influence of cylinder pressure cyclic variability on the assessment and ranking of the different radiating engine surfaces is investigated. A surface contribution analysis (SCA) within a wave based method (WBM) framework is adopted for the assessment of noise radiated from different vibrating surfaces of an engine structure. The method adopted consists in the decomposition of the boundary conditions of the WBM model, assuming the linearity of the vibrational problem associated to the generation of the vibrations on the structure surface, for which the superposition principle is valid. In order to investigate the cyclic variability of cylinder pressure, a Monte Carlo approach is adopted. Starting from measured cylinder pressures that exhibits cyclic variability, random Gaussian distribution of the equivalent force applied on the piston is generated. The results obtained from this analysis are used to derive correlations between cyclic variability and statistical distribution of the results. The statistical information derived can be used to advance the knowledge of the WBM and SCA applications when uncertain inputs are considered.

1. Introduction

Together with the reduction of fuel consumption and exhaust pollution, noise reduction is one of the main topics of interest in internal combustion engine development, because of the more and more strict noise legislation and the increasing customer demands. Engine noise can be separated into structure-borne noise and air borne noise. Structure-borne noise is generated from combustion and mechanical phenomena that occur inside the engine, it is transmitted through the engine structure and it is radiated from the external surface of the engine. Conversely, air borne noise is directly generated into the air in correspondence of intake and exhaust systems. The air borne noise can be significantly reduced adopting air intake and exhaust mufflers, therefore, surface radiated noise becomes the predominant acoustic issue. Covers, such as oil pans, valve covers and front gear covers, are important engine components used to contain liquids (oil and/or water) and, in many applications, also to reduce the noise emission of the internal components. It has been shown that most of the noise is radiated from covers and an optimal cover design can considerably improve the noise emission [1,2]. In order to understand where and how to improve the external covers and engine surfaces design, it is necessary to analyze and rank the different engine surfaces in terms of emitted noise. Experimentally, several methods can be used to rank the different radiating surfaces: Lead covering (also called shielding technique), surface vibrations technique, acoustic intensity technique and acoustic holography [3–5]. To reduce design and development timing and costs, computer-aided-engineering (CAE) methods are extensively used. In industrial applications the finite elements method (FEM) and the boundary element method (BEM) are the most widely used methods to predict the acoustic field in interior and exterior radiation problems.

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Specific methods within FEM and BEM framework were developed with the aim to analyze and rank different radiating surfaces of a body, such as panel contribution analysis (PCA) [6–8]. In addition to FEM and BEM, the wave based method (WBM) has been developed as an alternative method for solving steady-state acoustic problems in the mid-frequency range [9]. It is based on an indirect Trefftz approach [10–12] and the field variables are expressed in terms of globally defined shape functions, which are the exact solutions of the homogeneous governing differential equation, but which do not necessarily satisfy the boundary conditions [9,13]. The wave models are substantially smaller than equivalent FEM and BEM counterparts and exhibit an increased computational efficiency [14,15]. The WBM is nowadays applied to model many different problems, for example interior acoustic problems [13,16–18], exterior acoustic problems [19–23], plate and membrane problems [24–28], coupled vibro-acoustic problems [9,11,16] or poroelastic material modeling [29,30]. A wide overview on the WBM can be found in [31]. Within the WBM framework, also a surface contribution analysis (SCA) was proposed to assess and rank the different radiating surfaces of the investigated system [32]. In this paper the SCA is used to evaluate the noise contributions of the different radiating surfaces. SCA consists in the decomposition of the boundary conditions of the WBM model, assuming the linearity of the vibrational problem associated to the generation of the vibrations on the structure surface, for which the superposition principle is valid. In common industrial applications, the engine surface vibrations are derived from flexible multi-body dynamic (FMBD) simulations [33]. FMBD systems are non-linear systems that exhibit large rigid body motion with associated small flexible deformations of the bodies [34–36]. FMBD models of internal combustion engines may have inaccuracies, which are caused by parameter uncertainties: joint clearances, friction, lubrication, load estimation, material non-uniformities, manufacturing and assembly errors are examples of factors influencing the model uncertainties. These inaccuracies generate also variations in the acoustic response and in the assessment of the radiating surfaces.

In literature, several methods can be found to formally assess the effects of uncertainties in mechanical systems. The Monte Carlo (MC) approach is an extensively used method in dynamic models. It consists of repeated random sampling of a set of system parameters to obtain the uncertainty distribution via numerical simulation results [37–39]. Being computationally demanding, Latin Hypercube Sampling [40] and Bayesian methods [41,42] were introduced to overcome classical MC limitations. In this paper, a Monte Carlo methodology is applied to determine the influence of the variability of statistically independent excitations on numerical results of WBM for the computation of acoustic exterior radiation.

In particular the paper focuses on the influence of cylinder cyclic variability on the assessment of radiating surfaces via a SCA. Cyclic variability has been observed since the earliest scientific studies of internal combustion engines [43,44]. Although in the beginning the predominant understanding of cyclic variability was that cycle-to-cycle variations were of stochastic nature [45,46], there have been many attempts to analyze the cycle-to-cycle variations by applying deterministic methods from nonlinear dynamical systems and chaos theory [47–51]. In general, it can be said that the physiochemical processes in an internal combustion engine are influenced by many factors like composition of fuel air mixtures, amount of recycled gases in the combustion chamber, engine aeredynamics or engine operating conditions. In this paper the cylinder pressure experimentally obtained from engine on a test bed and the cylinder pressure variability is statistically treated and used as the input for the multi-body dynamic simulations. Surface normal velocities obtained from the FMBD simulations are used as boundary conditions for the WBM on which SCA is applied.

2. Wave based method for exterior radiation problems

2.1. Problem definition

Let us consider an exterior acoustic problem with a vibrating structure which boundary $\partial\Omega$ is surrounded by an unbounded 3-dimensional fluid domain Ω. The fluid is characterized by its speed of sound c and density ρ. Assuming that the system is linear, the fluid inviscid and isotropic and that the process is adiabatic, the steady state acoustic pressure field is governed by the homogeneous Helmholtz Eq. [52]

$$\nabla^2 p(\boldsymbol{r}) + k^2 p(\boldsymbol{r}) = 0 \tag{1}$$

where $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ is the Laplace operator, p the acoustic pressure, $\boldsymbol{r}$ the position vector, $k = \frac{\omega}{c}$ is the wave number (the ratio between frequency ω and speed of sound c). In Eq. (1) the source term is set to zero. There are three possible boundary conditions associated to this problem, assuming that the solid and the fluid structures are not coupled:

- Imposed normal velocity (Neumann boundary condition)

$$v_n(\boldsymbol{r}) = \frac{\mathrm{i}}{\rho\omega}\frac{\partial p(\boldsymbol{r})}{\partial \boldsymbol{n}} = \bar{v}_n(\boldsymbol{r}), \quad \forall\ \boldsymbol{r} \in \partial\Omega_v \tag{2}$$

- Imposed acoustic pressure (Dirichlet boundary condition)

$$p(\boldsymbol{r}) = \bar{p}(\boldsymbol{r}), \quad \forall\ \boldsymbol{r} \in \partial\Omega_p \tag{3}$$

- Imposed normal impedance (Mixed boundary conditions)

$$p(\boldsymbol{r}) = \overline{Z}_n(\boldsymbol{r})\, v_n(\boldsymbol{r}) = \overline{Z}_n(\boldsymbol{r})\frac{\mathrm{i}}{\rho\omega}\frac{\partial p(\boldsymbol{r})}{\partial \boldsymbol{n}}, \quad \forall\ \boldsymbol{r} \in \partial\Omega_z \tag{4}$$

where i is the imaginary unit, $\boldsymbol{n}$ is the normal vector and $\overline{Z}_n$ denotes the normal impedance. Furthermore, $\partial\Omega_p \cup \partial\Omega_v \cup \partial\Omega_z = \partial\Omega$. Considering an exterior radiation problem, where the acoustic waves are radiating towards infinity, the Sommerfeld radiation condition is applied on the boundary, Γ_∞ in order to ensure that no acoustic energy is reflected at infinity, see [53]:

$$\lim_{|\boldsymbol{r}|\to\infty}\left(|\boldsymbol{r}|\left(\frac{\partial p(\boldsymbol{r})}{\partial|\boldsymbol{r}|} + \mathrm{i}kp(\boldsymbol{r})\right)\right) = 0 \tag{5}$$

Γ_∞ is the boundary placed in the far field and represents the limit of the fluid domain in a numerical model (see Fig. 1a). As described in [21] and [54], the WBM includes an additional treatment to tackle exterior radiation problems with the introduction of an artificial truncation boundary that defines two sub-domains: a bounded part and an unbounded part. In the bounded region of the domain, the WBM formulation for interior problems is applied, whereas in the unbounded region, radiating functions, which satisfy the Sommerfeld radiation condition, are employed. The modeling strategy is shown in Fig. 1b, where an internal combustion engine is investigated.

2.2. Bounded region

In general, the WBM requires a convex domain to ensure convergence towards the exact solution [9,13] (see [55] for cases, where the WBM can be directly applied to non-convex domains). Therefore, it is necessary to decompose non-convex domains into a set of N_v convex