Journal of Sound and Vibration 396 (2017) 289–306

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Phenomenological methodology for assessing the influence of flow conditions on the acoustic response of exhaust aftertreatment systems

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ARTICLE INFO

Article history:
Received 4 August 2016
Received in revised form
30 January 2017
Accepted 13 February 2017
Handling Editor: P. Joseph
Available online 24 February 2017

Keywords:
Aftertreatment system
Acoustics
Transfer matrix
Test
Modelling

ABSTRACT

The increasing limits of standards on aerosol and gaseous emissions from internal combustion engines have led to the progressive inclusion of different exhaust aftertreatment systems (EATS) as a part of the powertrain. Regulated emissions are generally abated making use of devices based on monolithic structures with different chemical functions. As a side effect, wave transmission across the device is affected and so is the boundary at the exhaust line inlet, so that the design of the latter is in turn affected. While some models are available for the prediction of these effects, the geometrical complexity of many devices makes still necessary in many cases to rely on experimental measurements, which cannot cover all the diversity of flow conditions under which these devices operate.

To overcome this limitation, a phenomenological methodology is proposed in this work that allows for the sound extrapolation of experimental results to flow conditions different from those used in the measurements. The transfer matrix is obtained from tests in an impulse rig for different excitation amplitudes and mean flows. The experimental coefficients of the transmission matrix of the device are fitted to Fourier series. It allows treating the influence of the flow conditions on the acoustic response, which is manifested on changes in the characteristic periods, separately from the specific properties of every device. In order to provide predictive capabilities to the method, the Fourier series approach is coupled to a gas dynamics model able to account for the sensitivity of propagation velocity to variations in the flow conditions.

1. Introduction

Noise emission abatement in internal combustion engines is performed by the design of particular mufflers tuned to specific applications and market demands. The ability and design flexibility of these systems for noise attenuation, which is based on both dissipative and reactive features [1], has been widely proved from theoretical and experimental approaches [2]. Nevertheless, the increasingly constraining regulations on pollutant emissions, with US [3] and Europe [4] in front, have led to the inclusion of additional devices in the exhaust line. These exhaust aftertreatment systems (EATS) are primarily devoted to gas and aerosol emission abatement [5]. However, there is also general consensus on the fact that through flow

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http://dx.doi.org/10.1016/j.jsv.2017.02.033
0022-460X/

Nomenclature

Nomenclature

a	speed of sound
a_k	main Fourier series constant
a'_k	residual Fourier series constant
A	cross-section area
b_k	main Fourier series constant
b'_k	residual Fourier series constant
C	coefficient
D	monolith diameter
e	deviation Fourier series
e_f	absolute parameterization error
f	frequency
F	main Fourier series
I_A	impulse in test with device
I_B	impulse in test without device
Im	imaginary part
L	monolith length
N	vector dimension
p_{comp}	composed pressure
p_{inc}	incident pressure
p_0	unperturbed medium pressure
p_{ref}	reflected pressure
P	acoustic pressure
r	transmission matrix coefficient related with reflection
R^2	coefficient of determination
$R_{I_A I_A}$	autocorrelation of I_A
$R_{I_B I_A}$	cross-correlation of I_B against I_A
Re	real part
$\mathbf{S}$	scattering matrix
S_{ij}	scattering matrix term
$\mathbf{T}$	transfer matrix
t	transmission matrix coefficient related with transmission
V	mass velocity
w_w	monolith channel wall thickness
$\mathbf{Y}$	characteristic impedance matrix
Y	characteristic impedance

Greek letters

α	honeycomb cell size
γ	specific heat ratio
Δ	transmission matrix determinant
π	characteristic periods ratio
σ	cell density
τ	characteristic period of main Fourier series
τ'	characteristic period of deviation Fourier series

Acronyms

0D	zero-dimensional
1D	one-dimensional
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EATS	exhaust aftertreatment system
GPF	gasoline particulate filter
LNT	lean NOx trap
POC	particle oxidation catalyst
SCR	selective catalyst reduction
TWC	three-way catalyst

Subscripts

b	baseline operating point
exp	referred to experimental data
in	inlet
j	real or imaginary part of t or r coefficient
mod	fluid-dynamic model
n	Fourier series order
out	outlet
p	arbitrary operating point
pr	prediction

[6] and wall-flow [7] monolithic structures act as reactive and dissipative silencers due to its non-negligible influence on the unsteady wave dynamics [8].

The presence of EATS produces variations in the flow evolution upstream of the muffler. These comprise diffusion and expansion in the outlet and inlet volumes of each device, as well as local expansion and diffusion at the inlet and outlet interfaces of the monolith, respectively. Similar processes take place between monoliths separated by an intermediate chamber, as in devices composed of a Diesel Oxidation Catalyst (DOC) and a Diesel Particulate Filter (DPF) which are usual in Diesel engines for the control of unburnt hydrocarbons (HC), CO and particulate matter [5]. The removal of nitrogen oxides (NOx) takes usually place in isolated bricks. In heavy-duty Diesel engines, the leading concept for NOx removal is the Selective Catalyst Reduction (SCR) system, which presents higher conversion efficiency than Lean-NOx Trap (LNT) devices, and allows running the engine at maximum efficiency in fuel-sensitive applications [9]. In small Diesel engines, NOx abatement in the aftertreatment is to be performed by LNT devices, which exhibit lower cost than SCR [10] and are likely to substitute [11] or complement [12] the DOC. For these applications, the combination of LNT and SCR presents significant advantages in terms of increase in NOx conversion efficiency and of reduction in ammonia slip [13]. Other solutions being explored are related to the inclusion of NOx-removal functions into the DPF substrate [14] as a way to reduce the cost of the monoliths and the space requirements. Recently, non-ceramic solutions such as the particle oxidation catalyst (POC) are also being considered [15]. In gasoline engines, the Three-Way Catalyst (TWC) is a single device responsible of CO, HC and NOx emission reduction. However, new gasoline engine generations are requiring the inclusion of a Gasoline Particulate Filter (GPF) monolith to comply with particulate matter regulations [16].