Journal of Sound and Vibration 375 (2016) 1–18

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Development and experimental verification of a robust active noise control system for a diesel engine in submarines

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ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form
23 February 2016
Accepted 18 April 2016
Handling Editor: P. Joseph
Available online 25 April 2016

ABSTRACT

This paper presents the development and experimental validation of an ANC (active noise control)-system designed for a particular application in the exhaust line of a submarine. Thereby, tonal components of the exhaust noise in the frequency band from 75 Hz to 120 Hz are reduced by more than 30 dB. The ANC-system is based on the feedforward leaky FxLMS-algorithm. The observability of the sound pressure in standing wave field is ensured by using two error microphones. The noninvasive online plant identification method is used to increase the robustness of the controller. Online plant identification is extended by a time-varying convergence gain to improve the performance in the presence of slight error in the frequency of the reference signal.

1. Introduction

Exhaust noise of the combustion engine in general contains several harmonic components of the fundamental frequency (CFR – cylinder firing rate) that depend on the engine speed. The geometry of the manifold and of the tail pipe as well as the plant conditions (i.e. exhaust gas temperature, gas flow and boundary impedances) determine the prominence of individual harmonics in the exhaust noise spectrum outside the tail pipe. Tones with frequencies lower than 150 Hz are especially prominent in the noise spectrum of large-bore engines used in submarines. During the diving cruise with a snorkel, the diesel engine is operated with a unique revolution speed. This determines the acoustic signature of the submarine such that positioning and identification of the submarine are facilitated.

Active noise cancellation (ANC) methods are of interest here due to the physical limitations of passive measures at low frequencies. Thereby, the volume requirements of passive measures are often impractically high for submarine applications. ANC-systems in general use sensors (error sensors) to measure the disturbing noise (primary noise), a controller and actuators (secondary sources) to generate the secondary noise for canceling the primary noise. Additional sensors (reference sensors) can be used to reference the primary source.

An ANC-system in the exhaust line of a large-bore diesel engine faces serious challenges such as high temperature, high sound pressure levels (SPL), standing waves phenomena, a time-varying environment and slightly varying disturbance frequencies. In the case of applications with a non-acoustic reference sensor, also an offset or a mismatch in the estimation of disturbance frequencies negatively affects the performance. Various existing ANC approaches for exhaust

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http://dx.doi.org/10.1016/j.jsvi.2016.04.016
0022-460X/

Nomenclature

A	Tube area
b	Bandwidth parameter of a band-pass filter
c	Speed of sound
C_1, C_2	Constants of integration
d	Disturbance signal
e	Error signal of the controller
f	Frequency
g	Error signal of the online modeling
$\mathbf{h}$	FIR filter coefficients for the online modeling algorithm
J	Cost function of the LMS algorithm
k	Wavenumber
K	Amount of flanks in RPM sensor signal considered for CFR estimation
M	Mach number; number of sinusoids in a disturbance signal
n	Discrete time index
N	number of sensor marks used in RPM sensor
p	Acoustic pressure
P	Complex amplitude of the acoustic pressure; Primary plant response
$\mathbf{p}$	Impulse response of the primary path (FIR filter coefficients)
Q	Band-pass filter response
r	square wave signal of the RPM- sensor; radius of the tube
R	Reflection coefficient
$\mathbf{s}$	Impulse response of the secondary path (FIR filter coefficients)
S	Secondary plant response
t	Continuous time
T_s	Sampling time, $t = nT_s$
u	Signal samples buffer for the online modeling algorithm
v	Acoustic mass velocity
V	Complex amplitude of the acoustic mass velocity
w_0, w_1	Controller coefficients (FIR filter)
W	Controller response
x	Coordinate, reference signal
y	Controller output signal
Y	Characteristic impedance for waves in a pipe
Z_{is}	Internal impedance of a source
α	Acoustic pressure attenuation constant
β	Leakage factor
γ	Leakage term, $\gamma = 1 - \mu\beta$
ζ	Specific acoustic impedance
ϑ	Temperature
λ	Wavelength
μ	Convergence factor
ξ	Power estimation of the error signal
ϱ	Scaling factor for the online modeling
ϕ	Phase shift
σ	smoothing factor for signal power estimation
ω	Angular frequency
Ω	Normalized angular frequency, $\Omega = \omega T_s$

lines of a combustion engine do not address all these problems. Most use error microphones outside the exhaust line and, in the case of a feedforward controller for tonal disturbances, a tachometer to generate the reference signal [1–7]. Therefore, the problem of the observability of the sound pressure in the standing wave field inside the exhaust line is avoided. In ANC-systems using an acoustic reference sensor inside the exhaust line [8–14] and/or error microphones inside the exhaust line [15–19], it is assumed that they do not lie in the nodes of the standing wave field. To overcome the problem of time-varying plants, some of the considered ANC-systems [4–8] use either different online plant modeling methods or a robust controller.

An especially appropriate online plant modeling method for applications with high SPL of the primary source is the noninvasive online plant identification method [20–22]. Our experiments, however, show that the nominal performance of a tonal ANC-system with noninvasive system identification can be decreased hardly by a slight frequency mismatch in the reference signal.

This paper presents the development and experimental validation of an ANC-system designed for a particular application in the exhaust line of a submarine. The ANC-system is based on the feedforward leaky FxLMS-algorithm [23,24]. The observability of the sound pressure in standing wave field is ensured by using two error microphones. The noninvasive online plant identification method is used to increase the robustness of the controller. Online plant identification is extended by a time-varying convergence gain to improve the performance in the presence of slight error in the frequency of the reference signal.

2. Problem description

On the strength of constructive restrictions in submarines, the ANC-system has to be mounted directly behind the passive muffler. Tonal noise components canceled insufficiently by the passive muffler should be canceled additionally by the ANC-system. Sensors and actuators have to be placed along a duct segment of 800 mm length and 150 mm diameter, as sketched in Fig. 1. An electrodynamic loudspeaker serves as the actuator. Due to the high exhaust gas temperature, the loudspeaker has to be protected by a branch pipe containing a cooler. The error sensors have to be heat resistant. An engine speed sensor is available for reference signal generation.