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Robust active noise control in a car cabin: Evaluation of achievable performances with a feedback control scheme

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ABSTRACT

The application dealt with in this paper is the active attenuation of broadband noise (produced by the tire/road contact) in a car cabin, using only a feedback control scheme (1-DOF (one degree of freedom)). The objective of the proposed control methodology is to evaluate achievable performances according to the frequency bandwidth in which attenuation is desired. This is investigated numerically, by seeking a multi-input multi-output (MIMO) active noise control solution that reaches the best attenuation level, under explicit robustness constraints. The paper aims to (i) formalize the underlying optimization problem including performance and robustness indicators as well as industrial constraints, (ii) perform an effective MIMO identification, and (iii) provide an *a priori* control structure and then proceed to direct optimization of some meaningful parameters using a well-suited nonsmooth optimization solver. Finally, the simulation and experimental results obtained following the proposed methodology are shown and discussed.

1. Introduction

The principle of active noise control (ANC), which consists of attenuating an annoying noise with an anti-noise of the same magnitude and shifted by half a wavelength, was described for the first time in the 1930s in two patents (Coanda, 1930; Lueg, 1936). In practice, the level of difficulty associated with an ANC problem varies. For example, ANC in an open-ended duct, involving propagating waves, can be achieved by means of a 2-DOF control scheme (*i.e.* a pre-compensation coupled with a feedback control) since the disturbing noise can be measured both upstream of the actuator and at the end of the duct (Carmona & Alvarado, 2000; Hull, Radcliffe, & Southward, 1993; Kaiser et al., 1996; Peña, Cugueró, Masip, Quevedo, & Puig, 2008). In contrast, applications of ANC in enclosures need to deal with stationary waves. Good performances can still be obtained if the actuators and sensors are co-located, such as in active headphones or active headrest applications (Das, Moreau, & Cazzolato, 2013; Pawelczyk, 2004; Rafaely & Elliott, 1999). The difficulty increases when the actuators and sensors are not co-located, such as in the problem of attenuating engine noise at the position of passengers' ears in a car cabin using door loudspeakers. However, an advantage in this particular case is that the engine noise has a line spectrum whose frequency can be directly deduced from the measure of the engine speed (Cheer, 2012; Schirmacher, Hunkel, & Burghardt, 2012; Vau, 2009).

In the present paper, the considered application consists of attenuating low frequency broadband noise in a car cabin. The main source of this broadband noise is the road noise, which is generated by the tire/road contact. In this case, obtaining a measure of the perturbation is generally not feasible due to industrial costs and integration constraints. Moreover, the attenuation must be obtained not at some isolated frequencies but over a (wide) frequency range. The authors previously proposed a single-input single-output (SISO) robust multi-objective ANC control synthesis in Loiseau, Chevrel, Yagoubi, and Duffal (2015) and an overall methodology to compare the best achievable performances according to the number of sensor(s) and actuator(s) used (Loiseau, Chevrel, Yagoubi, & Duffal, 2016, 2017b). The current paper pursues the latter objective by considering the needs of the automotive industry, using only feedback and exploiting the available microphones and loudspeakers. Hence, this paper is an improved and extended version of the authors' initial work presented in Loiseau, Chevrel, Yagoubi, and Duffal (2017a). In particular, a far more complete overview of possible indicators is provided. The possibilities and limitations of all these indicators are fully discussed and illustrated with concrete results. This discussion, which is central when dealing with the evaluation of multivariable ANC solutions or aiming to compare multivariable ANC strategies, is missing in the current literature. Then, improved and additional results are provided and analyzed in more depth. The results presented in Loiseau et al. (2017a) were encouraging, but did not enable any conclusion about the achievable performances on the vehicle platform; this was pointed out as a perspective. In the present paper, this remaining problem is solved and clear conclusions are given

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with regard to the vehicle platform. Finally, this paper is more detailed and gives a more precise overview of the whole study conducted by the authors.

Solving the considered ANC problem requires two crucial points to be addressed: (i) obtaining an acoustic model that reproduces finely the system behavior over a sufficiently large frequency range and (ii) defining a generic control synthesis problem faithfully reflecting the industrial constraints.

Let us first consider how to obtain a model of the system. A direct way to derive an acoustic model is to solve the wave equation with the appropriate boundary conditions. This leads to a model of infinite dimension, which can generally be reduced to a finite dimension model by keeping only the predominant acoustic modes. However, this approach suffers from several drawbacks. First, purely acoustic models usually fail to reproduce the system behavior and coupling with structural dynamics must generally be taken into account (see, for example, Cheer, 2012; Fang, Kelkar, Joshi, & Pota, 2004). Secondly, realistic boundary conditions are usually complex to formalize and the simplifications made are the main source of error for analytical models (Fang et al., 2004). In addition, there is no systematic technique for estimating the damping. For these reasons, this paper opts for the identification approach.

Most methods used to identify an acoustic model for ANC (LMS, RLS, ARMA, ARMAX, OE) proceed in the time domain and look for discrete time models (Elliott, 2001; Ljung, 1999). Another approach presented in Petersen and Pota (2000) is to minimize the distance between the measured frequency response of the system and an adequate transfer function. This method is effective for narrow frequency ranges, but encounters difficulties for increased system dimensions and model order. Lastly, a method commonly used in ANC applications is subspace identification (McKelvey, Fleming, & Moheimani, 2000; O'Brien, Jr Watkins, Piper, & Baumann, 2000; Pota, Petersen, & Kelkar, 2002). This approach identifies either a continuous or a discrete time model, from either frequency or time domain data. It is not based on parametric optimization and consequently does not need any particular parametrization for the model. It does not suffer from the convergence problems encountered by iterative algorithms. Moreover, models are obtained directly in the state space and the frequency approach is well suited for systems with a high modal density and poorly damped modes (McKelvey et al., 2000).

In the present work, the subspace approach operating in the frequency domain was found to be one effective method of reproducing the system behavior over a large frequency range [20–1000] Hz. This large range is needed to achieve broadband attenuation safely with a feedback control scheme. In fact, as formalized by the Bode integral relation, the attenuation on the sensitivity function at certain frequencies is obtained at the price of an amplification at other frequencies. (This phenomenon is typically referred to as the "waterbed effect".) Thus, a feedback controller will contain dynamics outside the target frequency range (here [30–400] Hz, see Section 2.1) and the system behavior must be known over a wider range, which unfortunately results in high order models. As in Loiseau et al. (2015, 2016, 2017a, 2017b), the subspace method is used to obtain a continuous time model from frequency domain data (see McKelvey (2004) and Overschee and Moor (1996) for details on the corresponding identification algorithm). The authors also tested some alternative approaches such as the one based on Loewner matrices (Lefteriu, Ionita, & Antoulas, 2010). To date, They have led to results similar to those obtained with the subspace approach.

Concerning the control problem itself, the proposed control methodology aims to evaluate achievable performances depending on the frequency bandwidth in which attenuation is desired. It also concentrates on robustness, which is not the case of most existing adaptive control strategies. In fact, the extensive literature dedicated to this subject refers to the FxLMS adaptive control strategy and its numerous variants (Cheer, 2012; Elliott, Stothers, & Nelson, 1987; Sano, Inoue, Takahashi, Terai, & Nakamura, 2001; Sutton, Elliott, McDonald, & Saunders, 1994), whose robustness is not yet fully established. Elements of a comparison between the FxLMS strategy and the approach proposed in this paper can be found in Boultifat, Loiseau, Chevrel, Lohéac, and Yagoubi (2017). This is by no means the purpose of the current paper. However, it can be noted that the results obtained in Boultifat et al. (2017) in the SISO case show that the present strategy is better suited to evaluate achievable performances accurately.

Other approaches deal with robust control strategies, such as LQG (Liu, Fang, & Kelkar, 2003; Petersen, 2001) or standard $\mathcal{H}_\infty$ (O'Brien et al., 2000; Yang, van Niekerk, Parwani, Packard, & Tongue, 1993). Based on convex optimization problems, these approaches are certainly tractable and offer interesting solutions to some specific ANC problems. However, for broadband attenuation problems, control engineers are faced with high order models and highly constrained control problems, often leading to unsolvable problems or to solutions far from realistic specifications (too conservative).

The alternative approach proposed in this paper aims to formulate a multi-objective control problem, by specifying performance and robustness explicitly. Clearly, the underlying optimization problem is both non-convex and non-smooth. However, powerful non-smooth solvers now exist that enable a rapid convergence to local optima. Combined with an appropriate initialization step, they can solve the problem without pessimism.

The paper is organized as follows: first, the ANC problem and the experimental demonstrators are presented in Section 2. Then, an overview of performance and robustness indicators for ANC applications is given in Section 3. Section 4 describes the identification process used to obtain an acoustic model for the two demonstrators considered. Then, the proposed control strategy is introduced in Section 5. Finally, Section 6 is dedicated to analyzing the results and discussing achievable performances, while the conclusion summarizes the content and contributions.

2. Problem description

2.1. Automotive context and industrial specifications

Inside a car cabin, permanent noise mainly comes from three sources:

- aeroacoustic noise;
- engine noise;
- road noise.

Aeroacoustic noise, generated by the air flow around the vehicle, mainly affects high frequencies, while engine noise and road noise (generated by the tire/road contact) intervene at low frequency. To date, noise reduction inside cars has essentially been achieved through passive treatments. These technologies are based on a judicious adjustment of the mass, stiffness and damping of the different components of a car in order to reduce the noise either directly at its source or during its transmission to the cabin. Passive technologies provide a good level of comfort, especially when considering high frequency noise such as aeroacoustic noise. However, for low frequency noise such as engine and road noise, they require a large addition of weight. In order to meet challenging fuel consumption constraints, car makers are therefore looking for alternative technologies that reduce low frequency noise without a negative impact on consumption.

ANC solutions, which are essentially efficient at low frequencies, are seen as a promising alternative and some are already used to reduce engine noise (Cheer, 2012; Schirmacher et al., 2012; Vau, 2009). This noise has a line spectrum whose harmonics move according to the engine speed. By measuring the engine speed, the frequencies of the different harmonics are easily identified and those that emerge clearly from the background noise are reduced.

After the successful application of ANC to engine noise, the next step is to consider road noise reduction. Contrary to engine noise, road noise has a broadband spectrum (from approximately 30 to 400 Hz) coming from four (potentially independent) sources (the wheels). Moreover, the