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Design and experimental tests of active control barriers for low-frequency stationary noise reduction in urban outdoor environment

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ABSTRACT

Active noise control (ANC) techniques are based on the emission of an antiphase signal in order to cancel the noise produced by a primary source. ANC has been successfully applied especially for reducing noise in confined environments, such as headphones and ducts. In this study, we present an application of ANC concepts to the design of an anti-noise barrier for an outdoor environment and its experimental testing. Even though passive techniques are effective in noise reduction at middle-high frequencies, they become less efficient at low frequencies (below 300 Hz) due to the limited dimensions of commonly deployable barriers. In this paper, we analyze the properties of a low-cost active noise system able to efficiently operate on stationary, almost pure-tone, low-frequency noise, such as that produced by electrical transformers and reactors in power and transformation plants. A prototype has been implemented and on-the-field experimental tests have been carried out. The results (confirmed also by numerical simulations) demonstrate a remarkable efficiency in the far field, with a reduction up to 15 dB with respect to the absence of the ANC system.

1. Introduction

Active noise control (ANC) techniques [1–3] are nowadays becoming more and more refined and have reached a high level of maturity that allowed their integration into modern acoustic devices, mainly targeted to hearing aids, headphones [4] and propagation of noise in ducts [5]. In recent years, applications proposed for an open field scenario (open spaces, ambient noise propagation [6,7]) also appeared. This latter field poses the most challenging problems, being subject to wind, rain, temperature gradients, randomly moving sources with broadband emission spectrum, etc.

One of the most promising research topics explored in this field in the last decade consists of the development of active noise barriers (ANB) able to perform active control of the noise propagated in the *shadow* zone through the diffraction over the barrier borders. In ANB applications, the ANC techniques may be coupled with passive ones for the reduction of broadband noise. Passive methods, based on noise absorbing and insulating materials, are effective in the mid-high frequency range of the audible spectrum, whereas their use at low frequencies (e.g., in the range 20–300 Hz) implies the deployment of high dimension barriers, depending on the wavelength to be canceled, which are unfeasible for economic and environmental impact reasons. On the other side, ANC techniques are able to implement a fairly good control of low-frequency noise emissions.

In recent years, a certain number of promising studies appeared in the literature, showing the feasibility of ANB solutions in the open field [6–18]. The key issue in ANB design is the availability of fast converging algorithms and filters in order to adapt to fast changing scenarios, either due to the variability of the noise signal to be canceled or to the environmental changes. Early theoretical studies of actively controlled noise barriers were reported by Omoto and Fujiwara [10] that studied the application of active noise control - and achieved cancellation of sound pressure - at the diffraction edge of the barrier. In the following decades, a relevant number of papers explored ANB solutions and produced important theoretical and experimental results. ANB prototypes were reported by Ohnishi et al. [6,11], showing the feasibility of a feedback active solution working with an artificial stationary broadband source, with an additional noise attenuation of about 4–5 dB (with respect to the passive barrier) in a region up to 10 m behind the barrier. Many theoretical studies explored advanced control methods [13,14] and refined the initially proposed techniques. In [16], an analog circuit feedback control system is used to deploy an active noise barrier, whereas in [17,18], the advantages of directional secondary sources are investigated.

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Recently, the feasibility of an ANB solution with reductions of up to 10 dB in a controlled environment (anechoic room) has been demonstrated [7]. These results are promising if compared to the performance of passive anti-diffractive devices – usually placed on the top of the barrier - that allow an additional noise attenuation of only 1–2 dB with respect to a regular barrier to be achieved [19].

As to the features of possible noise sources in industrial contexts, there are plants and devices that produce almost-stationary low-frequency noise: one example is the case of electrical transformers and reactors in power generation and transformation plants. Even though such stations were originally built outside urban areas, as a consequence of urban expansion often they are now surrounded by residential buildings and the problem of noise reduction is relevant for people living in their neighborhood. Abating such type of noise by using only passive barriers, however, may be difficult. In the context of possible solutions for smart cities development, we present in this paper a technologically advanced ANB system aiming at reducing noise in the urban surroundings of power plants. The proposed solution uses the walls around the transformers of the power plant that are mandatorily deployed for safety reasons against accidental flames and fires. The dimensions of the walls, however, are not sufficient to cancel noise at low-frequencies. In this paper, we present the design of an ANC system for cancelling low-frequency stationary noise. The system uses the filtered-x least mean square (Fx-LMS) algorithm [1] to create the anti-noise signal that cancels out the primary source of noise. A testbed of the system, working in real-time, has been implemented and several experimental measurements to assess its performance have been performed. The results show that additional noise reduction (with respect to the absence of the ANC system) of more than 10 dB are achievable in the far field. The experimental results have been confirmed by computer simulations by using a finite element methods (FEM) software. Such simulations may also be useful to predict the system behavior in more general settings that were not covered by the experimental ones (an example is shown at the end of the paper).

The paper is organized as follows. In Section 2, the principle at the basis of the proposed ANC system is described. In Section 3, the control algorithm implemented in the prototype is presented. In Section 4, some computer simulations obtained by using a FEM software and aiming at investigating the influence of some geometrical parameters of the proposed system are shown. In Section 5, experimental results demonstrating the amount of noise attenuation experienced when the proposed ANC system is deployed are presented; some computer simulation results, to confirm the experimental ones, are shown as well. Some concluding remarks are given in Section 6.

2. Active noise control on a passive barrier

Noise control techniques, either active or passive, aim at minimizing the undesired noise, emitted from one or more *primary* sources, in a specific area of interest. The obvious solution is to act right at the primary noise sources, by developing more advanced devices (e.g., silent devices) or by enclosing them into a soundproof casing. This latter solution is often unfeasible due to physical constraints (e.g., heat dissipation), so that noise barriers became the main practical solutions applicable in the open field.

Noise barriers operate on the physical principle of diffraction that affects wave propagation through obstacle edges. Diffraction can be observed only if the relevant physical dimensions of the obstacle are at least comparable with that of the incident wavelength λ [20,21]. In the case of a barrier having height h, the requirement in order to have diffraction is $h > \lambda_{max}$, where λ_{max} is the largest wavelength present in the noise spectrum to be canceled. If the above condition is valid, the original noise signal is propagated in the shadow zone produced by the barrier mainly by diffraction (neglecting sound transmission through the barrier). The listener in the shadow zone is affected by "virtual" linear sources, generically denoted as P_{diff}, located over the barrier borders where diffraction takes place (see Fig. 1). An analytical model for P_{diff} is given by MacDonald [22,23] and it can be considered as a valid approximation if both source and listener are at a distance d much greater than λ_{max} from the border.

Since propagation analytical methods are quite complex, a general and practical technique for calculating the dimensions of a noise barrier can be retrieved from ISO 9613-2 (1996). This standard provides equations that allow the physical dimensions of a barrier to be correctly designed given the desired level of noise reduction at a specified position. In the case of a simple barrier with only one diffraction border the noise reduction Δ_b introduced by the barrier for each octave band of center wavelength λ, in the simplified version proposed in [24,25], is given by

$$\Delta_b = 10\log\left(3 + \frac{20}{\lambda}z\right)dB \tag{1}$$

where $z = r_1 + r_2 - r_d$ is the difference between the length of the indirect path $(r_1 + r_2)$ and of the direct propagation path (r_d), as indicated in Fig. 1. In order to have a high efficiency, relevant z values - with respect to the wavelength - are necessary. This may be a critical point when low-frequency components dominate the noise spectrum and an arbitrarily high barrier cannot be deployed.

In order to combat noise in the shadow area and design a noise barrier working in the open field, ANC techniques can be thought as a valid solution - in combination with and complementary to passive ones – to obtain additional noise reduction mainly at low frequencies. In this specific case, we have the possibility to place the active control sources exactly on the border of the barrier, where also the virtual diffraction noise sources are localized. ANC systems work by emitting an antiphase signal that cancels out the undesired noise at specific points in space. In the case of a barrier with negligible noise transmission through the barrier, the listener in the shadow zone is affected only by the "virtual" diffraction source P_{diff}. By placing the ANC system right on the border of the barrier, since both control sources and "virtual" diffraction noise sources are spatially coincident, one can expect to completely control the propagation of noise in the whole shadow zone protected by the barrier, independently of the distance of the listener, obtaining a relevant noise reduction also in the far field.

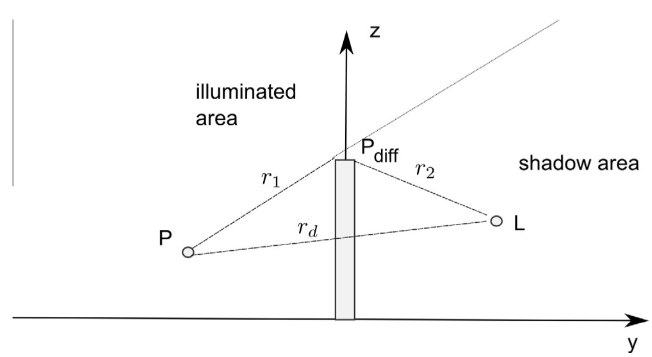

Fig. 1. A barrier divides the acoustic space into an "illuminated area", where the noise source have a direct acoustic path to a listener L, and a "shadow area", where noise is propagated through diffraction from the barrier border. The distance between the noise source P and the barrier edge and between the barrier edge and the listener L are denoted as r_1 and r_2, respectively, whereas r_d denotes the distance between P and L.