Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

On spatial spillover in feedforward and feedback noise control

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ARTICLE INFO

Article history:
Received 29 April 2016
Received in revised form
27 October 2016
Accepted 1 December 2016
Handling Editor: A.V. Metrikine

Keywords:
Spatial spillover
Feedback noise control
Feedforward noise control
Transmissibility

ABSTRACT

Active feedback noise control for rejecting broadband disturbances must contend with the Bode integral constraint, which implies that suppression over some frequency range gives rise to amplification over another range at the performance microphone. This is called *spectral spillover*. The present paper deals with *spatial spillover*, which refers to the amplification of noise at locations where no microphone is located. A spatial spillover function is defined, which is valid for both feedforward and feedback control with scalar and vector control inputs. This function is numerically analyzed and measured experimentally. Obstructions are introduced in the acoustic space to investigate their effect on spatial spillover.

1. Introduction

Active noise suppression has been extensively studied for several decades, and numerous techniques have been developed, analyzed, and tested, with several highly successful applications [1–3]. Noise suppression algorithms can be classified as either feedforward or feedback. Feedforward algorithms assume that a direct or indirect measurement of the disturbance is available, and this signal is passed through an adaptive filter to a control speaker [2,3]. These algorithms assume that the disturbance measurement is not corrupted by the control-speaker output, which means that the transfer function from the control input to the disturbance measurement is zero.

In some applications, however, it is difficult to measure the disturbance. For example, it is difficult for external sensors to measure the effect of broadband road and wind noise on the interior of the vehicle. If internal microphones are used, then the measurements include the effect of the control speakers. In this situation, feedback control is more appropriate than feedforward control. However, feedback control is susceptible to instability in the event of model errors.

Furthermore, although feedback control can suppress broadband noise, the Bode integral constraint implies that reducing the magnitude of the frequency response at the performance microphone is impossible at all frequencies [4–6]. For narrowband disturbances, this does not present a problem since the noise spectrum is confined to a limited bandwidth. However, for broadband disturbances, it is inevitable that, at least in some frequency range, the closed-loop noise level is amplified relative to the open-loop noise level. The challenge is thus to shape the closed-loop response so that *spectral spillover* has minimal effect on the closed-loop performance.

Beyond spectral spillover, yet another challenge is *spatial spillover*. Spatial spillover refers to the phenomenon where a controller may suppress noise at one location (the location of the performance microphone) but amplify it at another location (the location of an evaluation microphone). Due to restrictions in the design of a system, a performance

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http://dx.doi.org/10.1016/j.jsv.2016.12.002

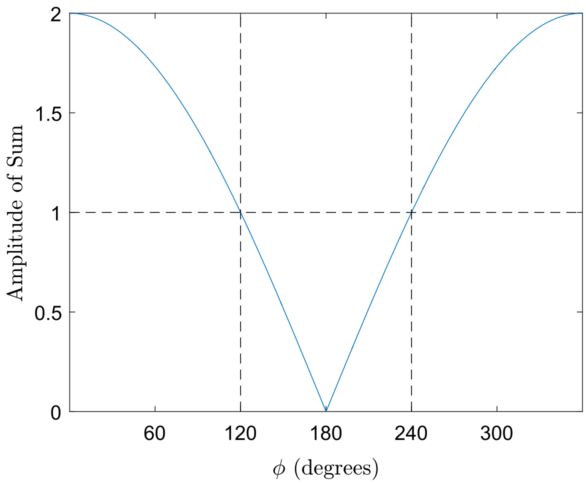

Fig. 1. Amplitude of the sum of two unit-amplitude sinusoids with identical frequency ω and relative phase ϕ. For $\phi = 180°$, perfect cancellation occurs, and thus, the amplitude of the sum is zero. For $\phi = 180 \pm 60°$, the amplitude of the sum is 1. The plot is based on the fact that $\sin(\omega t) + \sin(\omega t + \phi) = 2\cos(\phi/2)\sin(\omega t + \phi/2)$.

microphone may not always be placeable at all locations in which it is desirable to suppress noise. Thus, in the design phase, it is crucial to understand the relation between where the performance microphone is placed and evaluation locations where it is desirable to suppress noise.

The notion of spatial spillover defined in this paper concerns the decrease in the noise amplitude at the location of the performance microphone relative to its open-loop level as compared to the decrease in noise amplitude at the location of the evaluation microphone relative to its open-loop level. Consequently, spatial spillover is a measure of the relative effectiveness of the control at different locations. This notion is distinct from the fact, as shown in Fig. 1, that the sum of two unit-amplitude sinusoidal waves of the same frequency may possess any amplitude between 0 and 2 depending on the relative phase shift of the waves. Consequently, a disturbance sinusoid and a control-speaker sinusoid may add destructively at one location and constructively at another location depending on the phase shift between the waves at these locations. This notion is often used to estimate the bandwidth in which control is effective within an acoustic space. However, this phenomenon per se says nothing about the relationship between open- and closed-loop noise levels at a given location, and thus is not relevant to spatial spillover as defined and analyzed in this paper.

The goal of the present paper is to investigate the phenomenon of spatial spillover within a 3D acoustic space. To do this, we define a spatial spillover function for both feedforward and feedback control. It turns out that the spatial spillover function has the same functional form for both feedforward and feedback control and, in addition, is independent of the control in the case of scalar control. We also show that the spatial spillover function can be expressed as a ratio of transmissibility functions.

For illustrative 2DOF models, we consider feedforward and feedback controllers and compute the spatial spillover function. We then implement feedforward and feedback controllers in a series of noise control experiments with broadband disturbances. We measure the response at the locations of the performance and evaluation microphones, and we use this data to experimentally determine the spatial spillover function.

In certain applications, obstructions that are difficult to model may be present in the acoustic space, for example, passengers in a vehicle. We thus introduce obstructions between the performance and evaluation microphones in order to determine the effect on the spatial spillover function. The experimental results show that the presence of an obstruction can shift the magnitude and phase of the spatial spillover function relative to the acoustic space without the obstruction. A preliminary version of some of the results in this paper appeared in [7].

The contents of the paper are as follows. In Section 2, the spatial spillover function for feedforward control is derived, and numerical examples are presented in Section 3. In Section 4, the spatial spillover function for feedback control is derived, and numerical examples are presented in Section 5. Section 6 expresses the spatial spillover function in terms of transmissibility functions. Experimental results are presented in Section 7, and conclusions are discussed in Section 8.

2. Spatial spillover function for feedforward control

Consider the feedforward control problem shown in Fig. 2, where $z \in \mathbb{R}$ is the performance variable, $e \in \mathbb{R}$ is the evaluation variable, $w \in \mathbb{R}$ is the disturbance, and $u \in \mathbb{R}^{l_u}$ is the control input. Note that z, e, and w are scalar signals and that u may be either a scalar or vector signal depending on whether $l_u = 1$ or $l_u > 1$, respectively. The dynamics and signals may be either continuous time or discrete time.