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A novel design strategy for iterative learning and repetitive controllers of systems with a high modal density: Application to active noise control

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ABSTRACT

This paper describes the application of a novel design strategy for iterative learning and repetitive controllers for systems with a high modal density, presented in the companion paper, on two experimental case studies. Both case studies are examples of active structural acoustic control, where the goal is to reduce the radiated noise using structural actuators. In the first case study, ILC is used to control punching noise. An electrodynamic actuator on the frame of the punching machine is driven by the ILC algorithm which takes advantage of the repetitiveness of the consecutive impacts to reduce noise radiation. In the second case study, an RC algorithm is used to control the noise radiated by rotating machinery, which is often mainly periodic. A piezoelectric actuator incorporated in the bearing is driven by the RC algorithm which is capable of reducing harmonics of the rotational frequency of the shaft. Both applications show the practical usefulness of the novel design strategy.

1. Introduction

Noise pollution from modern industrial activities is an environmental problem of growing importance. At the moment, these noise problems are mostly addressed in a passive way (e.g. encapsulations, absorbing material, etc.). However, passive noise control techniques are inefficient at low frequencies, resulting in large installation spaces. Therefore, in certain applications, active solutions are a potential alternative, suitable for the reduction of low frequency noise. In contrast to passive control methods, which only use passive elements and consequently do not add energy to the controlled system, active control techniques rely on an external energy source to reduce the radiated noise. Depending on the type of actuators (acoustic/structural), two control strategies can be distinguished for the active control of noise: active noise control (ANC) and active structural acoustic control (ASAC). In ANC [1], acoustic actuators such as loudspeakers are used to generate a secondary sound field (the anti-noise) with the aim of attenuating a primary, disturbing sound field. ASAC, where structural actuators intervene in the vibrational pattern of a structure with the objective of attenuating the radiated noise level, can be an alternative, more efficient approach to tackle structure-borne noise problems [2]. Generally less actuators are required to achieve structure-borne noise reduction if ASAC is applied instead of ANC.

Two application fields where the potential of ANC and ASAC is evaluated nowadays, is the control of periodic noise radiated by rotating machinery [3] and the control of transient noise [4]. The most popular control algorithm in ANC and

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ASAC systems for rotating machinery is the filtered-X least mean squares (FxLMS) algorithm, which is an adaptive feedforward control technique. An adaptive technique is required since the controlled acoustic systems are often subject to changes: the spectral density of the disturbance is nonstationary, the controlled plant can vary substantially due to environmental influences, etc. The algorithm is based on the availability of a reference signal, like the fundamental frequency of the disturbing noise. In applications where the disturbance is periodic (e.g. rotating machinery) this can usually be provided by a tacho signal. This reference is filtered through a control filter to calculate the driving signal for the secondary actuator. In order to cope with the changes in the controlled system, the control configuration is augmented with additional sensors, installed at the locations where noise reduction is required. Based on these additional sensor signals, the control filter is adjusted to the varying primary noise field. The potential of the FxLMS-algorithm to obtain periodic noise reduction has been demonstrated in many applications [5]: active duct outlets [6], active control systems to suppress engine noise in car interiors [7], active control systems for the reduction of the propeller noise in aircrafts [8], etc. However, the performance of the FxLMS significantly decreases when the disturbance is transient instead of stationary. Adaptive algorithms require a certain adaptation time before convergence and optimal performance is attained. This adaptation time is not available in the case of transient noise, which explains the unsuitability of the popular FxLMS-algorithm for transient noise control purposes. In [9], it is even stated that the FxLMS-algorithm may become unstable in cases where the primary noise is impulsive. As a result, new types of algorithms are necessary, which are adapted to the specific transient character of the disturbance noise.

Especially in machine halls with production machines that generate impact noise, the radiated noise levels often exceed the ever more restrictive legal regulations regarding human exposure to noise. Examples of production machines radiating excessive impact noise levels are punching machines, forming presses, bending machines, drop forges, etc. In many of these impact noise problems, the same mechanical operation generates successive radiated noise pulses, which consequently have a repetitive character. Since iterative learning control (ILC) is a well-known technique to suppress a repetitive disturbance acting on a system [10], the potential of this technique with respect to the control of repetitive transient noise will be investigated in the first part of this paper. In the second part of the paper, RC, which is a control technique closely related to ILC suitable for suppressing periodic disturbances [11], is presented as a valuable alternative for the traditional FxLMS algorithm in the control of rotating machinery.

The applicability of the traditional ILC and RC design approaches, like the inverse model-based approach [12], the optimization-based approach [13,14] and the frequency-domain approach [15], is limited for the control of acoustic systems, which are typically characterized by a high modal density with lowly damped complex poles and zeros, possibly exhibiting a time delay. All these design approaches rely on a parametric system model, which is difficult to estimate in the case of acoustic systems. To bridge this gap, in the companion paper [16], a novel design strategy is presented, specifically adapted to such systems, and extended to RC design. In the procedure, the main objective is to fulfill the convergence criterion in a selected frequency range. This results in a controller which is robust for plant uncertainty and most effective at the system's resonance frequencies, a useful property in noise control applications.

The goal of this paper is to experimentally assess the performance and robustness of this novel strategy in ASAC applications. It will be shown that the controllers are robust for plant uncertainty and the influence of an inaccurate trigger signal in the ILC algorithm will be investigated. Therefore, this paper presents the application of this novel strategy in two case studies. In the first application, ILC is applied to control the transient noise of punching machines. The consecutive impacts are repetitive and the effect of one impact has died out before the next impact occurs, such that they can be considered as separate phenomena. With both requirements fulfilled, ILC is a suitable strategy for this application. In the second application, RC is applied to control a piezoelectric bearing in order to reduce the periodic noise radiated by rotating machinery, where the frequency of the noise is determined by the rotational speed.

2. Iterative learning control of punching noise

In this section, the ILC frequency-domain design strategy presented in [16] is applied to the problem of silencing a punching machine. A punching machine is a typical example of a production machine that radiates excessive impact noise levels. In order to meet the ever more restrictive legal regulations regarding noise emission and human exposure to noise, the conventional passive noise control techniques (e.g. enclosures, damping materials, etc.) become inadequate. Consequently, the possibilities of innovative concepts such as active structural acoustic control (ASAC) are explored. Since a high amount of the noise radiated by punching machines is structure-borne (mainly due to frame vibrations) [17], ASAC can be an efficient noise control technique in these applications. The potential of this technique is demonstrated on a scale model ($2\,\mathrm{m} \times 0.8\,\mathrm{m} \times 0.03\,\mathrm{m}$) of an industrial punching machine (Fig. 1). The scale model consists of an O-frame, a pneumatic cylinder, a hammer, a punch unit and a mechanism for the material supply. When the pneumatic cylinder is driven, the hammer moves downward and hits the punch unit, which cuts a hole in the supplied material. The dimensions of the O-frame (thickness, length, width, etc.) were defined such that the demonstrator can be considered as a representative scale model of industrial punching machines with a similar dynamic and acoustic behavior. The frame of this scale model has a large surface at the right side in order to stress the structure-borne noise radiation of the out-of-plane frame modes, which is the major noise source in industrial punching machines. The aim is to tackle these modes by an electromagnetic shaker in the corner of the frame, where all modes can be excited. Most of the noise radiated by this