Active structural acoustic control of repetitive impact noise

Gregory Pinte, Rene Boonen, Wim Desmet, Paul Sas
Katholieke Universiteit Leuven, Faculty of Engineering, P.M.A., B-3001 Leuven, Belgium
E-mail: gregory.pinte@mech.kuleuven.ac.be

Introduction

Industrial machines, which generate structure-borne impact noise, often produce noise levels exceeding the tresholds, imposed by legal regulations on noise emission. Until today, the research on active control focuses on harmonic noise. This paper presents the possibilities of active structural acoustic control of transient noise, produced by a repetitive impact excitation.

The presented research focuses on the development of feedback control algorithms. A linear time-invariant feedback controller was developed to drive the structural actuator. The performance of this time-invariant controller is limited for several reasons: time-variance of the controlled system, limited controller bandwidth, nonlinearities,... However, when the transient noise consists of successive impacts that exhibit a repetitive character, it is possible to extend the developed time-invariant feedback controller with a (causal or non-causal) learning behaviour, based on the additional information about the repetitiveness.

As test case, a thick plate ($500 \times 600 \times 15$ mm), excited by a hammer, is considered (figure 1). The goal of the research is to reduce the structural transient noise, generated by repetitive hammer impacts on the plate, by applying control forces on the plate. An accelerometer measures the generated plate vibrations at the impact location. This signal is sent to the input of the controller, which drives a structural actuator. This actuator is positioned outside the quadrant, where the hammer excites the plate, because in real applications it is often practically impossible to mount an actuator near the impact point. At each impact, the residual vibrations measured by the accelerometer, which cannot be controlled despite the action of the feedback controller, are measured and stored in memory. At the next impact, the control signal for the structural actuator is adapted based on the residual error at the previous impacts, such that the vibrations at the impact point and the radiated noise are reduced.

Optimal position of the actuator

In this section the optimal position for the structural actuator, outside the quadrant of the impact, is searched. A plant transfer function optimisation strategy, similar to the one proposed by De Man et al. [1], is used. The actuator location is optimized to achieve a control system which exhibits the properties of a system with collocated actuator and sensor i.e. a simple controller, robust to parametric changes. Therefore, a location for the actuator is searched such that, within the control bandwidth, the plant transfer function is provided with a high number of alternating poles and zeros (resulting in a simple, robust controller) and high resonance peaks (resulting in a high reduction). The optimal position is shown in figure 1, the corresponding plant transfer function P_{sec} with one pair of successive poles is plotted in figure 2. The inevitable successive poles can be compensated by an intermediate zero in the controller design.

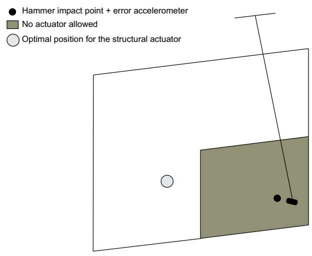

Figure 1: Test case: ASAC of a plate, excited by a hammer.

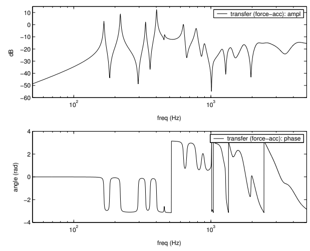

Figure 2: Plant transfer function between the structural actuator and the accelerometer.

Time-invariant feedback control

This section deals with the development of time-invariant feedback controllers for the structural actuator at the optimal position, defined in the previous section. The feedback controllers were designed based on an input-output approach (loopshaping). A model-based approach could not be used because the open-loop transfer function is not straightforward to model due to the high amount of plate resonances. The controller design starts from a proportional velocity feedback controller. By introducing a compensating zero in the controller between the two successive plant transfer function poles, the phase is pushed up by 180 ° and the bandwidth of the system increases from 500 Hz to 1250 Hz. At a frequency near the bandwidth of the system, a pole is added to the controller such that the amplitude of the open-loop transfer function is decreasing by 20 dB/dec at high frequencies above the bandwidth. The resulting controller $C = \frac{K}{s}\frac{s^2+2\cdot 0.05\cdot(2\pi 500)\cdot s+(2\pi 500)^2}{s^2+2\cdot 0.2\cdot(2\pi 1000)\cdot s+(2\pi 1000)^2}$ is very simple and robust. The reduction of the vibrations in the corner of the plate, which can be achieved by this time-invariant feedback controller, is shown on figure 4. The corner vibrations are considered as a good measure of the global reduction of the plate vibrations and the noise radiation of the plate. The overall reduction of the vibrations in the corner is 18 dB.

Causal Iterative Learning Control

In the presented linear time-invariant feedback controller, the repetitive behaviour of successive hammer impacts cannot be used. The reduction, achieved at the first impact, does not improve at the next impacts. A control technique that does use the additional, repetitive information of the disturbance is iterative learning control (ILC). A good survey of ILC, which is very popular in robotics and motion control systems, can be found in [2] and [3]. In ILC controllers, the input to the structural actuator is iteratively refined at each hammer impact, based on the remaining error at the previous impact. The basic ILC scheme is presented in figure 3: the input to the structural actuator at a new impact depends on the previous input and the remaining error at the previous impact, which are both filtered (by the $V(s)$-filter and the $W(s)$-filter) and stored in a memory.

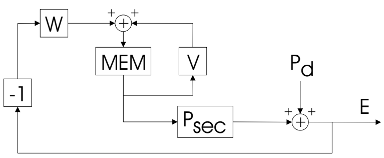

Figure 3: The basic ILC scheme.

For convergence of the ILC algorithm, the two learning filters $V(s)$ and $W(s)$ have to satisfy a criterion, which is derived in the frequency domain:

$$\|V - P_{sec}W\|_\infty < 1 \tag{1}$$

When this convergence criterion is fulfilled, it is proven that the remaining error will converge to:

$$E_\infty = \frac{V-1}{1-V+P_{sec}W}P_d \tag{2}$$

In conventional ILC, the learning filters are causal and only process input information from the past. Different strategies can be used to design the filters: H_∞, neural networks,... In this case, the causal filters are manually tuned in the frequency domain such that the convergence criterion is fulfilled and a small remaining error is achieved:

$$V = \frac{0.9 \cdot (2\pi 5000)}{(2\pi 5000) \cdot s + 1} \tag{3}$$

$$W = \frac{K}{s}\frac{s^2 + 2 \cdot 0.05 \cdot (2\pi 500) \cdot s + (2\pi 500)^2}{s^2 + 2 \cdot 0.2 \cdot (2\pi 1100) \cdot s + (2\pi 1100)^2} \tag{4}$$

The reduction of the vibrations in the corner of the plate after a high number of hammer impacts (the learning behaviour has converged) is shown in figure 4. It is clear that, even after the learning behaviour, no better results can be achieved by causal ILC than by time-invariant feedback control. Since time-invariant feedback requires no iterations, there is no reason to use causal ILC. The same conclusion can be found in some recent theoretical articles about ILC [4], which state the equivalence of causal ILC and time-invariant feedback control. In these articles, it is suggested to investigate the benefits of non-causal ILC versus time-invariant feedback control.

Non-causal Iterative Learning Control

Since the results of causal ILC were not satisfactory, the possibilities of non-causal ILC were explored. Contrary to causal learning filters, non-causal filters should look forward in time and use future time samples. However, because the learning filters are applied to signals from the previous impact, these future time samples are available at the next impact.

By introducing non-causal filters there is much more control design freedom to fulfill the convergence criterion and to achieve a smaller remaining error after a high number of impacts. Contrary to causal filters, a decrease of amplitude can be combined with a phase gain. The causal filters are also manually tuned in the frequency domain:

$$V = 0.997 \tag{5}$$

$$W = \frac{K}{s}\frac{1}{s^2 - 2 \cdot 0.05 \cdot (2\pi 500) \cdot s + (2\pi 500)^2} \tag{6}$$

Figure 4 shows that after the learning behaviour much better results can be achieved by non-causal ILC (25 dB reduction) than by time-invariant feedback control and causal ILC (18 dB reduction) .

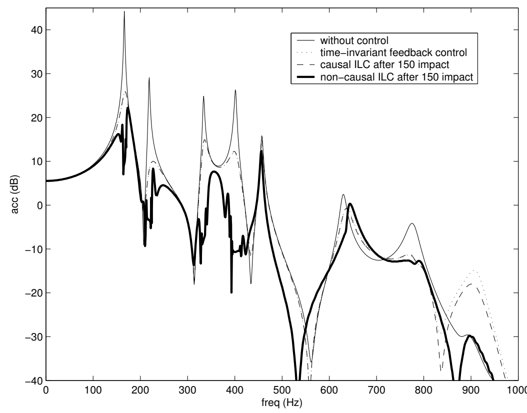

Figure 4: The reductions, achieved by the different controllers, in the corner of the plate.

References

[1] P. De Man, A. Francois, A. Preumont, "Robust Feedback Control of a Baffled Plate Through Vibroacoustic Optimization", 42nd AIAA Structural Dynamics conference (Seattle, April 2001)

[2] K. L. Moore, *"Iterative Learning Control for deterministic systems"*, (Springer-Verlag, London, UK, 1993)

[3] K.L. Moore, "Iterative Learning Control: An Expository Overview", Applied and Computational Controls, Signal Processing, and Circuits, **1**, No. 1, (1998)

[4] P.B. Goldsmith, "On the equivalence of causal LTI iterative learning control and feedback control", Automatica, No. 38, p. 703-708, (1998)