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ACTIVE CONTROL OF SLEEPER-INDUCED SOUND IN A HIGH SPEED TRAIN

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ABSTRACT

Vibration-induced noise in train cars is an area that receives a great deal of interest at the moment. Due to economical and environmental issues, manufacturers are cutting the weight-budget for future trains to achieve a lower total life-cycle cost. This has a negative impact on the interior noise and passenger comfort and to be competitive new methods to reduce the negative side effect are sought.

This paper describes an active control approach to isolating the car from bogie vibrations in such a way that the noise inside the car is reduced. An active control system with four inertial mass actuators fitted to an experimental light weight bogie were used to control bogie vibrations and noise inside the car. Several tests were performed in both a lab environment and on track at full speed.

INTRODUCTION

In the design of future trains the manufacturer has two important goals to achieve: low cost, both in terms of the actual material costs and the total life-cycle cost, and passenger comfort, in terms of noise and vibrations. In order to minimize manufacturing and total life-cycle costs low weight is essential but since a light structure will be more resonant, a mass reduction will have a negative impact on the noise inside the car, and thus on passenger comfort.

Train manufacturer Adtranz has developed an experimental bogie, the X15-5, which is 30% lighter than those fitted to the current line of trains, to be able to evaluate the effects of weight reduction, and to study the proposed solutions to counteract any negative side effects.

Due to the decrease in weight the X15-5 bogie is more resonant than its predecessors, and this results in increased interior noise. Measurements performed by Adtranz show that structure borne noise dominates in the region below 200 Hz, which makes it hard to compensate for by classical methods. Active control of noise and vibrations works best at low frequencies and as a part of Adtranz advanced technology program the question of whether or not active control could be used was raised.

One distinct source of vibration induced noise is the vertical oscillating movement in the bogie due to the passing of sleepers, and at a speed of 200 km/h the sleeper passage frequency (SPF) is approximately 85 Hz.

From an active control point of view this is a well suited problem, since the number of acoustic modes at these frequencies are fairly low and the excitation source is well defined. The aim of this study was to investigate whether it were possible to reduce the noise level inside a train car fitted with the experimental light weight bogie, using an active control approach.

The material presented in this paper emanates from two projects: a joint project between FFA (the Swedish Aeronautical Institute), Adtranz Sweden, ABB Corporate Research, The Royal Institute of Technology and the University of Karlskrona/Ronneby involving modelling and simulations as well as experimental work on different aspects of applying active control techniques to reduce noise in trains, see [1], followed by a joint project between Adtranz Sweden and the University of Karlskrona/Ronneby involving experimental studies of the bogie/car system as well as full-scale tests with a train comprising of five cars running at full speed on an ordinary track.

THE ACTIVE CONTROL SYSTEM

All experiments were performed on a prototype X2000 coach car fitted with the experimental light weight bogie. The bogie connects to the car at four connection points (AP1-AP4) at the end of the coupling beams which in turn are floating on air cushions mounted on the lower part of the bogie. Any vibrations that enter the car through the bogie will have to pass through these connection points in order to excite the car body structure.

Due to safety restrictions no alteration to the bogie itself could be made, and in order to insert force into the connection points a set of four inertial mass actuators were rigidly mounted externally at the coupling beam, close to the connection points.

The actuators were driven by a multiple input/multiple output (MIMO) filtered-X LMS (FXLMS) algorithm, schematically drawn in Figure 1, with K outputs and M inputs and a single reference.

The vector $\mathbf{w}(n)$ represents the adaptive filter weights for all K adaptive filters of order L stacked into one long vector, i.e.

$$\mathbf{w}(n) \equiv [\mathbf{w}_1^T(n)\ \mathbf{w}_2^T(n)\ \dots\ \mathbf{w}_K^T(n)]^T \tag{1}$$

where

$$\mathbf{w}_k(n) \equiv [w_{k,0}(n)\ w_{k,1}(n)\ \dots\ w_{k,L-1}(n)]^T. \tag{2}$$

The output signal vector $\mathbf{y}(n)$ is used to drive the K secondary sources, and each element $y_k(n)$ is obtained by filtering the reference $x(n)$ by the corresponding filter, $\mathbf{w}_k(n)$:

$$y_k(n) = \mathbf{w}_k^T(n)\mathbf{x}(n), \qquad k = 1, 2, \dots, K \tag{3}$$

where

$$\mathbf{x}(n) \equiv [x(n)\ x(n-1)\ \dots\ x(n-L+1)]^T. \tag{4}$$

The reference signal, $x(n)$, was taken from an accelerometer on one of the bearing boxes of the front wheelshaft of the bogie, and the output signals, $y_k(n)$, were fed to the

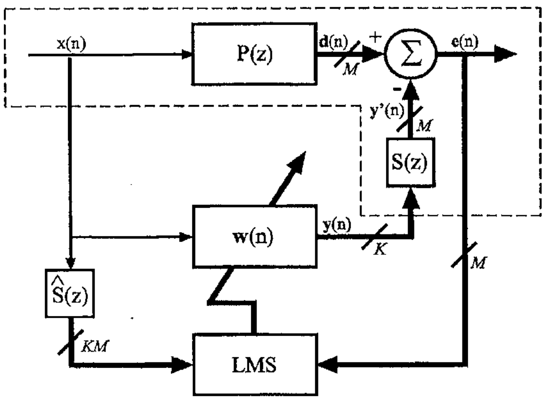

Figure 1: A schematic view of the car/bogie system (within the dashed area) and the controller. The reference signal, $x(n)$, was taken from a bearing box on the front wheelshaft and the output signal vector, $\mathbf{y}(n)$, was driving the actuators. The error signal vector, $\mathbf{e}(n)$, was taken from a set of microphones inside the car.

inertial mass actuators. The error signals were provided by a set of microphones inside the car.

Measurements of the coherence between the excitation and the noise inside the car gave a coherence of 0.95 indicating that it should be possible to significantly decrease the periodic noise caused by the sleeper passage frequency by preventing the vibrations in the bogie from exciting the carbody structure.

STABILITY AND OUTPUT LIMITING

When implementing an active control application two aspects are of great importance, besides the actual performance of the system: the long term stability and the limiting of the output signals. For simplicity, the following calculations will be done for the case of $K = 1$ and $M = 1$, but it is straightforward to extend the calculations to any choice of K and M.

The basic weight updating scheme of the LMS-algorithm:

$$\mathbf{w}(n+1) = \mathbf{w}(n) - \frac{\mu}{2}\nabla\xi(n) \tag{5}$$

where $\xi(n) = E[e^2(n)]$ is the expectation value of the error and μ is the step-length of the gradient decent, is simplified by using the instantaneous squared error, $\hat{\xi}(n) = e^2(n)$, instead of $\xi(n)$, giving

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu\mathbf{x}'(n)e(n). \tag{6}$$

where $\mathbf{x}'(n)$ is the result of filtering the reference signal $\mathbf{x}(n)$ with $\hat{\mathbf{S}}$, the estimate of the secondary path $\mathbf{S}$.

By adding a leaking mechanism to the scheme given in Equation 6, stability can be improved and the leaky-FXLMS weight updating scheme is formulated as

$$\mathbf{w}(n+1) = \nu\mathbf{w}(n) + \mu\mathbf{x}'(n)e(n) \tag{7}$$

where $0 < \nu \leq 1$ is the leakage factor, see [2].

The problem of limiting the output signal to the inertial mass actuators in order to avoid non-linear distortion can be solved by adding a second term containing the squared output term with a limiting factor, γ, to the cost function, see [3].

$$\hat{\xi}(n) = e^2(n) + \gamma y^2(n) \tag{8}$$

or equivalently by constraining the adaptive filter weights

$$\hat{\xi}(n) = e^2(n) + \gamma\mathbf{w}^T(n)\mathbf{w}(n). \tag{9}$$

The weight updating scheme then becomes

$$\mathbf{w}(n+1) = (1-\gamma\mu)\mathbf{w}(n) + \mu\mathbf{x}'(n)e(n) \tag{10}$$

where, by comparing Equations 7 and 10

$$\nu \equiv (1-\gamma\mu). \tag{11}$$

This weight updating scheme degrades the performance somewhat, but since the excess error power is proportional to $[(1-\nu)/\mu]^2$, see [4], this degradation can be kept at a minimum by making sure that $1-\nu$ is much smaller than μ.

LAB TESTS OF THE ACTIVE CONTROL SYSTEM

The first series of tests was performed in lab settings where a controlled environment with respect to primary excitation and external noise could be obtained. The primary excitation of the bogie was provided by four shakers connected to the wheel shafts, driven by a sinusoidal input signal at a frequency corresponding to the sleeper passage frequency. A time delay, corresponding to the distance between the front and rear weel shaft of the bogie, was added to the signal controlling to the rear pair of wheels. The reference signal was taken from an accelerometer on a bearing box on the front wheel shaft and the error signals were obtained by four microphones inside the car. The estimate, $\hat{S}$, of the secondary path was obtained off-line by a linear chirp excitation.

Pos	SPL ASAC Off	SPL ASAC On	Attenuation
1	$54dB$	$49dB$	$5dB$
2	$50dB$	$46dB$	$4dB$
3	$55dB$	$53dB$	$2dB$
4	$54dB$	$50dB$	$4dB$

Table 1: The time averaged narrowband noise levels and attenuation in the control microphones inside the car in the lab test

The target for the active control algorithm was the narrow band noise, centered on the excitation frquency, inside the car. This technique is often referred to as Active Structure Acoustic Control (ASAC), see [5], and the results are shown in Table 1.

FULL SCALE TESTS

The setup in the full scale tests was similar to the lab tests with inertial mass actuators in the connection points between the car and the bogie (AP1-AP4), and a total of 24 microphones placed in a grid with a spacing of 0.5m at 1.2m above the floor inside the car. Out of these 24 microphones, eight where used as error sensors while the remaining microphones were used for evaluation of the global performance. The microphone positions and the numbering scheme is depicted in Figure 2. As in the previous section, the secondary path estimate, $\hat{S}$, was calculated off-line.

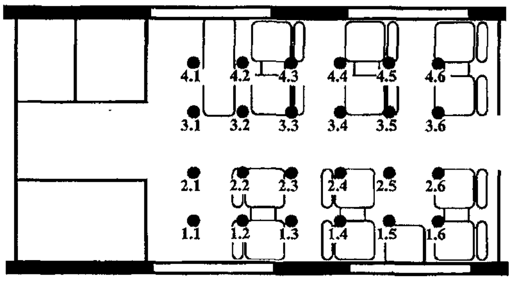

Figure 2: The microphone positions used in the full scale test of the ASAC system. The centre of the bogie is approximately 0.5m to the left of the first line of microphones (positions 1.1-4.1).

An example of the behavior of the ASAC system can be found in Figure 3 where a reference run, with the ASAC system switched off, is compared to a test run over the same stretch of track. The ASAC system was switched on after approximately 90 seconds of travel. The system was stable over the full stretch of track and handled transients well, as can be seen in Figure 3 where the peak after approximately 125 seconds stems from a railway crossing.

Several control microphone configurations were eavaluated and the results from one these can be found in Table 2. In this particular case microphones 2.2, 3.2, 2.3, 3.3, 2.4, 3.4, 2.5 and 3.5 were used as error sensors.

	SPL ASAC Off	SPL ASAC On	Attenuation
Average over all microphones	$58.3dB$	$55.0dB$	$3.4dB$
Maximum over all microphones	$62.6dB$	$59.1dB$	$7.9dB$
Average over all control mics	$60.1dB$	$53.9dB$	$6.2dB$

Table 2: The time averaged narrow band noise levels and attenuation inside the car during the full scale test.

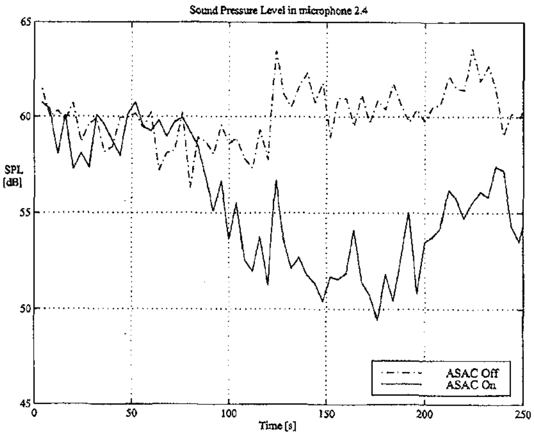

Figure 3: The noise level inside the car at one of the control microphones for a reference run (dashed) and a test run (solid). The ASAC system was activated after approximately 90 seconds of the test run.

CONCLUSIONS

The results from the various tests verify that a light weight bogie is more susceptible to excitation from the sleeper passage frequency than the original structure. It has also been shown that by applying an ASAC-approach using inertial mass actuators it is possible to achieve a sustained global average attenuation of the noise, induced by the sleeper passage frequency, of approximately 3 dB inside the car. The average attenuation of the noise in the control microphones was approximately 6 dB. For the active control algorithm it can be concluded that it converged, and reduced the sound pressure levels in the car in lab environment as well as when run at full speed on track, and that the output limitation inherent in the leaky implementation of the filtered-X LMS algorithm prevented the actuators from distorting due to high driving signals.

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