An Industrial Active Noise Control Application For an Enclosure

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Abstract

An unusual Active Noise Control (ANC) approach using structural sensors and actuators is investigated for its effectiveness in actively attenuating the sound radiation from an irregular enclosure excited by an internal sound field. The intention of the control strategy is to control the enclosure vibrations in such a way that the radiated sound field is minimized. For the case considered here the interior noise spectrum has most of its energy below the first enclosure structural resonance frequency, thus complicating the control design. Here the design of a suitable control system for this problem is described. This is followed by a discussion concerning the type and reliability of the equipment which is most appropriate, after which experimental results illustrating the performance of this approach are presented. The experimental data show a direct correlation between the reduction in enclosure surface vibration and the reduction in noise radiation.

Instruction

Nowadays, noise reduction is still a main concern, both to improve the work environment and to reach new customers where noise is a choice factor between two products providing the same services.

Although passive noise control is widely used in industry, there are relatively few industrial applications of active control, probably because of its unreliability (both in terms of control stability and in terms of embedded electronic devices) and because it is usually difficult and time consuming to implement.

Here, it is shown how a simple robust active noise control system can be used to attenuate noise radiated from an irregular enclosure at frequencies below the first enclosure structural resonance frequency. The robustness comes from two system properties: only structural sensors/actuators have been used; and the choice of an adaptive feed forward controller using a simple FXLMS control algorithm. The controller developed here could easily be applied in industry as it is robust, simple and small in size.

There are three main issues addressed in this paper: the use of structural sensors and actuators to control noise radiation, the type of control approach needed to drive the ANC system and the reliability of the real time system involved.

Structural Actuators/ Sensors to Control Acoustic Radiation

To actively attenuate noise radiated by a structure, a set of actuators and sensors has to be chosen. When the goal is to use the system in an embedded way, the first choice generally goes toward piezoelectric patches, as structural sensors/ actuators, because they are small, lightweight and low cost.

When the first structural modes have resonances that are quite high in frequency the location and the size of the piezo patches have to be carefully chosen. Due to the size and the location of the piezo patch, the observability and controllability become a issue; the piezo sensor is able to measure the response at most of the frequencies applied to the structure by the disturbance but it is only able to excite structural modes to which it is strongly coupled.

In addition, when the piezo patch is driven at relatively high voltage levels in order to produce an acceptable output, it generates harmonics of the applied frequency which may compromise the overall controller performance.

Acoustic actuators such as loudspeakers are also difficult and impractical to implement because of their size and the requirement to completely surround the sound source with them if global noise attenuation is to he achieved.

The most effective type of structural actuator which gives a large frequency and amplitude range of controllability is the shaker. For the classic electro-dynamic shaker, the main drawbacks are the weight, the cumbersomeness, the attachment difficulty, the required shaker

support structure and the noise radiation from the shaker body.

None of these problems occur if an inertial shaker is used. The weight of an inertial shaker can be adjusted depending on the control force that is required. As the shaker is mounted directly on the structure and it does not suffer from mis-alignment.

The excitation efficiency can also be optimized by tuning the shaker resonance frequency to be close to the frequency range that is to be controlled. For the work described here, an inertial shaker has been especially developed and optimized for the required dynamic range and force input requirements and the result is a petite device of 4cm diameter and 7cm height. It is illustrated in Fig. (1).

Figure 1: Inertial shaker used in the experiment.

For control of structurally radiated noise, either a structural sensor (eg. an accelerometer) or an acoustic sensor (eg. a microphone) can be used.

The most appropriate sensor will depend on the application and the surrounding environment. When the signal to noise ratio (S/N) is high, which means the background noise does not interfere with the signal of interest, acoustic sensors are the simplest to implement.

However, in a traditional workplace, it is difficult to keep them and the attached wiring out of the way and it is also difficult to ensure global noise control outside of the area immediately around the sensor.

The use of structural sensors would depend on the frequency bandwidth of interest, as the noise radiation is a function of the amplitude of excitation of radiation modes and not vibration modes [1–2].

Thus, a radiation mode model must be incorporated into the control system design. Any radiation mode is a well known linear combination of vibration modes, so a very accurate radiation mode model for a specific bandwidth which might include several radiation modes is difficult to achieve, as one radiation mode can involve a large number of vibration modes, resulting in the control design not being very robust.

The main advantages of structural sensors, is that they do not suffer from any acoustic interference and they do not cause inconvenience to personnel movement in the vicinity of the equipment or in the case of consumer products or parts they do not interfere with the use or assembly of the product.

For the case considered here, the resonance frequency of the first structural mode is higher than the frequency spectrum of interest (that is, the first mode resonance frequency is higher than 1kHz).

Thus there are no vibration or radiation modes that must be incorporated into the control system design. In other words, the transfer function between the inside enclosure noise and the structural sensor is only a constant gain as a function of frequency.

Another concern for the application of ANC to consumer products is that the active noise control system should not interfere with the actual assembly of the product to be controlled. As the desired controlled structure is an enclosure, neither sensor nor actuator can be put inside very easily. For feed forward control, which requires a reference signal that is not influenced greatly by the control source and has a high signal to noise ratio, an inside microphone would be ideal.

However, as the transfer function between the structural vibration and the inside noise is constant as a function of frequency for the case considered here, an outside structural sensor can be just as effective. However, it will be necessary to compensate for the feedback path from the control actuator to the reference sensor as this will be of significant amplitude.

In conclusion, for the example considered here regarding the design of a control system to attenuate structurally radiated sound, structural sensors and actuators have been chosen. Also, no structural or radiation modes are involved as the frequency range of interest is below the resonance frequency of the first mode.

These system properties will have a beneficial effect on the robustness and simplicity of the final control system. The next question to answer is what is the optimum type of control system for this application: feed forward or feedback?

Feedback/Feed forward

To be able to decide which type of control system is the most suitable, the inside disturbance type (eg.: white noise, periodic noise,...), the system to be controlled and the surrounding environment have to be considered.

The system, which is an irregular enclosure, has an average shell thickness of 3 mm, which results in a very high structural stiffness; consequently the structural resonance frequencies are quite high.

The surrounding environment, in which the noise has to be cancelled is an open space. The inside noise is a periodic noise with a frequency spectrum ranging from 50 Hz to 900 Hz. Spectral analysis indicates that the spectrum is composed mainly of harmonics of 50 Hz.

For this situation, it is clear that a feedback approach will not be very

effective as it is based on damping the resonant modes of the structure.

One possibility for feedback control may be to create a model of the irregular enclosure with virtual modes at the frequencies of interest but this approach has not yet been realised on any practical system.

The noise periodicity and features indicate that the feed forward approach is likely to give good results. However, it is still necessary to decide on the optimum number and locations of error sensors and control actuators to obtain the best result. This will be discussed in the following section.

Another consideration is the type of real time system that would be most suited to running the controller. Questions as to its reliability and how it may be applied to an industrial setting are answered in the next section.

Real time systems

In the past, real time experiments were reserved for applications with large budgets (the army and aerospace applications, for example). In 1978, Texas Instruments launched a toy able to deal with a numerical signal in real time. But it was not until 1985 that the first DSP card (Digital Signal Processor), which could be used in industrial systems, became available. The DSP card allows complex numerical operations, such as the Fourier transform, to be carried out at very high speed. Hardware which allows

the implementation and use of a control system in real time are of great interest in the industrial world, since the cost of these tools is rapidly reducing.

Two viable alternative approaches may be differentiated from the viewpoints of cost and ease of implementation.

The first approach involves using a DSP card, which is the most commonly used tool. The effective use of a DSP card alone requires knowledge of relatively low level machine language so that the control system can be programmed into the card.

To overcome this problem there are some software programs which do not require this knowledge, but on the other hand the choice of hardware is imposed by the software and the software provider. The most famous software is dSpace provided by the MathWorks company [3].

The second approach doesn't use a DSP card, but instead uses a standard input and output card and is based on the principle that the DSP limits the user from the practical and financial point of view.

The second approach uses an Operational Sys-tem (OS) and Freeware (QNX or Linux), dedicated to real time processing and able to be installed on whatever computer is available. The advantage of this approach is that it allows the design of embedded systems for direct application of the type FPGA (Field Programmable Gate Array), without the requirement for the designer to

have knowledge of machine language (VHDL).

This technology is currently rarely used because it is still new, but the interest from industry has been growing considerably in the past 7 years because of the viability and low cost.

The most famous software engines are XPcTarget [4] and RT-LAB [5] provided by MathWorks and Opal-rt respectively. The idea underlying these software packages, either dSpace, xPcTarget or RT-LAB, is to use other software already well developed from the theoretical point of view in the areas of mathematical calculations, signal processing, automation, and the generation of the codes such as C, FORTRAN, Matlab/Simulink or Labview, in order to dedicate it more to the restrictions of real time.

One of the original aspects of RT-LAB is the use of a cross-platform, open-source scripting language called Python, which is growing in popularity, particularly within technical applications. Its syntax is very close to m-script, which has become very popular among Matlab users. It is object-oriented and allows users to automate applications on any platform.

The RT-LAB API allows users to configure models and automate test runs using the Python language. Also, because Python is multi-threaded, it is possible to interface to multiple concurrent models, running on several target

processors.

This means that it is possible to program many different tests, even having data flow from one test platform to another, from a single operator station.

In other words, this functionality allows the generation of a statistical point of view of an experiment or process behaviour, which is a valuable tool for industrial applications.

Experiment Description

The experiment was performed on an irregular asymmetrical enclosure shaped like an ellipsoid cylinder with many irregular bumps and welded on a plinth, which was placed on a table.

Figure 2 shows a simplified schematic of the structure. A loudspeaker is inserted in the enclosure to simulate the pressure that the real inside disturbance would produce.

To be able to reproduce the real situation, the top lid and the main enclosure body of the enclosure have to be strongly coupled, hence the top lid has been welded to the main body.

The positions of the sensor have been selected with regard to the zone of highest radiation of the irregular enclosure, measured with a microphone that was moved around the outside of the enclosure. Four enclosure sections were found to be significant noise radiators: the top, the left and right sides and the bottom.

These results indicate that the position choices of the sensors and actuators depend on what surrounds the enclosure and what supports it; if the enclosure is in contact with another object such as a table, then that object could become a radiation noise amplifier.

A trial set of experiments showed that the best compromise between efficiency and number of sensors/actuators involved was reached when only one actuator on the enclosure top was used in combination with 3 error sensors (on the top, left and on the bottom) as shown in Figure 2.

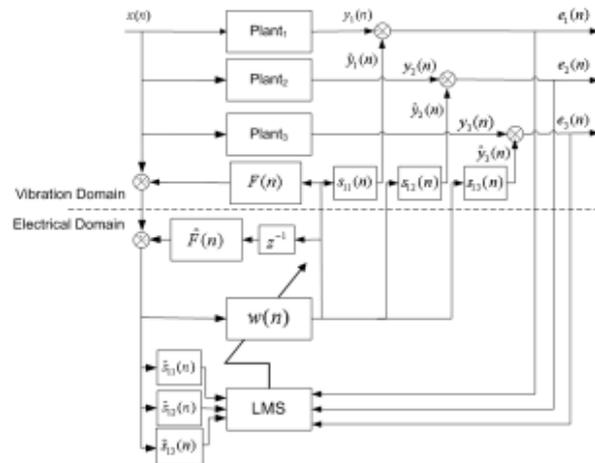In the figure, the bottom sensor does not appear for obvious perspective reasons. As the

Figure 3. Detailed diagram of the [1x1x3] MISO system showing the electronic part and the vibration/acoustic part

feed forward approach is used, a reference sensor is needed, which has been placed on the plinth.

The transfer function between the accelerometer output and the disturbance is, as mentioned before, only a constant complex gain.

The enclosure is made of steel; its general features are described in Table 1.

The sensors and accelerometers are amplified and the resulting signal passes through low-pass filters that are directly connected to the data acquisition card. For the output, a standard power amplifier is used to drive the shaker.

Vibration velocities were measured at 200 discrete points along the top of the enclosure using a Polytech PSV 400 scanning laser vibrometer to show the direct relation between the vibration reduction and the noise radiation reduction.

The sound radiation before and after implementation of the controller was measured using a set of 16 microphones surrounding the enclosure.

Control Design

The objective of the control system is to attenuate noise radiation from the enclosure.

Figure 2. Simplified diagram of the structure, showing the position of the error sensors, the reference sensor and the actuator.

x radius [a]	102 mm
y radius [a]	85 mm
Height [a] (h)	170 mm
Thickness [a] (t)	3 mm
Young's Modulus (E)	209×10^9 N/m^2
Density (ρ)	8000 kg/m^3

[a] as the shell is irregular, values are only order of magnitude.

Table 1. Enclosure features

As already discussed, a feed forward, single-reference/single-input/multiple-output (MIS0) FxLMS adaptive control algorithm has been selected as the optimum approach.

The robustness of the control system is enhanced by the use of an adaptive algorithm. If the enclosure features change through time due to material fatigue or small damages, or the environment changes so the wavelength of sound changes, the algorithm will adapt itself.

Figure 3 shows the details of the [1x1x3] MISO vibration control system used for the experiment. x is the reference signal, which for the case considered here is the equivalent of the enclosure interior noise.

The algorithm design for the experiment takes into account the feedback effects $F(n)$ of the actuator on the reference sensor [6-8]. An estimator of $F(n)$, $\acute{F}(n)$, is modelled to remove the contamination of the reference signal by the sig-nal from

$$w(n+1) = w(n) + \mu \left\{ e_1(n)\hat{S}_{11} + e_2(n)\hat{S}_{12} + e_3(n)\hat{S}_{13} \right\} \acute{x}$$

the actuator. $\acute{F}(n)$ is estimated simultaneously with the secondary $\acute{x}$ paths (s_{11}, s_{12} and s_{13}), which are estimated off-line using a standard LMS algorithm. Plant$_1$, Plant$_2$, and Plant$_3$ are the different paths of the disturbance to the sensors. The weight update equation for the

$$\hat{S}_{1\alpha}_{[N \times L - N \times N]} = \begin{bmatrix} \hat{s}_{1\alpha}(0) & 0 & \cdots & 0 \\ \vdots & \hat{s}_{1\alpha}(0) & \ddots & \vdots \\ \vdots & \vdots & & 0 \\ \vdots & \vdots & & \hat{s}_{1\alpha}(0) \\ \hat{s}_{1\alpha}(L-1) & \vdots & & \vdots \\ 0 & \hat{s}_{1\alpha}(L-1) & & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & \hat{s}_{1\alpha}(L-1) \end{bmatrix}$$

control filter weights is given by:

where $w(n)=[w_o(n) \dots w_N(n)]^T$ is the adaptive weight vector of length N, $x(n) = [x(n) \dots x(n-N-L+1)]^T$ is the input data vector, L is the estimator filter length of the s_{11}, s_{12} and s_{13} secondary paths and μ is the

step-size. $S_{1\alpha}$ is given by the following matrix with α = 1,2 or 3:

The experiment focuses on the vibration control over the bandwidth from 0 Hz to 900 Hz, hence all the output and input signals of the control system are low pass filtered using a filter with a cut off frequency of 900 Hz.

The MISO algorithm has been implemented in Simulink using RT-LAB software to provide the real-time system. The FxLMS algorithm was operating at a sampling frequency of 8 kHz, with a step size μ = 0.0001. w and $s_{1\alpha}$ have 300 and 200 coefficients respectively.

Experiment Results

The vibration level at 200 points across the enclosure top was measured using the laser vibrometer for the case with and without control representing the enclosure global behaviour. Figure 4 shows the 200 point average velocity spectrum.
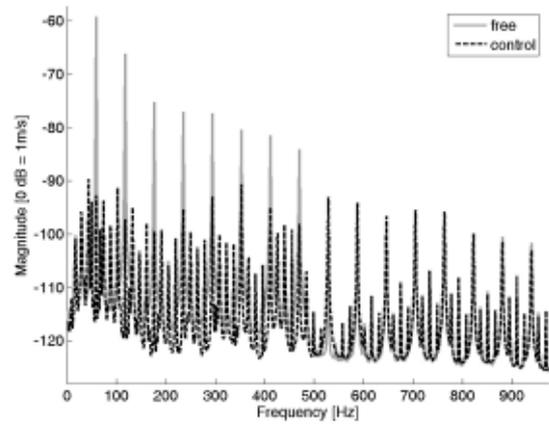
From Figure 4, it

Figure 4. Velocity average spectrum of the shell scanned area with and without control
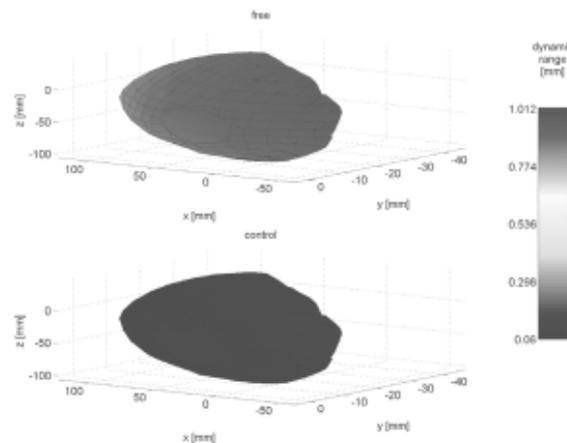

Figure 5. RMS of the scanned area

can be seen that the controller managed to heavily reduce the vibration of the enclosure in the scanned area. This general
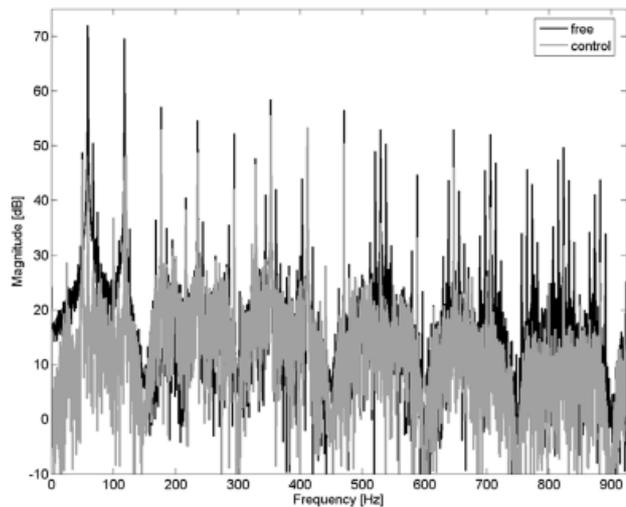

Figure 6. Microphone pressure power spectrum

impression is confirmed by inspection of the Root Mean Square (RMS) of the scanned area.

Figure 5 shows the RMS calculated for the cases with and without control. No measurements were done on the shaker actuator which is the reason why there is a big surface of interpolation in the middle of the scanned area of Figure 5.

The result of the vibration attenuation is a reduction in noise radiation. Figure 6 shows the noise radiation measured by the microphone (of an array of 16) that measured the worst case noise attenuation.

It can be seen from the frequency peaks in Figures 4, 5 and 6 that the vibration attenuation is directly related to the noise radiation attenuation.

Figure 6 indicates quite a high background noise level as the experiment was deliberately done in a standard room with a large amount of noisy equipment to simulate industrial conditions.

Conclusions

The major issues that have to be taken into account when designing an active noise control system for an industrial application have been discussed.

In particular, it has been shown that for an enclosure radiating sound at frequencies below the first structural resonance, it is possible to design an effective, simple feed forward system to significantly attenuate the radiated sound without using any sound field sensors such as microphones. The process was illustrated using a small irregularly shaped enclosure radiating sound into an industrial type environment.
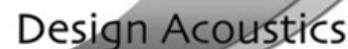
Acknowledgements

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