Internal model control of a washing machine casing for active noise reduction

Conference Paper · July 2017

24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

INTERNAL MODEL CONTROL OF A WASHING MACHINE CASING FOR ACTIVE NOISE REDUCTION

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Some of the most common noise sources in the human environment are devices and machinery. The active casing approach is a technique to reduce their noise emission by controlling vibration of their casings. Efficiency of this method has been confirmed by the authors in previous publications for several laboratory casings. The aim of this paper is to investigate the method for a real device casing, namely, a market-available and unmodified washing machine. For active noise control a feedforward control structure is usually employed. However, a useful reference signal is sometimes impossible to acquire due to, e.g., device structure preventing to place a sensor at appropriate location. Fortunately, often the dominant noise components are generated by rotating device elements, and thus they are tonal or multi-tonal. In such a case, alternatively to feedforward control, a feedback control strategy in the Internal Model Control (IMC) architecture can be used. In this paper, such strategy is applied for a real device casing, employing error microphones to estimate the reference signal. The Filtered-x Least Mean Square (FxLMS) algorithm in a multichannel structure is used to adaptively update control filter parameters. A low-frequency noise in the range up to 500 Hz is considered. Advantages and limits of the proposed approach are pointed out and discussed.

Keywords: active casing, active structural acoustic control, active noise control, internal model control, real device casing.

1. Introduction

An excessive noise generated by devices and machinery became the subject of high interest in recent years. A common protection mean is to apply passive sound insulating materials. However, passive barriers are often ineffective, especially at low frequencies, or are inapplicable due to increase in size and weight of the device, and its potential overheating. An alternative way is to use active control methods, by applying a set of sensors and actuators, and running a control algorithm [1, 2]. The sound radiation of an individual elastic plate and other barriers was analyzed, e.g. in [3, 4, 5, 6].

If a device generating noise is surrounded by a thin-walled casing, or if it can be enclosed in an additional casing, actuators can be applied directly to the structure, and as a whole it can be used as an active barrier improving acoustic isolation of the device [7]. Such technique is referred to as the active casing approach, and was successfully applied and further developed by the authors in previous publications [8, 9]. When appropriately implemented, it results in a global noise reduction instead of local zones of quiet.

The intention of this paper is to further develop the active casing approach, by applying it to the real device casing—the washing machine. The mechanical structure and laboratory setup are described in Section 2. An adaptive feedback control strategy in the Internal Model Control (IMC) architecture is used to control the casing walls vibration. A high number of control inputs is considered, which requires a considerable computational power to implement a control system according to real-time constrains. Therefore, the Switched-error FxLMS modification if employed [10], which reduces the computational demand. The control algorithm, and advantages and limits of such approach are pointed out and discussed in Section 3. Then, the control experiments are described and the results are presented in Section 4. The paper is summarised with conclusions and plans for future research.

2. The laboratory setup: a washing machine casing

The washing machine casing investigated in this paper is a third type of a casing employed by the authors in the role of an active casing. The considered structure is presented in Fig. 1. In contrast to laboratory casings used in the previous research (e.g. in [8, 11]), the real device casing is very irregular and inhomogeneous, what may affect the control performance. Each of the casing walls represent different features, i.e. bendings, embossments, etc.

In this preliminary stage of research, a loudspeaker placed inside the washing machine drum is used as the primary noise source. It allows for creating an environment similar to previously employed laboratory casings, enabling a comparison of vibroacoustic properties. However, an active control during real device operations (e.g. spinning cycle, etc.) will be considered in due course. Vibration isolation between the speaker and the drum is provided to ensure only acoustic excitation.

In front of each casing wall, a microphone is placed in the distance of $500\ \mathrm{mm}$ (referred to as the outer microphone). These microphones are used for control-related purposes—as error sensors. Additionally, to evaluate the noise reduction efficiency, five microphones are placed at several larger distances from the casing, corresponding to potential locations of the user (referred to as the room microphones). A schematic representation of the laboratory setup is presented in Fig. 2.

To control vibrations of the device casing, inertial actuators EX-1 are used. They are light-weight $(115\ \mathrm{g})$ actuators of small dimensions $(70\ \mathrm{mm})$, comparing to the size of the casing. They are mounted on the casing walls from the outside (although, it is only to facilitate the laboratory control experiments, in final applications they can be attached from the inner side). Three actuators are used per front, right and left wall. For the top wall, two actuators are used. The back and the bottom of

Figure 1: A photograph of the washing machine casing with attached actuators.

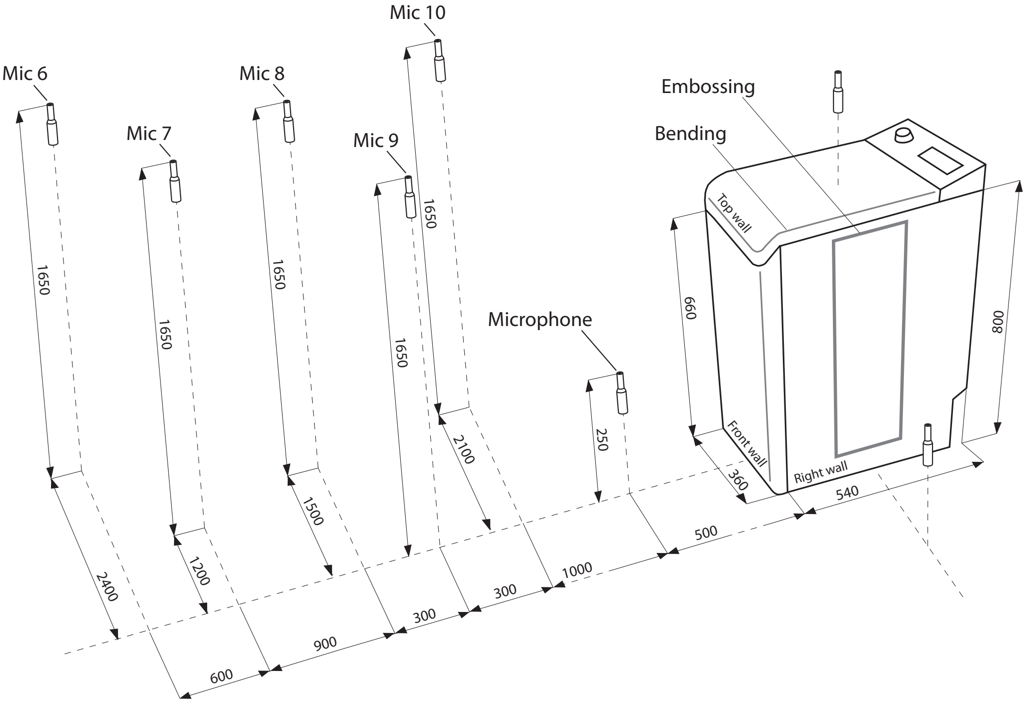

Figure 2: A schematic representation of the laboratory setup. All dimensions are given in millimetres [mm].

the casing are not controlled. The number of actuators and their placement is a result of analysis and optimization using a method that maximizes a measure of the controllability of the system. The optimization procedure provides an efficient arrangement of actuators that enable avoidance of uncontrollable resonances in the frequency range of interest. Moreover, the arrangement minimizes the energy necessary to control the resonances. The impact of the mass of the actuators is included in the optimization procedure. The method and mathematical model of casing walls are described in details in other publications of the authors [12, 13, 14].

3. Adaptive control strategy

In active noise and vibration control systems, a normalized Filtered-x Least Mean Square (FxLMS) feedforward algorithm is widely employed [15]. A reference signal can be obtained, e.g., by a microphone placed close to the noise source or by a attached vibration sensor. However, a useful reference signal is sometimes impossible to acquire due to, e.g., device structure preventing to place a sensor at appropriate location, hence the reference sensor is unable to provide an in-advance information about the primary noise. As a result the performance of such system can be degraded. Fortunately, often the dominant noise components are generated by rotating device elements, and thus they are tonal or multi-tonal. In such a case, alternatively to feedforward control, a feedback control strategy in the Internal Model Control (IMC) architecture can be used, which is based on the error signal only [16]. It allows to directly apply techniques well developed for feedforward control, including the FxLMS algorithm. For the active casing it has been found sufficient to use a scalar reference signal [16], which is an estimate of the primary noise at one selected j-th sensor obtained by subtracting from the selected error signal $e_j(n)$ the contribution of control signals from all actuators using models of respective secondary paths as shown in Fig. 3 and in the following equation:

$$x(n) = e_j(n) - \sum_{i=1}^{I} \hat{\mathbf{s}}_{ij}(n)^T \mathbf{u}_i(n) \; . \tag{1}$$

For the washing machine casing, the vibrational and acoustic cross couplings are of significant magnitude. It results in a requirement imposed on the control system to take into account all paths

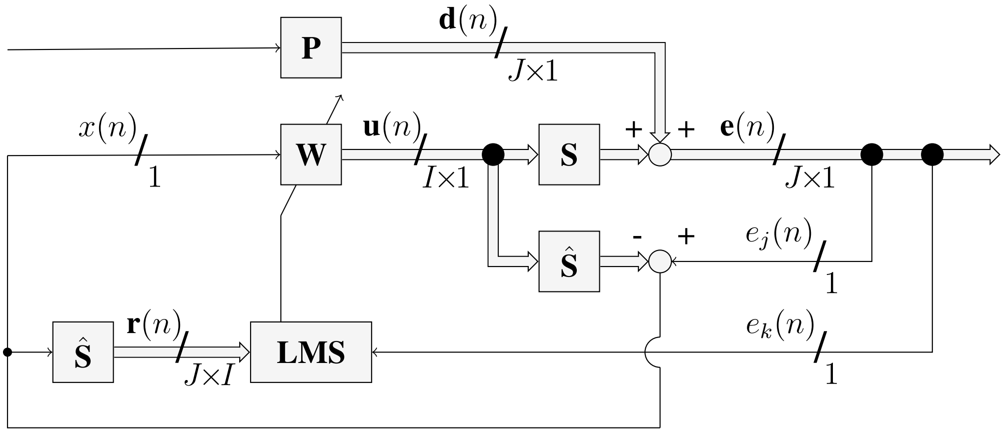

Figure 3: Multi-channel feedback IMC control system with the FxLMS algorithm.

between actuators and sensors (neglecting some of the paths may result in instability). However, such multi-input multi-output (MIMO) control system represent very high computational demand (in the considered system there are 11 inputs and 4 outputs). To respond to this feature, a switched-error modification is introduced to the control algorithm [10]. The modification consist in adaptation of all control filters according to only one error signal $e_k(n)$ (k-th out of J error signals), and cyclically changing the sensor which provides the signal (cyclically changing the k in the range from 1 to J). Such algorithm results in approximately J times reduced computation complexity, but it is less vulnerable to cross couplings of the structure compared to a control system where some of the paths are neglected (e.g. as in separated control systems for individual walls). However, as expected, the cost of it is the convergence speed. It is due to the fact that at once, control filters are adapting to only one of the error signals. It is approximately $2J$ times slower, but it is still a matter of only tens of seconds to converge, which is in accordance to predefined practical requirements. Further details of switched-error modification are provided in [10].

In the schematic representation of the control system given in Fig. 3, symbol $\mathbf{W}$ is the adaptive control filters vector (of dimension $(I \times 1)$, where I is the number of actuators), $\mathbf{P}$ is the primary paths vector (of dimension $(J \times 1)$, where J is the number of error sensors), defined between the reference and error sensors. Figure $\mathbf{S}$ stands for the secondary paths matrix of dimension $(J \times I)$ defined between the inputs of the actuators and outputs of the error sensors. These paths include electronics necessary for signal conditioning and data conversion. The symbol $\hat{\mathbf{S}}$ stands for the secondary path model. In turn, $x(n)$ is the estimated scalar reference signal, $\mathbf{r}(n)$ is the filtered-reference signals matrix of dimension $(J \times I)$, $\mathbf{u}(n)$ is the control signals vector of dimension $(I \times 1)$. Further, signals $\mathbf{d}(n)$ and $\mathbf{e}(n)$ are the primary disturbances vector and the error signals vector, respectively, both of dimension $(J \times 1)$, at positions of the error sensors where noise reduction is desired. Signal $e_j(n)$ is the j-th selected error signal for estimation of primary disturbance, as defined for the IMC architecture. Signal $e_k(n)$ is the k-th selected error signal currently employed for adaption and cyclically changed as previously described. In the control system configured for the washing machine casing, the number of actuators $I = 11$. On the other hand, the number of error sensors (outer microphones) $J = 4$.

The coefficients of i-th control filter at the $(n + 1)$-st sample, $w_i(n + 1)$, are updated for the error signals $e_k(n)$ according to the formula:

$$\mathbf{w}_i(n+1) = \alpha \mathbf{w}_i(n) - \mu(n) \mathbf{r}_{ik}(n) e_k(n) \ , \tag{2}$$

where $\mathbf{w}_i(n) = [w_{i,0}(n), w_{i,1}(n), \ldots, w_{i,N-1}(n)]^T$ is the vector of coefficients of the i-th adaptive Finite Impulse Response (FIR) control filter at sample n, and N is the filter order. Symbol $\mathbf{r}_{ik}(n) = [r_{ik}(n), r_{ik}(n-1), \ldots, r_{ik}(n-(N-1))]^T$ is a vector of regressors of the ik-th filtered-reference signal, $\mu(n)$ is a step-size, and $0 \ll \alpha < 1$ is the leakage coefficient.

The i-th control filter is used to calculate i-th control signal, $u_i(n+1)$, obtained as follows:

$$u_i(n+1) = \mathbf{w}_i(n)^T \mathbf{x}_u(n) \ , \tag{3}$$

where $\mathbf{x}_u(n) = [x(n), x(n-1), \ldots, x(n-(N-1))]^T$ is the vector of regressors of the reference signal. The ik-th filtered-reference signal is calculated as:

$$r_{ik}(n) = \hat{\mathbf{s}}_{ik}(n)^T \mathbf{x}_r(n) \ , \tag{4}$$

where $\hat{\mathbf{s}}_{ik}(n) = [\hat{s}_{ik,0}(n), \hat{s}_{ik,1}(n), \ldots, \hat{s}_{ik,M-1}(n)]^T$ is the vector of coefficients of the M-th order FIR model of the ik-th secondary path and $\mathbf{x}_r(n) = [x(n), x(n-1), \ldots, x(n-(M-1))]^T$ is a vector of regressors of the reference signal. It is justified to consider further reduction of the computational burden, as discussed in [17].

4. Experimental results

In this Section, experimental results for the washing machine casing are presented. Four walls of the casing are controlled to reduce the emission of noise generated by a primary noise source enclosed

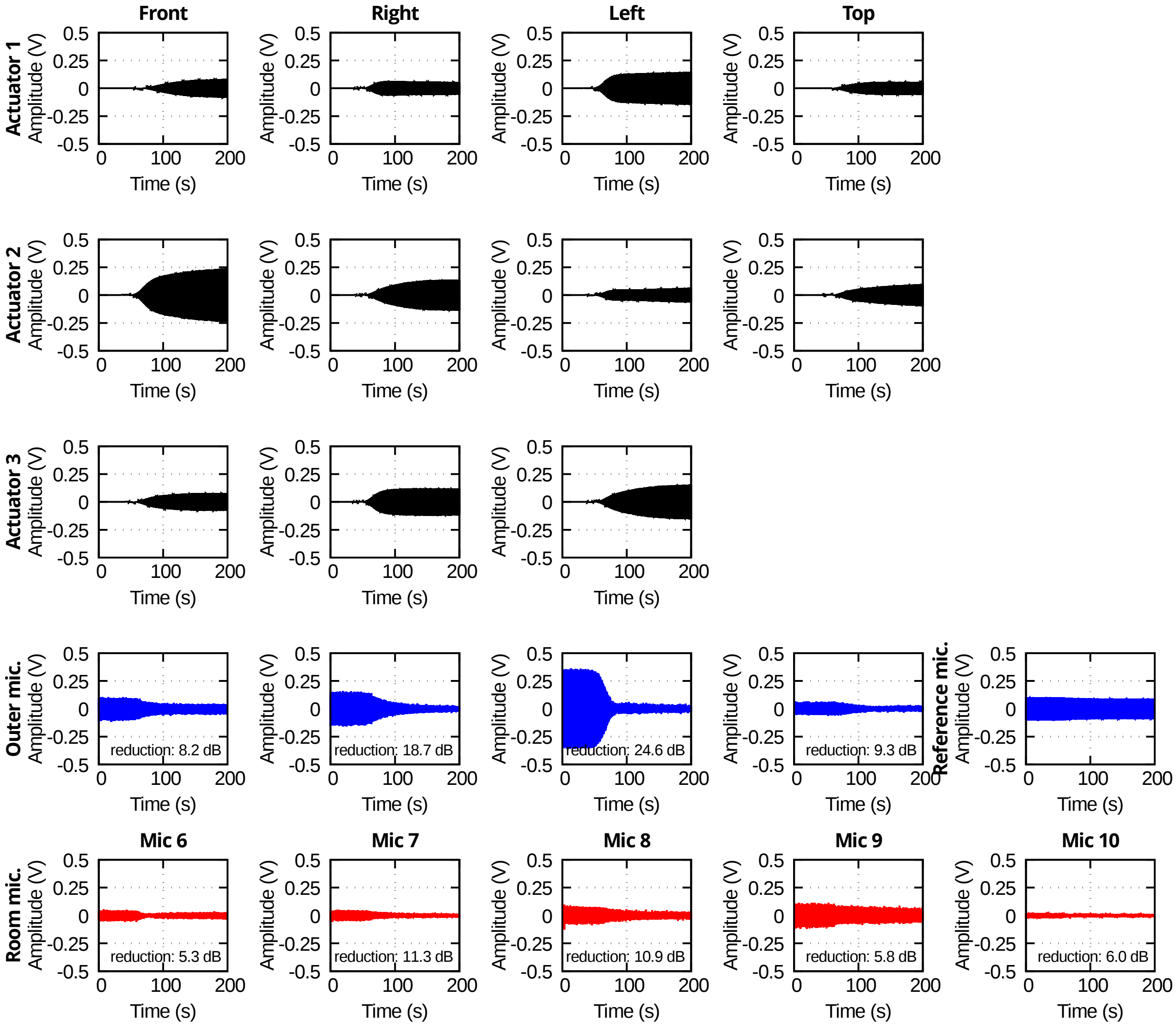

Figure 4: Time plots for experiment performed for the primary disturbance of 107 Hz and the washing machine casing. The outer microphones are used as error sensors.

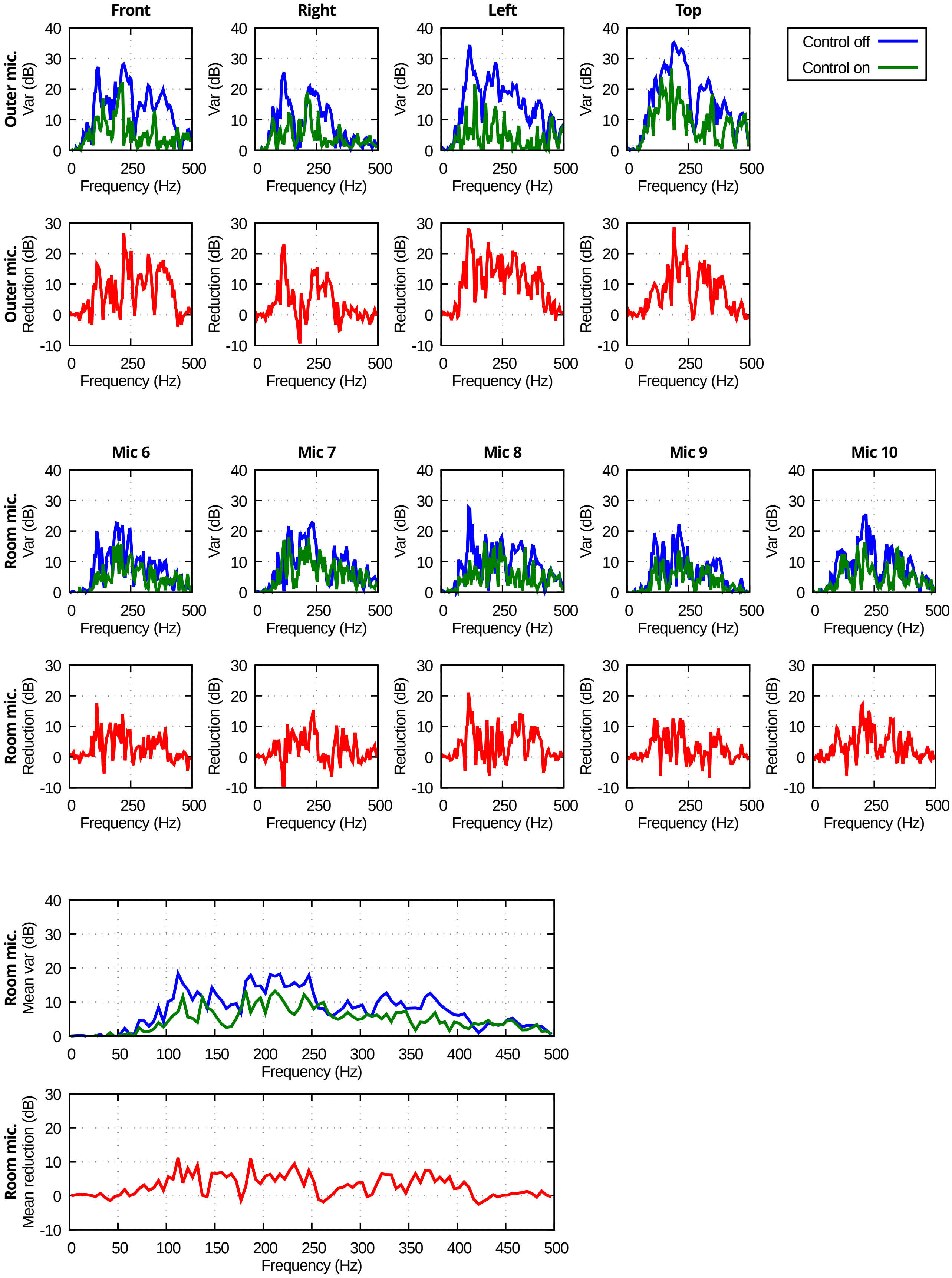

Figure 5: Frequency characteristics for the active control experiment performed for the washing machine casing. The outer microphones are used as error sensors.

in the casing. To achieve this goal, instantaneous square values of error signals are minimized by the feedback adaptive control system, controlling eleven inertial actuators. The error signal is obtained by the outer microphones. The primary disturbance is generated as a tonal signal of frequency incremented by $5\,\mathrm{Hz}$ in the range from $1\,\mathrm{Hz}$ to $500\,\mathrm{Hz}$. The considered frequency range includes the low frequencies where the speaker starts to transmit sound.

The control performance is evaluated as noise reduction level observed only by room microphones. For each frequency of the primary disturbance, a 200 seconds experiment was performed. During its initial phase the active control was off, and variance of the signal acquired by different sensors was estimated. Then, active control was turned on. When the control algorithm converged, final 5 seconds of the experiment were used to estimate the variance of the signal acquired by corresponding sensors.

Results of an exemplary experiment in the time domain are presented in Fig. 4. First three rows present control signals, where the convergence rate can be observed. In the fourth row, signals measured by microphones used in this experiment as error sensors are shown. In the fifth row of the Figure, signals measured by five room microphones are presented. The reference microphone measurement is also shown for completeness.

In Fig. 5 frequency characteristics for the experiment with the control system are presented. In the last row of the Figure, the mean reduction obtained at room microphones is shown. It is considered as the main point for evaluation of active control performance. Remaining plots present variances in dB scale of signals acquired by error sensors and individual room microphones, without (blue) and with (green) control. Additionally, bellow each individual frequency characteristic, a reduction characteristic is also presented, calculated as a difference between noise level without and with control (reduction is marked with red colour).

5. Conclusions

Active structural acoustic control of multiple walls of a market-available and unmodified washing machine has been performed. The feedback IMC adaptive control system with the FxLMS algorithm has been used. Its performance has been evaluated for multiple microphones in the room. Significant levels of global noise reduction have been obtained (achieving over 10 dB [18]), confirming high potential of the active casing approach to reduce excessive noise generated by real devices.

The evaluated configuration performed well for the whole considered frequency range (up to 500 Hz). Its performance was reliable and noise enhancement or convergence problems practically never occurred. The Switched-error FxLMS algorithm [10] has been employed, enabling to achieve significant global noise reduction with reduced computational demand. It is noteworthy that the microphones placed outside the casing can be replaced with structural sensors (e.g. accelerometers) utilizing the Virtual Microphone Control technique [19], therefore making the solution more practically feasible. In future research the authors intend to employ presented methods for active reduction of device noise during its regular operations (e.g. spinning cycle, etc.).

Acknowledgement

The research reported in this paper has been supported by the National Science Centre, Poland, decision no. DEC-2014/13/B/ST7/00755, and the Ministry for Higher Education and Science.

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