Active Noise Control for Dishwasher noise

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Abstract. The dishwasher is a useful home appliance and continually used for automatically washing dishes. It’s commonly placed in the kitchen with built-in style for practicality and better use of space. In this environment, people are easily exposed to dishwasher noise, so it is an important issue for the consumers, especially for the people living in open and narrow space. Recently, the sound power levels of the noise are about 40 – 50 dBA. It could be achieved by removal of noise sources and passive means of insulating acoustical path. For more reduction, such a quiet mode with the lower speed of cycle has been introduced, but this deteriorates the washing capacity. Under this background, we propose active noise control for dishwasher noise. It is observed that the noise is propagating mainly from the lower part of the front side. Control speakers are placed in the part for the collocation. Observation part of estimating sound field distribution and control part of generating the anti-noise are designed for active noise control. Simulation result shows proposed active noise control scheme could have a potential application for dishwasher noise reduction.

1. Introduction
Dishwasher is one of home appliance for automatically washing dishes instead of hands. This automatic service will provide us convenience, but also acoustic noise. Because the dishwasher is commonly placed close to living space, people are easily exposed to dishwasher noise. This problem can be more crucial for consumers who live in open and narrow space, and even want to operate it overnight. That’s why people consider the level of noise as well when they choose dishwasher. The Table 1 shows the noise of top 10 dishwashers in 2015 by expert reviews (Top Ten Reviews). The level of noise power is not that high correlated with the ratings, but low-noise dishwasher must be more attractive to consumers.

For low-noise dishwasher, people have redesigned noisy part and insulated it with sound absorbers or blanket of thermoplastic material. Also, there is an active noise control approach [1]. However, this method is developed to reduce only narrowband noise by motor. Under this background, we propose open-loop active noise control for dishwasher noise and verify the feasibility by numerical simulation.

| Dishwashers | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-------------|----|----|----|----|----|----|----|----|----|----|
| Lw (dBA)    | 42 | 48 | 42 | 45 | 50 | 47 | 44 | 46 | 42 | 46 |

Table 1. The level of noise power in top 10 dishwashers in 2015
2. Noise in dishwasher

As we mentioned, built-in style is common and its stronger growth is anticipated. So, we consider noise in built-in dishwasher. In this case, all sides except the front are covered by cabinets. So we can assume the noise radiates through the front side. Then, we set microphone array and measure radiating noise outside like Figure 1. In Figure 2, we observed the noise is radiating mainly from the front side, especially the lower part. We focus on this property and design active noise control for global reduction of noise radiating outside from the lower part of front side of built-in dishwasher. We call the surface, which is coincident with the front side and bounded like the box with broken line in Figure 1, reference surface in this paper.

Figure 3 shows spectrogram of noise measured at 1m distance from dishwasher. It contains periodic noise and broadband noise. The frequencies of periodic noise are coincident with multiple of those of pump motor or vane motor. In perceptual level of noise spectrum, we consider the frequency range of interest is from 100 Hz to 500 Hz.

![Figure 1. experimental set-up (Box : reference surface)](image1)

![Figure 2. The pressure distribution of frontal surface of dishwasher.](image2)

![Figure 3. Spectrogram of noise measured at 1m distance from the front of dishwasher.](image3)
3. Active noise control for dishwasher noise
Active noise control (ANC) is a method of reducing unwanted noise by generating antiphase sound. It has been used in duct system, transformer, and headset and so on. The most common ANC algorithm is Filtered-X Least Mean Square (FXLMS) algorithm [2]. It is an adaptive algorithm updated by signal measured from physical microphone called error microphone. It means that if we apply this algorithm for dishwasher, we must place one or more microphones somewhere in living space. It’s not practical because it can disturb people and the algorithm can diverge by disturbance from voice of people, music sound and so on. Even for global reduction, it needs lots of microphones to observe overall noise. So, we consider ANC without any error microphone and propose open-loop ANC for dishwasher noise.

3.1. Assumption
Before we design ANC algorithm, we have some assumptions. First, the noise is radiating through the lower part of the front side. It’s already observed in preliminary experiment. We don’t consider any noise radiating except that part. Second, ground and front plane including front side of dishwasher are infinite plane and acoustically rigid boundary. With this assumptions, we can regard radiating outside from dishwasher as sum of free field propagating sound and reflected sound at the boundary. Third, free-field assumption is applied.

3.2. Open-loop ANC algorithm
Based on the assumptions, we can predict sound field by noise if we know the pressure distribution on the surface at the lower part of front side. With this concept, we design ANC algorithm including observation part and control part. Observation part is estimating pressure distribution on the reference surface and control part is determining control gains for input to speakers. This concept is already used in active window system [3], but each part should be modified for the dishwasher system. The total block diagram is simply expressed as Figure 4. We have a frequency-domain approach and following mathematic formulas are expressions for single frequency in discrete space.
3.2.1. Observation part
In the paper of active window system [3], they can assume the noise as plane wave and estimate the pressure distribution \( S \) on the reference surface with baffle window assumption. But, it’s not possible in dishwasher. Instead, we use MIMO linear model \( H_{RS} \) [4] using reference signals \( R \). Then, the pressure distribution is estimated as:

\[
S' = H_{RS} R
\]

where \( R = [R_1, R_2, \ldots, R_p]^T \), \( S' = [S'_1, S'_2, \ldots, S'_0]^T \), and

\[
H_{RS} = \begin{bmatrix}
H_{R_1S_1} & H_{R_2S_1} & \cdots & H_{R_pS_1} \\
H_{R_1S_2} & H_{R_2S_2} & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
H_{R_1S_0} & \cdots & \cdots & H_{R_pS_0}
\end{bmatrix}
\]

The reference signals should be high coherent with acoustic pressure signals on the reference surface. For this, we should premeasure both of signals from reference candidates and acoustic pressure signals on the reference surface using such as a microphone array, and determine the best combination of reference signals based on multiple coherence [4] and causality condition. Then, we can achieve the linear model as:

\[
H_{RS'} = G_{R'R} G_{RS} \quad \text{where } G_{R'R} = E\{R'R^T\}, \quad G_{RS} = E\{R'S_q\},
\]

and \( H_{RS'} \) is a row for estimating \( S_q \) which is pressure at one point in the reference surface. Then, \( H_{RS'} \) corresponds to the observation part in Figure 4.

3.2.2. Control part
For global reduction, we should place control sources as close to noise sources as possible. If the transfer paths of noise sources would be well determined, we could use them. However, it’s not well determined yet. Instead, we observed that dishwasher noise is radiating outside through the reference surface. So, we consider placing control sources aligned with the surface. Then, we determine the number of control sources and how to arrange them in section 4.

To get the control gain for control sources, the interior space is assumed as semi-infinite space in the paper of active window system [3]. In dishwasher, we consider method of images [5] about reflection of radiating noise by ground. In this case, the space of radiating noise can be semi-infinite space. Then, we can apply the same approach in the control part with the active window system. However, the surface for the cost function should be modified. The surface was hemi-sphere. In case of dishwasher, there could be another home appliance or wall in the front and the distance is not long enough to satisfy free-field assumption for the frequency of interest. We consider cost space instead of cost surface. The cost space is all space far from the reference surface with more than 1 meter. Then, the cost function is expressed as:

\[
J = \sum_i |N_i + Y_i|^2,
\]

where \( N \) is pressure by noise source and \( Y \) is pressure by control source. From the reference signals, we can estimate the pressure in the cost space as:

\[
N' = G_{N'S'} S' = G_{N'S'} H_{RS} R, \quad \text{where } N' = [N_1, N_2, \ldots]^T, \quad G_{N'S'} = \begin{bmatrix}
G_{N_1S_1} & G_{N_2S_1} & \cdots & G_{N_pS_1} \\
G_{N_1S_2} & G_{N_2S_2} & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
G_{N_1S_0} & \cdots & \cdots & G_{N_pS_0}
\end{bmatrix}
\]
Here, $G$ is free-field Green’s function. Also, $Y = \begin{bmatrix} Y_1 & Y_2 & \cdots \end{bmatrix}^T$ can be expressed as:

$$Y = G_{Y|C}C = G_{Y|C}T_{spk}KR,$$

(5)

where $C = \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_M \end{bmatrix}$, $T_{spk} = \begin{bmatrix} T_{spk,1} & 0 & \cdots & 0 \\ 0 & T_{spk,2} & \vdots & \vdots \\ 0 & \vdots & \ddots & 0 \\ 0 & \cdots & 0 & T_{spk,M} \end{bmatrix}$.

Here, $C$ is control source, $M$ is the number of control source, $T_{spk}$ is the transfer function control input to control source including the dynamics of speaker, and $K$ is the control gain which we should determine. This is calculated to minimize the cost function $J$ as:

$$J = \sum (Y|C - N|S)R^2S^2,$$

(6)

where $(G_{Y|C}T_{spk})^{-1}G_{N|S}$ corresponds to the control part in Figure 4.

4. Computer simulation

To verify feasibility of proposed ANC, we implement computer simulation. First, we check how much reduction is possible with control sources aligned with the reference surface. We consider loudspeakers for generating control sources. The lowest frequency is 100 Hz in the frequency range of interest so that the size of loudspeaker should be big enough to cover the range. We consider a 3-inch loudspeaker due to the limited height. Loudspeakers physically have some volume. The area, which noise is radiating through, depends on where and how many to place them. We consider placing them symmetrically, widely, and having equal interval. The candidates of number of speakers are one to five. Based on premeasured pressure distribution on the reference surface, we calculate the expected reduction performance by the candidates. Figure 5-6 shows the simulation result of an example using 4 speakers. Figure 7 shows the expected total reduction performance in cost volume as the number of speakers. The more speakers we use, the better performance we get. When we consider the performance and the cost, 4 speakers seem to be enough.

In the second simulation, we check how accurate when we take MIMO linear model for the estimation of pressure distribution on the reference surface. We set 13 accelerometer and 10 microphones at expected noise source including motors and at surface in expected transfer path including outside surface of tub, kickplate and so on. Unfortunately, we could not place any sensors inside tub because it could be disturbed by water hitting though it is waterproof sensor. Also, we measure the pressure distribution on the reference surface at the same time. The frequency range of interest is up to 500Hz. We consider the lower limit of wavelength of 500 Hz and place microphone arrays. The more signals we refer, the more accurate estimation is possible. We consider that three reference signals are enough and choose the combination to minimize the estimation error. Figure 8 illustrates microphone array with loudspeakers and Table 2 show the estimation error between $S$ and $S'$ on the reference surface by definition as:

$$\text{estimation error} = 10 \log_{10} \left( \frac{E^E}{S'S} \right),$$

(7)
Figure 5. The Sound Pressure Level (SPL) of radiating noise from dishwasher with ANC off. (This is a cross section that is parallel to side of dishwasher and passes the center of dishwasher. The left square expresses the dishwasher in side view)

Figure 6. The Sound Pressure Level (SPL) of radiating noise from dishwasher with ANC on. (This is a cross section that is parallel to side of dishwasher and passes the center of dishwasher. The left square expresses the dishwasher in side view)

Figure 7. The expected total reduction performance in cost volume by number of speakers.

Figure 8. Illustration of 4 control speakers and 27 measuring points on the reference surface.

Table 2. Estimation error at each measured point : dB(dBA)

| Number of Speakers | Reduction(dB) |
|--------------------|---------------|
| 1                  | -24.2(-14.6)  |
| 2                  | -26.3(-17.6)  |
| 3                  | -25.3(-16.4)  |
| 4                  | -25.0(-17.3)  |
| 5                  | -25.1(-18.1)  |
| 6                  | -23.8(-17.0)  |
| 7                  | -24.5(-16.7)  |
| 8                  | -25.4(-17.7)  |
| 9                  | -23.4(-16.1)  |
| 10                 | -26.9(-17.9)  |
| 11                 | -28.1(-18.9)  |
| 12                 | -27.4(-18.0)  |
| 13                 | -27.7(-19.8)  |
| 14                 | -27.8(-19.7)  |
| 15                 | -27.0(-18.7)  |
| 16                 | -27.2(-18.1)  |
| 17                 | -27.2(-18.4)  |
| 18                 | -25.7(-17.8)  |
| 19                 | -26.3(-15.6)  |
| 20                 | -27.0(-15.7)  |
| 21                 | -26.7(-15.4)  |
| 22                 | -27.7(-17.9)  |
| 23                 | -27.6(-17.5)  |
| 24                 | -27.1(-17.1)  |
| 25                 | -26.8(-16.4)  |
| 26                 | -26.8(-16.6)  |
| 27                 | -25.7(-16.1)  |
5. Conclusion
In this paper, we propose ANC for dishwasher noise. We observed that the noise is mainly radiating outside through the lower part of front side of dishwasher. For global reduction, we propose to place control sources aligned with the reference surface. The acoustic pressure distribution on the reference surface is achieved by MIMO linear model using reference signals. The control gain for control sources is determined to minimize the cost function with some assumptions. The simulation result shows proposed ANC scheme could have a potential application for dishwasher noise reduction.

In practice, the performance certainly get lower because the simulation is based on some assumptions and the frequency-domain approach has no consideration about causality. In the future work, the MIMO model and the control gain should be determined in time-domain approach in order to consider causality condition including time delay by loudspeaker, real-time processor and so on. Then, ANC experiment will be implemented to verify the performance of proposed ANC.

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