The 11th International Conference on Modelling, Identification and Control (ICMIC2019), Tianjin, China, 13-15 July 2019.

A study on geometrical factors based Active Noise Control for narrowband noise cancellation using PD-like Fuzzy Logic Control

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Abstract: This study considers the significance of geometrical configuration on the noise cancellation performance in the three-dimensional linear propagation medium for the compact source, and proposes a Proportional Derivative - Fuzzy Logic Control (PD-like FLC) scheme for active noise control (ANC). There are two contributions of this study. The first one is to make a comparison between two types of FLC, Mamdani-type and Takagi, Sugeno and Kang (TSK)-type as Mamdani-type is the most common choice for PD-like FLC and TSK-type works better with nonlinear problem and complex system. The second contribution is to investigate the effect of different distance ratios on cancellation performance or degree of cancellation. Matlab/Simulink bench tests are provided. The simulation results reveal that the TSK-type PD-like FLC performs better and different distance ratios result in different cancellation performance and the difference is significant. The optimal degree of cancellation can be achieved if both transducers placed close to the secondary source.

Keywords: PD-like fuzzy logic control, Feedforward ANC system, Acoustic feedback, Distance ratio

1 Introduction

In real life, narrowband noises generated from rotating machines like diesel vehicles and large cutting machines will have negative effects on people's daily life and living environment [1]. Currently, there are two widely used noise cancellation approaches, passive approach and active approach [2]. Compared with the passive approach, the active approach has better performance for noise cancellation in low frequency domain. [3], [4]. The essential and basic principle of the ANC is superposition in which the secondary acoustic wave can interfere with the primary acoustic wave to create a local silent zone around the observation point [5], [6].

The historical development of ANC can date back to 1936 when Lueg registered his patent in America [3]. In 1987, Leitch and Tokhi had completed a milestone work while they proposed that different geometrical configuration has a significant on degree of cancellation in the three-dimensional linear propagation medium, which provides an instruction for ANC schemes used in this paper [3]. Since the environment and the noise source are changing with time, therefore, the controller of the ANC system must include the adaptive filter to cope with time-varying variants [5], [6]. Relevant adaptive algorithms are thus proposed with the aim of optimizing the coefficients to achieve the optimal cancellation performance and the fuzzy logic control (FLC) is one of the best methods. The FLC is superior to other conventional control design methods as there is no requirement for the precise mathematical expression and information. It can model the complex real world based on expert knowledge which can deal with nonlinearities naturally existed in the ANC system due to the transducers and the secondary path [7]. It has different forms, such as Proportional-Integral (PI)-like, Proportional-Derivative (PD)-like and Proportional-Integral-Derivative (PID)-like. Currently, researches on PD-like FLC are more than PI-like FLC and the reason is that the PI-like FLC requires more rise time and settling time [8]. Several researchers have already applied PD-like FLC to different engineering problems [8], [9], [10], [11] and experimental and simulation results have already demonstrated its superior to the conventional controller. In this paper, based on geometrical feedforward ANC system proposed by Leitch and Tokhi in 1987 [3], a feedforward ANC scheme with a finite impulse response (FIR) filter is proposed. The PD-like FLC is selected as the parameter adjustment mechanism. In this system, the reason for FIR filter is simplicity. There are two main contributions of this paper. The first is that the novel proposed PD-like FLC algorithm explore another way of application of FLC in the active noise control. The second is that the investigation of effect of different distance ratios on the degree of noise cancellation could provide instructions for daily life practice.

The rest of the studies includes, Section 2 reviews the theory of Leitch and Tokhi's system and PD-like FLC. Section 3 provides the schematic diagram of the feedforward ANC system. Section 4 provides two case studies to test the cancellation capabilities of the proposed feedforward ANC system and explore the effect of the distance ratio on the overall cancellation performance. Section 5 gives some conclusions and future prospects.

2. Literature review

2.1. System description with consideration about geometrical consideration ([3], [12])

Figure 1 is the block diagram of the feedforward ANC system. The primary acoustic wave $p(t)$ is emitted from the primary source and then the detector detects it. After that, the electrical signal is transmitted to the controller to process. The output of the controller then transmit to the loudspeaker to generate the secondary source. The cancellation happens at the observation point.

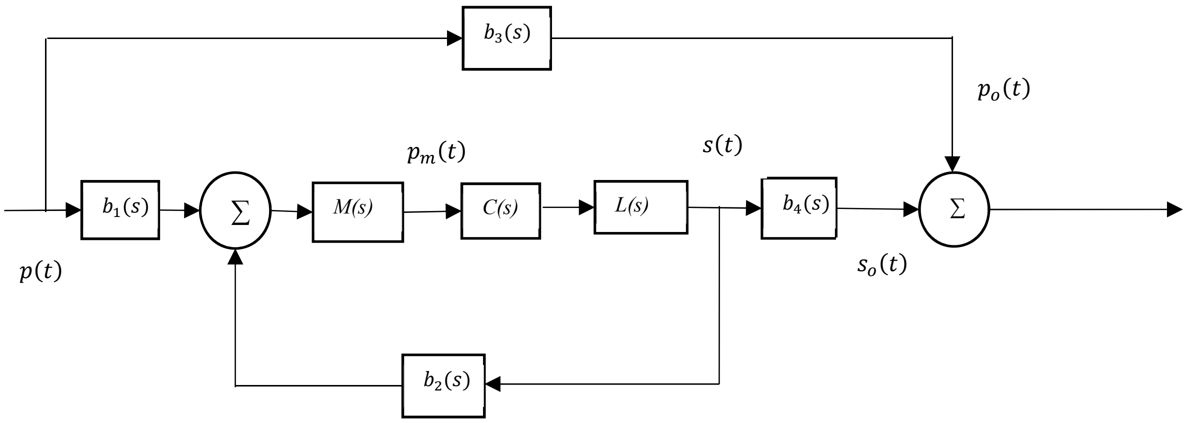


Figure 1. The block diagram of physical factors based feedforward ANC system ([3], [12])

Where
$p(t)$: the primary signal
$s(t)$: the secondary signal
$p_o(t)$: the primary signal at the observer point
$p_m(t)$: the detected signal at the detector
$s_o(t)$: the secondary signal at the observer point
$b_1(s)$: transfer characteristics/function of the acoustic path between the primary source and the detector
$b_2(s)$: transfer characteristics/function of the acoustic path between the secondary source and the detector
$b_3(s)$: transfer characteristics/function of the acoustic path between the primary source and the observer
$b_4(s)$: transfer characteristics/function of the acoustical path between the secondary source and the observer
$M(s)$: transfer characteristics/function of microphone
$L(s)$: transfer characteristics/function of loudspeaker
$C(s)$: transfer characteristics/function of controller
The function $b_1(s)$, $b_2(s)$, $b_3(s)$ and $b_4(s)$ are all constructed based on a time-delay transfer function and the mathematical expression in a complex *s* domain as

$$b_i(jw) = \frac{constant}{d_i} e^{-j\omega\frac{d_i}{c}}, \ \ i = 1,2,3,4 \tag{1}$$

where *c* denotes the speed in the propagation medium.
The condition for the complete cancellation is

$$P_o(s) + S_o(s) = 0 \quad , \tag{2}$$

where $P_0(s)$ corresponds to the frequency response of $p_o(t)$ and $S_0(s)$ means frequency response of $s_o(t)$.

The expression for the controller is

$$C(s) = \frac{b_3(s)}{M(s)L(s)(b_2(s)b_3(s) - b_1(s)b_4(s))} \tag{3}$$

In terms of implementing the feedforward ANC system displayed in figure 1, two physical constraints need to be notified.

The first one is that

$$b_4 < b_3 \tag{4}$$

The second one is that

$$\frac{b_1}{b_2} = \frac{b_3}{b_4} \tag{5}$$

The first condition implies that the electrical signal delay should be shorter than the acoustic wave delay and the second condition shows the critical distance ratio condition corresponding to the infinite gain controller, which is impossible in both experimental and practical life. In summary Tokhi and Leitch's theory provides a solid fundamental part of the research study in this paper.

2.2. PD-like Fuzzy logic control

For successful and commonly traditional controller design methodologies like state-space, root locus and Nyquist, the fundamental and compulsory requirement is that the model is linear and stationary. However, in the real world, systems are normally highly nonlinear and complex containing uncertainty and incomplete information and these methodologies cannot perform well. Fuzzy logic, which is proposed by Professor Lotfi Zadeh in 1965, is an excellent methodology for modelling real world problem without requirements for precise mathematical expression. The FLC contains four parts, fuzzification, inference mechanism, rule-base and defuzzification. The fuzzification is to transfer crisp inputs to fuzzy sets through membership functions (MFs). The inference mechanism and rule-base are the main part of the FLC, which can resemble human's reasoning and inference ability. There are three common types of fuzzy models, Mamdani-type, Takagi, Sugeno and Kang (TSK)-type and Tsukamoto-type. The process of design FLC starts from input-output selection. Here the relationship between the input and output can be written in different forms, such as PI-like, PD-like and PID-like. Normally, PD-like FLC is the preferred choice due to the permitted advantages in a short rise time and settling time. The second step is to select MFs. Currently, there are four commonly used MFs, triangular-shape, trapezoidal-shape, Gaussian-shape and Bell-shape. In this paper, different types of fuzzy model use different MFs for their input and output variables. The final step is to generate a rule map. As well known, the FLC is based on expert knowledge and the 'if-then' rules are the main form of presenting expert knowledge. Therefore, it is essential to carefully make sure the rule map with iteratively trial and error. In this paper, two rule map, 25-rules map and 36-rules map are provided for each type of FLC and details are provided in the following section.

3. Proposed feedforward ANC system

The schematic diagram of the proposed single channel geometrical arrangement based feedforward ANC system for noise cancellation in the three-dimensional non-dispersive propagation medium is shown in Figure 2.

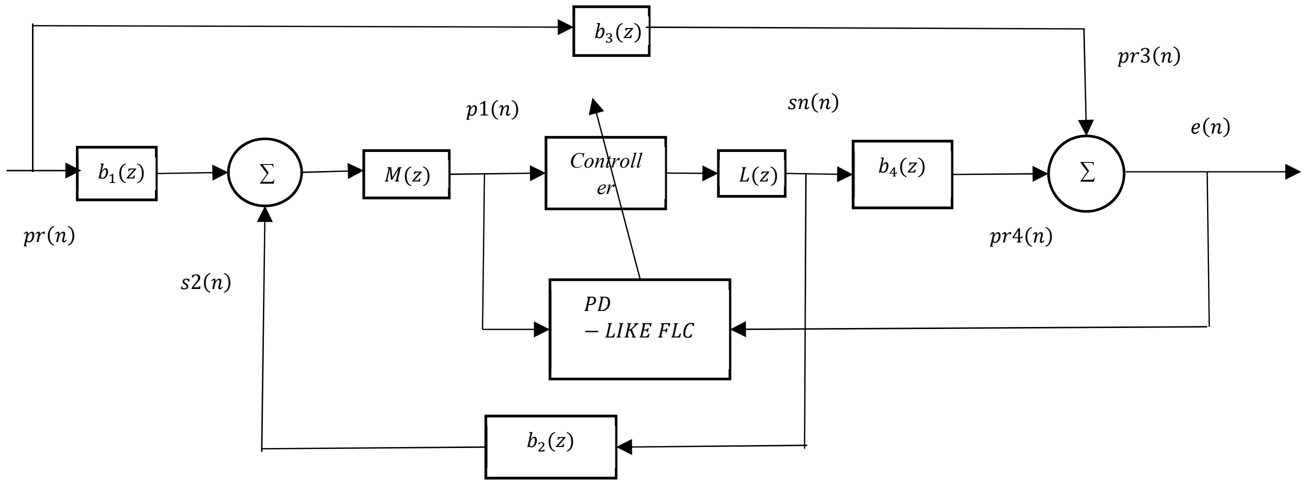


Figure 2. Proposed feedforward ANC system with consideration about the acoustic feedback and the distance ratio

Next step is to introduce the PD-like FLC, which is the essential part of the ANC system for tuning the coefficient value for the FIR filter. Here two types of PD-like FLC are introduced briefly with focus on MFs and rule map introduction.

3.1 TSK-type

The first step here is to select the input and output parameters/variables. Normally, the error and change of error are commonly selected as input variables and in this system, the combined signal and change of combined signal are used as input variables. The combined signal consists of the error signal and the acoustic feedback signal.

The second step is to select the MFs and confirm the rule map. In this system, for the input variables, the Gaussian MFs is used due to popularity and for the output variable, the zero-order TSK model is used in terms of simplicity. The fuzzy linguistic labels are Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB). The 25-rules map is displayed in table 1 as follows.

Table 1. 25-rules for TSK-type

	NB	NS	Z	PS	PB
NB	CF_2	CF_2	CF_3	CF_4	CF_1
NS	CF_2	CF_4	CF_4	CF_1	CF_6
Z	CF_3	CF_4	CF_1	CF_5	CF_6
PS	CF_4	CF_1	CF_5	CF_5	CF_7
PB	CF_1	CF_6	CF_6	CF_7	CF_7

3.2 Mamdani-type

The input and output selections are same as TSK-type. The triangular MFs is used for both fuzzification and defuzzification process while the centroid point method is used for defuzzification. The significant change for this type is that 'Negative Medium (NM)' and 'Positive Medium (PM)' are added to the family of fuzzy labels. The 36-rules map is displayed in table 2.

Table 2. 36-rules Mamdani-type

	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

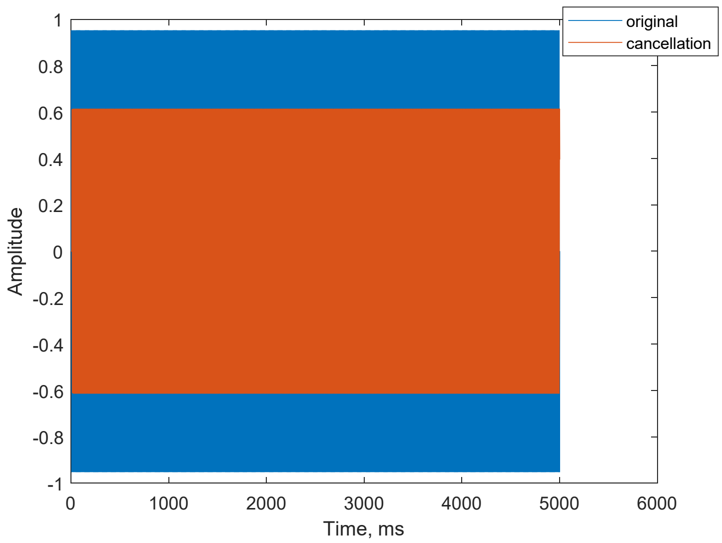
3.3 Comparisons between these two types

Mamdani-type FLC and TSK-type FLC are both commonly used FLC and the biggest difference between these two types is how crisp outputs generated from fuzzy sets. For Mamdani-type, the advantage is that it is good at describing the expertise more intuitive and human-like manner while the disadvantage focused on the substantial computational burden and less flexible in system design. For TSK-type, it is an attractive technology for control problems, especially for the nonlinear problem as it works well with optimization technique and adaptive technique and has the advantage of computationally efficient. The deficiency of the TSK-type is lack of interpretability [13], [14].

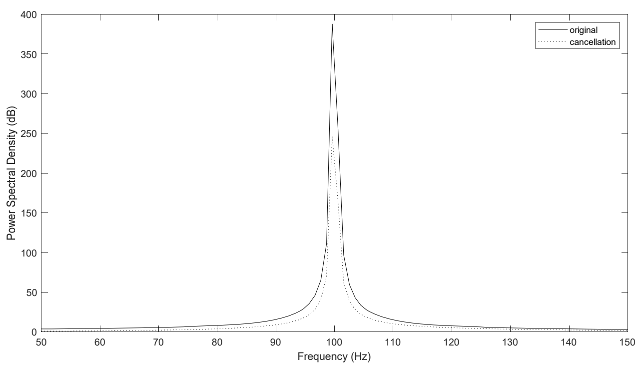
4. Case Studies

In this section, the proposed feedforward ANC system is implemented in a computer program based on Matlab/Simulink platform and two case studies are performed to test its cancellation capability and to investigate the effect of the distance ratio on the cancellation performance for noise in the three-dimensional propagation medium. The sampling frequency for each study is 1000 *Hz* and the simulation time is 5 seconds.

Case 1: This study intends to demonstrate the cancellation capability for the proposed feedforward ANC system. The standard type of narrowband noise is used here as the primary noise source. Firstly, the TSK-type based ANC system is used. Both time domain and frequency domain analysis are provided in figure 3.



a) Time domain

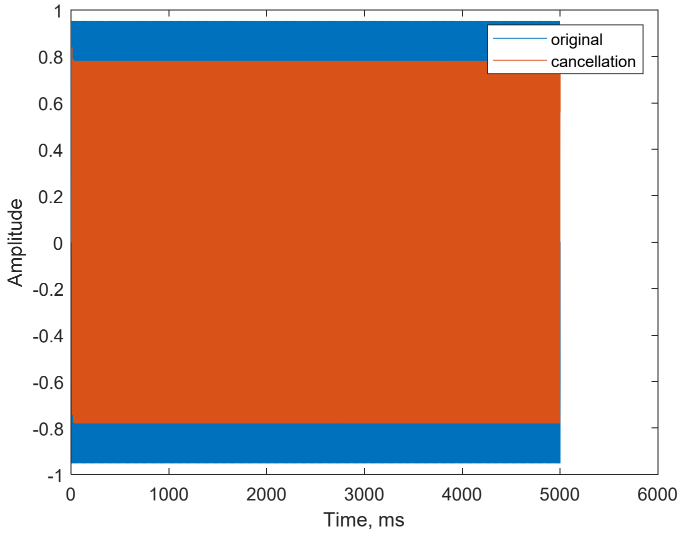


b) Frequency domain

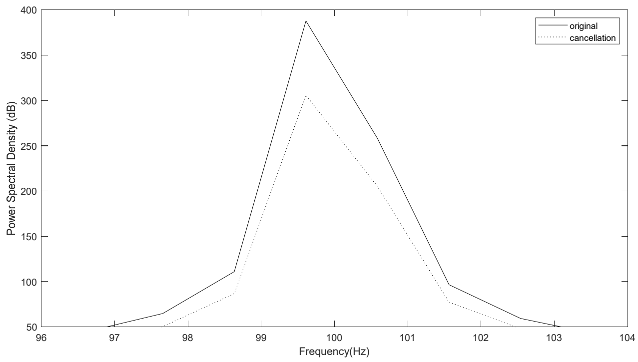
Figure 3. Identify the cancellation capability of proposed TSK-type based feedforward ANC system

Time domain analysis in figure 3a reveals that the amount of cancellation in terms of amplitude magnitude can be up to nearly 40% and frequency domain in figure 3b illustrates that the amount of cancellation in terms of the power spectral density is reduced by nearly 150 dB.

Secondly, the Mamdani-type based ANC system is used and both time domain and frequency analysis are provided in figure 4.



a) Time domain



b) Frequency domain

Figure 4. Identify the cancellation capability of proposed Mamdani-type based feedforward ANC system

Time domain analysis in figure 4a reveals that the amount of cancellation in the field of amplitude can be up to nearly 20% and frequency domain in figure 3b illustrates that the amount of cancellation in the field of power spectral density is reduced by nearly 100 dB.

In summary, simulation results from both time domain and frequency domain demonstrate the cancellation capability of the proposed PD-like FLC based feedforward ANC system and cancellation performance of TSK-type is superior to cancellation performance of Mamdani-type.

Case 2: This case is to investigate the effect of different distance ratio on noise cancellation performance. Meanwhile, as the narrowband noise widely exists in daily life, the simulation results can also provide several tips for implementation in real life.

First, the TSK-type based ANC system is selected and frequency domain analysis is provided as follows.

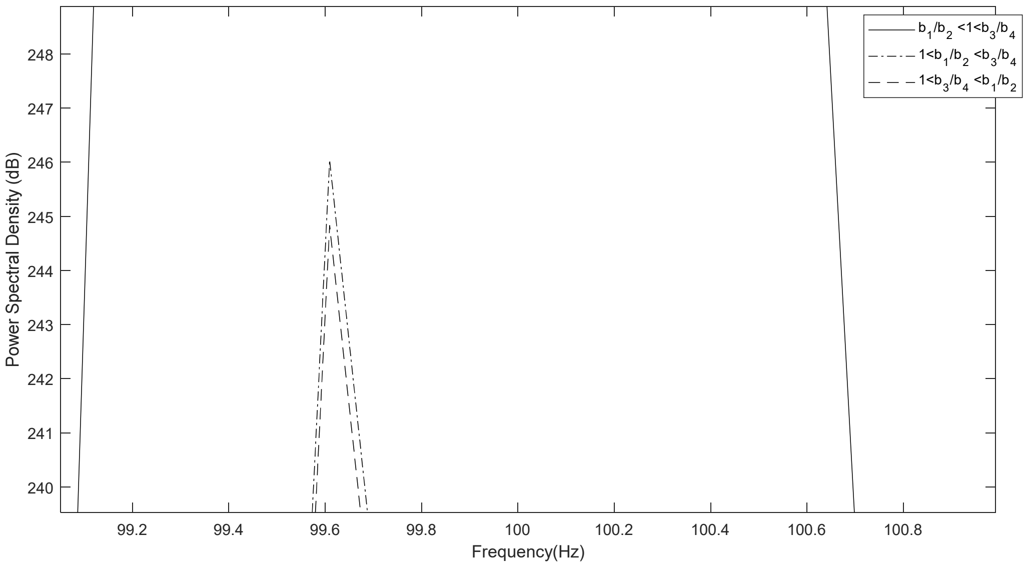


Figure 5. Comparison between different types of distance ratio (TSK-type)

Simulation result from figure 5 illustrates that cancellation performance under different distance ratio condition is different. Among these three conditions, the distance ratio for the optimal cancellation performance is $1 < \frac{b_3}{b_4} < \frac{b_1}{b_2}$ and the corresponding physical meaning is that both transducers are placed closed to the secondary source and the distance ratio for the detector is bigger than the distance ratio for the observer. Meanwhile, the difference between $1 < \frac{b_1}{b_2} < \frac{b_3}{b_4}$ and $1 < \frac{b_3}{b_4} < \frac{b_1}{b_2}$ is approximately 1dB, not big enough.

Second, the Mamdani-type based ANC system is tested and frequency domain analysis is provided as follows.

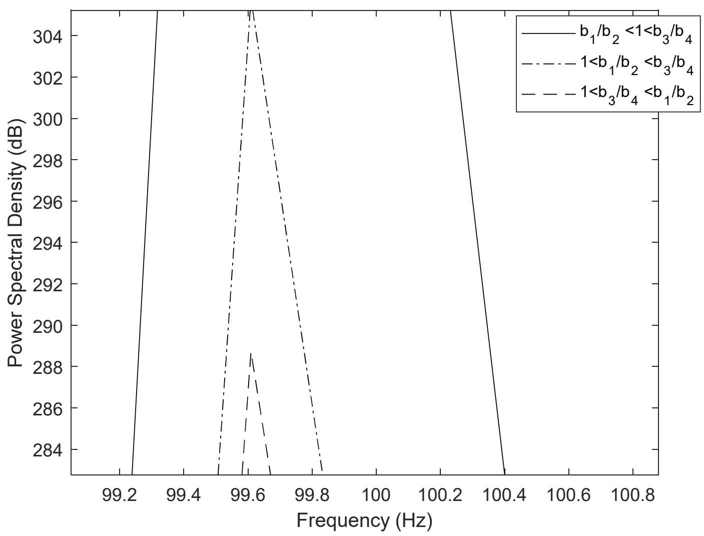


Figure 6. Comparison between different types of distance ratio (Mamdani-type)

Simulation result from figure 6 reflects that the effect of the different distance ratio on the noise cancellation performance is significant while employing the Mamdani-type PD-like fuzzy logic control. Same as the TSK-type, the distance condition corresponding to the optimal cancellation performance is $1 < \frac{b_3}{b_4} < \frac{b_1}{b_2}$. The difference between $1 < \frac{b_1}{b_2} < \frac{b_3}{b_4}$ and $1 < \frac{b_3}{b_4} < \frac{b_1}{b_2}$ increases to 7 dB compared with TSK-type. These simulation results imply that in the real life, the geometrical location of these transducers can be adjusted to satisfy the different specified requirement for cancellation.

5. Conclusions

A PD-like FLC based feedforward ANC system is proposed and studied. Simulation results from the cancellation capability test for both types demonstrate both Mamdani-type and TSK-type based PD-like FLC can achieve the aim of cancellation and the performance is better while employing the TSK-type PD-like FLC. The study aimed at investigating the effect of the distance ratio shows that the effect of physical distance on cancellation performance is significant. The optimal distance condition is that both transducers are placed closer to the secondary source. These findings provide practical instructioms for narrowband noise cancellation in real life. Further work will try to refine the rule map and MFs selection to achieve better cancellation performance.

6. Acknowledgments

The first author would like to acknowledge partial finance support from –the Department of Engineering, Design and Mathematics, UWE Bristol. The first author is grateful to the Editor-in-Chief, Associate Editor and anonymous reviewers for their careful reading and constructive comments

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