FEASIBILITY OF A LENGTH-LIMITED PARAMETRIC SOURCE FOR ACTIVE NOISE CONTROL APPLICATIONS

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In a previous work presented by the authors in ICSV20, we proposed a theoretical framework to generate a length-limited parametric source for active noise control (ANC). The length-limited parametric source consists of two parametric loudspeakers on the same axis. Two separate ultrasonic carrier frequencies are applied to the different parametric loudspeakers, resulting in different absorption lengths. By controlling the input phases and amplitudes of the two parametric loudspeakers, their secondary sound waves can suppress each other in the overlapped area but retain in the difference area. An advantage of the length-limited parametric source in active noise control is its ability to target a specific control region while minimizing the spillover effect of the conventional parametric source. However, the theoretical framework from the previous study has not been experimentally validated, and this paper aims to do the latter. A concentrically-nested parametric loudspeaker, which is driven by two ultrasonic frequencies with user-controllable settings, was built to conduct this experiment. The experimental setup consists of National Instruments’ data acquisition modules and Brüel & Kjærs’ microphones. The sound field along the length of the two absorption distances was measured to evaluate the suppression achieved in the overlapped region and retention in the difference region. Two types of signals were tested in the length-limited parametric source setup: (1) single tone and (2) linear chirp. In a non-adaptive ANC setup, a length-limited parametric beam was employed as the ‘anti-noise’ source to locally control the noise source produced by a conventional loudspeaker. From the experimental observations, further investigations can be conducted to improve the length-limited effect for narrowband signals.

1. Length-limited parametric secondary sources in ANC

One limitation of active noise control (ANC) systems, which utilises dynamic speakers as anti-noise sources, is the physical difficulty in collocating the noise source and anti-noise source to achieve an ideally wide ‘quiet-zone’.1 Thus, ANC systems usually produce localised ‘quiet-zones’ resulting in an undesired increase in sound pressure level (SPL) at areas outside the ‘quiet-zones’, also known as the ‘spill-over’ effect. Moreover, even if the aim of the ANC system is to produce a localised ‘quiet-zone’, the ‘spill-over’ effect cannot be avoided due to the Omni-directional nature of dynamic speakers. On the contrary, a highly-directive ‘anti-noise’ source generated by a parametric loudspeaker could potentially reduce the ‘spill-over’ area.
Parametric speakers generate highly-directive audible sound beams based on the self-demodulation effect in the nonlinearity of air. Since Brooks et al., numerous researchers have tested ANC systems with parametric ‘anti-noise’ sources. Notably, Kidner et al. have reported a reduction in the ‘spill-over’ area when a parametric anti-noise source was simulated based on the numerical solution of the Khokhlov-Zabolotskaya-Kuznetsov (KZK) equation. However, the ‘spill-over’ effect still exists in the area of the sound beam between the parametric source and the ‘quiet-zone’ location. To further reduce the ‘spill-over’ effect in ANC systems using parametric anti-noise sources, an ANC structure using a length-limited parametric anti-noise source was proposed.

The length-limited parametric source, shown in Figure 1, is based on the principle of ANC, where two beams on the same axis (with one at the same amplitude but out-of-phase with the other) nullifying each other in the overlapped region. Through simulations using the numerical solutions of the KZK equation, it has been shown that a parametric beam with a higher carrier frequency (shorter absorption distance) was able to reduce the ‘spill-over’ effect caused by the beam with a lower carrier frequency. Hence, this paper aims to experimentally verify the existence of a length-limited parametric source and to deploy the length-limited beam (as the anti-noise source) in a simple non-adaptive ANC system.

2. Physical implementation of the length-limited source

With reference to simulations conducted in the previous study by the authors, the generation of the length-limited source is formulated based on the same source equations (Eq.(1) and Eq.(2)) employing the double-side band modulation (DSBAM) technique.

\[ p_1 = p_0 [1 + m_1 \sin(\omega_1 t + \phi_1)] \sin(\omega_2 t) \]  
\[ p_2 = p_0 [1 + m_2 \sin(\omega_2 t + \phi_2)] \sin(\omega_2 t) \]

However, the center frequencies \( \omega_1 \) and \( \omega_2 \) are set to 25 kHz and 40 kHz respectively, based on the ultrasonic emitters (25 kHz and 40 kHz) that will be used in the experiment. The initial sound pressure \( p_0 \) of the source equations is set to 124 dB on the surface of both type of emitters.

Based on the environmental parameters of the test environment (temperature at 23°C and humidity at 50%), the absorption distances are approximately 13.7 m and 6.5 m for 25 kHz and 40 kHz parametric beams respectively. Since the absorption distance of the 40 kHz beam is shorter, its parameters will be varied such that the optimum reduction is observed in the region where both beams overlap. Thus, the phases, \( \phi_1 \) is fixed at \( \phi_1 = 0^\circ \) and \( \phi_2 \) varies from \( \phi_2 = 0^\circ \) to 330° at intervals of 30°; and modulation indices, \( m_1 \) is fixed at \( m_1 = 1 \) and \( m_2 \) varies from \( m_2 = 0.5 \) to 0.9 at intervals of 0.2.

As both beams have to be located on the same axis and generated from the same source location, a concentrically-nested parametric loudspeaker was proposed and built. The parametric speaker is made up of an inner hexagonal array of 36 (40 kHz) emitters and an outer annular ring of 36 (25 kHz) emitters, as shown in Figure 2. The arrays are driven separately by two analog outputs.
3. Experimental validation of the length-limited source

The long absorption distances of the 40 kHz and 25 kHz emitters (~7 m & 14 m respectively) coupled with the short Rayleigh distances (~1.5 m for both and beam loses directivity in the far-field), required a test environment that has sufficient length and is not affected by the reflections caused by the lost in directivity. Thus, the experiment was confined in a 9.5 m long PVC pipe with an internal diameter of 0.16 m.

The generation and real-time parameter control of the DSBAM signals and data acquisition of acoustic measurements was developed in a system design software (NI Labview) and implemented in a mix of hardware setup, as shown in Figure 2. In the setup, the parametric array is placed at one end of the 9.5 m pipe and driven by two separately amplified DSBAM signals from the NI PCI-6733 output module. Acoustic measurements are made by lowering the B&K 4961 multi-field microphone into the centre of the pipe at predefined distances from the parametric array (0.2 m to 4 m at intervals of 0.2 m, 4 m to 9.2 m at intervals of 0.4 m). Acoustic data from the microphone is acquired via the NI 9234 analog input module for post-processing. At each distance point, acoustic data is acquired for every combination of the varying \( m_z \) and \( \phi_e \) values (i.e., 3\( \times \)12 = 36 data points per distance point).

In line with the previous study, the experiment was conducted with the same modulating frequency, \( \omega_d = 2\pi \times 1.5 \text{kHz} \). In addition to the 1.5 kHz single tone modulating frequency, the experiment was also conducted for a linear chirp from 0.5 kHz to 3 kHz with duration of 1 s.

3.1 Single Tone

Figure 3 shows the sound pressure level (SPL) plots of the 1.5 kHz single tone, for \( \phi_e \) from 0° to 330° along the entire length of the pipe at the defined locations, and for \( m_z = 0.5 \) (Figure 3(a)), \( m_z = 0.7 \) (Figure 3(b)) and \( m_z = 0.9 \) (Figure 3(c)). From comparison of results plotted in Figure 3, a trend of reduction can be observed in the first 4 m when the phase of the 40 kHz source, \( \phi_2 = 150° \). By observation, the most significant reduction is achieved when \( m_z = 0.9 \) at \( \phi_2 = 150° \).

To determine the SPL reduction due to the shorter 40 kHz beam, a 1.5 kHz tone was generated with only the 25 kHz source. Figure 4 shows the comparison between the SPLs of the 1.5 kHz tone without the 40 kHz source and the length-limited beams with \( m_z = 0.5, 0.7 \) and 0.9 at \( \phi_2 = 150° \). The average SPL reduction is determined in the first 6.4 m of the pipe, which corresponds to...
the absorption distance of 6.5 m for the 40 kHz source, and are: (1) 5.57 dB reduction for $m_2 = 0.5$, (2) 7.59 dB reduction for $m_2 = 0.7$, and (3) 9.82 dB reduction for $m_2 = 0.9$.

![Figure 3: SPL values of the 1.5 kHz single tone along the length of the pipe for (a) $m_2 = 0.5$, (b) $m_2 = 0.7$ and (c) $m_2 = 0.9$, for $\phi_2$ from 0° to 330°.](image)
3.2 Linear Chirp

The linear chirp test is signal is of 1 s duration from 0.5 kHz to 3 kHz. Figure 5 shows the averaged SPL plots of the linear chirp for $\phi_2$ from 0° to 330° against the distance from the parametric source in the pipe. The plots are generated for $m_2 = 0.5$ (Figure 5(a)), $m_2 = 0.7$ (Figure 5(b)) and $m_2 = 0.9$ (Figure 5(c)). From Figure 5, reduction can be observed at $\phi_2 = 180^\circ$, but the length-limited effect is minimal at $m_2 = 0.5$. To further investigate, additional SPL values were measured for $m_2$ values of 0.2, 0.3 and 0.4 at $\phi_2 = 180^\circ$ to determine the optimal value to achieve a length-limited effect. Figure 6 shows the linear chirp averaged SPL plot of the 25 kHz source only and the length-limited beams at $\phi_2 = 180^\circ$ for $m_2$ values of 0.2, 0.3, 0.4, 0.5, 0.7 and 0.9, along the length of the pipe. By observation, the largest reduction in the first 6.4 m is at $m_2 = 0.4$. Quantitatively, the average SPL reductions in the first 6.4 m are: (1) 7.89 dB reduction at $m_2 = 0.2$, (2) 8.94 dB reduction at $m_2 = 0.3$, (3) 10.24 dB reduction at $m_2 = 0.4$, (4) 5.54 dB reduction at $m_2 = 0.5$, (5) 4.48 dB reduction at $m_2 = 0.7$, and (6) 2.21 dB reduction at $m_2 = 0.9$.

Due to the large reduction observed in the length-limited area, the SPL reductions in the length-limited area have to be determined to verify the existence of the length-limited beam. The reductions in the length-limited area are: (1) 7.18 dB reduction at $m_2 = 0.2$, (2) 8.76 dB reduction at $m_2 = 0.3$, (3) 10.44 dB reduction at $m_2 = 0.4$, (4) 7.04 dB reduction at $m_2 = 0.5$, (5) 7.60 dB reduction at $m_2 = 0.7$, and (6) 5.54 dB reduction at $m_2 = 0.9$. Thus, a length-limited effect is not evident for a linear chirp modulating frequency.
Figure 5: SPL values for the linear chirp signal along the length of the pipe for (a) $m_2 = 0.5$, (b) $m_2 = 0.7$ and (c) $m_2 = 0.9$, for $\phi_2$ from $0^\circ$ to $330^\circ$. 
Comparision between 25 kHz Beam and Length-limited beams

Figure 6: Comparison of linear chirp dB values along the length of the pipe between the 25 kHz source length-limited beams.

ANC of 1.5kHz Tone at 8 m

Figure 7: SPL values of local ANC at 8 m with a length-limited parametric source as the ‘anti-noise’ source.

4. ANC with a length-limited parametric ‘anti-noise’ source

Since the existence of a length-limited parametric source has been validated experimentally for the single tone case, the feasibility of deploying a length-limited parametric source for ANC applications can be tested. Using the same experimental setup, a noise source (1.5 kHz single tone) generated by a conventional speaker (GENELEC 1029A) is introduced at the 8 m position in the pipe. The distance of 8 m was chosen as it is greater than the absorption length of a typical 40 kHz parametric array (~6.5 m) and within the length-limited area (~6.5 m to 14 m). A length-limited beam generated with $\phi_2 = 150^\circ$ and $m_2 = 0.9$ will be used as the ‘anti-noise’ source to generate a single tone (1.5 kHz) for local control of the conventional noise source at 8 m. In contrast to traditional ANC, the phase and amplitude of the noise source at 8 m is adjusted such that there is optimum cancellation by the length-limited ‘anti-noise’ source.
SPL values along the length of the pipe for local control at 8 m are plotted in Figure 7. The conventional noise source at 8 m was reduced by 18.40 dB from 58.56 dB to 40.16 dB. The discrepancy in the waveform for the first 7.6 m of the length-limited beam is due to perturbations caused by the downstream reflections of the conventional noise source at 8 m.

5. Conclusion

This paper investigated the feasibility of deploying a length-limited source in a local ANC setup. Firstly, an experimental validation of the length-limited source proposed in a previous study was conducted for three types of test frequencies. The experiment was confined in a 9.5 m long PVC pipe and SPL measurements were taken at predefined intervals along the pipe. A reduction of 9.82 dB for single tone was achieved in the length of the pipe corresponding to the absorption distance of the 40 kHz beam. However, there is no conclusive evidence of the length-limited beam formation for a linear chirp. Next, the local ANC of a noise source generated by a conventional speaker at the 8 m position of the pipe was demonstrated. An 18.40 dB reduction of a 1.5 kHz single tone noise at 8 m was achieved with the length-limited parametric ‘anti-noise’ source. Based on the results, local ANC was achieved with reduced ‘spill-over’ effect for a single tone. Although it has been preliminarily shown that a length-limited source can be applied in ANC applications for single tones, it is worth noting the perturbations caused by the beating phenomenon between the carriers of the two parametric sources. Further investigation is required to prevent the introduction of unwanted difference frequencies due to the beating effect.

REFERENCES