Use of peak filter for online secondary path modeling in a feedforward active ship-noise cancellation system

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The injected auxiliary noise used in online secondary path modeling method often disturbs the convergence of control filter and increases the residual sound field energy of the active noise cancellation (ANC) system. To mitigate this problem, an improved online secondary path modeling method is proposed, in which the transfer function of secondary path is reconstructed by a peak filter. The frequency response of new transfer function remains unchanged at the frequency band of the noise to be cancelled; while the other bands are attenuated deeply. With this system the simulation experiment of active ship-radiated noise cancellation is accomplished. The result shows that new system's noise cancellation capability is improved and residual sound field energy (including channel response to injected auxiliary noise) is smaller than conventional system without peak filter because of the simplified transfer function of secondary path and reduced energy disturbance between control filter and modeling filter.

1 Introduction

Much research [1-3] about secondary path modeling has been done for its importance to active noise control (ANC) technique. Some online modeling methods have been developed aiming at the time-variant sound channel, which can be classified for two sorts approximately. For the first one the injected auxiliary noise is not needed [4]. On the contrary, the additional white noise source that is not correlative to noise to be cancelled is used for the second one in order to estimate the transfer function (TF) of secondary path through capturing channel response to modeling noises using error sensors and adaptive algorithm, as the result the optimization coefficients of secondary path TF will be obtained under least-mean-square (LMS) [5-11]. This kind of method can avoid the correlative disturbance between anti-noise and modeling noise (or so-called control filter and modeling filter) in a certain extent, obtain signal-independent secondary path TF in the whole band, and easily be applied in multi-channel ANC system.

But some shortages still are found in both theoretical analysis and experiments. Firstly, the error noise (we can call it error output of ANC system) after the destructive interference between anti-noise and noise to be cancelled remains in the sound field and is received by error sensors (used to measure error output both for noise cancellation and path modeling) and is involved in the process of estimation of secondary path TF, which shall affect the accuracy and speed of modeling. Secondly, the energy of injected modeling white noise energy should be strong enough to ensure modeling accuracy, but the strong white noise in sound field also influences the convergence of adaptive control filter. Thirdly, the secondary path response to modeling white noise will remain in the sound field and counteract the noise cancellation efforts of whole ANC system, i.e. the both the error output of ANC system and modeling noise remain in the sound field after convergence. Considering the first matter, prediction error filter [8-9] is introduced into ANC system by Sen M. Kuo and Zhang Ming based on some other researchers' work [5]. To solve the second question, new modeling filter control procedure was proposed [10-11] in which the energy of injected white noise will be reduced step by step with the convergence of modeling filter. But there are still some flaws in it, so they damage the robust stability of system: The controlling method is so sensitive that sometimes the great changing of white noise energy is triggered accidentally by irregular fluctuation of noise to be cancelled or secondary channel TF. It increases the divergence probability of the system. In this paper, a new feed-forward ANC system based on online secondary path modeling using peak pre-filter is proposed to try to solve these questions.

Only narrowband active noise cancellation system is concerned here. We try to use a peak filter or a band-pass filter with tiny pass-band to reconstruct the secondary path, which will be located before the real path. Consequently, a new impulse response controllable man-made secondary path is assembled. In this way, white noise can pass without any distortion in the interesting frequency bands or points, and it will be attenuated greatly in other bands. So the disturbance between control filter and modeling filter will be decreased, the residual energy of system in the sound filed will be less after system convergence. The brief theoretical analysis and simulation experiment about ship radiated noise active control have been done in the following sections.

2 System structure

As mentioned in the first section, a kind of exponential peak filter can be used now:

$$H(f) = \frac{1}{1 + \frac{4\pi^2\left[\prod_{i=1}^{N}(f - f_i)\right]^2}{\gamma^2}} \tag{1}$$

Where the f_i, $i = 1,2,...$ are center frequencies of pass-band and also the frequencies where the noises to be cancelled exist. Constant γ is used to control the band width. If the number of disturbing linear spectrum noises is small and they are close, the filter TF can be designed as Eq.2:

$$H(z) = G\frac{(z-1)(z+1)}{(z-\rho e^{i2\pi f_0})(z-\rho e^{-i2\pi f_0})} \tag{2}$$

For the linear spectrum noises at f_1 and f_2, the filter center frequency will be set at $f_0 = \frac{f_1 + f_2}{2}$, ρ is the constant to control band width, and G is used to get unit impulse response. Of course, there are also some other types of peak filters can be applied.

The new man-made secondary path TF can be expressed as $H_{pref}(z) = H(z)S(z)$, where $S(z)$ is the real path. Now we can control $H_{pref}(z)$ by controlling peak filter $H(z)$. That just is what we want. The system diagram is illustrated in Fig.1.

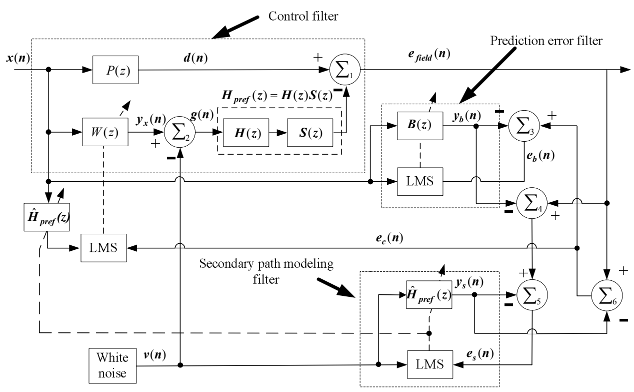

Fig.1 Structure diagram of proposed ANC system.

It consists of tree adaptive filters $W(z)$, $B(z)$ and $\hat{H}_{pref}(z)$. We can call them control filter and prediction error filter and secondary path modeling filter respectively. $\sum_i$, $i = 2,3,4,5$ means addition operation in circuit, $\sum_1$ is the destructive interference of sound waves.

About the adaptive iterative methods to get filter coefficients, both $B(z)$ and $\hat{H}_{pref}(z)$ belong to LMS algorithm, and $W(z)$ belong to Filtered-x LMS. The difference between proposed system and conventional one is modeling filter is used to estimate $H_{pref}(z) = H(z)S(z)$ but not the real path $S(z)$ here. When the whole system gets convergence status, the noise in the sound field will be changed to:

$$U_{field}(z) = U_x(z) + V(z)H_{pref}(z) \qquad (3)$$

where $U_x(z)$ is the noise error output which is correlative to reference input $x(n)$, $V(z)H_{pref}(z)$ is the secondary path response to injected auxiliary white noise.

Comparatively, the noise in circuit is:

$$U_s(z) = U_{x'}(z) + U_v(z) \qquad (4)$$

where the $U_{x'}(z)$ is the error output which is also correlative to reference input $x(n)$. $U_{x'}(z)$ will be less than $U_x(z)$ when the modeling filter $\hat{H}_{pref}(z)$ gets convergence. At the same time we will get $U_v(z)$ which is the modeling error in circuit. It is correlative to white noise $v(n)$.

After the convergence of ANC system, the noise components $U_{field}(z)$ in sound field and $U_s(z)$ in circuit both are supposed to be weakened remarkably.

Of course the destination of ANC technique is to reduce noise energy in sound field rather than only in the circuit. In the proposed system it's easy to understand the energy $V(z)H_{pref}(z)$ is much smaller than $V(z)S(z)$ because of the tiny narrow band of peak filter $H(z)$. Here the energy existing in the sound field for the conventional ANC system is given by:

$$U'_{field}(z) = U_x(z) + V(z)S(z) \qquad (5)$$

Compare Eq.3 with Eq.5, obviously, $U_{field}(z)$ is less than $U'_{field}(z)$, in other words, the new system is quieter.

On the other hand, for conventional system, the high secondary path response energy shall influence the convergence of control filter, especially during the course of filter coefficients updating, strong white noise response probably causes system unstable even divergent. It will be better to use peak filter to reconstruct the secondary path because the pre-filtered white noise with lower energy enhances the importance of error output of control filter, system convergence will be easier. We can see it in the following experiment.

3 Simulation experiment

The ship radiated noise spectrum is composed of both strong linear spectrum and broad band continual spectrum. Cancel the stable and strong linear spectrum is our simulation destination.

Strong linear spectrum of ship self-noise is the important information source for target detection and identification, and also is the main disturbing source for its own sonar system equipped on the ship. The control to ship radiated noise is an important potential application of ANC technique.

Fundamental frequency is $f_1 = 960$ Hz, double harmonic and ternary harmonic exist. Sampling frequency is 8 KHz, data length is 1 second. The power spectrum and wave shape in time domain are shown in Fig.2.

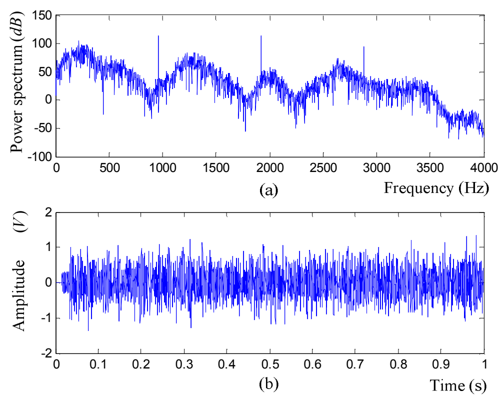

Fig.2 Main input of ANC system.

(a) power spectrum and (b) wave shape.

The cancellation results of conventional system are shown in Fig.3. The linear spectrum noises have been reduced about 45dB in both circuit and sound field. But in fact the total energy of the sound field has been increased because of the existing of secondary path response to injected auxiliary white noise when the modeling white noise is not pre-processed.

Let's see the processing results using proposed system now. The modeling result is shown in Fig.4. The real line is the real TF of secondary path, and the dashed line is what we get from modeling filter. The arrow points at the places where the center frequencies of peak filter are located. Apparently, the man-made secondary path suppresses those noises in the bands we don't need, but the amplitude response at the frequency points where we are interested in is estimated well.

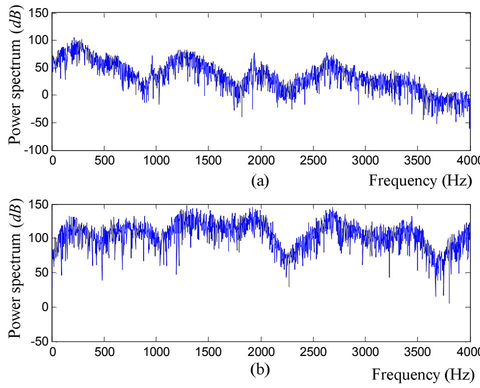

Fig.3 Power spectrum of error output of conventional ANC system in both (a) circuit and (b) sound field.

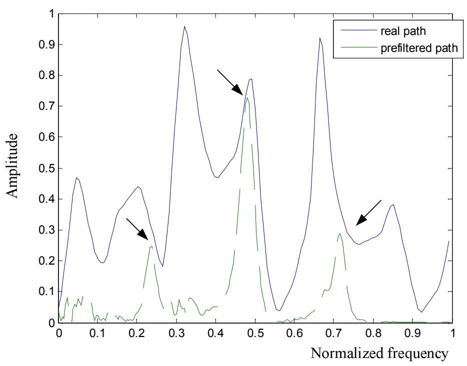

Fig.4 Normalized secondary path transfer functions of both (a) real path and (b) estimated path.

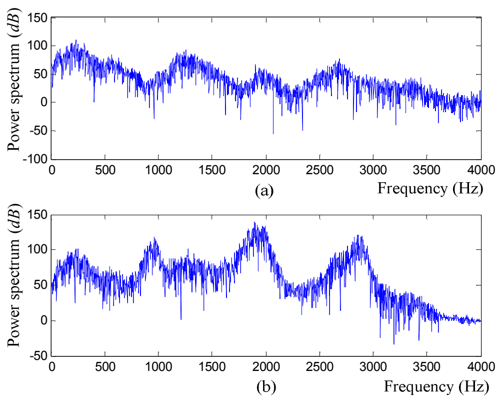

Fig.5 Power spectrum of error output of proposed ANC system in both (a) circuit and (b) sound field.

The final noise cancellation results are shown in Fig.5. Compared to Fig.3 (a), the linear spectrum noise cancellation result using the proposed system is better than conventional one. The disturbing between control filter and modeling filter is less for the reduced energy of modeling white noise. In the new system, the value of noise cancellation quantity is about 80dB. The most important thing is the sound field is quieter after system convergence: the energy of the sound filed of proposed system is less than conventional one 21.7dB.

4 Conclusion

White noise is often used in online secondary path modeling ANC system, but the additional injected white noise damages the quiet of sound field after system convergence. It's even very dangerous for some special application where importing a new sound source is sensitive. Maybe the proposed system structure is helpful for improving the ANC performance. In a word, the proposed system has some advantages:

1, reducing the complexity of secondary path in a certain extent.

2, reducing the energy disturbance between control filter and modeling filter.

3, reducing the residual energy of sound field after system convergence.

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