行政院國家科學委員會專題研究計畫成果報告

應用多率信號處理方法於主動噪音制系統以降低電子延遲

Reduction of electronic delay in active noise control systems – a multirate signal processing approach

計畫編號：NSC 90-2212-E-009-038
執行期限：90 年 08 月 01 日至 91 年 07 月 31 日
主持人：白明憲　DME 機械工程系
計畫參與人員：賴見汶　DME 機械工程系
黃士韋　DME 機械工程系

一、英文摘要

Electronic delay has been a critical problem in active noise control systems. This is true whether a feedforward structure or a feedback structure is adopted. In particular, excessive delays would create a causality problem in a feedforward ANC system of a finite length duct. We suggest a multirate signal processing approach for minimizing the electronic delay in the control loop.

二、緣由與目的

A great majority of ANC systems to date have been realized by digital systems[1]. Although digital systems provide many advantages over the analog counterpart, they suffer from several design constraints. In particular, the electronic delay during analog-to-digital (AD) conversion and digital-to-analog (DA) conversion, lowpass anti-aliasing and reconstruction (or smoothing) filtering has been a critical problem in active noise control systems. These delays along with other inherent delays resulting from computation and transducer dynamics might pose design constraints on ANC systems, which could become quite severe when the application of interest has strict space limitation, e.g., active mufflers for motorcycles. Excessive delays could create causality problems in a feedforward ANC system of a finite length duct if the noise of concern is broadband and random in nature.

To combat with the delay problem in the control loop, we proposes a digital signal processing scheme based on the multirate concept that is a fast growing area in many applications.[2-3] In this approach, digital controllers are required in decimation and interpolation of discrete-time signals. To enhance computation efficiency, a polyphase method is employed in filter design[4-6]. In the multirate ANC system, a factor of 8 was used for upsampling and downsampling. This resampling process raises the nominal sampling frequency of controller 2 kHz to 16 kHz during AD/DA conversion, which significantly reduces the sample delays. To this end, optimization procedures in frequency domain based on H_1, H_2 and H_∞ norms, respectively, are utilized in the design[7-9].

三、結果與討論

Experiments were undertaken to compare the performance of spatially feedforward duct ANC systems with and without multirate implementation. A wooden duct of length 440 cm and cross-section 25cm×25cm was constructed for the experiments. A TMS320C32 DSP equipped with four 16-bit analog IO channels is utilized to implement controller. The sampling frequency is chosen to be 16 kHz. The up/down sampling factor is selected to be 8, rendering a nominal sampling rate 2 kHz for the digital controller $C(z)$.

Considering the cutoff frequency of the duct (approximately 700 Hz) and the poor response of the control speaker at low frequency, we chose control bandwidth from 200 to 600 Hz.

In order to examine if the multirate approach is an effective method for designing low-speed digital filters in conjunction with high-speed IO channels, an experiment is conducted for comparing the conventional low sampling rate method and multirate rate method with H_2 optimal filter. Fig. 1. shows the experimental results obtained from DSP implementation of both methods.

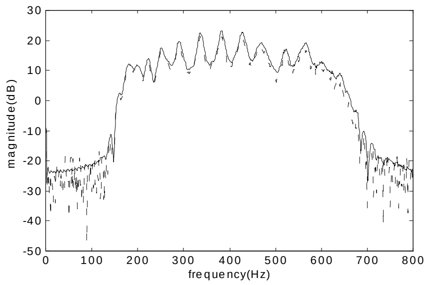

Fig 1

Good agreement can be found in the magnitude response within the control bandwidth 200-600 Hz. However, the phase response deserves more explanation. At low sampling rate (2 kHz), the IO delay (ϕ_T) of the conventional implementation is approximately 1.5 samples. The controller must be advanced using previewed by 1.5 samples to compensate for the delay. By multirate implementation, where the sampling rate is raised to 16 kHz, the IO delay can be reduced to only 0.7 samples (on 2 kHz basis). The controller is then previewed by 0.7 samples to compensate for the delay. These two compensated phase responses are shown in Fig. 2.

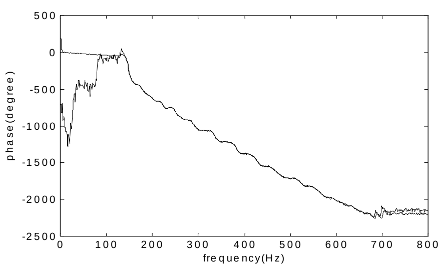

Fig 2

Good agreement can be seen in the phase response within the control bandwidth 200-600 Hz, while discrepancy below 200 Hz could be due to the poor signal to noise ratio outside the band.

An experiment is then undertaken to compare various optimal filter designs used in multirate implementation (16 kHz). The result of the conventional low sampling rate implementation (2 kHz) is also included for reference. Broadband random noise is used as the primary noise. Various systems are implemented by using the scenario: the first case is the conventional ANC without multirate implementation; while the next three cases are multirate ANC with H_1, H_2, H_∞ optimal filters, respectively. The experimental results are shown in Fig. 3.

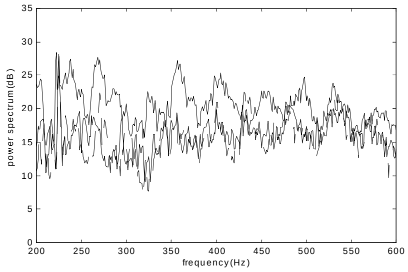

Fig 3

Significant attenuation of noise has been obtained throughout the control bandwidth.

As indicated in the results, the multirate approach is able to provide better performance with less hardware complexity than the conventional implementation. The multirate structure based on the polyphase representation achieves not only reduction of electronic delay but also enhancement of performance of ANC controller. In particular, the multirate ANC with H_2 optimal filter appears to yield the best performance (total attenuation 4.8 dB and maximum attenuation 17.3 dB). Thus, in next experiment, we shall focus our discussion only in the multirate ANC with H_2 optimal filter.

At this point, one question will naturally arise. What is the limit of shortest length that one is able to achieve by using the multirate approach in the spatially feedforward duct ANC system? On the basis of delay estimation procedure, the total electronic delay is estimated as 1.6 samples. To ensure a causal controller, this in turn renders the minimal length 23 cm, which is a remarkable improvement owing to the considerable reduction in the analog filter delay and digital IO delay. However, for shorter lengths, the conventional method begins to lose performance, whereas the multirate method remains effective in achieving broadband attenuation, as shown in Fig. 4.

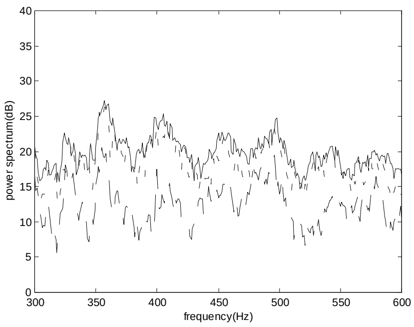

Fig 4

As expected, the performance deteriorates with decreasing length.

四、計畫成果自評

This project suggests three potential contributions. First, this work represents the first application of a multirate ANC system to duct problems. Second, the significance of delay to the spatially feedforward system with strong acoustic feedback is thoroughly examined in the paper. Third, details of how one should implement the multirate scheme in the context of ANC applications are presented, and how effective the approach would bring forth with regard to physical dimension is quantitatively evaluated. A detailed analysis of causality for spatially feedforward ANC systems reveals that electronic delay dictates the minimal upstream measurement microphone spacing. A multirate approach has been developed in this work for reducing the electronic delay in the control loop. Analog lowpass filters were replaced by direct decimation and interpolation, through the use of digital filters. The computation efficiency is further enhanced by a polyphase representation, where the phases of lowpass filters must be carefully designed to avoid unnecessary delays. Frequency domain optimization procedures based on H_1, H_2 and H_∞ norms, respectively, are utilized to facilitate the FIR filter design. Experimental results demonstrated the effectiveness of the multirate approach in suppressing a broadband random noise in a spatially feedforward duct ANC system. In particular, the H_2 design yielded the best results because it has the smallest phase shift in lowpass filtering.

However, there remain some possibilities for improvement of the proposed techniques. For instance, better FIR filter design should be sought, concentrating on the vicinity of cutoff where distortions are likely to arise. The up/down sampling factor (currently 8) should be increased to further reduce the delay. The active controller was implemented as a fixed digital filter in this paper. However, in an adaptive system, this multirate technique can be highly useful. On the basis of this work, these aspects shall be explored in the future research.

五、參考文獻

[1] *S. M. Kuo and D. R. Morgan, Active noise control systems: algorithms and DSP implementations (New York, John Wiley and Sons, 1995).*

[2] *R. E. Crochiere and L. R. Rabiner, Multirate digital signal processing. (Prentice Hall, Englewood Cliffs, NJ, 1983).*

[3] *P. P. Vaidyanathan, Multirate systems and filter banks. (Prentice Hall, Englewood Cliffs, NJ, 1993).*

[4] *P. P. Vaidyanathan, "Design and implementation of digital FIR filters," in Handbook on Digital Signal Processing, edited by D. F. Elliott, Academic Press, Cambridge, UK, 55-172 (1987).*

[5] *M. Bellanger, G. Bonnerot and M. Coudreuse, "Digital filtering by polyphase network: application to sample rate alteration and filter banks," IEEE Trans. on Acoust. Speech and Signal Proc., **ASSP-24**, 109-114 (April 1976).*

[6] *P. P. Vaidyanathan and V. C. Liu, "Classical sampling theorems in the context of multirate and polyphase digital filter bank structures," IEEE Trans. on Acoustics, Speech and Signal Proc., **ASSP-36**, 1480-1495 (Sept. 1988).*

[7] *J. S. Arora, Introduction to optimum design.*

(New York, McGraw-Hill, 1989).

[8] *S. Boyd, L. Vandenberghe, and M.Grant, "Efficient convex optimization for engineering design," Proc. IFAC Symp. Robust Contr. Design. (Rio de Janeiro, Brazil, Sept. 1994).*

[9] *A. Grace, Matlab optimization toolbox. (The Mathw*

行政院國家科學委員會補助專題研究計畫成果報告

※※※※※※※※※※※※※※※※※※※※※※※※※※

※　　　　　　　　　　　　　　　　　　　　　　　　※

※　信號處理方法於主動噪音制系統以降低電子延遲　※

※　**Reduction of electronic delay**　※

※　**in active noise control systems -**　※

※　**a multirate signal processing approach**　※

※　　　　　　　　　　　　　　　　　　　　　　　　※

※※※※※※※※※※※※※※※※※※※※※※※※※※

計畫類別：□個別型計畫　　□整合型計畫

計畫編號：NSC　90－2212－E－009－038

執行期間：90 年 08 月 01 日 至 91 年 07 月 31 日

計畫主持人：白明憲

計畫參與人員：賴建汶、黃士韋

本成果報告包括以下應繳交之附件：

□赴國外出差或研習心得報告一份

□赴大陸地區出差或研習心得報告一份

□出席國際學術會議心得報告及發表之論文各一份

□國際合作研究計畫國外研究報告書一份

執行單位：交通大學機械工程學系

中　華　民　國　91 年 07 月 29 日