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Active structural acoustic control of helicopter interior multifrequency noise using input-output-based hybrid control

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ABSTRACT

This paper presents the recent advances in reduction of multifrequency noise inside helicopter cabin using an active structural acoustic control system, which is based on active gearbox struts technical approach. To attenuate the multifrequency gearbox vibrations and resulting noise, a new scheme of discrete model predictive sliding mode control has been proposed based on controlled auto-regressive moving average model. Its implementation only needs input/output data, hence a broader frequency range of controlled system is modelled and the burden on the state observer design is released. Furthermore, a new iteration form of the algorithm is designed, improving the developing efficiency and run speed. To verify the algorithm's effectiveness and self-adaptability, experiments of real-time active control are performed on a newly developed helicopter model system. The helicopter model can generate gear meshing vibration/noise similar to a real helicopter with specially designed gearbox and active struts. The algorithm's control abilities are sufficiently checked by single-input single-output and multiple-input multiple-output experiments via different feedback strategies progressively: (1) control gear meshing noise through attenuating vibrations at the key points on the transmission path, (2) directly control the gear meshing noise in the cabin using the actuators. Results confirm that the active control system is practical for cancelling multifrequency helicopter interior noise, which also weakens the frequency-modulation of the tones. For many cases, the attenuations of the measured noise exceed the level of 15 dB, with maximum reduction reaching 31 dB. Also, the control process is demonstrated to be smoother and faster.

1. Introduction

From the perspective of frequency, the low frequency rotor harmonics and high frequency structure-borne tones generated by gearbox are the two primary components of helicopter interior noise. The high tones, often 10 to 20 dB higher than the broadband noise spectrum, are generally considered as the most intrusive and irritating components of noise in a typical helicopter interior [1]. This kind of structure-borne noise is generated by the main gearbox, whose meshing vibrations are primarily transmitted through supporting struts to the airframe, which then radiate sound into the cabin. Because of the key structural role played by the struts, there is little scope to apply conventional passive isolation techniques

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Table 1
Concise summary of the ASAC tests on helicopters.

Items	S-76 (1998)	MD900 (2002)	BK117 (first) (2004)	BK117 (second) (2006)	BELL407 (2014)
Control objectives	800 Hz	836/900/1533 Hz	1500/1900 Hz	750/1500/1900/2550 Hz	235/260/265/290 order
Control algorithm	HHC	Fx-LMS	Parallel-form Fx-LMS	Parallel-form Fx-LMS	PC-LMS
Actuator	6 proof-mass actuators (transmission beam)	16 piezoelectric actuators (radiating surface)	21 piezoelectric actuators (support strut)	21 piezoelectric actuators (support strut)	14 piezoelectric actuators (support strut)
Feedback strategy	32 microphones (Inside the cabin)	16 microphones (Inside the cabin)	7 three-axis accelerometers (bottom of the struts)	7 three-axis accelerometers (bottom of the struts)	16 accelerometers (Receiving panel)
Flight tests	10–20 dB (Total)	3.5–4.5 dB (Total)	1500/1900 Hz	750/1500/1900/2550 Hz	235/260/265/290 order
			4.5/5.0 dB (120kts)	5.7/4.0/19.5/6.2 dB (120kts)	5/8/2/5 dB (Ground tests)

in this application [2]. Meanwhile, active noise control (ANC) is less effective in controlling the mid-to-high frequency noise [3]. During the past two decades, active structural acoustic control (ASAC) technology has been employed to attenuate the gear meshing tones. In ASAC, reduction of radiated noise is obtained by changing the response of the fuselage through structural inputs rather than by directly exciting the acoustic medium, when compared with the principle of ANC. Specifically, the system uses secondary vibration actuators installed on the vibration transmission paths to control the gear meshing vibrations so as to reduce the sound radiation. The actuators' outputs are controlled by the algorithm integrated in a hardware controller.

The first reference with ASAC appeared around 1990 [4]. Then this technology was introduced to helicopter around 1997. Among a series of ASAC tests carried out on helicopters, two main approaches can be distinguished. On the one hand, the vibro-acoustic responses of MD900 radiating surfaces are controlled by actuators directly attached on them [5]. On the other hand, active techniques are applied on S-76, BK117 and BELL407 to block forces in the vibration transmission paths towards the noise radiation panels [1,6–8]. However, a system with many radiation panels may become complex and expensive for a large number of actuators needed. Then the second approach offers advantages over the first approach. Table 1 lists partial information of the ASAC tests on helicopters. Apparently, control algorithm is one of the core technologies concerning an ASAC system.

As shown in Table 1, typical ASAC control algorithms can be divided into two control strategies: feedforward control based on Filtered-x Least Mean Square (Fx-LMS) algorithm [6,7,9,10] and feedback control originated from the Higher Harmonic Control (HHC) algorithm [1]. Fx-LMS algorithm is a kind of feedforward controller which is effective for narrowband disturbance rejection without an accurate model, but its availability depends strongly on the correlation between reference signal and undesired vibration/noise [11,12]. As for the HHC algorithm, it is based on linear system assumption and can accomplish steady-state multifrequency control well. However, the update rate of this method is usually slow. Also, it cannot perform well in situations where the controlled frequency is relatively high or the disturbance and the system parameters change rapidly [13]. In addition, the possible instability of a feedback algorithm and the amplification of higher frequencies are the restrictions for obtaining good results [14].

On the other hand, because multiple mid-to-high gear meshing harmonics are usually selected as control objectives, an algorithm with relatively lower computational burden and stronger self-adaptability is required in a helicopter ASAC system. To accomplish multifrequency control with the conventional LMS algorithm, very large number of filter coefficients [11] or parallel-form Fx-LMS containing the same number of frequency components can be adopted [15–17]. However, both of these ways may bring heavy computation load, which in turn decreases the algorithm's self-adaptability. In addition, the frequency-modulation between reference signal and error signal, caused by parallel-form, may slow down the convergence process significantly or even cause control divergence.

Recently, the authors have developed a hybrid least mean square-discrete model predictive sliding mode controller (LMS-DMPSMC) to suppress low frequency helicopter vibrations [18]. The target system states can be guided to approach signals with complex spectra precisely by a well-designed feedback DMPSMC law. Then better multifrequency control ability can be obtained. In addition, the introduction of feedback loop avoids the parallel-form whilst having faster convergence speed and stronger adaptive control ability. These advantages are all attractive to an ASAC system. However, the performance of the algorithm still needs to be improved accordingly when employed.

To this end, we devise a novel input-output-based DMPSMC algorithm so as to achieve good helicopter interior noise control effect. Unlike the existing control strategy in the previous work, the proposed algorithm in this paper is built upon a controlled auto-regressive moving average (CARMA) model, which only needs the past and current values of the input and output of the system. Thus the introduction of the algorithm is accompanied by the specially deduced procedures of identifying single-input single-output and multiple-input multiple-output systems. In a practical setup, the hybrid controller is developed based on a state space model, which is sufficient for low frequency vibration suppression [18]. However,