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Multiple-source multiple-harmonic active vibration control of variable section cylindrical structures: A numerical study

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ABSTRACT

Air vehicles, space vehicles and underwater vehicles, the cabins of which can be viewed as variable section cylindrical structures, have multiple rotational vibration sources (e.g., engines, propellers, compressors and motors), making the spectrum of noise multiple-harmonic. The suppression of such noise has been a focus of interests in the field of active vibration control (AVC). In this paper, a multiple-source multiple-harmonic (MSMH) active vibration suppression algorithm with feed-forward structure is proposed based on reference amplitude rectification and conjugate gradient method (CGM). An AVC simulation scheme called finite element model in-loop simulation (FEMILS) is also proposed for rapid algorithm verification. Numerical studies of AVC are conducted on a variable section cylindrical structure based on the proposed MSMH algorithm and FEMILS scheme. It can be seen from the numerical studies that: (1) the proposed MSMH algorithm can individually suppress each component of the multiple-harmonic noise with an unified and improved convergence rate; (2) the FEMILS scheme is convenient and straightforward for multiple-source simulations with an acceptable loop time. Moreover, the simulations have similar procedure to real-life control and can be easily extended to physical model platform.

1. Introduction

In the fields of aeronautics, astronautics and navigation, the suppression of unwelcome vibration and noise has drawn much attention and effort from researchers and engineers, since over-vibrations of vehicles (e.g., aircrafts, space crafts and submarines) may reduce structural strength, ride comfort, detection ability and stealth. Most of the vibrations are caused by rotational machines (e.g., engines, propellers, compressors and motors), making spectrum of radiated noise multiple-harmonic and low-frequency [1,2]. It is difficult to reduce such noise by traditional passive vibration control (PVC). Fortunately, active vibration control (AVC) technology which has been developed since 1970s is considered to be a very promising technology to reduce the multiple/low frequency noise [3].

AVC is a multi-disciplined subject combining vibration theory, control theory, material science, computer science, etc. The core component of the AVC system is control algorithm (applications of control theory). There are two categories of control algorithms applied to AVC: off-line controller design methods and on-line controller design methods. The off-line controller design methods contain optimal control (typically LQG and LQR) [4], pole placement [5], robust method [6],

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positive position feed-back (PPF) [7], etc. Their controllers are fixed once designed and strongly rely on the analytical model of controlled plant. Thus, these methods cannot handle time-varying systems. The on-line controller design methods mainly include adaptive methods and intelligent methods. Typical intelligent methods, such as artificial neural network (ANN) [8] and genetic algorithm (GA) [9], are able to handle time-varying and even non-linear systems. However, it is difficult to determine the model dimension (e.g., the number of layers and neurons in ANN) and adjust the parameters. Adaptive methods mainly include model reference adaptive control and self-tuning control [10,11], the research on which is active since they are both adaptable and relatively simple. The most popular adaptive method in active noise control (ANC) is called filtered-reference LMS (FXLMS) algorithm, which is essentially a variant of model reference adaptive control [12]. FXLMS have many structures, such as broadband feedforward, narrowband feedforward, feedback and hybrid, in which the narrowband feedforward algorithm is specialized for the periodic vibration cancelation [13]. In the narrowband feedforward FXLMS algorithm, the vibration of a certain observation point can be controlled by single secondary source regardless of which primary source(s) it is generated by; different frequency component of noise can be suppressed individually [14]. Thus, this algorithm is able to deal with multiple-source and multiple-harmonic application. In AVC, the presence of the secondary path (i.e., the transfer path between the secondary source and the observation point) will generally cause instability of the LMS algorithm. This is because the error signal is not correctly "aligned" in time with the reference signal owing to the secondary path [13]. The idea of FXLMS algorithm is to apply a secondary path model to "align" the phases of reference signals, so that they are in accordance with that of error signal. However, such "phase alignment" operation also introduces amplitude scaling to the reference signals. Hence, the convergence rate of difference frequency component is different and the overall convergence rate is restricted by the slowest one. In this paper, we apply two approaches to speed up the convergence of the narrowband feedforward FXLMS algorithm. One is to rectify the amplitudes of the reference signal using inverse secondary path model [15,16]. The other one is to apply conjugate gradient method (CGM) instead of steepest descent method (SDM) for a faster optimization speed.

Cylindrical shells are widely used as major structures in the above-mentioned vehicles. A considerable number of researchers have committed themselves to study the dynamic behavior and sound radiation control of cylindrical shells [17–19]. In these studies, modeling of the structure is usually one of the most important parts. For AVC, a model generally plays two roles: (a) as known conditions to design the controller; (b) as a controlled plant when conducting a control simulation. More specifically, an analytical model is usually used for the off-line controller design, and a data-based model (also called identified model) is usually used for on-line controller design. In the AVC simulation, an analytical model can act as a controlled plant if it is simple. However, for a complex plant, the analytical model is difficult or even impossible to obtain. Fortunately, with the development of computer technology, finite element (FE) model has been introduced as the controlled plant in AVC simulation system. Some researchers integrated the control algorithm into the CAE software (e.g., ANSYS) [20–22]. Some other researchers extracted the state space model from the FE model [23,24] or directly solved the dynamic response of the FE model [25], and then conducted the control on the extracted numerical model. The biggest challenge to embed the FE model into AVC simulation is the computational complexity, hence the present works mainly focus on simply structures like beam and slab. In this paper, we face up to this challenge and reduce the computation complexity by a variety of measures including model reduction, preprocessing, and recurrent solving. We named such FE model based AVC simulation scheme as finite element model in-loop simulation (FEMILS) to show the difference to analytical model based simulation or transform-domain simulation. The FEMILS is a time domain point-by-point simulation, whose procedure and structure is extremely similar to that of real-life control. Moreover, it is convenient for multiple-source (including primary and secondary sources) AVC simulations.

Summarily in this paper, a stepped-up multiple-source multiple-harmonic (MSMH) active vibration suppression algorithm is proposed based on reference amplitude rectification and conjugate gradient method (CGM). A finite element model in-loop simulation scheme is also proposed. As a case study of both of them, dynamic analysis and AVC is carried out on a variable section cylindrical structure. Three different cases (i.e., single-source and single-harmonic, single-source and multiple-harmonic, multiple-source and multiple-harmonic) are considered. The stepped-up MSMH algorithm is substantiated to be effective in all the cases with an improved convergence speed and the FEMILS scheme is also verified to be convenient and effective for multiple-source AVC simulation. The paper is structured as follows: Section 2 formulates the principle of the stepped-up MSMH algorithm; Section 3 describes the scheme of FEMILS based on a variable section cylindrical structure; Section 4 carries out numerical investigations with three cases; the conclusions are presented in Section 5.

2. Principle of stepped-up MSMH AVC algorithm

Many noises are periodic, such as those generated by engines, compressors, motors, fans, and propellers. Narrowband feedforward FXLMS algorithm is a method that specialized for periodic noise reduction and has been received many attentions [13,14,16]. As a variant of narrowband FXLMS feedforward method, Fig. 1 shows a stepped-up multiple-source and multiple-harmonic (MSMH) algorithm based on reference amplitude rectification and conjugate gradient method. To control the vibration of a certain point only one secondary source is needed in this algorithm. The residual vibration (error