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Time-domain approach for multi-exciter random environment test

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ABSTRACT

This paper presents a time-domain method for multi-exciter random environment tests. Traditional random environment test theory has been formulated in the frequency domain, where an important step is taking the inverse of the frequency response function matrices (FRFMs). The accuracy of this inversion tends to be poor, particularly at frequencies near lightly damped resonances. The currently used control algorithms face difficulties in suppressing abnormal spectral lines caused by this inverse problem. In this paper, traditional formulations of the environment test are reformed, and the time-domain method is adopted; this results in a more precise inverse operation in environment tests. To achieve this, reference spectra are converted into time-domain response signals. The finite long driving signals are derived by the state-space method with estimated state vectors. During the process, the inverse of rank-deficient Toeplitz matrices are stabilized with truncated singular value decomposition (TSVD) to suppress all abnormally high-level components in the driving forces; thus, overall, the spectra lines produced by noise within the frequency band are filtered out. A numerical simulation of a single-axis random vibration test of a cantilever beam is conducted using the traditional frequency-domain procedure (FDP) and the proposed time-domain procedure (TDP). The response spectra generated by both procedures are tested by control algorithms, and the result shows that responses generated by the proposed TDP are more easily controlled. The conditions of stability for both the FDP and the TDP are also determined and introduced in the simulation. Moreover, a multi-axis vibration experiment further validates the effectiveness of the TDP.

1. Introduction

Dynamic environment tests are performed to ensure that devices can withstand the vibrations that are encountered during their service lifetimes in their environments. Several types of common inputs are used to simulate environmental excitations: random, shock, swept sine wave or their combinations. As a first test, a random environment test is conducted with only one exciter. However, there are circumstances that cannot be simulated properly in this manner. It is noted in the MIL-STD-810G that the most practical environment endured by a material should be reproduced with multiple exciters. Therefore, the multi-exciter-test (MET) method has been involved in the MIL-STD-810G since 2008.

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In an environment test, the power spectra of the article being tested should be identical to the preset reference spectra that have already been studied and stipulated for various types of experiments under military standard 810G [1]. However, uncertainties, such as measurement noise, model errors and unexpected environmental disturbances, always decrease the accuracy, and the response spectra may significantly exceed their tolerances at certain frequencies, particularly when FRFMs are severely ill conditioned. The problem caused by ill-conditioned FRFMs has been observed since Smallwood and Paez [2] proposed the frequency-domain procedure for the multi-exciter random environment test in 1993. The authors suggested using singular value decomposition (SVD), where meaningless small singular values are set to zero. This step is actually the truncated SVD (TSVD) applied to FRFMs. In practice, regularization on singular values can be used to obtain more precise response spectra as an alternative to discarding a portion of the singular values when there are only a small number of inputs and outputs. Moreover, the thresholds of truncation can be difficult to set. In 1999, an update of the control algorithm for the multi-exciter random environment test was again proposed [3] by Smallwood. This control algorithm is devoted to reducing the mismatch between response spectra and reference spectra. However, the algorithm will diverge if the mismatch is great at frequencies where FRFMs are severely ill conditioned. The weakness of this algorithm has been stated clearly by Cui et al. [4]. Underwood and Keller [5,6] determined that the frequencies at singularities or near singularities are also the frequencies at which the measurements of FRFMs contain the largest errors. Accordingly, an adaptive control method was developed that can update the frequency response estimates. The details of the adaptive method are covered by patents, and we do not know its effect on controlling response spectra when FRFMs are severely ill conditioned. In 2011, Cui et al. [4] proposed a forward matrix power algorithm for multi-exciter response control. In practice, their algorithm removes the risk of control instabilities but is ineffective in suppressing extremely large response spectra at frequencies where singularities of FRFMs arise. Ramkrishna et al. [7] suggested a frequency-domain input identification method for vibrational environment testing of flexible structures in 2013. Their method of computing drive signals is different from the traditional approach proposed by Smallwood [2], where ill-conditioned FRFMs are not of interest in Ramkrishna's article. Johansson and Abrahamsson [8] deduced the controllability and error bounds to improve test rig performance in environment tests. The authors stated that uncontrollable response spectra tend to be large in lightly damped mechanical systems. Although a number of studies have suggested that the ill-conditioned problem in a vibration environment test should be handled with severe caution, few articles have presented concrete measures. People tend to directly employ control algorithms [3–5] to address all abnormal spectral lines without regard to their causes. However, control algorithms are not always useful, and a relatively large mismatch between response spectra and references is less likely to be controlled. In the domain of input estimation, ill-conditioned problems are thought to be related to noise in the measured responses and extremely small singular values of FRFMs [9,10]. The traditional Smallwood procedure or FDP does not contain steps for noise filtering or singular value management. Therefore, the goal of this article is to propose a new procedure, where small singular values of FRFMs are considered, and the number of abnormal spectral lines is reduced.

The article is organized as follows. Section 2 presents the basic formulations, including the discrete equation in state space as well as the traditional environment test formulations proposed by Smallwood and Paez [2]. Section 3 proposes the updated environment test equations using the time-domain approach and the TSVD method. A relevant criterion for selecting regularization parameters of the rank-deficient Toeplitz matrix is also introduced. In Section 4, the overall procedure is applied for a multi-input, single-axis numerical simulation of a cantilever beam. Both response spectra and their control results are observed using both the FDP and the TDP. Section 5 presents the multi-axis experiment used to validate the numerical outcomes. Finally, a discussion and the conclusions are summarized in Section 6.

2. Basic formulations

2.1. Dynamics of linear systems

The equation of motion of an N-degree-of-freedom system can be written as

$$M\ddot{\mathbf{x}} + C\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{L_f}\mathbf{f}, \tag{1}$$

where $\ddot{\mathbf{x}}$, $\dot{\mathbf{x}}$ and $\mathbf{x}$ are the system's response components representing acceleration, velocity and displacement, respectively; $\mathbf{M}, \mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices, respectively; $\mathbf{f}$ is the vector of external excitation forces that act on the structure; and $\mathbf{L_f}$ is the mapping matrix for the input forces.

2.2. Discrete equations in state space

The equation of motion of the structure shown in Eq. (1) can also be expressed in a continuous state space form as

$$\dot{\mathbf{z}} = \mathbf{A}_c\mathbf{z} + \mathbf{B}_c\mathbf{f}, \tag{2}$$

where