Mechanical Systems and Signal Processing 111 (2018) 643–662

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Control algorithm update for multi-input multi-output random environment test

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ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form 15 November 2017
Accepted 20 November 2017

Keywords:
Multi-input multi-output
Vibration environment test
Random
Ill-condition
Control algorithm

ABSTRACT

When conducting multi-input multi-output (MIMO) random vibration environment test, response spectral lines of under test article may exceed their tolerances and some of them can hardly be controlled by control algorithms. The cause of this phenomenon is the high level noises in the input forces, which are induced by the inverse of the ill-conditioned frequency response function matrices. These spectral lines may even trigger the instability of control algorithms and eventually result in an accidental test shutoff. The classical control algorithm for MIMO random vibration environment test contributed by Smallwood is analyzed theoretically and experimentally in the paper to reveal its weakness on dealing with this kind of error. An updated algorithm is proposed on the basis of inverse theory to overcome the difficulty of controlling these stubborn spectral lines. The main idea of the work is to reduce the level of noise components in input forces by regularizing singular values of ill-conditioned frequency response function matrices. An adjusting rule is set up according to the auto-power spectra tolerances. A simulation and an experiment are supplied in the paper to verify the effectiveness of the updated algorithm, the results are satisfactory.

1. Introduction

Traditionally, vibration environment test is conducted with only one exciter. However, there are circumstances which cannot be simulated properly with this manner. It is pointed out in the MIL-STD-810G that most practical dynamic environments endured by materiel should be reproduced with multiple exciters. Thus, the Multi-Exciter-Test (MET) method has been involved in the MIL-STD-810G since 2008.

In the MET, frequency response function matrices (FRFMs) are used to generate dynamic forces by inverse operation. Once they are severely ill-conditioned at some frequencies, the noises in the driving forces will be amplified to unacceptable levels. Moreover, these frequencies are often close to the lightly damped resonant peaks, at which even small level driving inputs could produce relatively large responses. Thus, some spectral lines will greatly overstep their tolerances and they cannot be adjusted by most control algorithms. This paper is intended to solve the problem.

Since 1978, Smallwood et al. [1–8] have delivered a good number of articles about multi-shakers vibration test. All their works established the foundation of MIMO test. The ill conditioning in environment test has long been noticed since the system of MET was built. The earliest method of generating pseudo-inverse of ill conditioned FRFMs by Smallwood [2] is to remove the offending row and column from FRFMs, invert the reduced matrix, expand and insert a row and column or zero

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https://doi.org/10.1016/j.ymssp.2017.11.032
0888-3270/

back. In 1993, Smallwood and Paez [5] suggested using singular value decomposition (SVD) to eliminate meaningless small singular values. His way of solving the problem is similar with Powell [9], who consisted in cancelling the lowest singular values considered like noise. When Smallwood [7] proposed his random control algorithm in 1999, a further emphasis was made that great care must be taken at frequencies where the FRFMs were ill conditioned. However, no concrete method or related experiment was described in that paper. Afterwards, Underwood et al. [10–12] also made some progresses in MIMO environment test. In 2001, Underwood and Keller [10] discussed the control of singularities that exist in FRFMs of under test systems. They suggested to use the ratio of the smallest to the largest singular values to decide the ill-conditioned degree. In 2002, Underwood [11] expounded several noteworthy problem of MIMO random, MIMO swept sine, MIMO transient wave and MIMO long-term response waveform control. He suggested that measurement noise, nonlinear response and a large dynamic range could seriously affect the condition number of FRFMs at various frequencies, eventually, the quality of control would be affected. He also stressed in this paper that many of these negative effects could be mitigated by good mechanical system design of the components of under test systems and good choices for how the actuators are attached to the test fixtures. In shock and vibration handbook [12], Underwood introduced numerous applications and tools that are available on digital computers for the solution of shock and vibration problems. Again, he emphasized the importance of singular problem. Due to business reason, the advanced methods for MIMO test are mostly proprietary and not published. At the same time, some researchers tried to develop their own control algorithms to achieve a better control results. To avoid the divergence brought by Smallwood's algorithm, Cui [13] developed matrix power control algorithm as a substitution. Although the application of this algorithm can successfully avoid the divergence, the algorithm itself is ineffective in suppressing above-mentioned abnormal spectral lines and its ability in controlling cross-power spectra is weak. Therefore, an update of Smallwood's algorithm for the adaption on singular problem is still a good option for MIMO random vibration control.

Although there are some differences, the singular problem in environment test is similar with the problem of estimating precise drive forces in input identification. Some other references can supply inspiring ideas to stabilize the inverse problem. In 1979, Bartlett [14] applied the least square scheme to determine forces of an experimental helicopter model. After, several successful experiments [15–17] were conducted. But, the accuracy of the identified forces was not satisfactory. Although inverse problem is seemingly unsolvable, there are still some methods to enhance the inverse stability. By introducing regularization filters, one can directly change singular values to minimize the influence from the amplified noise [18]. But the thresholds of these filters are sometimes difficult to be accurately constructed and none of them has been used in the MIMO random vibration control till now.

The following section provides a brief overview of the theory on MIMO random vibration test and the details can be obtained from Smallwood's works [1–8].

2. Theory on MIMO environment test

2.1. Driving signal generation and the disturbance of noise

The configuration of the environment test is shown in Fig. 1. The frequency response function matrices G of the system under test are initially measured, and the original L is calculated from reference spectrum R. The driving spectrum D is obtained with a random phase matrix P. The driving signal x in time domain is then generated by inverse FFT and time domain randomization. The response signal y is measured and the power spectrum matrix S_{yy} is calculated. S_{yy} is compared with the reference spectrum R and a corrected new L_{new} is obtained by the control algorithm. After, the driving spectrum D is updated and the new driving signal x is generated. The process is continued until the end of the test.

According to Fig. 1, the control target of an n inputs n outputs random vibration environment test is to keep the power spectrum of response to be identical to the reference spectrum R, i.e.

$$S_{yy} = R \tag{1}$$

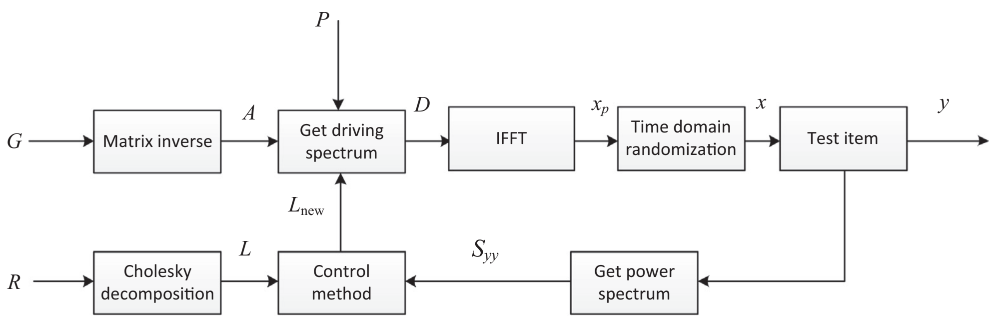

Fig. 1. Block diagram of MIMO random vibration test.