Reliability Study of Identification-based Active Control

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ABSTRACT

The reliability of vibration control systems is influenced by uncertainties in dynamic parameters of structure, the characteristics of controller, and external excitations. When designing controllers for structures with unspecified or unavailable specifications, identification methods for estimating dynamic parameters and controller design offer a practical solution. However, controllers based on identification methods are subject to two main sources of error: modeling inaccuracies and identification errors. By comparing the performance of controllers designed using identification methods with those based on assumed models, it is possible to evaluate the impact of identification accuracy on control effectiveness. This approach minimizes the negative effects of uncertainties in structural parameters while reducing the costs associated with intelligentization. In this study, uncertainties considered in structural parameters and external excitations. Initially, a primary control system was designed, and the structure was identified using the stochastic subspace identification based on recorded responses. Subsequently, a secondary controller was designed based on identification. The failure function was defined as maximum difference in displacement response of the upper story of structure between two controllers. Using this metric, the reliability of control system was estimated. The results showed that the identification-based controller achieved a success rate of 99.75% compared to original controller. However, the statistical distributions of the performance indexes for the identification-based controller exhibited a lower mean and higher standard deviation than those of assumed-model-based controller. This improvement is likely influenced by the lower accuracy and higher estimated damping ratios of the identified structures, which contribute to increased reliability of identification-based controller.

KEYWORDS

Stochastic subspace identification, Monte Carlo simulation, system identification, reliability, active control.

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1- Introduction

The reliability of vibration control, is studied by considering uncertainties in excitations and structure and controller parameters. The reliability becomes critical due to parameter errors affecting force magnitude/direction and structural stability. While system identification methods help estimate dynamic parameters for structures with unknown properties [1], modeling errors and intertwined uncertainties continue to challenge exact system characterization. Recent advances include high-dimensional reliability analysis [2], Monte Carlo simulations with neural networks [3], and fault-tolerant semi-active control using MR dampers [4]. Integration of health monitoring and Vibration control has shown particular promise, with continuous monitoring improving dynamic property estimation and enabling adaptive control through sensor fusion [5], as demonstrated in combining damage identification with semi-active control [6] and real-time stiffness adjustment methods [7].

In light of the emerging trend of integrating system identification with control strategies, a novel framework is developed in this study. An active control system is first designed based on the LQR method, assuming nominal system parameters. The structural model is then identified using the Stochastic Subspace Identification (SSI) algorithm, based on displacement responses under external excitation. A new control system is subsequently designed using the identified parameters. By defining a failure function that quantifies the discrepancy between the original and identified control systems, the reliability of the control strategy is assessed through Monte Carlo simulation.

2- Technical Methodology

In the modeling phase, an 11-DOF, 2D model of the primary structure [8] first develop (nominal system). Then 1,200 models generate for Monte Carlo simulation assigning appropriate probability density functions to the structure's dynamic parameters. These models then identify based on their displacement responses to random Gaussian white noise excitation. after coordinate transform and discrete to continuous system transformation, the vibration control performance of both the original and random models evaluates under the El Centro earthquake excitation. benchmark indexes based on RMS and maximum response of original and identified structures use for reliability evaluation.

$$J_2 = \left(\max_{t,i}\left|x_i^c(t)\right|\right) / \left(\max_{t,i}\left|x_i^{uc}(t)\right|\right) \tag{1}$$

$$J_6 = \left(\max_{t,i}\left\|x_i^c(t)\right\|\right) / \left(\max_{t,i}\left\|x_i^{uc}(t)\right\|\right) \tag{2}$$

3- Results and Discussion

To provide an overview of identification accuracy, the main structural properties were identified based on displacement response data, with the results and MAC diagrams between modeshapes of identified and original system presented in Figure 1. The findings (See Table 1) indicate high accuracy in identifying natural frequencies, while damping ratios were estimated with greater error.

$$MAC_{\phi_i,\phi_o} = \left(\phi_i^T \phi_o\right) / \left(\sqrt{\phi_i^T \phi_o \phi_i^T \phi_i}\right) \tag{3}$$

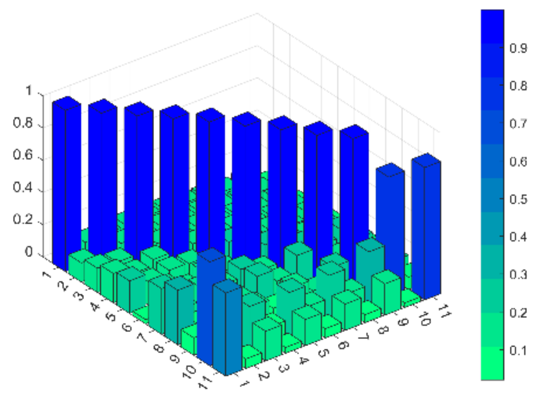

Figure 1. 2D and 3D MAC diagrams for modeshapes between identified and original system

Table 1. Identified structural properties based on displacement responses to generated GWN by SSI

Mode No	1	2	3	4	5	6	7	8	9	10	11
ω error (%)	1	0	0	0.2	0.1	0.2	0.3	0.4	0.7	0.8	0.5
ζ error (%)	32.70	29.20	15.20	0.40	2.70	4.50	22.40	6.90	2.30	0.40	16.90

Following system identification and transformation to physical coordinates, vibration control was implemented on both the original and identified structural models, with benchmark performance indices evaluated for original controller are J_2=0.302 and J_6=0.222 and for identified controller are J_2=0.225 and J_6=0.158. The results demonstrate that the identification-based controller achieved superior performance by not only reducing structural responses compared to the uncontrolled case, but also outperforming the controller designed for the original structure in meeting control objectives. The successful performance of the identification-based controller across all evaluation metrics confirms the potential of this methodology for structural vibration control under uncertain conditions.

In Figure 2, the results obtained for the two groups of systems are presented in the form of probability density distribution diagrams assuming a normal distribution for the performance indicators.

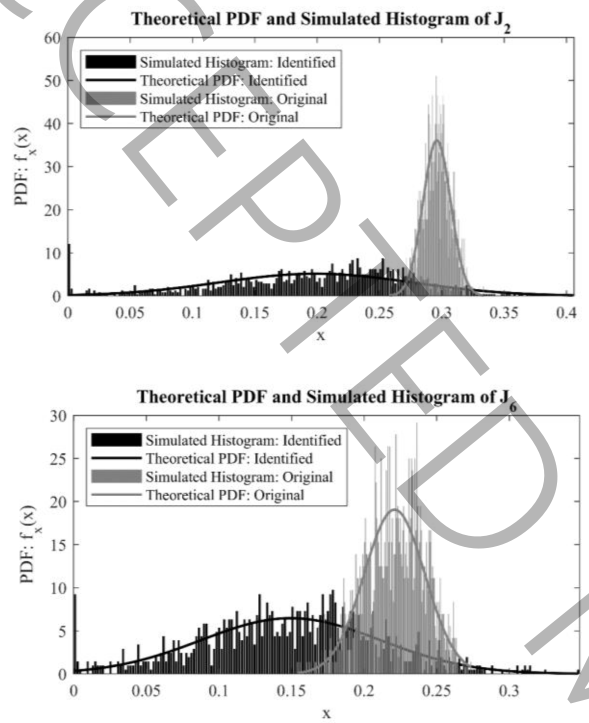

Figure 2. The probability density function of the performance indexes for the original and identified structures

The results indicate that the identification-based controller demonstrates superior performance with a 25% reduction in mean performance indices compared to the original controller, though with greater variability in outcomes as evidenced by higher standard deviations. Reliability analysis of the system (by choosing the limit state function as the difference between maximum of displacement response of the top stories of two controlled systems) reveals a remarkably low failure probability of just 0.25%, corresponding to a 99.75% success rate, validating the robustness of the identification-based control methodology.

4- Conclusion

This study demonstrates that identification-based controllers achieve superior average performance (with lower mean values) compared to conventional approaches, despite showing greater outcome variability. The developed probabilistic methodology enables reliable control design for structures with uncertain properties, successfully establishing performance thresholds for key response parameters while quantifying operational reliability under uncertainty. Notably, the stochastic subspace identification process - though producing seemingly inaccurate damping ratio estimates - paradoxically enhances controller robustness. For real-world structures lacking precise parameters, the proposed identification-based approach using health monitoring data not only meets but frequently exceeds deterministic methods' performance, offering a practical and often superior vibration control solution.

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