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Experimental estimation of transmissibility matrices for industrial multi-axis vibration isolation systems

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ABSTRACT

Vibration isolation is essential for industrial high-precision systems to suppress external disturbances. The aim of this paper is to develop a general identification approach to estimate the frequency response function (FRF) of the transmissibility matrix, which is a key performance indicator for vibration isolation systems. The major challenge lies in obtaining a good signal-to-noise ratio in view of a large system weight. A non-parametric system identification method is proposed that combines floor and shaker excitations. Furthermore, a method is presented to analyze the input power spectrum of the floor excitations, both in terms of magnitude and direction. In turn, the input design of the shaker excitation signals is investigated to obtain sufficient excitation power in all directions with minimum experiment cost. The proposed methods are shown to provide an accurate FRF of the transmissibility matrix in three relevant directions on an industrial active vibration isolation system over a large frequency range. This demonstrates that, despite their heavy weight, industrial vibration isolation systems can be accurately identified using this approach.

1. Introduction

Vibration isolators are widely used in high-precision systems, such as wafer scanners [1], scanning tunneling microscopes [2,3], and measurement systems in general [4,5]. These isolators are used to isolate machinery from floor and base frame vibrations. A key performance indicator is the transmissibility function [5,6]. For single-axis systems, the transmissibility function describes the transfer function from base frame vibrations to payload vibrations. For multi-axis systems, the transmissibility function is extended to a transmissibility matrix, where its performance metric is often posed in terms of scalar norms [6,7]. Amongst vibration isolation, the concept of transmissibility functions has a key interest in a wide range of applications, for example operational modal analysis [8,9], and operational transfer path analysis [10,11].

The frequency response function (FRF) of the transmissibility matrix can be estimated from experimental data by placing accelerometers or geophones on both the base frame and the isolated payload of the machine [12]. In, e.g., [6,13,14], several methods for transmissibility matrix measurements are developed where external shaker constructions are used to ensure that the base frame is sufficiently excited. This enables an accurate estimation of the FRF, both unbiased and with a small variance [15]. However, these methods are often not applicable because industrial machines are often too heavy for

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commercially available shakers to support and excite the system. Moreover, in industry it is important to provide sufficiently accurate models on the one hand with the least-costly identification experiment on the other hand [16]. Therefore, estimation methods that allow the machine to perform under operating conditions are highly preferred. Such methods rely on environmental base frame excitations, e.g., floor vibrations [17]. These methods can result in a reasonable estimation, as long as the environmental vibrations provide sufficient spectral power in all relevant directions to obtain a sufficient signal-to-noise ratio (SNR). Available methods are restricted to those that can deal with random excitations, because the environmental vibrations are not known beforehand and are typically non-periodic. In this regard, spectral analysis is often used [18,19], which assumes that either the base frame or the payload excitation is measured free of noise. However, sensor noise on both the base frame and payload measurement leads to an error-in-variables identification problem [20,21], which may subsequently lead to biased estimates [22,23].

Several methods are proposed in literature to improve the estimation results for systems that can only be partly identified. A first example is output-only or operational modal analysis [8,9] which can provide eigenfrequencies and mode shapes, but does not give an FRF which represents an input–output relation. A second example is found in methods that augment FRF measurements with finite-element modeling, e.g., [24], but these methods need intervention regarding meshing, model order selection, and so on. A third example is frequency-based substructuring [25,26] in which separate parts of the system are identified independently and merged afterwards, but this method is sensitive for large uncertainty propagation errors [25]. Moreover, none of these methods provides a validation regarding the actual performance of the assembled system in closed-loop. The latter is important, since control loops might deteriorate performance due to changing system dynamics and noise amplification [27–29]. Therefore, none of these methods is further pursued in this paper.

Although vibration isolation is essential in high-tech equipment, there is a lack of a systematic approach to estimate the FRF of the transmissibility matrix for heavy-weight systems. The first contribution of this paper is to show a non-parametric identification method to estimate the FRF for such systems in multiple directions, where a combination of floor and shaker excitations is used to maximize the base frame excitation power. The second contribution is a method to evaluate the spectral power and directions of the base frame excitations, and how its result can be used for input design of the shaker excitation signals. In this respect, the proposed method can be seen as optimal input design [16]. A third contribution is given by the application of the identification and input design methods to a heavy-weight active vibration isolation system. This leads to an accurately estimated FRF of the transmissibility matrix in the frequency range of interest, i.e. between 1 and 100 Hz, and in three relevant directions. These results show that the presented methods, which are applicable for vibration isolation systems in general, are particularly suited for systems that are too heavy to be sufficiently excited by shakers during operating conditions.

The paper is organized as follows. The experimental setup and the transmissibility matrix are described in Section 2. The main problem considered in this paper is defined in Section 3. The non-parametric identification method is presented in Section 4, and the input excitation analysis and design method is presented in Section 5. The experimental results and validation are presented in Section 6, and the major conclusions are given in Section 7.

2. Active vibration isolation system

2.1. System description

The system used throughout this paper for validation purposes is the Active Vibration Isolation System (AVIS) shown in Fig. 1. The AVIS consists of two main parts: (i) an isolated payload of 289 kg, and (ii) a base frame (BF) that is supported by the floor. The payload and BF are connected by four isolator modules (IM). These isolator modules provide a low stiffness and

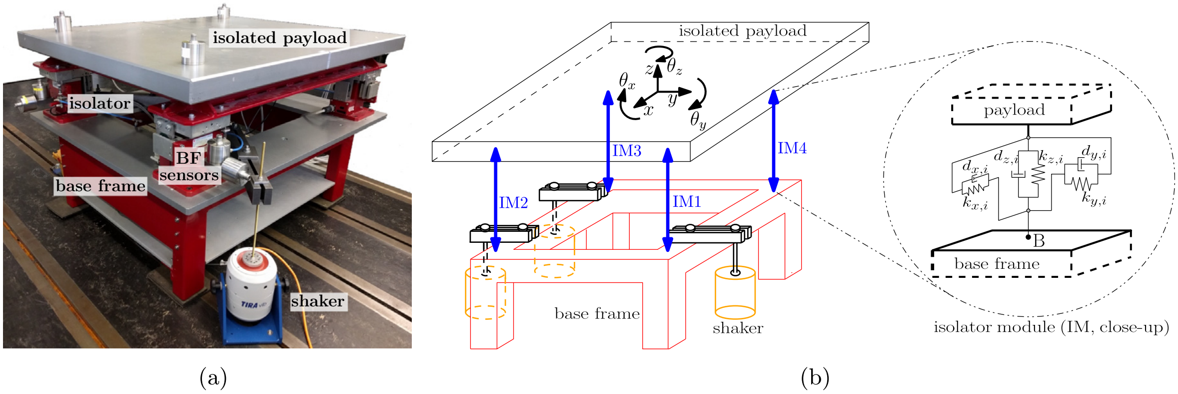

Fig. 1. AVIS used for validation of the non-parametric identification method: (a) photograph, (b) schematic representation showing the base frame, payload, four isolator module locations, and three shaker locations.