Measurement 78 (2016) 309–321

Contents lists available at ScienceDirect

Measurement

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

Optimum design of mounting components of a mass property measurement system

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ARTICLE INFO

Article history:
Received 15 May 2015
Received in revised form 22 September 2015
Accepted 9 October 2015
Available online 19 October 2015

Keywords:
Centre of mass
Moment of inertia
Finite element simulation
Torsional pendulum

ABSTRACT

Measurement of inertia properties of aerospace vehicle and submarine are vital to meet the intended motion objectives. The Moment of Inertia (MOI) is calculated by measuring the frequency of free torsional oscillation of the object mounted on a nearly friction less air bearing. For getting accurate measurement and to nullify the effect of undesired vibrations, the stiffness of the different components of the mounting and fixture (torsion rod, flexure) should be maintained appropriately. The optimum design of torsion rod and flexure is based on ensuring desired natural frequencies in different modes. Initiating with an analytical approach, the actual dimensions of the components are determined based on natural frequencies obtained by finite element analysis of the components. Simulated results are verified with experimental results.

1. Introduction

Inertia properties are important inputs in the dynamic analysis of vibration and motion leading to structural optimisation and comfort or safety analysis for many systems like turbo machineries [1] ground vehicles [2], robotic manipulators [3,4] and aircrafts [5]. Ten inertia properties of an object are comprised of its mass, three coordinates of the centre of mass and six independent entries of the inertia tensor [6]. While the diagonals of the tensor are the moments of inertia, the symmetric off-diagonal components are the products of inertia. In view of the complex interior and exterior features of complete systems including cables and fittings [1–5] and the non-uniform density distribution for layered materials and sandwich structures [7,8], the use of existing mathematical tools or commercial packages for the determination of these properties by numerical integration could either be cumbersome or involve approximations. The consequent errors, even if small, may lead to substantial error in the predicted dynamics. Direct measurement is an alternative to the use of analytical tools.

Schedlinski and Link [9] reviewed different methods of measuring the inertia properties. Conventional methods involve both static and dynamic procedures. While the static procedure of either simple weighing or multipoint weighing provides the mass, a suspension method or a balancing method is popularly used to find the centre of mass. Relatively safer and popular dynamic methods of extracting the inertia tensor are executed by measuring the time periods of free oscillations of gravitational, torsional or multi-filar pendulum about or along different axes [10–12]. Two major deficiencies in using these conventional methods are using different machines to execute static and dynamic procedures and setting a body in different orientations for the complete execution of a dynamic method. For a large and irregularly shaped body, changing the setting a number of times is difficult and time consuming.

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http://dx.doi.org/10.1016/j.measurement.2015.10.017
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Fdlekrug and Sinapius [5] used a hydraulic robot together with general equations of motion to obtain all the inertia properties simultaneously from the time-domain data for different input motions. High risk of damage, difficulty in mounting complex objects on the machine and quite involved post-processing of the captured data through solving a set of nonlinear equations keep the use restricted for relatively simple and small objects. More recent dynamic methods that can handle large and irregular bodies [9,13–15] rely on excitation of multiple vibration modes in a single setting. But these methods are expensive, sensitive to measurement noise and require capturing many intermediate variables rendering the uncertainty analysis difficult [12]. The knowledge of the uncertainty bound is quite important in situations like designing the control and guidance of aerospace vehicles, say [16]. For such precision applications, the conventional procedures are preferred over the modern techniques.

The conventional procedures and the corresponding measurement systems need to be perfected further for enhancing the precision. Gopinath et al. [16] discussed the design aspects of a high-precision inertia property measurement system. They conceptualized a single machine on which a wide range of objects could be set and reset with minimal external intervention. The bearing and the flexure are the two most critical components of the system. During the static tests, the bearing should allow easy rotation of the object to proper orientations so as to bring down the uncertainty by acquiring multiple measurements. During the dynamic tests, the bearing must ensure nearly free oscillation. All these test objectives would demand near-zero bearing friction. In a recent study [17], such a design has been pursued in a great detail. At this stage, it is imperative to carry out a design analysis for the flexure that forms the central theme of the work reported next.

The analysis detailed next pertains to the design of a flexure for realizing a single-machine inertia measurement system conceptualized by Gopinath et al. [16]. In the next section, the major features of the system are described. Section 3 pertains to the design of the system on the basis of an available air bearing. The simplified design is based on a lumped formulation aiming wide separation of frequency of the unwanted excitation modes with respect to the targeted torsional mode. A design analysis has been presented in Section 4 through modal analysis carried out by a finite element method and a corresponding experiment. For the finite element analysis, the axial stiffness of the bearing has been found out by using an existing analysis [17]. The finite element analysis has also been employed to capture the effect of eccentric loading and a bound for the expected uncertainty in the dynamic measurement.

2. System descriptions

The major features of the inertia measurement machine to be designed are schematically presented in Figs. 1 and 2 details the flexure, since its design in the context of the overall machine is an important aspect of the analysis carried out here. The major dimensions of the system are furnished in Table 1. Two V-blocks on the left and right side, a fixture top plate, two C-channels in front and back, two fixture bottom plates at the right and left side and an adaptor together comprise the object holding arrangement. During the measurements, the object needs to be reoriented and dynamically excited for number of times. There is an actuation mechanism connected with the holding arrangement (not shown in the figure) to initiate oscillation while the torsion rod is clamped within the disc brake. Prior to the initiation of the oscillation up to the end of acquiring the dynamic readings, air is continuously supplied from the compressor through the air bearing. Also during reorienting the object, the air is allowed to flow through the bearing to provide friction free support.

The bearing has a rotor and a stator supported on three pneumatic jacks. Air enters the bearing from an external compressor through a nozzle at the inlet of the air passage machined within the body of the stator in the form of interconnected holes. From the other ends of the holes, the air comes out into the radial and axial gaps between the stator and the rotor. There is one radial gap inside the stator bore. Two axial gaps, one at the bottom and one at the top of the stator form the outlet of the air to be discharged at the ambient. A variation of the gap pressure from a high value set by the compressor to the ambient pressure provides an axial force lifting the rotor from the stator top. This allows the object along with its holding arrangement to float freely under near-zero friction. Under such conditions, smooth and accurate reorientation and free yawing oscillation of the object can be accomplished.

The flexure in Fig. 2 comprises of a central hub in the form of an annular cylinder and an outer rim of square section connected together by four arms, each having a square section. By threaded joints at the hub, the flexure is connected to the torsion rod. Similar joints at the rim connect the flexure with the adaptor. The objective of using a

Table 1
Major dimensions of the system.

Description	Size (mm)	Description	Size (mm)
Outer diameter of rotor	500	C-channel	750 × 75 × 6
Inner diameter of rotor	240	Outer diameter of adapter bottom part	300
Height of the rotor	100	Outer diameter of adapter top part	260
Outer diameter of stator	600	Inner diameter of adapter	190
Inner diameter of stator	243	Height of adaptor	70
Height of the stator	99.97	Flexure outer ring diameter	182