

AN IMAGE PROCESSING METHOD TO DETERMINE THE DAMPING EFFECT PRESENT IN THE MOMENT OF INERTIA MEASUREMENTS PERFORMED ON AN AILERON

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ABSTRACT

This paper focuses on a practical, low budget image processing approach developed to quantify the damping effect on moment of inertia measurements performed with an inverted torsional pendulum. Several measurement cases were realized to measure the damping effect on MoI measurements of an aileron. Method takes advantage of an ordinary camcorder and a software tool to obtain the oscillation profiles. The damping effect was quantified based on free vibration having single degree of freedom with damped response. Based on the measurements and the results obtained by the methodology, it has been seen that the error due to the assumption of undamped conditions affects the measurements far less than the error sources embodied in the inverted torsional pendulum method.

Keywords: Moment of Inertia, Inverted Torsional Pendulum, Damping, Image Processing.

KANATÇIK İÇİN YAPILAN ATALET MOMENTİ ÖLÇÜMLERİNDE SÖNÜMLEME ETKİSİNİN BELİRLENMESİNDE KULLANILAN BİR GÖRÜNTÜ İŞLEME YÖNTEMİ

ÖZET

Bu makalede, ters çevrilmiş burulma sarkacı ile yapılan Kütle Atalet Momenti (KAM) ölçümündeki sönümleme etkisinin belirlenmesinde kullanılan pratik ve düşük maliyetli bir görüntü işleme yöntemi üzerinde durulmuştur. Sönümleme etkisinin KAM ölçümü üzerindeki etkisinin anlaşılması için iki farklı ölçüm konfigürasyonu oluşturulmuş, sıradan bir kamera ve ücretsiz bir video analiz yazılımı ile salınım profilleri çıkarılmıştır. Bu profiller ve tek serbestlik dereceli sönümlemeli serbest salınım denklemi kullanılarak sönümleme miktarı bulunmuştur. Yapılan ölçümler ve uygulanan yaklaşımdan elde edilen sonuçlara göre, sönümlemenin ölçüme olan etkisinin ihmal edilmesi, ölçüm sonuçlarını cihazdaki diğer hata kaynaklarına göre çok daha az etkilemektedir.

Anahtar Kelimeler: Atalet Momenti, Tersine Çevrilmiş Burulma Sarkacı, Sönümleme, Görüntü İşleme.

1. INTRODUCTION

Accurate measurement of moment of inertia (MoI) plays an extremely important role for the operational success of aerospace vehicles. For satellites, MoI is the predominant input to the attitude and orbit control system which is responsible for the maneuvering of the satellite [1]. Likewise, aircrafts also require accurate maneuverability which again depends on MoI [2]. If the wing accelerates in a rotational sense due to twist, the position of the control surfaces such as

ailerons, elevators, and rudders will lag behind the wing due to the moment of inertia of the control surfaces [3,4].

There are several ways to obtain MoI of a body. For simple bodies, MoI can be obtained from a CAD model [5] or derived analytically [6]. However, for more complex bodies like aircrafts consisting a number of subsystems/payloads integrated to the main structure, determination of MoI is a difficult task. Subsystems and elements having irregular and

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intricate shapes lead to the complicity of finding MoI theoretically about a particular axis. For these kinds of bodies MoI has to be found experimentally. The following experimental techniques have been practiced [6-14] and published in the open literature:

- Trifilar (three-wire) torsional pendulum (TTP) [7,8,11],
- Bifilar (two-wire) torsional pendulum [10],
- Compound pendulum [6],
- Inverted torsional pendulum (ITP) [9, 12-14]

In one of these studies Ringegni et al. [7] showed that the errors in MoI measurement performed with TTP decreases with the increase in the length of the pendulum, period of oscillation and radius of the pendulum lower disk. Furthermore, the improper centering of the body on to the lower disk was reported as another source error. In accordance with this, Tang et al. [8] stated that if the mass center of the body is not in line with the TTP axis, an undesired longitudinal oscillation will occur along the pendulum. To eliminate this, usage of a universal joint was recommended to assure that the center of gravity (CoG) of the body aligns with the pendulum axis. Lyons [9] examined various hardware improvements and methodologies for improving modelling accuracy in TTP approach. To do this, damping effects were incorporated to the model analytically and errors due to linearization were mitigated by making accurate rig tare measurements using objects with known moments of inertia. However, precessional motions of the pendulum were an issue because only direct measurements of pendulum period for each oscillation were made with an optical sensor. Pendulum precession caused aliasing problems and variations in the measured rotational period.

On the other hand, a detailed nonlinear model of the bifilar pendulum was developed by Kane [10] primarily to examine the effects of uneven pendulum geometries without considering the damping effect. The model was used to show that torsional motions of the bifilar pendulum are not significantly affected by uneven pendulum wire lengths or misaligned principal axes.

Dowling et al. [11] quantified the uncertainty of the ITP method using various suspension lengths. Experimental data were collected on a cylindrical solid with known mass properties and partial differential equations were derived to calculate the uncertainty. Repeated experiments were made to estimate the errors due to measurements of mass, period of oscillation and distance from the axis to the center of mass. The results showed that the pendulum method was relatively insensitive to measurement errors of mass but was quite sensitive to errors in the period of oscillation.

Besides the error sources inherent in the techniques discussed above, viscous damping is another source which should also be taken into account [15]. Air dragged or pushed by surfaces of the device under measurement (DUM) can increase the MoI dramatically. For example, solar panel of a satellite normally does not encounter air friction in space, yet the friction is present during the measurements performed on earth and this causes higher MoI readings [16]. To eliminate this drag effect which causes the difference in the MoI, a better approach is to make a second measurement in an environment filled with helium, extrapolate the results to find the values that would normally be obtained under vacuum i.e. with no drag [16]. However, to perform such a measurement, the whole set-up should be placed in a special helium chamber which is most of the time unpractical. As an alternative, the current study proposes a practical low-budget approach based on image processing [17] to determine the effect of viscous damping for the measurement of MoI done with an ITP.

2. THEORETICAL BASIS OF ITP METHOD TO FIND MOI

In this study, the MoI measurements were performed with a Space Electronics KSR6000 model mass properties measurement device which utilizes an ITP to measure MoI. Basically, the main idea of ITP method is to determine the moment of inertia based on the variation of oscillation period of different configurations. As can be seen in figure 1, a torsion bar extends from the upper surface of the bearing to a clamping mechanism at the bottom of the rod. During MoI measurement, the lower end of the torsion rod is temporarily clamped to create an inverted torsion pendulum. The test surface of the measurement device and the payload (test object) are automatically twisted to an initial angle and released. A photoelectric sensor assembly mounted on the measurement device measures the period of oscillation. In addition to these, in order to preclude the Coloumb friction from the system, a spherical air bearing pivot is located under the rotary table.

For this type of device, moment of inertia can be expressed by the following equation [15],

$$I = C T^2 \quad (1)$$

where I is the moment of inertia of the body about the axis of rotation, T is the period of oscillation and C is a constant which is a function of modulus of rigidity, diameter and the length of the bar and specific to the measurement device.

3. METHOD TO MEASURE DAMPING EFFECT

The methodology explained in the previous section does not incorporate the effect of damping. However, damping is present in the system due to the medium (air) in which the measurements are carried out and imperfect elasticity of the torsional rod and its omission may lead to errors. In order to incorporate the effect of damping on MoI measurement, a practical approach will be introduced in this study.

3.1. Test Set-Up and Measurement Configurations

According to this approach, the whole measurement sequence was recorded by means of an ordinary (30 fps & 720p) camcorder, after which the variation in the oscillations were obtained by video analysis software. In order to measure the amplitudes by the software, a tracking marker was added to the set-up as illustrated in figure 2. Since the camcorder is located on the side of the mass properties measurement device (figure 2), what is recorded by the camcorder becomes a two dimensional projection of rotary harmonic oscillation. For the present device, considering the fact that oscillations occur between -0.4° and $+0.4^\circ$, oscillations projected onto the video are treated as linear motion.

With this set-up, two measurements were performed. In the first measurement, in order to introduce more viscous and structural damping, an aileron having large surface area was selected as payload. In the second set, a comparison sample having a similar MoI but smaller surface area with respect to aileron was used with the goal of eliminating the viscous damping. In figure 3-4, snapshots taken during the measurements of the aileron and comparison samples are shown, respectively.

An open source video analysis software, “Tracker - v4.85” was used to acquire oscillation profiles from the recorded videos. For the software to recognize the motion in the video, a marker was placed on the fixture. The marker which can be seen in Figure 5 is optimally designed to meet the needs of the software having high contrast patterns with different sizes. After deciding which pattern to use, software automatically tracks the pattern throughout the video, tabulates and plots the collected data. In addition to these properties, it is also possible to convert relative distance generated by the software into real life distances by using a known scale in the video. For this purpose, marker was designed with a scale on itself. It should also be noted that it becomes harder to detect patterns as they move faster. For this kind of cases, camcorders either with higher shutter speeds or higher frame rates should be utilized.

3.2. Processing and Utilization of Oscillation Data

The degree of damping in a system can be defined in terms of successive peak values in a record of a free oscillation. If the amplitude of any peak is A_1 and amplitude of next peak is A_2 , logarithmic decrement between two adjacent peaks is given as [6]:

$$\Delta = \ln \left(\frac{A_1}{A_2} \right) \quad (2)$$

Normally, it is enough to use a few measured peak values to obtain decrement provided that the recording device has a high fps and spatial resolution capability. However, due to the limitations imposed by the present camcorder (low fps and spatial resolution), the actual peaks occurring in reality cannot be captured accurately.

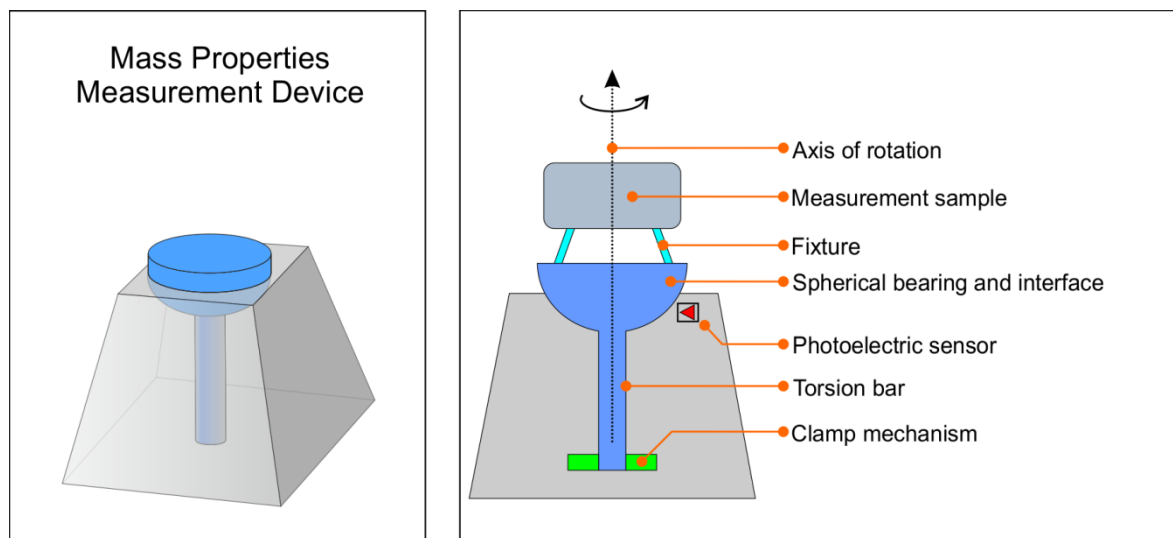


Figure 1. Schematics of the mass properties measurement device.

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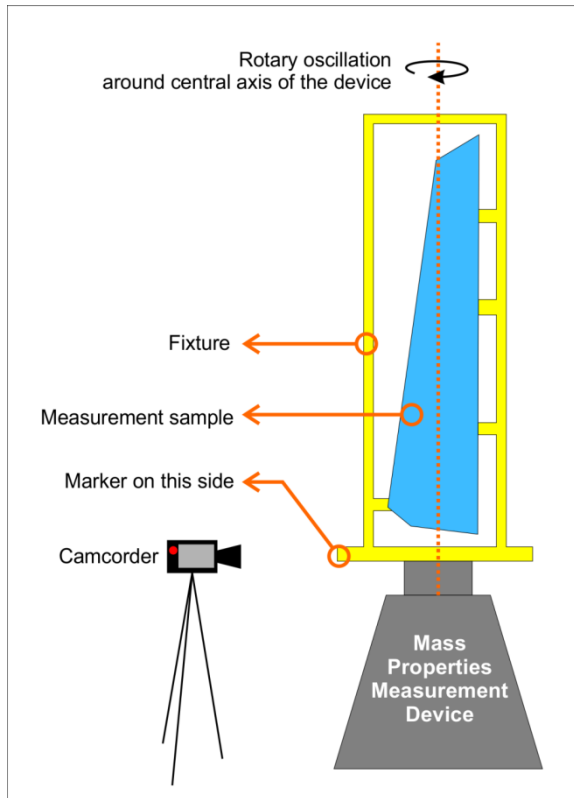


Figure 2. Test set-up.

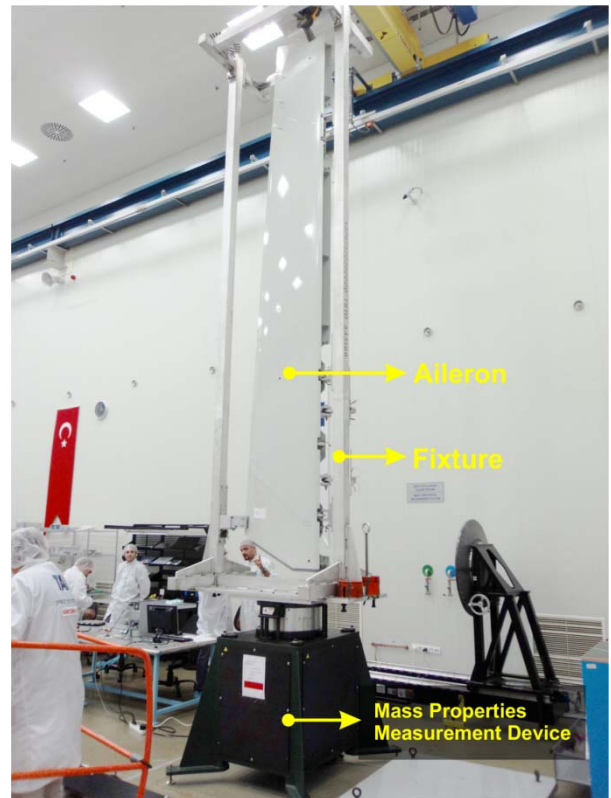


Figure 3. Aileron measurement.



Figure 4. Comparison sample measurement.

Therefore using only peak values from the raw data is not a reliable option. A better alternative is to perform a curve fitting for the entire set of data and obtain the decrement regime from this curve. For the curve

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fitting, Least Absolute Deviations (LAD) technique was selected which minimizes the sum of the absolute values of the vertical residuals between points generated by the function and corresponding measured data.

The equation for free vibrations having a single degree of freedom with damped (underdamped) oscillations was used to generate the fitting curve which can be given as [6]:

$$A = A_0 e^{(-\gamma t)} \cos\left(2\pi \frac{t}{T_d}\right) \quad (3)$$

where γ is the damping coefficient, t is time of the recorded frame, e is Euler constant, T_d is the period of damped oscillation, A_0 is the initial amplitude and A is instantaneous amplitude. In accordance with LAD technique, once the curve fit with the desired accuracy is obtained, T_d and γ which characterize the curve are also obtained simultaneously. In figure 6, the performance of the curve fit for damped oscillations is shown on a zoomed plot in order to illustrate the effect of damping effect whereas the complete curve is shown in figure 7.

Recall that we are trying to calculate the undamped MoI i.e. the MoI without the effect of damping. For this purpose, we need the undamped angular frequency of the oscillations ω_u which can be calculated by [6]

$$\omega_u = \sqrt{1 + \left(\frac{\Delta}{2\pi}\right)^2} \omega_d \quad (4)$$

where

$$\omega_d = \frac{2\pi}{T_d} \quad (5)$$

and Δ is calculated using the peak points obtained from curve fit. Knowing ω_u , one can calculate the period of undamped oscillations, T_u , by using the following expression:

$$T_u = \frac{2\pi}{\omega_u} \quad (6)$$

Finally, using (1) with the known values of T_d and T_u , damped and undamped MoI can be found, respectively.

4. RESULTS AND DISCUSSION

The MoIs obtained for the configurations described above are given Table 1. Inspection of the results reveal that for the set-up and the configurations under consideration, effect of damping on MoI are in the order of 10^{-6} kg.m² and can be neglected for practical purposes. Moreover, when the differences in MoI for aileron and sample are compared, it can be seen that the MoI of aileron is approximately twice the sample's MoI. This can be attributed to higher viscous damping acting on the aileron which has large surface areas with respect to sample.

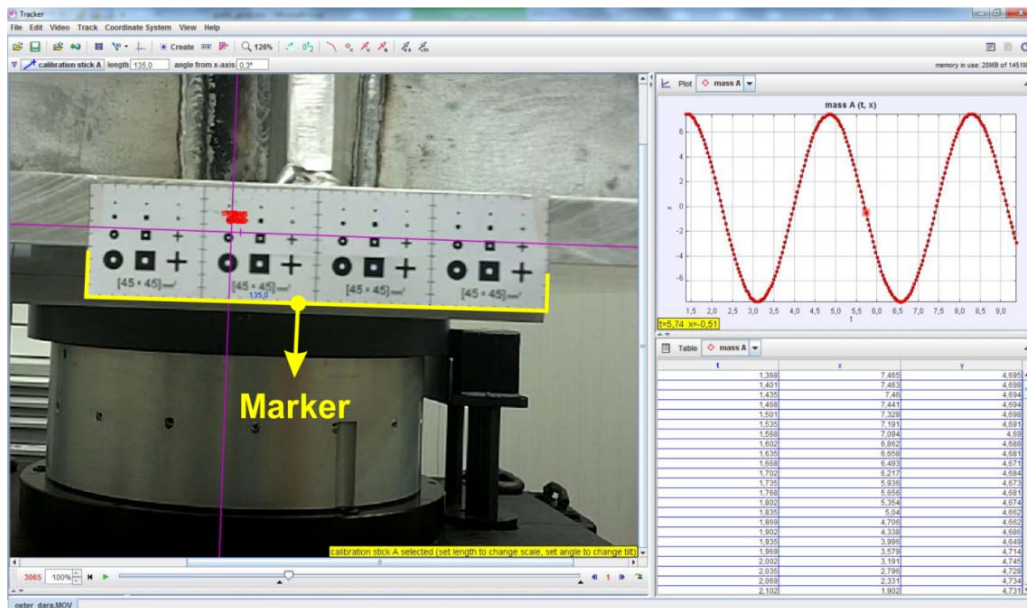


Figure 5. A snapshot taken from the graphical user interface of the software.

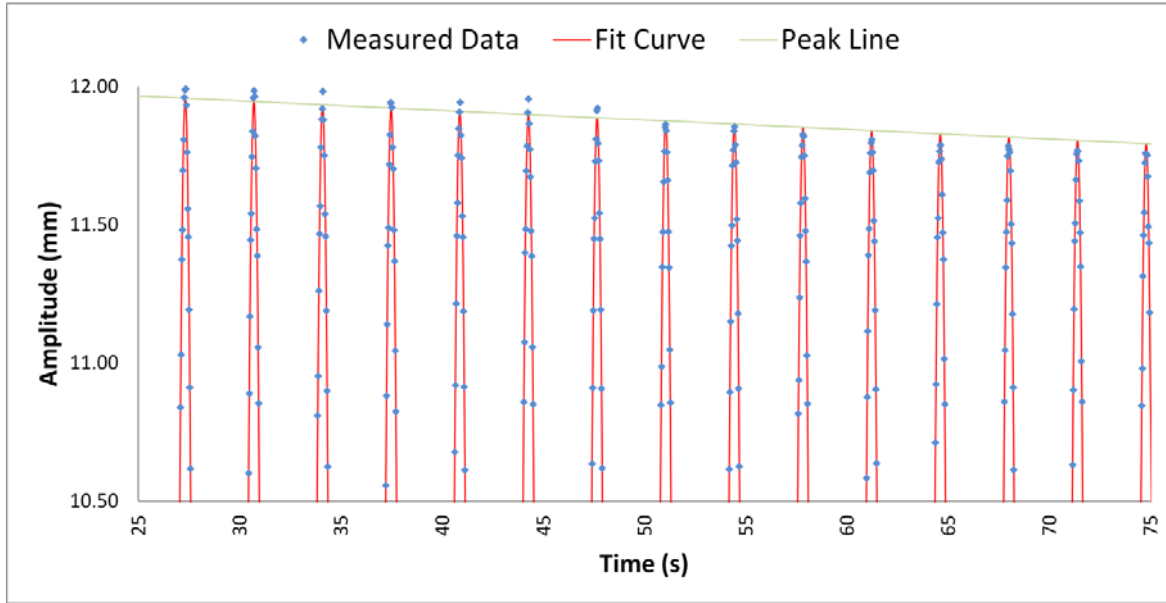


Figure 6. Curve fit for damped oscillations close to peak values.

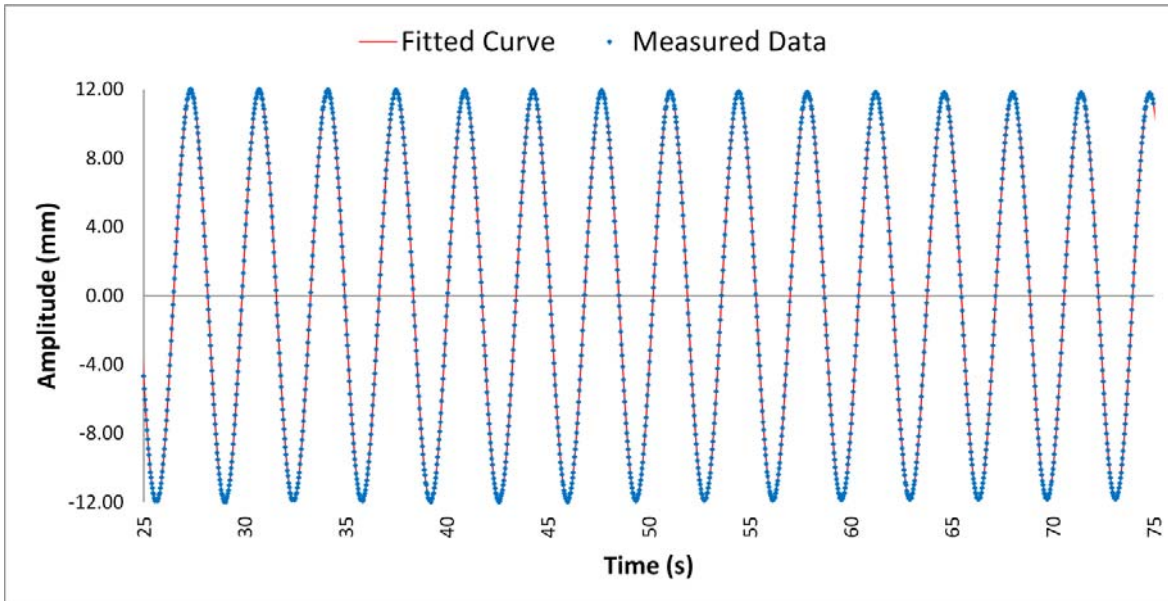


Figure 7. Curve fit for damped oscillations close to peak values.

Besides the damping effect, there are other error sources [12-14] related to inverted torsion pendulums which must be taken into account. The order of magnitudes and the source of these errors are given in Table 2.

When the Table 2 is investigated, it is seen that the largest error source is due to the timing accuracy of mass properties measurement device. In order of significance, mass measurement, fixture loading and fixture centering errors are the other sources of errors all of which are much larger than the contribution of damping on the overall error.

5. CONCLUSIONS

In what preceded, a practical low-budget approach for the assessment of the damping effect on MoI measurements performed by a mass properties measurement device based on inverted torsional pendulum was described. The methodology is based on recording the harmonic oscillations by means of a camcorder and then post-processing the video to obtain the period and amplitudes of damped oscillations using readily available software.

Table 1. MoIs calculated for different configurations.

Measurement	Surface Area (m ²)	MoI - damped (kg.m ²)	MoI – undamped (kg.m ²)	Difference (kg.m ²)
Aileron	14.5	198.842977	198.842967	10.3 x 10 ⁻⁶
Sample	2.5	198.572458	198.572453	5.1 x 10 ⁻⁶

Table 2. Source of errors in ITP.

Error Source	Amount of Effect (kg.m ²)	Cause
Timing Error	±0.04	Error coming from timing accuracy in measuring of period of oscillations
Mass Measurement Error	±0.03	Error coming from weighing device affecting MoI via CoG calculations
Fixture Loading Error	±0.0005	Tilting of the fixture due to the mass of the payload
Fixture Centering Error	±0.0005	Resulting from production tolerances of fixture

Measurements were carried out for an aileron having large surface area and a sample payload having a significantly smaller surface area, both of which possessing a similar MoI. As expected, it was seen that the effect of damping was larger for the payload having larger surface area. However, the effect of damping on the overall MoI measurements was insignificant for the set-up and payloads under consideration.

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VITAE

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He graduated from Space Engineering Department of İstanbul Technical University in 2008. After his graduation, he started to work in İTÜ pSAT-1 Cubesat Project as a test and design engineer. In 2009, he started to work in Turkish Aerospace Industries, Inc. (TAI). He has expertise in the fields of vibration testing, acoustic testing and mass properties measurement of satellites and satellite equipment.

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