INERTIA PARAMTER IDENTIFICATION FROM BASE EXCITATION TEST DATA

Ulrich Füllekrug(1) and Carsten Schedlinski(2)

(1) DLR Institute of Aeroelasticity
Bunsenstraße 10, 37073 Göttingen, Germany
Phone: +49 551 709 2421, Fax: +49 551 709 2862,
E-Mail: Ulrich.Fuellekrug@dlr.de

(2) ICS
Lortzingstraße 20, 63225 Langen, Germany
Phone: +49 6103 922440, Fax: +49 6103 922442
E-mail: sched@ics-solutions.de

ABSTRACT

With the purpose to further investigate and improve a method for the identification of inertia parameters, tests with flexible test structures have been carried out. Reference data for the inertia parameters were obtained from a Finite Element model and from conventional weighing and pendulum measurements.

For the realization of the base excitation a six-axis vibration simulator was utilized. The base forces were recorded with a special Force Measurement Device (FMD), and the base accelerations of the test structures were measured by accelerometers. Each of the 3 translational and 3 rotational axes of the multi-axial test facility was driven by a sine sweep signal with an appropriate base acceleration input.

The application of the identification algorithm to the measured data showed that an acceptable identification of mass and mass moments of inertia is possible. However, a highly accurate identification of the center of gravity location could not be achieved. The results of the analyses are discussed and the advantages and limits of the present method are pointed out. Recommendations for the practical application and improved center of gravity identification are given.

Keywords: *Inertia parameters, base excitation, multi-axial test facilities, vibration testing.*

1. INTRODUCTION

During the development and qualification process of spacecraft it is required to determine the inertia parameters like mass, center of gravity and moments of inertia. Usually, specialized test facilities are utilized for this purpose. However, the extended capacities of the Ariane 5 launcher allow now for heavy spacecraft. The available mass and inertia measurement equipment at ESTEC is currently not capable of measuring structures weighing more than 2.7 tons.

In previous studies [1, 2] it was concluded that the direct physical parameter identification method utilizing base excitation test data might serve as an appropriate alternative to the classical weighing, static balancing and pendulum testing methods. However, this method requires six axes base excitation, and the interface forces have to be measured in addition to the response accelerations. The measurement of interface forces and the modal identification from base excitation are described e.g. in [3, 4, 5].

A first investigation on inertia parameter identification was carried out by ATOS, Netherlands, and ICS [6]. The moments of inertia were identified with an accuracy of better than 1.5 %, which was within the target range. The identified center of gravity coordinates, however, were not considered sufficiently accurate, and no reasons for the mismatch were found. In order to further investigate the subject, ICS and DLR performed a new study for ESTEC [7, 8, 9]. The six axes vibration test facility MAVIS (**M**ulti **A**xis **Vi**bration **S**imulator) of DLR in Göttingen was utilized to generate the required base excitation test data. The new study was aimed at further investigating the method and to make recommendations for future applications and spacecraft testing.

2. THEORETICAL BACKGROUND

2.1. Basics of Identification Method

Most inertia parameter methods allow only for the identification of a reduced set of the ten inertia parameters (see [2]). Thus several measurements or tests are required in order to identify the complete set. However, some methods are capable of identifying all ten inertia parameters simultaneously. The direct physical parameter identification method as described in

[1] and [2] seems to be the most promising of these methods, and it may be an alternative to classical weighing, static balancing and pendulum testing methods in terms of testing time and possible accuracy achievements.

The direct physical parameter identification method focuses on a fit of system matrices to measured vibration response data. Measurements of the accelerations of the structure are required together with the applied forces and moments, while all translational and rotational motions of the structure need to be excited.

Multi degree-of-freedom base excitation may be applied to the structure, e.g. on a six axes vibration table. A prerequisite for the validity of linear equations of motion is that the rotational amplitudes and velocities are sufficiently small. Furthermore the structure has to be mounted on a force measurement device (FMD). The measured interface forces are then interpreted as applied loads to the ideal free/free system.

Frequency domain measurement data are best suited to estimate the inertia parameters utilizing the direct physical parameter identification method, since it simplifies the elimination of the influences of the structure's elasticity on the response. Separation of the rigid and the elastic system response is generally possible even if the first elastic natural frequency is very low. The extraction of the rigid body response can be regarded as the problem of extrapolating the frequency response to frequency zero.

In [2] the linearized equations of motion of a rigid body with respect to an arbitrary reference point A have been developed for small angular motions and small angular velocities:

$$\left[\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{bmatrix}, m\begin{bmatrix} 0 & z_{AC} & -y_{AC} \\ -z_{AC} & 0 & x_{AC} \\ y_{AC} & -x_{AC} & 0 \end{bmatrix}\right]\begin{Bmatrix} \ddot{x}_A \\ \ddot{y}_A \\ \ddot{z}_A \\ \ddot{\alpha}_A \\ \ddot{\beta}_A \\ \ddot{\gamma}_A \end{Bmatrix} = \sum_i \begin{Bmatrix} f_x \\ f_y \\ f_z \end{Bmatrix}_{P_i} - \begin{Bmatrix} 0 \\ 0 \\ mg \end{Bmatrix} \tag{1a}$$

$$\left[m\begin{bmatrix} 0 & -z_{AC} & y_{AC} \\ z_{AC} & 0 & -x_{AC} \\ -y_{AC} & x_{AC} & 0 \end{bmatrix}, \begin{bmatrix} \Theta_{xx} & \Theta_{xy} & \Theta_{xz} \\ \Theta_{yx} & \Theta_{yy} & \Theta_{yz} \\ \Theta_{zx} & \Theta_{zy} & \Theta_{zz} \end{bmatrix}_A\right]\begin{Bmatrix} \ddot{x}_A \\ \ddot{y}_A \\ \ddot{z}_A \\ \ddot{\alpha}_A \\ \ddot{\beta}_A \\ \ddot{\gamma}_A \end{Bmatrix} = \sum_i \begin{Bmatrix} t_x \\ t_y \\ t_z \end{Bmatrix}_{P_i} + \sum_i \begin{bmatrix} 0 & -z_{AP_i} & y_{AP_i} \\ z_{AP_i} & 0 & -x_{AP_i} \\ -y_{AP_i} & x_{AP_i} & 0 \end{bmatrix}\begin{Bmatrix} f_x \\ f_y \\ f_z \end{Bmatrix}_{P_i} - mg\begin{Bmatrix} y_{AC} \\ -x_{AC} \\ 0 \end{Bmatrix} \tag{1b}$$

where:

m	-	mass
$\ddot{x}_A, \ddot{y}_A, \ddot{z}_A$	-	translational accelerations at reference point A
$\ddot{\alpha}_A, \ddot{\beta}_A, \ddot{\gamma}_A$	-	rotational accelerations at reference point A
x_{AC}, y_{AC}, z_{AC}	-	center of gravity with respect to reference point A
$x_{AP_i}, y_{AP_i}, z_{AP_i}$	-	coordinates of point P_i with respect to reference point A
$(f_x, f_y, f_z)_{P_i}$	-	forces at point P_i
$(t_x, t_y, t_z)_{P_i}$	-	moments at point P_i
$(\theta_{xx}, \theta_{yy}, \theta_{zz})_A$	-	moments of inertia with respect to reference point A
$(\theta_{xy}, \theta_{xz}, \theta_{yz})_A$	-	products of inertia with respect to reference point A
g	-	gravitational constant (9.81 $^{m}/_{s^2}$)

It is in most cases not possible to measure the accelerations directly at the reference point A. Thus $\{a\}_A = \{\ddot{x}_A \ \ \ddot{y}_A \ \ \ddot{z}_A \ \ \ddot{\alpha}_A \ \ \ddot{\beta}_A \ \ \ddot{\gamma}_A\}^T$ is estimated from the relation $\{a\}_M = [G]_A \ \{a\}_A$ where $\{a\}_M$ represents the measured accelerations for the measured degrees of freedom and $[G]_A$ is a pure geometric transformation matrix:

$$\{a\}_A = \left([G]_A^T \ [W] \ [G]_A\right)^{-1} [G]_A^T \ [W] \ \{a\}_M \tag{2}$$

with: $[W]$ - optional weighting matrix

For a single point P_i, for example, $[G]_A$ takes the form as shown in Eq. 3

$$[G]_A = \begin{bmatrix} 1 & 0 & 0 & 0 & z_{AP_i} & -y_{AP_i} \\ 0 & 1 & 0 & -z_{AP_i} & 0 & x_{AP_i} \\ 0 & 0 & 1 & y_{AP_i} & -x_{AP_i} & 0 \end{bmatrix} \quad (3)$$

Theoretically Eqs. 1 could directly be used to identify the inertia parameters. Yet to reduce the number of unknowns an estimation vector according to Eq. 4 can be defined.

$$\{\sigma\} = \{m \quad mx_{AC} \quad my_{AC} \quad mz_{AC} \quad \Theta_{xxA} \\ \Theta_{yyA} \quad \Theta_{zzA} \quad \Theta_{xyA} \quad \Theta_{xzA} \quad \Theta_{yzA}\}^T \quad (4)$$

Reassembling Eqs. 1 then yields an equation system, which can be solved for the ten inertia parameters contained in the estimation vector.

In order to account for elastic influences as well, the estimation vector can be extended by appropriate auxiliary parameters. However, this will not be discussed in detail in this publication.

2.2. Pretest Analysis

The performance of a pretest analysis for the investigated Clumod structure led to the following points that should be considered for inertia parameter identification from base excitation testing [7]:

- achieve enforced accuracy with respect to calibration of the measurement chain (pickup sensitivities, time delays of filter boards, geometry of setup, etc.)
- avoidance/reduction of elastic effects by proper pickup placement (i. e. on rigid locations); not possible for load cells (elastic effects will show in any case on the force data)

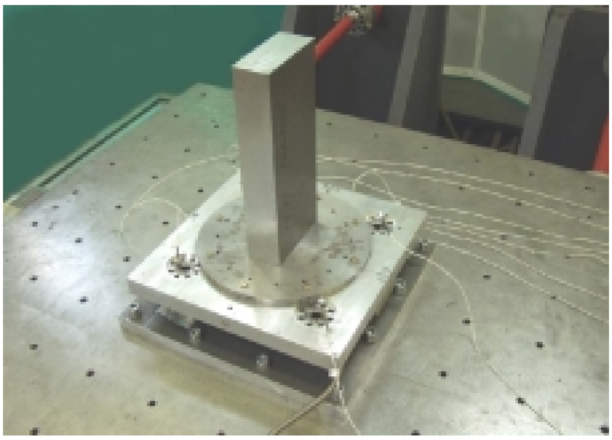

Figure 1: FMD, circular disk and Cuboid

- avoidance of poor conditioning of base acceleration and force data by defining appropriate base excitation patterns
- thorough assembly of FMD (avoidance of possible pre-tensioning or pre-stressing)
- pretest and evaluation of pretest with known calibration mass, favorably backed up by analytical data

Especially important are the proper calibration of the sensors next to an optimal accuracy of the measured forces, since these points have proven to be most relevant for a proper identification of the center of gravity.

3. TEST STRUCTURE AND REFERENCE DATA

3.1. Test Structure

With the purpose to investigate the inertia parameter identification method, tests with an elastic structure were performed. This section describes the investigated test structure and explains how reference data for the inertia parameters were obtained.

The FMD itself is always part of the test setup. Therefore the inertia parameters of the FMD need to be identified first. However, the inertia parameters of the FMD cannot be precisely identified with classical methods. This is due to the fact that those parts of the masses of the load cells, which are contributing to the measured dynamic forces, are unknown. For this reason, a special test setup was utilized which enables the identification of the inertia parameters of the FMD.

The utilized test setup consists of a simple Cuboid, which is mounted to the cover plate of the Force Measurement Device by using a circular disc. Fig. 1 shows the Cuboid, the circular disc, and the Force Measurement Device.

The Cuboid consists of a simple homogenous, rectangular block and is manufactured of aluminum. The dimensions of the Cuboid are in length *160 mm*, breadth *70 mm*, and in height *400 mm.* At the bottom side the Cuboid has 4 threaded holes of diameter M8, which are used to screw it to the circular disc. The circular disc is manufactured of steel. It has a diameter of *351.0 mm* and a height of *14.5 mm*. The inertia parameters of the Cuboid and circular disc could be determined by weighing and from the geometry with very high accuracy [8].

The test structure Clumod (**Clu**ster **Mod**el) is a laboratory-type test structure and was specially designed

Figure 2: Test structure Clumod with four blades

and manufactured for the development and verification of modal identification methods. Clumod consists of a hollow central mast and four perpendicularly mounted rectangular blades. The overall height is about *1.6 m* and the total mass amounts to about *47 kg*.

Fig. 2 shows the Clumod with four blades. The main parts of Clumod are the bottom flange, the central mast, and the four blades.

The bottom flange, the central mast, and the four blades are made of steel. The shorter upper blade contains a thin layer of silicone in its neutral axis. In this way a non-uniform damping of the structure is realized. Due to symmetries the structure is dynamically characterized by clusters of eigenfrequencies. The silicone layer in the neutral axis of the shorter upper blade causes a variation of damping of the vibration modes.

With the purpose to have a smaller and a higher elastic influence, the test structure Clumod was employed in two different configurations. The configuration with the higher elastic influence consists of the original Clumod with four blades; see Fig. 2. For the configuration with lower elastic influence the two upper blades and one of the lower blades were removed.

3.2. Analytical Determination of Inertia Parameters

In order to have an analytical description of the test structure Clumod, a Finite Element (FE) model was established. The main cause for the creation of the Finite Element model was to precisely predict the inertia parameters like total mass, center of gravity, and moments of inertia. The second cause was to get insight into the dynamic behavior and to predict the eigenfrequencies and mode shapes.

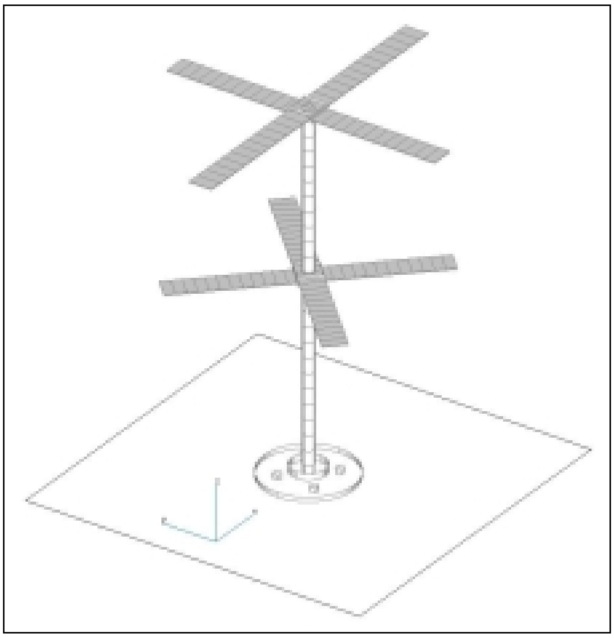

Figure 3: FE-Model of Clumod with four blades

For the setup of the Finite Element model the detailed design data were utilized. In order to achieve good results for the inertia parameters, special care was spent to include very precisely the dimensions of all parts. Also, all cutouts and holes were taken into account and accordingly considered. For the discretization mainly beam and plate elements were used. The Finite Element model of Clumod with four blades exhibits 257 nodes and 152 elements. It is shown in Fig. 3.

The FE model was then employed for the computation of the inertia parameters. The results for Clumod with four blades are listed in Table 1. The table specifies the total mass, the center of gravity (CoG) in x, y and z-direction, and the moments of inertia (MoI) related to the center of gravity. All parameters are given with respect to the FE coordinate system. The table also lists the results of conventional measurements of inertia parameters.

The eigenfrequency analysis of Clumod with four blades shows that 11 modes shows are present in the frequency range from *5.7 Hz* to *15.5 Hz*. They are characterized by the fundamental bending of the blades and the fundamental bending and torsion of the mast. A frequency cluster occurs around *12.3 Hz* with four bending modes of the lower blades. Higher bending modes of the blades and the mast occur in the frequency range above *37.7 Hz*.

For Clumod with one blade only 5 well-separated modes are present in the frequency range up to *50 Hz*. The lowest eigenfrequency with the fundamental mast bending occurs at *11.6 Hz*.

3.3. Conventional Measurement of Inertia Parameters

The inertia parameters of Clumod with one and four blades were also experimentally identified by conventional weighting and pendulum measurements. For all measurements the respective tolerances were determined and calculated.

The total mass of Clumod was simply measured by using a calibrated balance. The tolerance for the measured mass was computed from the resolution of the balance, the relative error and a digit error. The center of gravity in z-direction was measured by suspending Clumod with a crane and a steel wire rope at its top and supporting its lower part with a calibrated balance. The tolerances depend on the accuracy of the balance and the accuracy of measuring the distances between the point of support, the attachment point of the steel wire rope and the bottom of Clumod.

The moments of inertia (MoI) were determined by suspending Clumod with steel wire ropes and measuring the time of several cycles of vibrations in the gravity field. The moments of inertia Θ_{ii} were calculated from

$$\Theta_{ii} = \frac{m\, g\, s_1\, s_2\, T^2}{4\, \ell\, \pi^2} \qquad (5)$$

where m is the mass, g the gravitational acceleration constant, s_1 and s_2 the distances from the center of gravity (CoG) to the attachment points of the ropes, T the time period for one cycle of oscillation, and ℓ the length of the ropes.

Fig. 4 shows the test setup for measuring the moments of inertia of Clumod with four blades.

Figure 4: Measurement of moments of inertia for Clumod with four blades

Parameter	FE Analysis	Measurement	Deviation
Mass m	47.230 *kg*	47.400 *kg*	0.36 %
CoG x	0.0 *mm*	0.0 *mm*	0.00 %
CoG y	0.0 *mm*	0.0 *mm*	0.00 %
CoG z	603.3 *mm*	603.0 *mm*	-0.05 %
MoI Θ_{xx}	20.144 kgm^2	20.353 kgm^2	1.03 %
MoI Θ_{yy}	20.410 kgm^2	20.528 kgm^2	0.58 %
MoI Θ_{zz}	2.289 kgm^2	2.278 kgm^2	-0.48 %

Table 1: Inertia parameters of Clumod with four blades

3.4. Comparison of Inertia Parameters

The inertia parameters from FE analysis and measurements are listed in Table 1 for Clumod with four blades. The table shows that the deviations are very small in most cases. The deviations between FE analysis and measurements are in most cases smaller than the computed tolerances of the measurements itself. Only for the total mass the deviation is a little higher than the tolerance of the measurements. Altogether it can be concluded that the accuracy of the parameters is quite high.

3.5. Test Setup

For the realization of the base excitation the six-axis vibration simulator MAVIS (**M**ulti **A**xis **Vi**bration **S**imulator) was utilized. A photograph of MAVIS with Clumod is shown in Fig. 5.

The data acquisition was performed with a 72-channel time domain data acquisition system. With this system all measured signals like accelerations of the vibration table, base forces, and accelerations of other accelerometers were recorded. The data acquisition system was also employed for the generation of the base excitation signals and for the control of the vibration test facility MAVIS.

The forces were measured with a special Force Measurement Device (FMD). The FMD consists of a cover plate and four pre-stressed 3-component force sensors. Fig. 6 shows the bottom side of the FMD. In this figure also the summation box is visible. The summation box sums up the signals of those force sensors, which are on the same line of action.

The FMD was mounted to the vibration table of MAVIS by a special mounting plate. Special care was taken for the fixation of the force elements onto the mounting

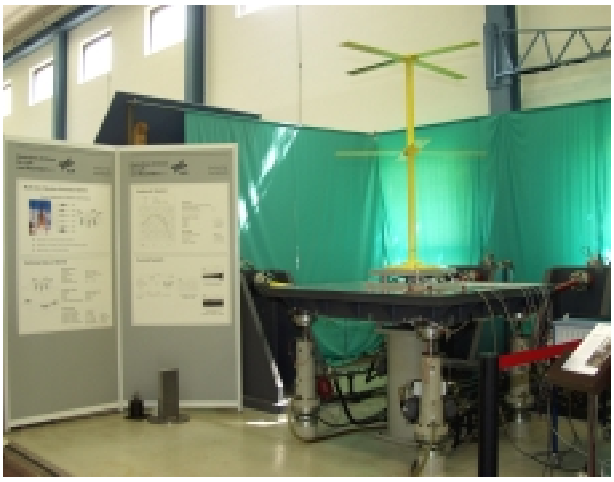

Figure 5: Test setup with MAVIS and Culmed

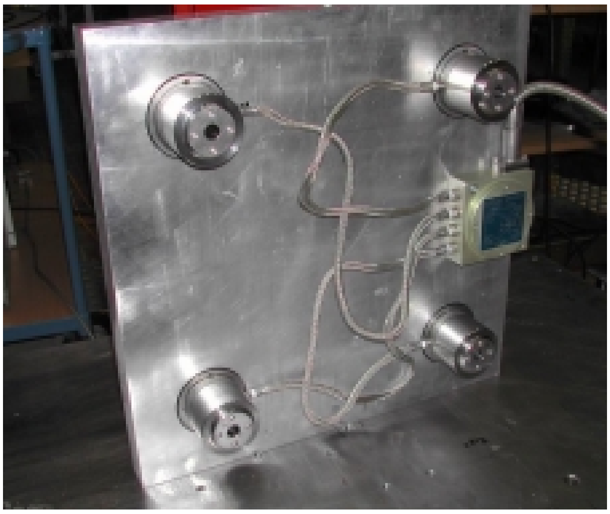

Figure 6: Bottom side of the FMD

plate. Following the instructions of the FMD manufacturer, an aluminum foil was placed under two opposing force element in order to avoid any teetering and to enable an assembly free of mechanical stresses.

The base accelerations of the test structures were measured on the one hand by accelerometers at the vibration table plate, which are also used for the control of MAVIS. In addition, accelerometers were installed at the cover plate of the FMD.

4. TEST PERFORMANCE AND TEST DATA EVALUATION

The tests for the identification of the inertia parameters were performed at the test laboratory of the Institute of Aeroelasticity at DLR Göttingen in early summer 2002. With the test setup for Cuboid, Clumod with one blade and Clumod with four blades sine sweep runs were performed for each of the 3 translational and for each of the 3 rotational axes. The measured signals consist of the 6 base accelerations of the MAVIS vibration table, 8 signals of the FMD force sensors, and 8 signals of the accelerometers on the FMD.

The sine sweep signal excitation was applied in the frequency range from *4.0 Hz* to *32.0 Hz*. The frequency increased with *2 oct/min* and thus the total duration of each sweep run was about *90 s*. The nominal base acceleration input was about *2.5* m/s^2 for the translational axes, about *3.0* rad/s^2 for the rotational axes α and β (lateral) and about *6.0* rad/s^2 for the rotational axis γ (vertical). The time domain signals were recorded by the data acquisition system and digitized.

The first step of the test data evaluation consisted in the computation of the frequency spectra. In order to achieve accurate results the peak reference hold technique was utilized. For this computation the overlap of the single data blocks was set to *90%*, the block size was selected to 8,192 data points, and 53 averages were taken. Next, the resulting frequency spectra were interpolated to a frequency grid with a resolution of *0.05 Hz.*

The force measurement device delivers 2 combined forces for both, the x- and y-direction, and 4 single forces in the z-direction. From these 8 force signals the resulting forces and moments of the FMD were be computed. As reference point the center of the force-measuring plane was used.

Base accelerations from the accelerometers on the FMD were calculated according to

$$\{\ddot{u}_0\}_F = [T]\{\ddot{u}_{accel}\} \qquad (6)$$

see also [5]. Here $\{\ddot{u}_0\}_F$ is the vector with the 6 DoF base accelerations of the reference point F (center of the force measuring plane) and $\{\ddot{u}_{accel}\}$ is the vector with the measured accelerations on the FMD. $[T]$ is a transformation matrix and can be calculated from

$$[T] = \left([G]_F^T [G]_F\right)^{-1} [G]_F^T \qquad (7)$$

The geometry matrix $[G]_F$ is formed by the coordinates and the measurement directions of the accelerometers on the FMD (see also section 2.1).

The dynamic masses of a structure under base excitation are described by Eqs. 8 (see [5])

$$f_{0k}(\omega) = H_{kk}^{mass}(\omega) \cdot \ddot{u}_{0k}(\omega) \qquad (8a)$$

$$f_{0k}(\omega) = \left(\sum_{r=1}^{n} \frac{\omega^2}{\omega_r^2 - \omega^2 + 2\varsigma_r \omega_r \omega i} \cdot \mu_{rk} + M_{Sk} \right) \cdot \ddot{u}_{0k}(\omega)$$
(8b)

It relates for the reference point *0* the base acceleration $\ddot{u}_{0k}(\omega)$ of base axis *k* to the base force $f_{0k}(\omega)$ of the same axis. In the equation ω_r denotes the natural frequency, ς_r the viscous damping ratio, μ_{rk} the effective mass, and M_{Sk} is the static mass (or moment of inertia) of the structure for axis *k*. The equation shows that the interface forces depend on the modal properties as well as on the inertia properties of the structure. The transfer function $H_{kk}^{mass}(\omega)$ has the physical unit '*kg*' or '*kgm*^{2}'. Therefore the transfer function is also called dynamic mass or apparent mass function.

With the previously calculated spectra of the resulting forces, moments and base accelerations the dynamic masses of the tested structures can be computed. One simple way for computing the dynamic masses consists of dividing the resulting forces or moments by the acceleration of the respective active axis. However, due to undesired motions of the vibration table into the direction of other axes these dynamic masses may be inaccurate.

A more consistent way for the computation of the dynamic masses is based on the Eq. 9

$$\{f_0(\omega)\} = \left[H^{mass}(\omega)\right]_{6x6} \cdot \{\ddot{u}_0(\omega)\} \qquad (9)$$

where the cross coupling of base axes is taken into account. To eliminate the effects of cross coupling it is required to drive all coupled axes. In the general case where all six axes are coupled, it is required to perform six test runs and to excite each of the base axes. Whenever six linearly independent base accelerations can be realized, the complete matrix $\left[H^{mass}(\omega)\right]_{6x6}$ can be computed. Inserting measured data in Eq. 9 results in

$$\left[S_f(\omega)\right]_{6x6} = \left[H^{mass}(\omega)\right]_{6x6} \cdot \left[S_u(\omega)\right]_{6x6} \qquad (10)$$

where

$$\left[S_f(\omega)\right]_{6x6} = \left[\{f_0(\omega)\}_1 \quad \{f_0(\omega)\}_2 \quad \cdots \quad \{f_0(\omega)\}_6\right]_{6x6}$$
$$\left[S_u(\omega)\right]_{6x6} = \left[\{\ddot{u}_0(\omega)\}_1 \quad \{\ddot{u}_0(\omega)\}_2 \quad \cdots \quad \{\ddot{u}_0(\omega)\}_6\right]_{6x6}$$

The base force vector $\{f_0(\omega)\}_1$ represents the frequency domain data from the first test run and the vector $\{\ddot{u}_0(\omega)\}_1$ comprises the related accelerations. The matrix of dynamic masses $\left[H^{mass}(\omega)\right]_{6x6}$ can then be calculated from

$$\left[H^{mass}(\omega)\right]_{6x6} = \left[S_f(\omega)\right]_{6x6} \cdot \left[S_u(\omega)\right]_{6x6}^{-1} \qquad (11)$$

A prerequisite for the matrix inversion is the fact that $\left[S_u(\omega)\right]_{6x6}$ is regular. Matrix $\left[S_u(\omega)\right]_{6x6}$ becomes singular if the six base axes perform linearly dependent motions. The degree of singularity can be checked and visualized by a suitable condition number. Plotting the condition number versus frequency reveals those frequency ranges that are not suitable for further analysis.

The results of the tests can be at best presented by the computed dynamic mass functions. As explained above, the elements of the main diagonal of matrix $\left[H^{mass}(\omega)\right]$ relate an interface force or moment into the direction of one axis to a base acceleration of the same axis. For $\omega = 0$ the dynamic mass function $H_{k,k}^{mass}(\omega)$ yields the static mass or moment of inertia for axis *k* (see Eq. 8).

Figs. 7 to 9 show examples for the dynamic masses of the test setup with the Cuboid, Clumod with one blade and Clumod with four blades. The dynamic mass functions of the Cuboid present themselves practically as straight lines for magnitudes and phases. This is due to the fact that the test structure is rigid in the investigated frequency range. For Clumod with one blade and Clumod with four blades several resonances are clearly visible. Also, it can be seen that the extrapolation of the functions to $\omega = 0$ may be affected significantly stronger by errors and inaccuracies as the straight-line extrapolation of the Cuboid.

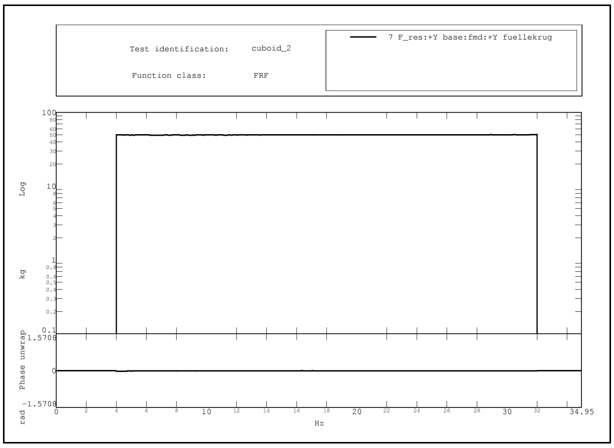

Figure 7: Dynamic mass of Cuboid

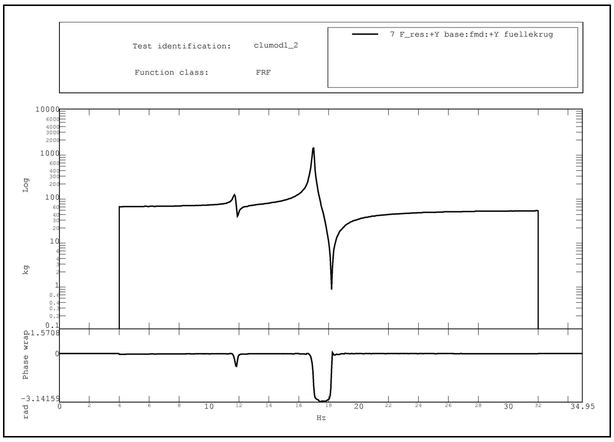

Figure 8: Dynamic mass of Clumod with one blade

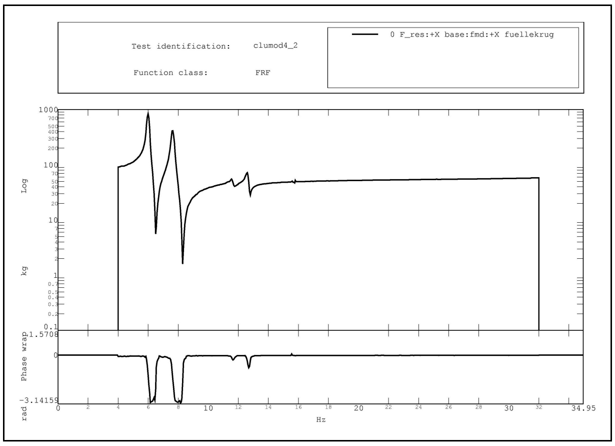

Figure 9: Dynamic mass of Clumod with four blades

The dynamic masses as well as the raw frequency spectra of the measured signals form the basis for the inertia parameter identification [7, 9].

5. APPLICATION OF THE INERTIA PARAMETER IDENTIFICATION METHOD

From the test data obtained via base excitation testing on the MAVIS facility the inertia parameters were identified utilizing an improved identification software [7].

First, the known inertia parameters of Cuboid and the circular disc were utilized to identify the inertia parameters of the FMD. The inertia parameters of the FMD were identified for different frequency ranges and identification algorithm parameters. It could be shown that the variation of the identified mass and moments of inertia are comparatively small. However, a rather large variation can be observed with respect to the center of gravity.

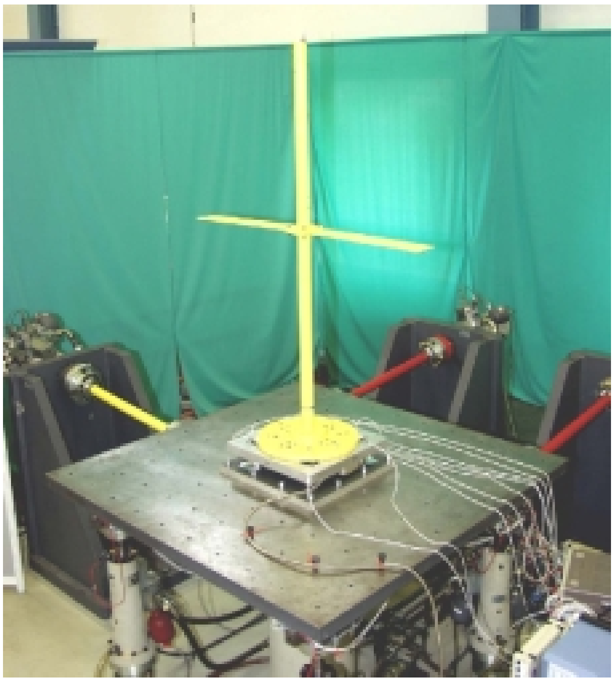

Figure 10: Test setup for Clumod with one blade

For Clumod with one blade, data of base excitation tests according to the test setup shown in Fig. 10 were evaluated.

The identification of inertia parameters for Clumod with one blade was performed by utilizing different frequency ranges and identification algorithm parameters. Like for the FMD a rather large variation can be observed with respect to the center of gravity.

The comparison with reference data according to [8] is presented in Table 2. The mass, and the moments of inertia θ_{xx} and θ_{yy} were identified with deviations smaller than *3 %* which is within the target range. The deviations for the center of gravity in y and z directions, and the mass moment of inertia θ_{zz}, however, clearly exceed the targeted limits, and no obvious reason for this could be found. Thus the identification was not fully successful.

Parameter	Identified	Reference	Deviation
Mass m	33.92 *kg*	32.95 *kg*	2.94 %
CoG x	0.39 *mm*	0.00 *mm*	0.39 *mm*
CoG y	-5.45 *mm*	0.00 *mm*	-5.45 *mm*
CoG z	283.61 *mm*	270.60 *mm*	13.01 *mm*
MoI Θ_{xx}	6.56 kgm^2	6.42 kgm^2	2.18 %
MoI Θ_{yy}	6.93 kgm^2	6.00 kgm^2	15.50 %
MoI Θ_{zz}	0.75 kgm^2	0.77 kgm^2	-2.60 %

Table 2: Comparison of inertia parameters of Clumod with one blade

For Clumod with four blades, test data of the base excitation measurements as described above were utilized. However, no meaningful inertia parameter identification results could be obtained. The reasons are the large elastic effects that are present in the test data.

6. SUMMARY AND CONCLUSIONS

In order to further investigate the capabilities of inertia parameter identification from base excitation test data, a study was conducted for ESTEC by ICS and DLR. This study aimed at further investigating the method and to make recommendations for future spacecraft tests. Furthermore improvements of the existing identification procedure and software were developed, and a verification with test data, obtained from base excitation testing on the six axes vibration table facility MAVIS of the DLR in Göttingen, was performed.

Since the identification algorithm proved to be reasonably stable during the pretest analyses it may be concluded that the observed lack of accuracy is again due to the quality of the test data although special care has been taken to obtain the data.

Thus for practical reasons the following conclusions may be drawn:

- an acceptable identification of the center of gravity location could not be achieved, and is not likely under the present testing capabilities
- an acceptable identification of mass and mass moments of inertia is possible, however, no reliable indicator to asses their quality is available

In order to improve the situation the following subjects should be investigated:

- thorough exploration of FMD accuracy (especially with respect to eventually unmeasured moments)
- higher redundancy of pilot accelerations to provide an improved basis for estimating the base accelerations
- base excitation patterns different from uniaxial excitation, or more than six base excitation patterns for a higher redundancy of the inertia parameters in the measured data

Only if the absolute accuracy of the measured accelerations and forces can be assured, a satisfactory identification of all ten inertia parameter becomes feasible. For the time being, a combined approach may be envisaged: the center of gravity can be identified with the help of classical methods while the moments of inertia can be extracted from base excitation test data utilizing the developed procedure.

REFERENCES

[1] C. Schedlinski and M. Link, “On the Identification of Rigid Body Properties of an Elastic System”, Proc. of the 15th International Modal Analysis Conference (IMAC), pp. 1588–1594, 1997.

[2] C. Schedlinski and M. Link, “A Survey of Current Inertia Parameter Identification Methods”, *Mechanical Systems and Signal Processing*, Vol. 15, No. 1, pp. 189–211, 2001.

[3] C. Schedlinski and M. Link, “On the Benefits of Utilizing Measured Interface Forces for Physical and Modal Parameter Identification”, Proceedings of the CEAS International Forum on Aeroelasticity and Structural Dynamics, Vol. 3, Rome, Italy, 1997.

[4] U. Füllekrug and M. Sinapius, “Force Measurement in Vibration Testing -Application to Modal Identification-”, *International Journal of Acoustics and Vibration*, Vol. 6, No. 2, pp. 51–56, 2001.

[5] U. Füllekrug, “Utilization of Multi-Axial Shaking Tables for the Modal Identification of Structures”, *Philosophical Transactions of the Royal Society*, Vol. 359, No. 1786, pp. 1753–1770, 2001.

[6] W. Teichert and C. Schedlinski, “Demonstration of Inertia Parameter Measurements using FMD and HYDRA”, Final Report, ATOS Netherlands, ATOS-NL-RP-014-01, ESTEC PO 173148, 2001.

[7] C. Schedlinski, “Study - Inertia Parameter Identification utilizing Base Excitation Test Data”, Final Report, ESTEC Contract No. 1681/02/NL/PA, ICS, 2003.

[8] U. Füllekrug, “Inertia Parameter Identification from Base Excitation Test Data -WP 1: Reference Data and Test Documentation-”, Internal Report, DLR-IB 232-2003 C 04, DLR Institute of Aeroelasticity, 2003.

[9] U. Füllekrug, “Inertia Parameter Identification from Base Excitation Test Data -WP 3: Test Data Evaluation-”, Internal Report, DLR-IB 232-2003 C 05, DLR Institute of Aeroelasticity, 2003.