NEW LARGE MASS PROPERTY MEASUREMENT FACILITY EXPERIENCE WITH THE FIRST THREE TEST SPECIMENS

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ABSTRACT

ESA/ESTEC has invested in a new mass property measurement facility, which was commissioned early 2006. This investment was justified from operational point of view by the following requirements

- allowing for complete moment of inertial and centre of gravity measurements for specimen mass up to 5000 kg
- improving the accuracy of the measurement results
- reduce the test duration for spacecraft mass property measurement campaigns

All three were considered equally important in relation to system level requirements for current and future 'standard' spacecraft.

Briefly the possible measurement principles are explained. The arguments for the selected design are recalled, and the general concept of the facility is presented. The selected measurement strategy is explained in detail. Benefits and limitations are summarised. The strategy for determination of measurement uncertainties are explained, and illustrated for the first three test specimens.

An outlook is given for further possible optimisation of test sequence and data evaluation.

1. INTRODUCTION

ESA/ESTEC has invested in a new mass property measurement facility, which was commissioned early 2006. Since then three measurement campaigns have taken place and two are following shortly.

This new M80/MPMA facility consists of a Moment of Inertia (MoI) machine which in standard configuration is used in combination with a Mass Property Measurement Adapter. This MPMA is an accurate positioning tool mounted on top of the M80 MoI machine. It is used to support and move the test object into pre-defined positions required to perform a sequence of MoI measurements. The obtained data are evaluated to determine CoG height, and the complete MoI tensor.

The new mass property measurement facility has several advantages compared to the existing facility:

- Specimens with larger mass can me measured.
- Since the handling effort is reduced a 3-axes measurement campaign duration can be reduced by 1-2 days.
- The accuracy of lateral MoI measurements is improved.
- The complete MoI tensor is measured.

A similar facility was earlier realised at Thales Alenia Space in Cannes. Their experts supported also the development of the ESTEC facility. Main suppliers of the facility were Schenck and APCO.

Mass property measurements are performed in three steps: Initially the mass and lateral CoG are measured. Afterwards on the M80/MPMA the vertical centre of gravity (CoG) is measured followed by moment of inertia measurements about typically 16 different axes through the CoG. The specimen positioning is automated. Tools for data evaluation are available.

Below typical requirements are recalled and most commonly used measurement principles listed before the details of the measurement process are described. Finally the results of the test campaigns are presented.

2. TEST OBJECTIVES

Mass property measurements are performed to

- demonstrate compliance to launcher requirements
- demonstrate compliance to AOCS requirements
- gain confidence in the S/C mass (or FEM) model

2.1. Launcher Requirements

Most launcher handbooks have only requirements for the position of lateral CoG, e.g. for

- Soyuz
  The spacecraft CoG offset (static imbalance) should not exceed 15 mm.
- ARIANE5
  The CoG of the spacecraft must stay within a distance d ≤ 30 mm from the launcher longitudinal axis (for S/C up to 4500 kg).

For both launchers there is no predefined requirement for spacecraft dynamic balancing. However, these data have a direct effect on spacecraft separation.

2.2. AOCS Requirements

AOCS requirements on knowledge of mass, CoG and MoI can vary depending on the mission. No general statement can be made.

2.3. ECSS Tolerance Recommendations

The ECSS Testing standard (ECSS-E-10-03A) recommends the following tolerances for the measurements on spacecraft level (chapter 5.3.4.4.2):

Mass ± 0.25%
Centre of gravity ±10 mm
Moment of inertia ±2.5 % relative to S/C CoG

2.4. Discussion of Requirements

In the following we will consider measurement tolerances with 95% probability and 90% confidence. Such a specification is essential to avoid comparing apples with pears.

Mass measurements can be done very accurately; in most cases 0.25% accuracy can be easily achieved. However large lightweight structures might require adapters to fit them on weight scale with suitable measurement accuracy since those are usually small.

Deviating from ECSS recommendations many projects ask for 1 to 5 mm accuracy of lateral CoG co-ordinate measurements. This will ensure that a statement of compliance to launcher requirements is not too much ‘polluted’ by measurement errors.

The moment of inertia tensor is usually filled with large diagonal terms and much smaller off-diagonal terms. On the new facility an accuracy of 2.5% with respect to diagonal values can be achieved for specimens from ±700 kg mass onwards. A lighter specimen like the SMOS PLM was measured with 5% accuracy.

3. BASIC PRINCIPLES

The general description of equations of motion of a rigid body can be found in many standard text books. These equations are the basis to identify a physical model fitting to the available measurement data. It is common practice to use a simplified model assuming that

- the rotational velocities are small
- quadratic terms of rotational velocities are negligible

As a consequence we obtain an almost linear model with ten parameters: the mass, three centre of gravity co-ordinates and six moment of inertia components. It is only almost linear since it contains the product of mass and CoG co-ordinates.

Theoretically it is possible to identify all 10 unknowns simultaneously. However, it requires one complete data set in which all parameters are observable.

It is known that measurement errors decrease if the number of simultaneously identified parameters can be reduced. This is advisable since the equations can be easily decoupled. Mass and the location of the centre of gravity (i.e. 4 unknowns) of the test specimen can be identified using the static equilibrium equations of force and torque.

3.1. Mass and CoG Measurements

Most methods start with mass determination by weighing followed by a static CoG measurement method, typically interface force measurement, suspension or balancing.

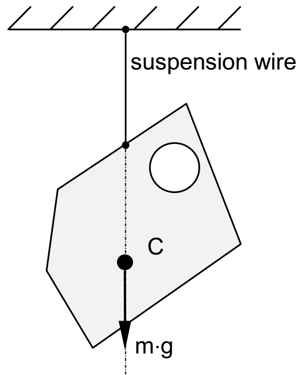

FIG 1. Principle of suspension method

Static force measurement requires subtraction of two measurements of equally amplitude. Therefore a better accuracy is achieved for the static balancing method since only the residual overturning moment is measured directly. One measurement per CoG component is required.

Static balancing is the method used at ESTEC since long and it remains the preferred method for the lateral CoG measurements even if the MPMA facility is used.

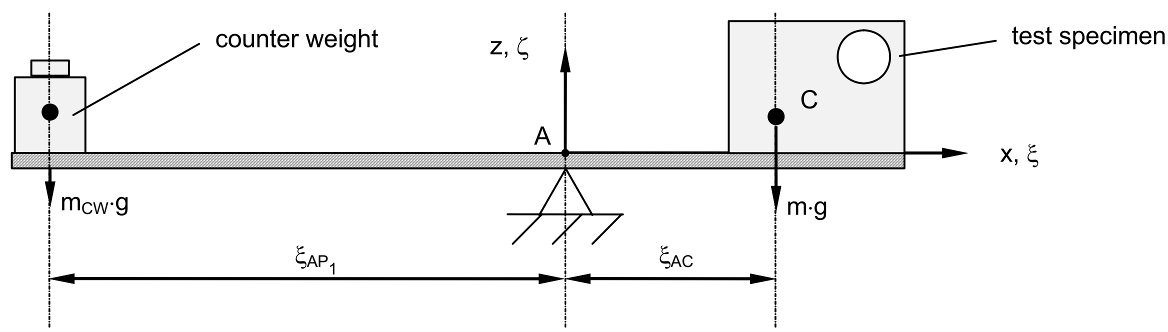

FIG 2. Principle of static balancing method

3.2. MoI Measurements

Measurements of moments of inertia require rotational accelerations. Therefore the dynamic equations of motion have to be used, but usually in its linearised form. Assuming small rotational velocities imply test limitations, which have to be respected during measurements.

In principle dynamic methods are capable of identifying all ten inertia parameters simultaneously. Nevertheless in almost all cases prior knowledge of mass and CoG values is taken into account.

There are mainly two measurement principles, either with or without interface force and torque measurements. The latter are based on measurements of pendulum frequencies. The restoring torque can be generated by the gravitation in case of wire suspension or by a torsion spring with known stiffness. At least six tests with different rotation axes are needed in order to identify all six inertia parameters. Hereby it is required that the rotation axes intersect in one single point.

It should be noted that on the old ESTEC MoI facility only four independent tests were performed, i.e. the products of inertia between lateral and vertical axis were usually not identified. The new facility allows easily performing more than six tests with different rotation axes. The intersection point is chosen to be close to the specimen CoG. Nevertheless the measurement principle is not changed compared to the other facilities. But specimen positioning and data evaluation is automated.

3.3. Modified vertical CoG measurement

The old ETSEC mass property measurement facility is equipped with an L-shape adapter to determine the vertical spacecraft CoG. It requires horizontal mounting of the test specimen and has a mass limit of about 3000 kg.

The new facility derives the CoG not by static balancing but indirectly from MoI measurements about different parallel axes. The specimen is moved to typically 20 positions along the MPMA. Each MoI measurement is the sum of the MoI about the specimen CoG and the parallel axis (or Steiner) term. Drawing the MoI value over the position co-ordinate results in a parabola, see FIG 3 and FIG 4. The minimum determines the axis closest to the specimen CoG.

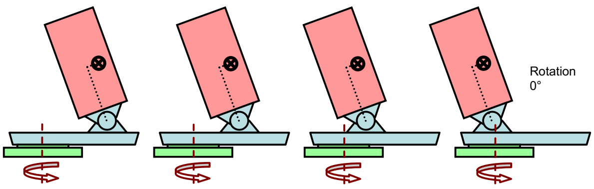

FIG 3. Translation of specimen wrt. rotation axis

For the vertical CoG measurement the specimen is tilted and the projection of the CoG co-ordinate is been measured. A correction for known lateral CoG offsets can be done analytically or by rotation of the specimen by 180 degree about the vertical axis and repetition of the measurement. The lateral CoG offset is eliminated if the average of the minima of the 0˚ and 180˚ parabola is taken.

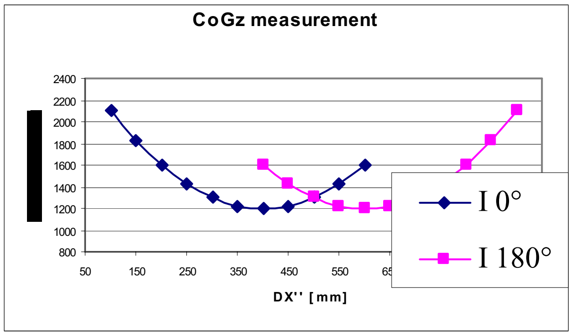

FIG 4. Parabolas for MoI values

Note that no specimen handling or L-shape adapter is required. The specimen positioning is automatically performed by a PLC.

4. ACHIEVABLE MEASUREMENT ACCURACY

The measurement accuracy is always a combination of an achievable accuracy of the facility and the scatter of repeated measurements. In many cases the error contribution due to machine accuracy is equal or larger than the measurement scatter. Machine error contributions are caused e.g. by accuracy of measurement devices, positioning error, or sensitivity to environmental parameters.

4.1. MoI measurement accuracy

The primary measurement results of the M80/MPMA facility are moments of inertia about the machine axis. The supplier quotes a MoI measurement accuracy of better than 0.1%. This value has been confirmed during the acceptance tests. Since the inertia of the MPMA adapter is 8000 kgm^2, the minimum error is therefore less than 8 kgm^2. The smallest specimen tested so far on the facility was the SMOS PLM with 350 kg mass and about 170 kgm^2 inertia about the CoG. The customer required less than 5% MoI error. This target was achieved. The scatter of repeated measurements was less than 3%.

For specimen MoI from 320 kgm^2 onwards (± 700 kg mass) the measurement accuracy will be better than the 2.5% recommended by ECSS.

4.2. CoG measurement accuracy

The lateral CoG measurements are still performed on the Schenk WM50/6 facility. The expected CoG error is 0.3 mm with a minimum of 0.1 kgm for specimens with a mass < 333 kg. The possible error in specimen positioning has to be added.

The vertical CoG value is derived form the MoI measurements. The accuracy is influenced by the positioning accuracy of the MPMA, the measurement accuracy of the position, the MoI measurement accuracy and the accuracy of the curve fit. Since the latter is only known after completion of the measurements only a global indication of the accuracy can be given. For a typical specimen of 2000 kg an error in the order of 2-3 mm is expected. For SMOS PLM PFM (350 kg) an error of ±3.1 mm was obtained.

5. TEST CAMPAIGNS PERFORMED SO FAR

5.1. Acceptance test with LSS dummy

The first test campaign was performed to qualify the M80/MPMA facility. The test specimen was the LSS spoke wheel, a dummy used for load and performance tests on our facilities. In the used configuration it has a mass of 3063 kg, lateral CoG offset of 1-2 mm and a vertical CoG coordinate of 1750 mm. The MoI terms are in the order of 3000-4000 kgm^2.

The test objectives were

- To measure vertical CoG coordinate and MoI values of the test specimen
- To perform a general verification of the facility and operation procedures
- To define relevant parameters for real test campaigns
- To confirm the achievable accuracy of the facility

Because of the last objective the specimen was initially measured on the existing WM50/6 facility. The achievable accuracy of this facility is quoted to be ±0.5 mm for the vertical CoG and ± 1% for the MoI with a minimum error of 50 kgm^2. (To recall: the uncertainty of the MPMA MoI measurement is ±0.1% with a minimum error of 8 kgm^2).

The picture below shows the LSS dummy on the L-shape for vertical CoG and lateral MoI measurements.

FIG 5. LSS Dummy on L-shape of ‘old’ WM50/6 facility

After the complete test campaign it had to be concluded that the vertical CoG uncertainty of the WM50/6 facility might be larger than the assumed one. For heavy specimen the expected error is rather better than ±2 mm.

The same specimen was mounted on the new M80/MPMA facility. The picture below shows the specimen in one of the about 40 measurement positions. In order to qualify the CoG estimation procedure the measurements have been repeated for 20, 30 and 40 deg inclination angle and once more with the specimen rotated by 90 deg.

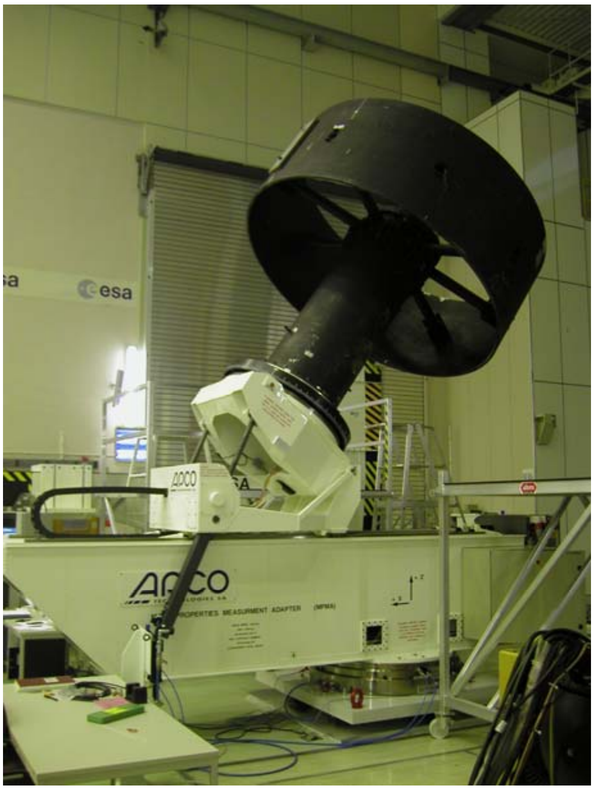

FIG 6. LSS dummy on M80/MPMA facility

In the figure below the 4 measurement results are compared to the value obtained with the WM50/6 facility including uncertainty intervals. The scatter of the values is less than 2 mm, i.e. <0.1 % of the measured value.

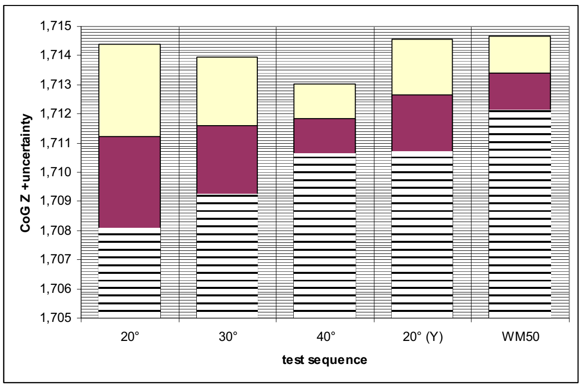

FIG 7. CoG measurement result comparison

The uncertainty interval on the new facility is an evaluation of measurement scatter of repeated measurement. Further 0.25 mm uncertainty was added for the systematic errors of the facility. This is the only measurement were we have 1 order of magnitude higher errors of measurement scatter compared to systematic errors. The implication is that the CoG measurement uncertainty can only be confirmed after test performance and evaluation of measurement scatter.

The main contribution to the size of the uncertainty interval is caused by the movement of the air. During real testing it is therefore ensured that the air conditioning in the whole area is switched off, the number of people inside the clean room is limited to 2 or 3 and opening doors is strictly forbidden during measurements. The scatter of the obtained measurements is on-line monitored and unsatisfactory measurements are repeated.

The MoI comparison between the old and new facility showed differences in the order of 1 to 14 kgm^2. This is below the minimum measurement error, thus it is a proof that both facilities measure the same values.

5.2. VEGA PLMEC test campaign

The first real test specimen was the VEGA PLMEC build by CASA and delivered to ELV as payload for the first VEGA launch. The picture below shows it directly after mounting on the facility and removal of the hoisting equipment.

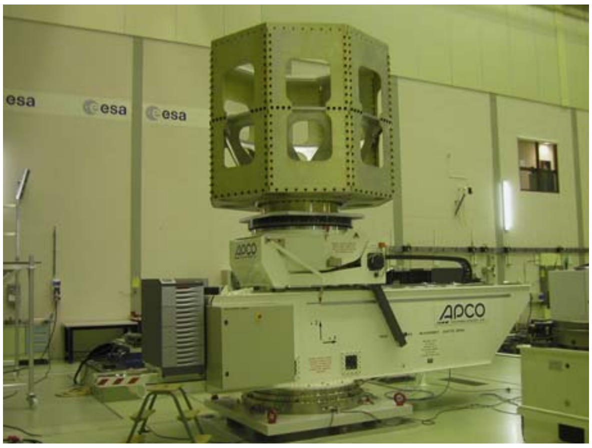

FIG 8. VEGA PLMEC in mounting position

Because of the very high accuracy of the MoI measurement it is essential that all non structural parts (e.g. cable harnesses) are well attached to the specimen. Supporting e.g. accelerometer or thermocouple cables externally on a tripod next to the specimen is not possible anymore. It would make the vertical CoG measurement too inaccurate.

The specimen mass was 1060.74 ± 0.22kg.

The following results are obtained for the CoG:

Lateral CoG (WM50/6)	-0.75 ± 1 mm
	-0.01 ± 1 mm
Vertical CoG (M80/MPMA)	+1306.9 ± 8 mm

The following results are obtained for the MoI:

MoI vertical W50/M6	887.02 ± 0.23 kgm^2
MoI vertical M80/MPMA	887.06 ± 8 kgm^2
MoI horizontal M80/MPMA	1003.55 ± 8 kgm^2
	1002.82 ± 8 kgm^2

The vertical MoI was obtained twice. Since the specimen was already mounted on the WM50/6 for lateral CoG measurements it was a minor effort to perform also this measurement.

The MPMA scatter of the measurements indicated an error of 1-2 kgm^2 and 0.1 kgm^2 for the WM50/6

The difference in vertical MoI result for MPMA and WM50/6 (0.04 kgm^2) indicates that the systematic error of the facility is rather exaggerated. It is based on the supplier information. However, in the clean room at ESTEC many parameters (temperature, pressurised air, …) are tightly controlled, thus the measurement environment is therefore much better than average.

Nevertheless, even with the given uncertainty the required measurement tolerance was achieved. The vertical CoG accuracy is not excellent (but sufficient). Measures were defined to improve it for future campaigns by tighter control of the individual measurement and pressure fluctuations inside the clean room.

5.3. SMOS PLM PFM test campaign

SMOS PLM PFM was a test specimen of only 350 kg. Nevertheless it was decided to perform the mass property measurements on the new facility because

- The test duration is shorter
- Less handling is required

The facility is specified for specimens heavier than 700 kg. For the planned measurements a specific evaluation was performed taking into account mass, centre of gravity and inertia properties of the SMOS PLM PFM specimen. The results show that the accuracy required in the SMOS PFM MPM procedure could be met.

The specimen mass was 364.84 ± 0.1kg.

The following results are obtained for the CoG:

Lateral CoG (WM50/6)	-9 ± 1 mm
	-7.1 ± 1 mm
Vertical CoG (M80/MPMA)	+684.2 ± 3.1 mm

The following results are obtained for the MoI:

MoI vertical W50/M6	193.58 ± 3 kgm^2
MoI vertical M80/MPMA	193.53 ± 8 kgm^2
MoI horizontal M80/MPMA	168.91 ± 8 kgm^2
	157.49 ± 8 kgm^2

The MPMA scatter of the measurements indicated an error of 4.5 kgm^2 and 3 kgm^2 for the WM50/6. Also here almost the same value is obtained for the vertical MoI giving good confidence in the procedures in place for averaging the measurements.

The customer specifications were met, although without margin for the 5% accuracy requirement for the MoI values.

6. CONCLUSION

All the described test campaigns were executed without major problems. The expected facility performance in terms of measurement accuracy and operation aspects is achieved.

After the next two test campaigns it is intended to perform a review of all the measurements taken in view of a possible further reduction of test duration and the design of test sequence for result error minimisation.

The experience shows that a 3-axis test campaign duration can be reduced from 4 or 5 days to 3 days. The test requires less customer personnel since the specimen handling effort is reduced. From operation point of view the facility usage is straight forward and data evaluation is properly realised.

7. ACKNOWLEDGEMENT

The principle of the facility was first realised by Thales Alenia Space in Cannes. The development and implementation at ESTEC was managed by Gaetan Piret. Thomas Flucke supported the creation of data evaluation tools during his internship at ETS.