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Progress in the realization of the INRIM centrifugal balance for mass measurements in space

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Abstract—**The paper describes the features of the centrifugal balance developed at INRIM, which is a suitable weighing instrument for accurate mass determination of small object in weightless conditions. A new measurement model is proposed, which allows to measure any kinds of objects, solid and not with an accuracy comparable to a classic laboratory balance.**

Keywords—mass measurement; weightless conditions; centrifugal balance.

I. INTRODUCTION

In view of a possible realization of a balance to be used on board of the International Space Station (ISS), INRIM has been involved in a project for the development of a suitable balance working in weightless conditions. Measurement of mass in weightless conditions cannot be made through the classic gravitational balances used on Earth. A different approach is then required, by taking advantage of the inertial properties of the mass.

Some methods, for mass measurement under microgravity conditions have been proposed such as the use of the characteristic frequency of vibration [1-3], with an accuracy generally not better than $1 \cdot 10^{-3}$. A different inertial method, based on the measurement of centrifugal forces was first experimented at INRIM (formerly IMGC-CNR)[4].

The latest balance prototype was realized in 2005. This balance was suitable to measure small solid object (full scale value of 150 g), it was the only balance designed to measure the mass of objects in weightless conditions to an extended uncertainty better than $3 \cdot 10^{-5}$.

Recently, the control system and the equations model have been improved in such a way that the balance is able to measure with small uncertainties different kinds of objects (solids, liquids, powders, gel, organic tissues).

In this paper the centrifugal method as well as the design and the features of the balance are briefly described, and the new calibration method is shown.

II. THE CENTRIFUGAL METHOD

The centrifugal force F_c acting on the object rotating round an axis is given by
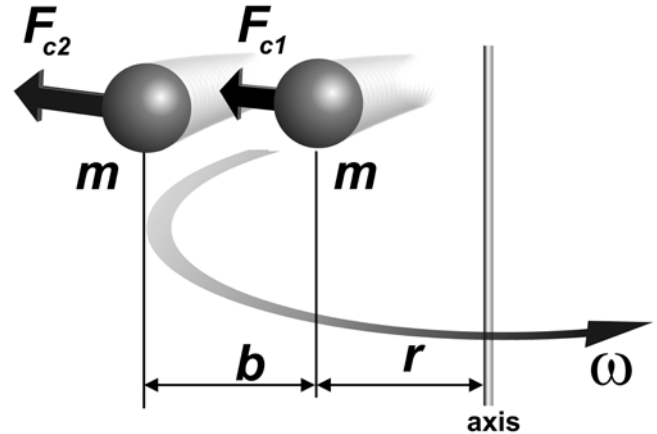

Figure 1: The centrifugal method

$$F_c = m \cdot r \cdot \omega^2 \qquad (1)$$

where m is the mass of the object, r is the distance of its centre of gravity from the rotation axis , and ω is the angular speed around it.

The mass m of the object can be obtained, provided that the other quantities in (1) are known. The problem concerns the evaluation of r. Only in the case of a homogeneous and geometrically regular body, the position of its centre of gravity and in turn its distance r from the rotation axis, can be estimated with good accuracy.

This problem can be solved considering two measurements with the object radially displaced at two different radial positions, where the displacement b between the two positions is well known (see Fig. 1).

In this way

$$F_{c1} = m \cdot r \cdot \omega_1^2 \qquad (2)$$

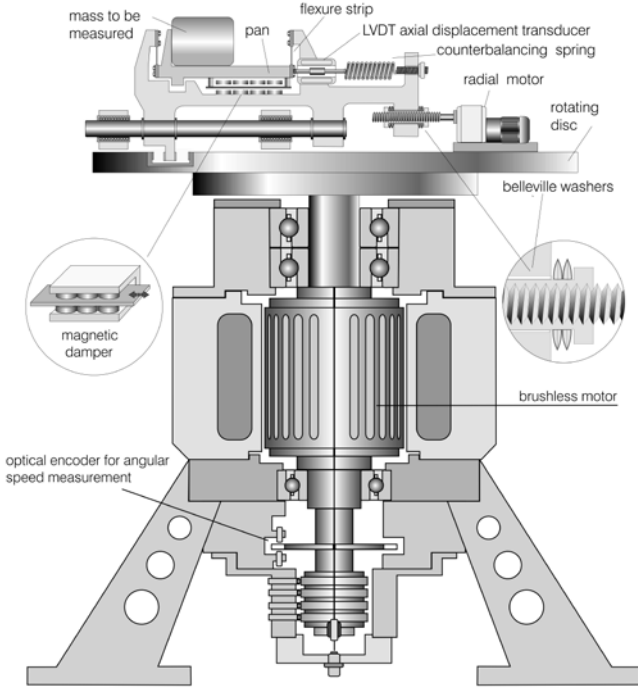$$F_{c2} = m \cdot (r + b) \cdot \omega_2^2 \ . \qquad (3)$$

Figure 2: Scheme of the BIC1 and BIC2 balances

The mass m of the object can be easily obtained

$$m = \frac{1}{b}\left(\frac{F_{c2}}{\omega_2^2} - \frac{F_{c1}}{\omega_1^2}\right) \quad (4)$$

and it no longer depend on the value of r, but only on the radial displacement b.

In principle two different operational modes can be applied if one of the two quantities, F_c or ω, is held constant in both measurements:

- *constant-force* F_c

$$m = \frac{F_c}{b}\cdot\left(\frac{1}{\omega_2^2} - \frac{1}{\omega_1^2}\right) \quad (5)$$

- *constant-speed* ω

$$m = \frac{F_{c2} - F_{c1}}{b\omega^2} \quad (6)$$

It must be pointed out that the centrifugal method can be applied to any kind of object, provided that the value r would not change between the two measurements taken at different radial positions. With the *constant-speed* configuration, the force acting on the object under measurement increases while it moves toward the external radial position, therefore this method is appropriate only for rigid objects. On the contrary with the *constant-force* configuration, where the rotational speed is automatically adjusted to maintain the field of the centrifugal forces acting on the object constant in both radial positions, even non-rigid objects can be measured.

III. THE PREVIOUS PROTOTYPES BIC1 AND BIC2

Two previous prototypes (BIC 1 and BIC 2), were both based on the centrifugal method with the *constant-force* configuration, In Fig. 2 the scheme of the two prototypes is shown. On board of a rotating disc, a pan with the object to be weighed can move radially between two positions; in addition the pan is subjected to a force exerted by a spring. During the rotation the centrifugal force is balanced by the centripetal force generated by the spring. A sensor monitors the position of the radial pan: it allows the main motor to rotate the disc at the equilibrium speed ω_1, that is, when the radial pan reaches its rest position. The whole platform is then radially moved toward its outer position at the known distance b, then the control reduces the rotating speed to ω_2 to get the same equilibrium between centripetal and centrifugal force. The value of the gross mass (object and radial pan) can be easily derived from (5) since F_c and b are known values, characteristic of the balance. The net mass of the object is finally obtained by subtracting the mass of the radial pan, determined once and for all.

BIC 1 was a prototype realized to demonstrate the feasibility of the centrifugal method: its relative uncertainty was about 10^{-2}, that is 2-3 g with a 250 g of full scale.

The construction of the prototype named BIC 2 began at IMGC-CNR, supported by the Italian Space Agency (ASI), in view of a possible use on board the International Space Station. This prototype was designed to fulfil the requirements typical of a space applications (weight, dimensions, materials, electric parameters, reliability, safety), and to improve the performance. Final tests on the ground-model showed an uncertainty of 100 mg with a full-scale of 500 g, that is $2\cdot10^{-4}$ in relative terms.
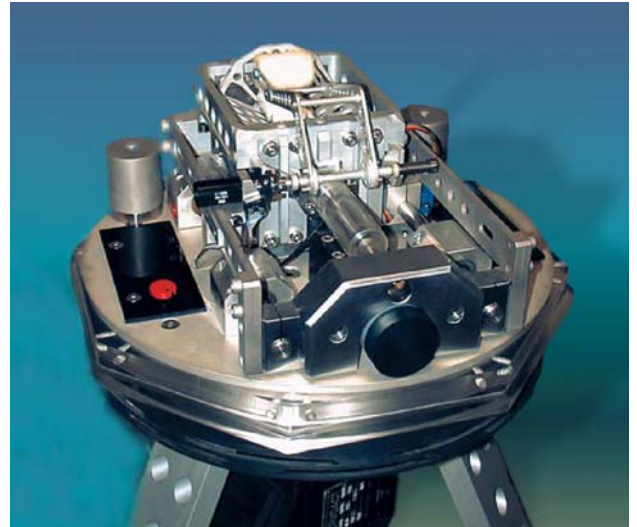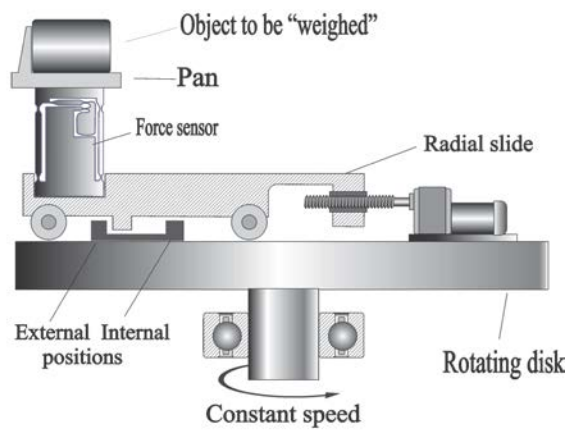

Figure 3: The BIC2 balance
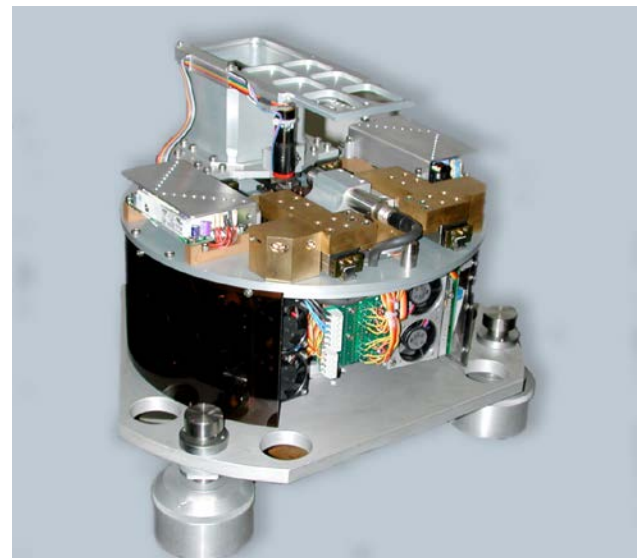
Figure 4: Scheme of the balance BIC3

Figure 5: Picture of the centrifugal balance BIC 3.

The BIC 2 was essentially similar to BIC 1, but with a thermal control of the spring (used as the reference force), and to the electronics on board the rotating disc. To obtain better results, a different approach had to be adopted and the BIC 3 was realized.

IV. THE BALANCE PROTOTYPE BIC3

BIC 3 is the 3rd prototype of the inertial centrifugal balance realized at INRIM, which was completed in 2005 [5].

BIC 3 was developed to fulfil the requirements suggested by some of the potential users of the ISS, interested to an instrument able to monitor the growing of biological specimens during experiments on board the ISS. A scheme and a picture of BIC 3 are shown in Fig. 3 and Fig. 4 respectively. The main improvement was the measurement of the centrifugal force by a beam derived from a commercial electronic balance having capacity 200 g and resolution of 0.1 mg. Contrary to the classic application, in this particular configuration the beam is placed vertically instead of horizontally in order to measure radial horizontal forces. To increase to a maximum the load of the inertial balance, the beam and the pan assembly, when unloaded, has been balanced as possible, making it almost insensitive to the centrifugal field.

The pan was designed and its mass adjusted to achieve an almost perfect balancing of the group which, unloaded, generates very limited residual centrifugal forces, of the order of a few mN.

The rotating disc contains the whole structure of the inertial balance which is driven by a stepping motor, the speed ω is determined with a relative uncertainty of $1 \cdot 10^{-6}$. It is electrically connected to the outside through slirings, which are used to supply the electronics and connect via RS232 the onboard microprocessor to the external computer.

The measurement group (beam, pan and object) is radially displaced by a d.c. motor, the positions are determined by two stops realized by a low thermal-coefficient material (Invar®). The same system is used to radially move in the opposite direction a counter-balancing mass.

In addition the radial displacement b of the beam of 22 mm is measured by a laser-diode Michelson interferometer having an accuracy of 0.1 μm.

In order to avoid the impact of the air against the beam, the radial pan and the object under measurement are housed inside an aluminium enclosure, a lid can be opened when the balance is at rest, for loading/unloading the objects to be weighed.

As the electromagnetic compensation system of the beam requires a centrifugal field stable in direction and value, as is the gravitational field, otherwise it does not provide a valid measurement, the rotation speed must be constant within a few parts in 10^6. This performance was obtained by the direct coupling of the rotating disc to the motor shaft.

For a correct operation on Earth surface, a requirement, no longer required while operating in space, is the perfect verticality of the axis, this is to avoid force measurements variable with the same frequency of the rotation.

The main features of the balance are:

- diameter 300 mm
- height 250 mm
- weight 10 kg
- speed from 50 to 100 rpm
- centrifugal acceleration about 1 g or less
- measurement time less than 1 min

- capacity 150 g
- weighing chamber has a diameter of 3 cm and 4 cm height

Initially the BIC 3 was tested by using the *constant-speed* configuration, hence was able to measure only rigid objects. Only recently, the measurement method has been improved in such a way to maintain constant the centrifugal force during the radial displacement of the pan toward the external radial position. As discussed in section II, with *constant-force* configuration also compressible objects can be weighted.

V. THE CALIBRATION METHOD

In a traditional balance the reading m_w is given in term of mass, actually the reading is proportional (in principle is linear) to a force F which is converted in terms of mass m, on the contrary, on the use of the centrifugal balance we are interested to the force which can be determined from the reading m_w

$$F_c = f(m_w) \qquad (7)$$

The calibration curve can be estimate by the calibration of the centrifugal balance with mass reference standards.

The adopted method consists to fit the differences of the readings of the balance corresponding to F_{c1} and F_{c2}, obtained at constant speed with different values of loads. As an example the results at 66.6 rpm are given in Fig. 6 and Fig.7, typically the maximum residual is less than 0.2 mg. From the results, the response of the balance can be assumed linear, and from the slope of the fit, obtained at different speeds, which is proportional to $b\omega^2$, the proportional coefficient can be determined, so that $F_c = C\,m_w$.

As at the Earth surface the object is subjected to a vertical gravitational force the load on the beam balance produces no linear effects. In addition, the pan when unload is also sensitive to the centrifugal force.

In previous model, suitable for the *constant-speed* configuration, the mass measurements obtained by Equ. 6 were corrected by using a second order polynomial equation [5]. This approach was not satisfactory for the use both at *constant-speed* and *constant-force,* hence a new equation model has been implemented.

Taking into account the no-linear effects, the assumed models for the two centrifugal forces are

$$F_{c1} = \left[m_0 + m(1+\alpha)\right] r\omega_1^2 + \vartheta \qquad (8)$$

$$F_{c2} = \left[m_0 + m(1+\alpha)\right](r + b)\omega_2^2 + \vartheta \qquad (9)$$

where, m_0, α and ϑ, in addition to C, are parameters to be estimated by the calibration procedure.

From (8) and (9)

$$m = \frac{1}{1+\alpha}\left(\frac{F_{c2} - F_{c1}}{\omega^2 b} - m_0\right) \qquad (10)$$

for the *constant-speed* configuration, and

$$m = \frac{1}{1+\alpha}\left[\frac{F_c - \vartheta}{b}\left(\frac{1}{\omega_2^2} - \frac{1}{\omega_1^2}\right) - m_0\right] \qquad (11)$$

for the *constant-force* configuration.

In order to obtain the parameters m_0, α, θ and C, the balance was tested by using mass standard in the range from 10 g to 150 g, at different angular speeds, as an example in Fig. 8 the results at 50 g are shown.
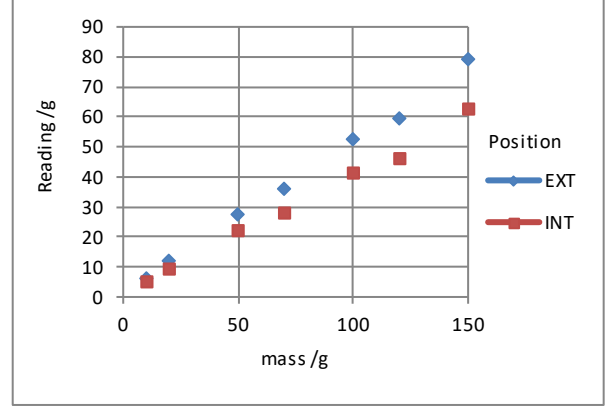

Figure 6. Results at a constant speed of 66.6 rpm (internal force F_{c1}, external force F_{c2}).
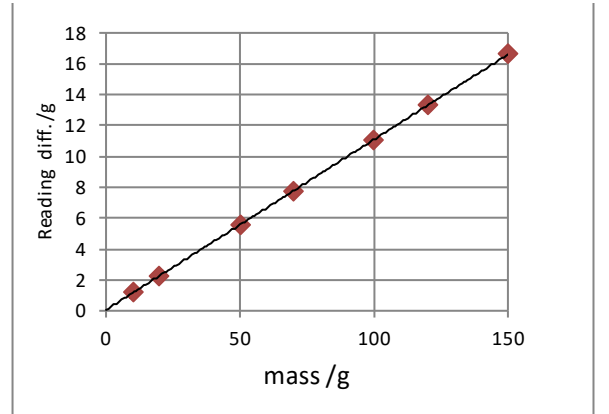

Figure 7. Fitting of the reading difference at a constant speed of 66.6 rpm, maximun residual is 0.15 mg
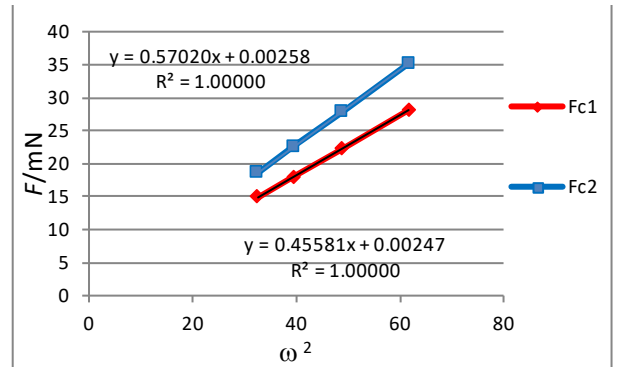

Figure 8. Fitting of the measurements at 50 g at different angular speeds.

Parameter	Value
C	9.7358 m s^{-2}
m_0	0.5140 g
α	1.30×10^{-4}
θ	0.022 mN

Table 1. Parameters estimated

	Mass/g	F const.	ω const.	Δm./g
Water	21.888	21.887	22.004	0.117
Sugar	19.613	19.613	19.617	0.004
Gel	18.672	18.673	18.677	0.004

Table 2. Measurements with no solid substances

The parameters m_0, α and θ and C were determined by the least square method, they are given in Table 1.

These parameters have been validated using the balance with the two configurations, *constant-force* (Equ.10) and *constant-speed* (Equ. 11) in the range from 10 g to 150 g.

Fig. 9 shows the residuals for both configurations, the maximum residual is within 3 mg.

The mass uncertainty has been evaluated considering the following contributions

- reading repeatability $u(m_w)$=0.4 mg

- no linearity =1.6 mg

- radial displacement $u(b)$= 0.3 μm

- angular speed $u(\omega)/\omega$=1×10^{-6}

The evaluated expanded uncertainty is $U(m)$= 5 mg.

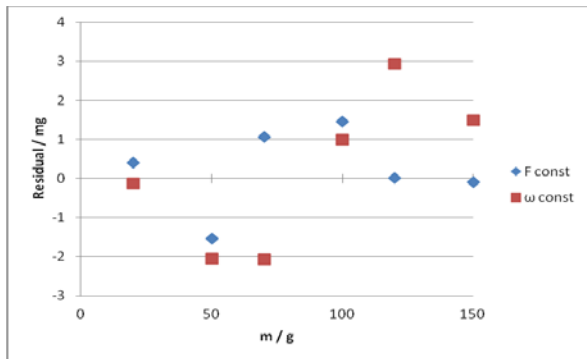In practice at constant force we are interested to the difference of speeds and at constant speed we are interested in the difference of force. As the difference of speed is more accurate than the difference of force, the results at constant force are usually more accurate.

This new model has been validated with no solid substances contained in (not full) vial glass, as water, gels and sugar, of about 20 g, some results are shown in Table 2.

With the constant force configuration the results are very accurate and as expected there are problems at constant speed. With water the results obtained with the constant speed method are not consistent. With sugar and gel the difference is less evident.

VI. CONCLUSIONS

The centrifugal balance realized at the INRIM is an instrument able to weigh small object in weightless conditions.

With respect to the previous methods, a new model has been developed in order to use the balance with the two configurations: constant force and constant speed. This last one allows to measure no solid substances, this was not possible for the previous models. The uncertainty for both configurations is 3×10^{-5} on the whole range of 150 g.

In space the performances would be better, because on the ground the vertical gravitational field makes measurements more severe than in space.

On the base of this prototype a development of a flying model would be easily possible.

Figure 9. Residuals obtained with the BIC 3 calibration at *constant-force* and *constant - speed* configuration.

REFERENCES

[1] W. E. Thornton, J. Ord, NASA Tech. Report N74-11867, chp.8, 1974.

[2] T. Ono, H. Uozumi, O. Honda and K. Nagata, Measurement, 22, 87-95, 1997 .

[3] Y. Fujii el al., Rev Sci Instrum. 79 (5) 056, 2008

[4] A. Rivetti et al., IMGC Internal Report P209, 1994.

[5] A. Rivetti, G. Martini, F. Alasia, G. La Piana, L. Gatti, Microgravity Science and Technology 20 (1), pp 7-15, 2008.