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Beam Horizontality Determination in the LNE Kibble Balance Experiment

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Summary:

Determination of a mass in the LNE Kibble balance experiment requires, among other things, a precise control and knowledge of position and spatial orientation of its major comparator force element : the beam. This paper presents, with simple geometric assumptions, our automated method to determine, in vacuum, and without any additional device, the ideal beam setpoint position to use during weighing phase

Keywords: beam, Kibble balance, precision measurements, uncertainty.

Introduction

The Kibble balance principle consists of the comparison between virtual electromagnetic and mechanical powers measured during interlaced static and dynamic phases [1], [2].

One requirement for reducing unwanted force during weighing (or static) phase is to balance the beam as close to its horizontal position in order to not be sensitive to horizontal parasitic forces. Indeed, the aim of the static phase is to measure a vertical force F_z without bias. However, if a parasitic force F_x (horizontal and parallel to the longitudinal axis of the beam) is exerted at the end of the beam, with a beam separated from the horizontal by an angle α, a relative biais ε_{F_z} on F_z appears [3]:

$$\varepsilon_{F_z} = \alpha \frac{F_x}{F_z} \quad (1)$$

The LNE Kibble balance beam is a single-piece symmetrical 100 mm length arms with three double flexure pivots [4], [5] . Under charge, these three centers of rotation are aligned by design and therefore define the segment which is supposed to be aligned with the horizontal during a static phase. The challenge remains to be able to match this segment with the horizontal line in order to maintain ε_{F_z} on the order of 10 ppb.

Experimental conditions

During weighing phase, the weight of a standard mass m subject to a gravitational acceleration g is balanced by the Laplace force F_z exerted on a coil, immersed in a magnetic induction field B, in which flows a current I. The servo control error signal is provided by the vertical position of the beam end, relatively to a fixe point, measured by a compact commercial interferometer.

At any time the vertical position of the coil is measured by three interferometers relatively to three points materialized by the apex of three corner cube reflectors equally distributed on the perimeter of its circular support.

In a same way three position sensors based on vertical propagating Gaussian beams intercepted by screens located at the periphery of the coil support are used to measure the coil displacement in the horizontal plane (x and y).

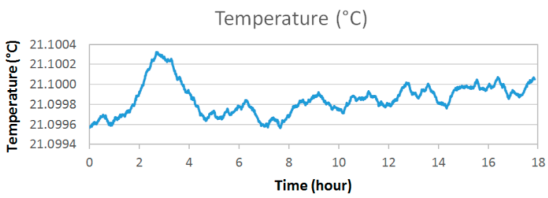

Fig. 1. Temperature of the magnetic circuit during the experiments

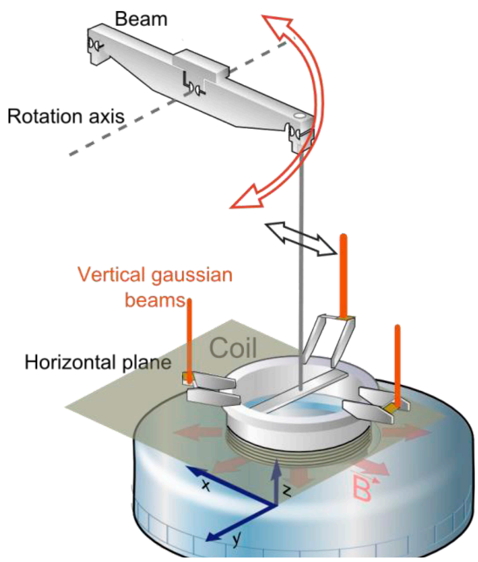

Fig. 2. Schematic view of the experimental set up. From top to bottom: balance beam, coil suspension, coil immersed in the magnetic circuit.

The most stable environmental conditions are required: the whole balance must have reached, in vacuum, a thermal equilibrium, in particular the magnetic circuit.

Fours heating resistors driven by a regulation system maintain the temperature of magnetic circuit at a fraction of millikelvins (Fig. 1).

Hypothesis and principle

The method consists in monitoring and relating the coil displacement with the beam position during a weighing phase when a low frequency (~5.10^{-5} Hz) sinusoidal setpoint is applied to the beam position (Fig. 1). If the coil is hanging vertically and its sensor Gaussian beams are vertical, then the coil position in the horizontal plane (xOy), reach an extremum when the beam crosses its horizontal position. During the process the beam end path travel is an arc of circle whose vertical projection is the coil trajectory. Even if the rotation beam axis is itself tilted with respect to the horizontal, the trajectory of the coil continues to present a turnaround point when the horizontality of the beam is crossed.

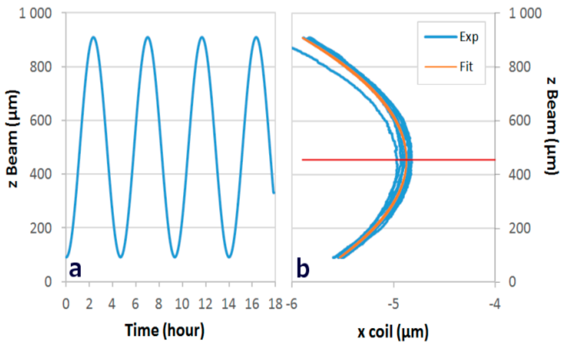

Fig. 3. a) Low frequency sinusoidal movement of the beam, b) Vertical beam displacement according to horizontal coil displacement during a horizontality beam determination. The red horizontal line shows the horizontal position of the beam end.

Improvements

In usual weighing mode, beam displacement imply also a vertical displacement of the coil immersed in the magnetic circuit, therefore, a non-uniform vertical magnetic field in the explored range, could add a bias in our measurements. To avoid this issue, the LNE kibble balance design allows to maintain constant the vertical position of the coil, despite the beam oscillation, since the balance beam plus its suspension can be moved as a single element [2], by activating the translation stage used in dynamic phase.

Measurements

The beam can be balanced between two mechanical stops spaced 1 mm apart, the lower one being our position reference (0 µm). A current is injected and adjusted in the coil in order to slowly oscillate the beam with an 0.8 mm amplitude at the end.

The vertical motor of the translation stage is commanded to move in an opposite way to always nullify the vertical coil motion.

Simultaneously, the three Gaussian beam signals are acquired with an integration time of 10 s and converted to *x* and *y* positions.

Results

Fig.3 shows in its left part, the evolution of the vertical imposed displacement of the beam end versus time; in the right part the blue line represents the corresponding measured horizontal excursion of the coil. As expected, the coil reaches repeatedly (8 times) an extremum. The coil trajectory can be locally and fit to a parabola (orange line) and finally the horizontal beam position can be extracted (red line), in this case at 455 µm. Repeated measurements show dispersion less than 10 µm. Estimation of the uncertainty associated is still under investigations.

Conclusion

The beam is used in the weighing phase as a force comparator. It must be aligned with the horizontal to reduce the contributions of some parasitic forces to negligible levels. The technique used to carry out this alignment is a non-perturbative method which allows an automated determination of the beam horizontally position, in a mass determination conditions i.e. in vacuum, and with no additional devices.

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