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ADDRESSING MECHANICAL DESIGN AND CONSTRUCTION ISSUES FOR A TWO PAN KNIFE-EDGE KIBBLE BALANCE

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Abstract: New concepts for the operation of the Kibble (watt) balance using common moving and weighing modes have recently been proposed. In order to fully evaluate the advantages and issues arising from such a configuration NPL is constructing a technology demonstrator based on a 5 kg mechanical two-pan knife-edge balance. This paper describes the design and manufacture of the mechanical components for this balance and highlights the issues that need to be addressed for the successful implementation of such an apparatus at the 1 ppm uncertainty level.

Keywords: Kibble balance, mass, kilogram, redefinition, mechanical design.

1. INTRODUCTION

The International System of units (SI) will be revised in 2018 to link the base SI units to fundamental constants of nature [1]. As part of this restructuring, the SI unit of mass, the kilogram, will be redefined in terms of the Planck constant (*h*). This presents the opportunity for mass to be realised not only by a number of individual National Measurement Institutes (NMIs) but also over a range of nominal values.

Existing Kibble balances are expensive and time consuming to construct and operate partly due to the precise alignments of the current carrying coil in a highly stable magnetic field [2]. This partially results from the requirement to perform the 'weighing' and 'moving' phases separately in a conventional Kibble balance. Kibble and Robinson [3] showed that, under certain conditions, a Kibble balance that uses the same mechanism for weighing and moving is insensitive to errors caused by coil misalignment. Robinson [4] discussed a design for a Kibble balance in which the 'weighing' and 'moving' mode are combined. In this approach, a bifilar (twisted pair) coil [5] replaces the conventional single conductor winding. One of the conductors then carries the weighing current whilst the other conductor measures the EMF induced by the motion of the coil.

As part of the development process towards a simpler Kibble balance the National Physical Laboratory (NPL) is constructing a basic Technology Demonstrator 1 (TD1) to evaluate the modes of operation proposed by Robinson [4] using a bifilar wire coil.

2. MECHANICAL DESIGN REQUIREMENTS

2.1 Details of the donor balance

The balance beam, arrestment mechanism, knives and planes are from a Stanton Instruments HD5 two-pan mechanical balance as shown in figure 1 with knives and planes manufactured from synthetic sapphire (Corundum).

Figure 1. Stanton Instruments HD5 two-pan balance

2.2 Arrestment system

The arrestment mechanism in the original balance comprised a mechanical lever that rotated a cam pushing a central rod upwards that picked up the balance beam on kinematic mounts. To enable the arrestment mechanism to operate remotely when the system was under vacuum the arrestment lever was replaced with a stepper motor to drive the cam mechanism as shown in figures 2 and 3.

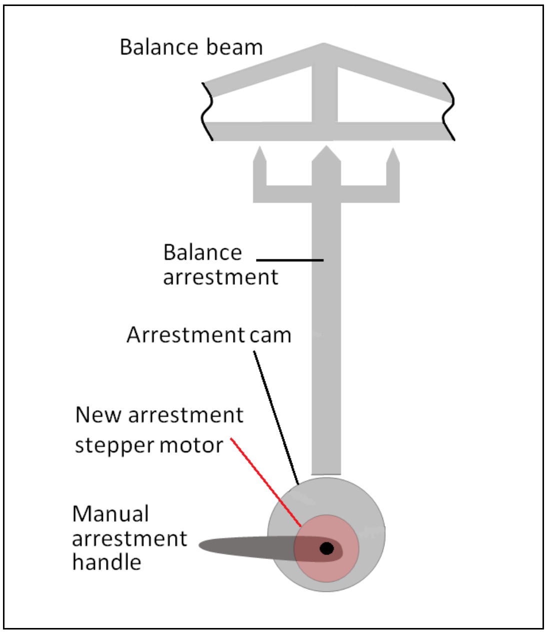

Figure 2. Substitute of stepper motor for original arrestment handle

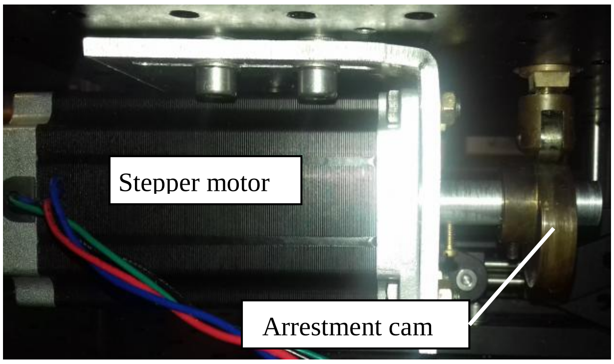

Figure 3. Stepper motor driven arrestment mechanism

2.3 Load transfer system

The load transfer system permits loading of spherical mass artefacts with diameters in the range from 40 mm to 50 mm to the mass pan as shown in figure 4. A stepper motor drives the transfer system giving ± 12 mm movement of the lifting arm above or below the mass pan. This requirement was essential to ensure there was enough clearance between the lifting arm and the mass pan during moving operations. The mass pan manufactured from aluminium has three spherical 5 mm diameter titanium balls imbedded at 120° angles on a 15 mm diameter circle to support mass artefacts. The load transfer arm, also manufactured from aluminium, has three 5 mm diameter titanium balls at 120° angles on a larger 36 mm diameter circle.

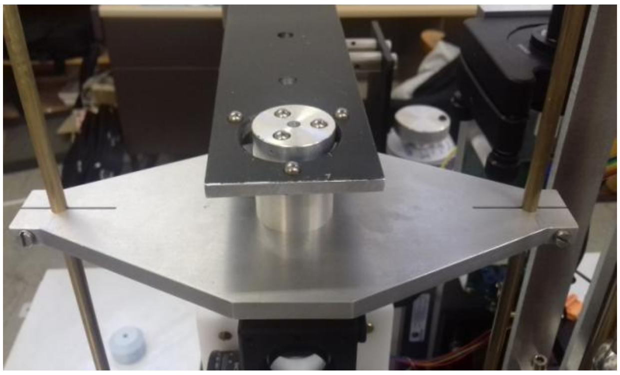

Figure 4. Mass pan and load transfer system

2.4 Coil Suspension

Two coil suspension mechanisms are required as shown in figure 5. The right hand suspension supports the mass pan, the interferometer retroreflector and the coil used to drive the balance during the moving phase. The left hand suspension supports the main coil. The coils and mass pan are mounted on 6 mm thick aluminium plates, connected together using 5 mm diameter brass rods. Each pan hangs from the balance end-knives using a sapphire plane and a pin and cone pivot point below the plane allowing the whole suspension mechanism to hang freely from the centre line of the sapphire knife. During balance arrestment, cone and vee kinematic mounts support the hanging elements (shown in figure 6).

Figure 5. TD1 balance showing coil and mass suspension

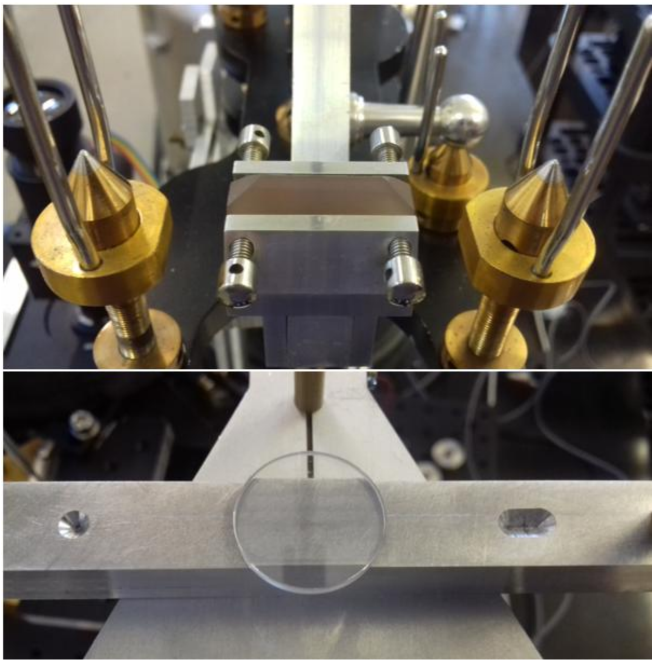

Figure 6. Cone and vee arrangement for pan support

3. COIL MANUFACTURE

3.1 Bifilar coil winding

The principles behind the application of bifilar wound coils to Kibble balances described in [4, 5] apply to these coils. A twisted pair of bifilar wire was manufactured from insulated copper wire with approximately 1 turn per millimetre using a bespoke wire-winding rig shown in figure 7. Three computer controlled stepper motors wound the coil from two single conductor containing bobbins on the rotating lower disc which in turn supplied twisted wire to the 'take-up' bobbin on the upper stepper motor. The third stepper motor, and a guidance mechanism, moved the bobbin to provide uniform layers of twisted pair.

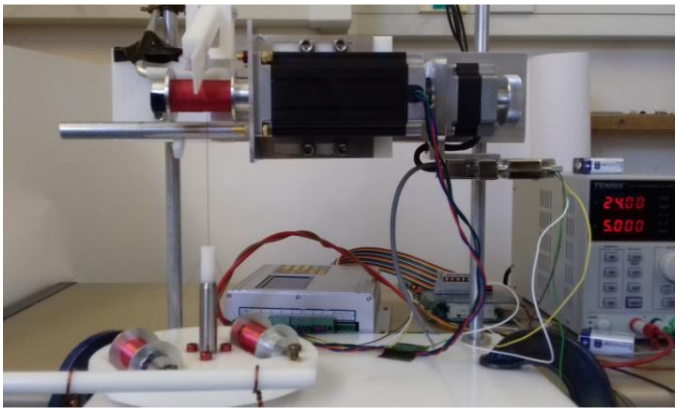

Figure 7. Bifilar coil winding system

3.3 Coil production

Bifilar coils produced for this TD1 Kibble balance used a modification to the wire-winding rig (figure 7) to wind the previously made bifilar wire directly onto an aluminium former. It is intended to manufacture a freestanding coil using a suitable glue to bond the turns together. Techniques for this are being investigated.

4. MAGNET

4.1 Design considerations

The design of the magnet is a critical consideration in the construction of a Kibble balance. For effective operation, the coil needs to sit in a uniform radial magnetic field. There are a number of ways to achieve this. Current Kibble balances use different configurations of permanent magnets and yokes [6], designs can be either open or closed magnets. So that the coil can easily be inserted and removed, TD1 is intended for use with an open magnet construction.

4.2 TD1 magnet design

Figure 8 shows the preliminary design for the TD1 magnet. A (half) cross-section through the design is shown with rotational symmetry about the r = 0 line. The red area is the permanent magnet, the purple is the mild steel yoke, the light blue are assembly components (made of aluminium) and the orange areas represent the coils. The design has the advantage that the magnetic field produced has a null point mid-way between the coils. The detailed design of the magnet has been optimised using finite element analysis to minimise stray magnetic fields and to optimise the linearity the fields around the position of the coils. The magnetic field generated by the magnet assembly will be about 0.4 T.

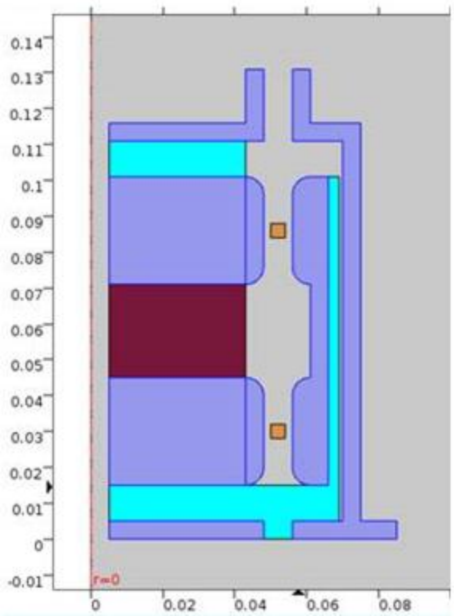

Figure 8. Magnet assembly

5. VACUUM SYSTEM

5.1 System considerations

The main considerations of the vacuum system were to achieve a pressure that eliminated any corrections in the interferometer system due to air refraction and made corrections due to buoyancy of the mass artefacts negligible. Selecting an operating pressure below 0.1 Pa met both of these requirements. The vacuum chamber also needed to be large enough to accommodate the donor balance, support frame and associated equipment.

5.2 Feedthrough requirements

Vacuum feedthroughs are required to supply power and control to the stepper motors controlling the arrestment of the balance and load transfer mechanism. Feedthroughs are also required for supplying current to the drive and measurement coils. The interferometer required a fibre optic vacuum feedthrough connection to the external laser and a feedthrough was necessary to provide a connection to an autocollimator used to measure the angle of the central knife-edge of the balance. Two ports were also required for connecting a valve to allow the chamber to return to air and to connect a gauge to measure the pressure within the chamber.

5.3 System design and evaluation

The vacuum chamber design comprised two parts; the top being a stainless steel bell jar with an internal diameter of 812.8 mm and external height of 719.1 mm, and the bottom section being a square aluminium plate with sides of 889.0 mm and a thickness of 25.4 mm as shown in figure 9.

Figure 9. TD1 vacuum chamber

The bottom plate has four QF50 ports for vacuum feedthroughs and an ISO 160 port for connection to the vacuum pumping system.

A two stage pumping process obtained a vacuum within the chamber; the first stage used a Leybold Trivac D25B rotary pump to reduce the pressure below 10 Pa and a Leybold Turbovac 340M turbomolecular pump mounted directly on to the ISO 160 port reduced the pressure below the 0.1 Pa target. An MKS 925C MicroPirani^{TM} gauge measured the pressure level within the vacuum chamber. Tests on the performance of the vacuum system successfully achieved a pressure of 0.01 Pa after 30 minutes of pumping with the turbomolecular pump at full speed.

6. PRELIMINARY RESULTS

Initial measurements have been performed in vacuum with the balance in an equilibrium position without any load on the mass pan. Measurements started in air before evacuating the chamber with pressure reaching 0.01 Pa after 30 minutes of pumping. The results of the measurement (figure 10) showed a typical pumping curve expected due to the change in buoyancy of the balance suspension system and pans as the air was removed from the chamber. In total, the measured mass of the suspension system and pans changed by about 80 mg from air to vacuum. Once the pressure had dropped to 0.01 Pa no observable additional changes in mass occurred and reasonably good mass stability was obtained. At this time the interferometer system was not able to operate in vacuum and coil position was determined using a simple, non-optimised, servo system with beam angle measured using a relatively low-resolution autocollimator. This limited the resolution of the measurements though some of the instability observed after 30 minutes of pumping may have been due to residual outgassing of the balance components. These preliminary results indicate that the donor balance should have adequate performance to allow TD1 to operate at the ppm level or below.

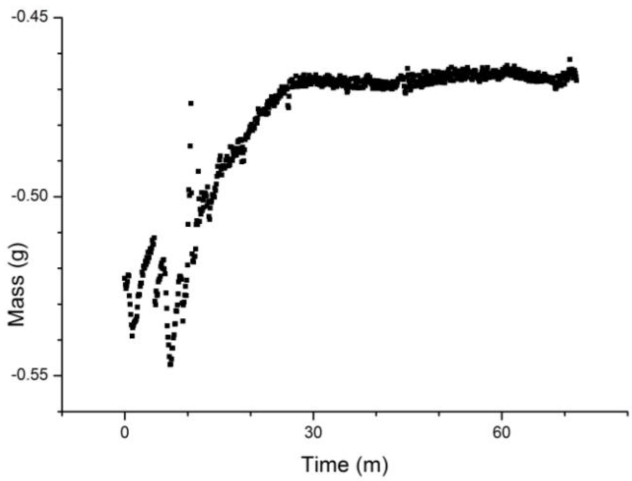

Figure 10. Measured change in mass during evacuation of the chamber.

7. CONCLUSIONS

The National Physical Laboratory has constructed Technology Demonstrator 1 (TD1), to test novel concepts associated with a simplified form of Kibble balance. TD1 has been designed to evaluate a new type of coil formed from a bifilar twisted pair of conductors enabling the balance to implement and test the procedures described in [4].

The vacuum system has been fully evaluated and a pressure of 0.01 Pa was reached after 30 minutes of pumping. Measurements made at vacuum had a standard deviation of 1.0 mg and with improvements to the coil and magnet and interferometer systems, it will be possible to achieve performance at the sub-ppm level.

An NPL constructed coil winding system has successfully produced 1 turn per mm bifilar wire from which a coil has been constructed. Initial measurements of the mass change of the balance suspension components on evacuation of the chamber showed that the mass changed by 80 mg due to the removal of the air buoyancy effect, with little further changes in mass after 30 minutes of pumping.

Further optimisation and testing of TD1 are required and the results will provide the basis for a next generation of simplified Kibble balance that is both easier to manufacture and operate but still capable of measuring SI mass at the parts in 10^8 level.

Following on from TD1, a second technology demonstrator (TD2) will be built based on a seismometer type construction [3] (illustrated in figure 11). TD2 will evaluate the novel mechanical construction, particularly with respect to the flexure strips and a magnetic-levitation system to support and move the central element of the balance.

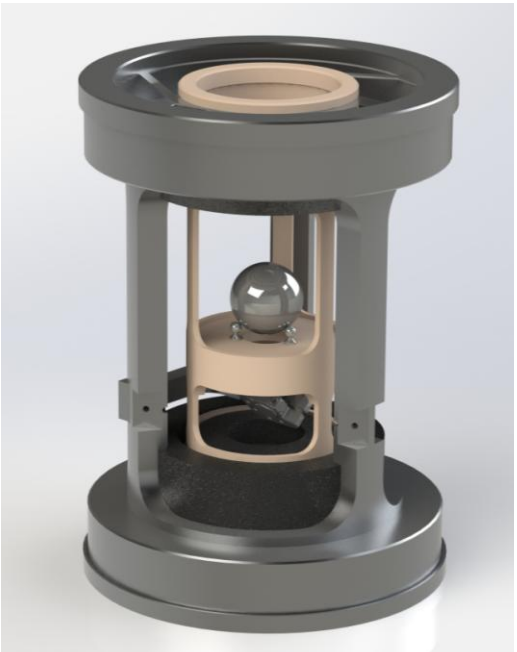

Figure 11. Concept design for "seismometer" Kibble balance construction.

Once fully evaluated, TD2 will allow NPL to produce the final Kibble balance instrument with a target production date of 2020.

9. ACKNOWLEDGEMENTS

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