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Development of an electromagnetic spring for use with a high accuracy surface texture measuring probe

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ABSTRACT
This report describes the development of an electromagnetic spring that is used with a high accuracy surface texture measuring probe on the NPL Areal Instrument. The spring needed to be capable of floating the mass of the probe (around 6 g) and applying a probing force onto the surface being measured (0.1 mN). The report describes initial experiments with a single coil and magnet arrangement and then describes the use of a two coil arrangement that ensures that the force on the surface stays constant as the probe is moved over its full displacement range (0.1 mm).

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Approved on behalf of the Managing Director, NPL,
by Dr Ian Severn, Knowledge Leader, Engineering
Measurement Team, authorised by Director,
Engineering & Process Control Division

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1. INTRODUCTION

The Engineering Measurement Team at the National Physical Laboratory is developing a directly traceable instrument for the measurement of areal surface texture. The instrument under development uses a probe fitted with a diamond stylus that contacts the surface being measured but exerts a very low force upon it (around 0.1 mN). This report describes the design and test of a suitable method for both balancing the static load that the probe exerts on the sample surface (*i.e.* its weight) and applying a suitable force to keep the stylus in contact with the surface. The basic design and operation of the instrument is described elsewhere (Leach, *et. al.* 2006).

2. SPECIFICATION

A fundamental requirement of the probe was that it should be capable of exerting a stable downward force on the surface of the sample under test of approximately 0.1 mN while operating over a vertical range of at least 0.1 mm. In the final instrument the probe is required to work within an air bearing designed to provide lateral stiffness with virtually frictionless axial (vertical) movement. The probe has to support a toroidal magnet (see section 3) and a lens that forms part of a laser interferometer that measures the axial displacement of the probe. These, and other practical requirements, determined that the mass of the probe would be in the region of 6 g, and constrained its diameter to a maximum of 9 mm. Figure 1 is a schematic representation of the probe assembly *in situ* in the areal surface texture measuring instrument. It shows the relative positions of the key components: the coil, the toroidal magnet, the air bearing, the lens, the sample and the stylus.

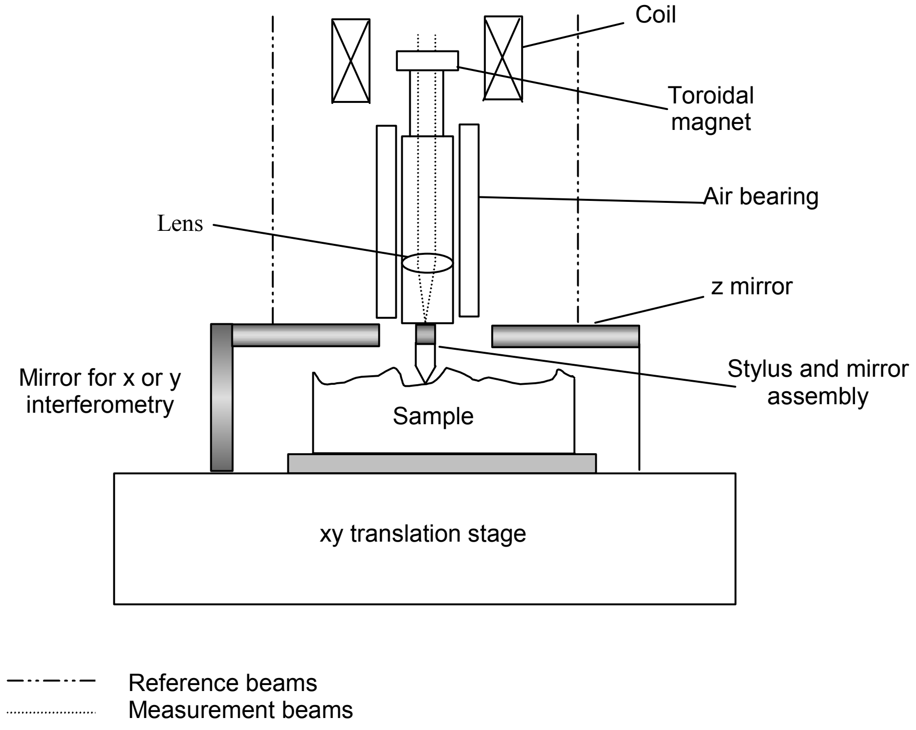

Figure 1 The probe on the new NPL areal surface texture measuring instrument

3. INITIAL DESIGN

The main design challenge was to find a means of counterbalancing the weight of the probe whilst allowing for fine adjustment of the required residual force of 0.1 mN. A mechanical spring with the required sensitivity would be difficult or impossible to construct within the confines of the instrument so the most obvious approach was to utilise some form of adjustable magnetic device.

A readily available commercial tin-coated NdFeB permanent magnet with annular form was chosen as the basis of the design, since it possesses a high field strength to weight ratio, is magnetically stable and of a suitable size to attach to the probe. Several possibilities were considered for producing a magnetic field to surround the probe in order to attract this magnet:

- An un-energised cylinder of a ferromagnetic material (for example, iron or steel).
- A cylindrical permanent magnet.
- A current applied to a coil wound on a cylindrical former.

The first possibility was eliminated because it would provide insufficient force to support the weight of the probe. Calculations using the second method showed that although the method would be feasible in terms of providing enough force to support the probe it would be impossible in practice to provide the stability and sensitivity to maintain the required residual force.

Calculations demonstrated the theoretical feasibility of the third method so tests were designed to determine its practicability.

4. INITIAL DEVELOPMENT

Although the probe was designed to work in an air bearing in the final instrument, the essential experimental requirement was to determine the characteristics of the interaction between the permanent magnet, which would be fitted to the probe, and an energised coil assembly. To simulate this, the permanent magnet was glued to a Macron[1] tube attached to a solid brass base, and the assembly placed on the scale pan of a Mettler AT201 200 g electronic balance. A specially designed translation unit allowed the coil assembly to be moved vertically over a range of 15 mm with the magnet centred axially within it. In order to minimise any effects on the coil's magnetic field the frame of the unit was constructed from aluminium and stainless steel materials, while the ferromagnetic translation stage was mounted remotely from the coil. The apparatus is shown in Figure 2.

[1] 'Macron' - a proprietary machineable ceramic material

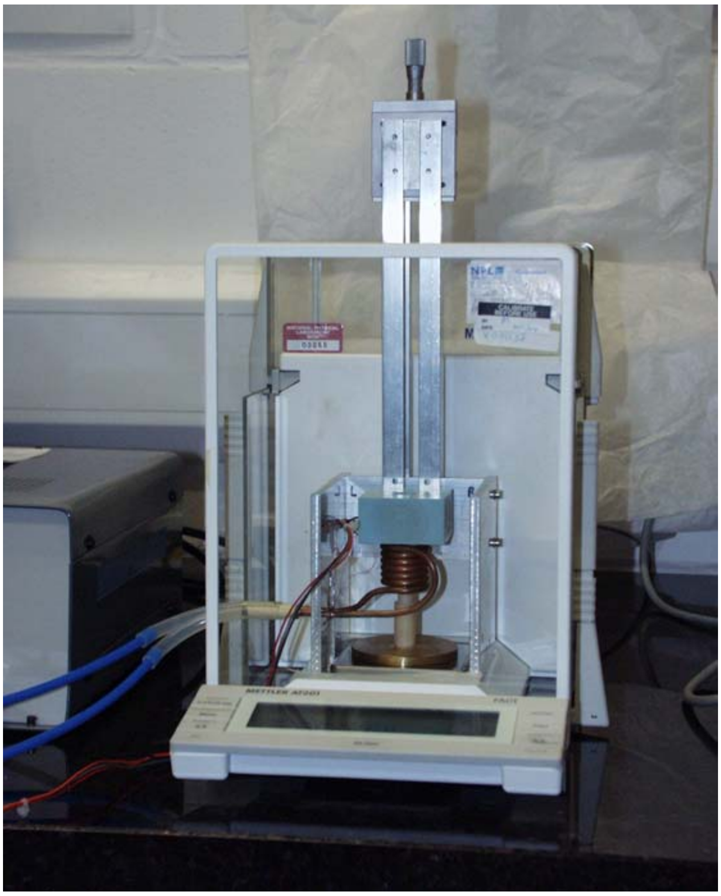

Figure 2 Coil assembly under test

Measurements carried out by NPL's Applied Electrical Group on eleven samples of the permanent magnets had shown that their magnetic moment was 61.6 mA $m^2 \pm \sim 3\%$, and that the magnetic axis of each magnet corresponded to its physical axis. Based on this magnetic moment, it was calculated that a field strength of approximately 0.94 T m^{-1} would be required to counterbalance the weight of the probe.

The first coil assembly tested comprised a single winding of about 80 turns of 0.44 mm diameter enamelled copper wire on a 20 mm diameter Macron former. It was fitted to the test apparatus shown in Figure 2 with the coil connected to a power supply *via* a circuit that provides a constant, precisely controllable current. This circuit was originally designed at NPL for use on an instrument for measuring low thrust (Hughes and Oldfield 2003). The coil was then moved vertically in increments of 0.25 mm and the reading on the balance measured at each increment.

Figure 3 shows the balance reading plotted against the coil position (relative to a datum where the magnet was aligned mid-way along the coil's axis), for direct currents of 100 mA, 200 mA and 500 mA. Since the object of the experiment was essentially to determine a method to counterbalance the weight of the probe, the units used on the ordinate of the graph are in grams weight. Although usually scaled in units of mass, electronic platform balances in fact measure the gravitational force (*via* a transducer) of an object placed on the pan, *i.e.* an object with a mass of 6 g will exert a force of approximately 58.8 mN (6 x 9.8 mN) on the scale pan[2].

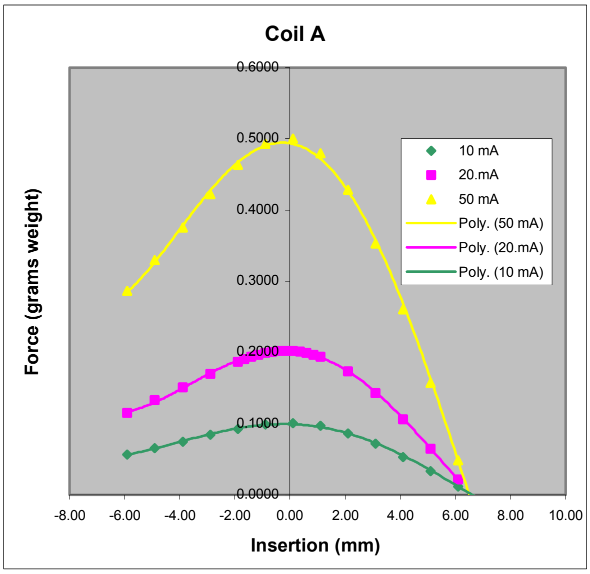

Figure 3 Graph showing tail off of force with insertion distance

Figure 3 illustrates that the force on the probe tailed off too rapidly on either side of the maximum value to provide enough stability over the required vertical range of the probe's movement. It also shows that a current of 50 mA would support a maximum mass of just under 0.5 g. Therefore, since the magnetic field produced by an energised coil is directly proportional to the current, approximately 600 mA would be required to counterbalance the weight of the probe. Attempts to repeat the experiment at this current failed because the balance reading became unstable. This was ascribed to the heating effect of the current, described later in this report, but could also be due to the magnetic effect of the coil on the operation of the pan balance (Davis and Gläser 2003).

Two identical coils placed on the same axis with a current passing in the *same* direction in each coil will, when separated by the correct distance, exhibit a region of constant magnetic field strength near the mid point between them. If each coil consists of a single turn the theoretical optimum separation is equal to the radius of the coils (a Helmholtz coil). Conversely, if the current is passed through both of the coils in *opposite* directions they will exhibit a region of constant field gradient. In this case, for single turn coils, the theoretical optimum separation is equal to the diameter of the coils (a Maxwell pair).

The on-axis field strength of a simple coil can be calculated using the equation

$$B = \frac{\mu_0 in}{2(r_2 - r_1)}\left[x_2 \ln \frac{\sqrt{r_2^{\;2} + x_2^{\;2}} + r_2}{\sqrt{r_1^{\;2} + x_2^{\;2}} + r_1} - x_2 \ln \frac{\sqrt{r_2^{\;2} + x_1^{\;2}} + r_2}{\sqrt{r_1^{\;2} + x_1^{\;2}} + r_1} \right],$$

2 At sea level on the Earth

where B represents the magnetic field strength, μ_0 represents the permeability of free space ($4\pi \times 10^{-7}$ H m^{-1}) , i represents the current, n represents the number of turns per unit length of the coil, r_1 represents the inside radius of the coil, r_2 represents the outside radius of the coil, and x_1 and x_2 represent the on axis distance from each end of coil to measurement point.

The above equation was used to calculate the resultant field strength when applied to both coils of a Maxwell pair (Figure 4) and (for comparison) a Helmholz coil (Figure 5). This enabled field strength and gradient to be plotted as functions of the coil dimensions, separation, resistance, current and number of turns.

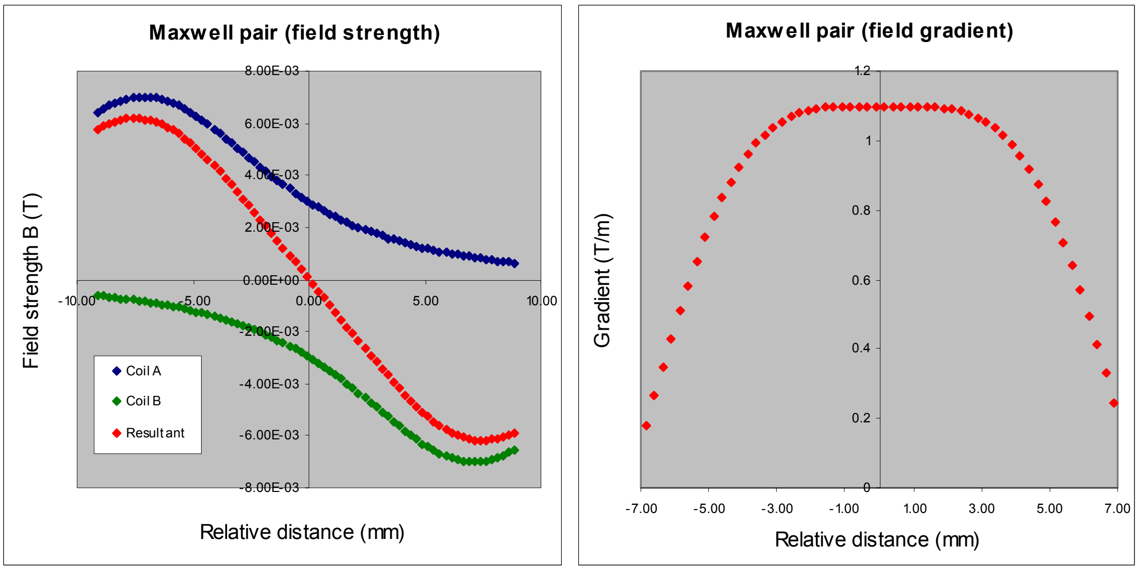

Figure 4. Graphs showing the theoretical field strength (left) and field gradient (right) relative to the distance between a permanent magnet and the physical centre of a Maxwell pair at optimum separation

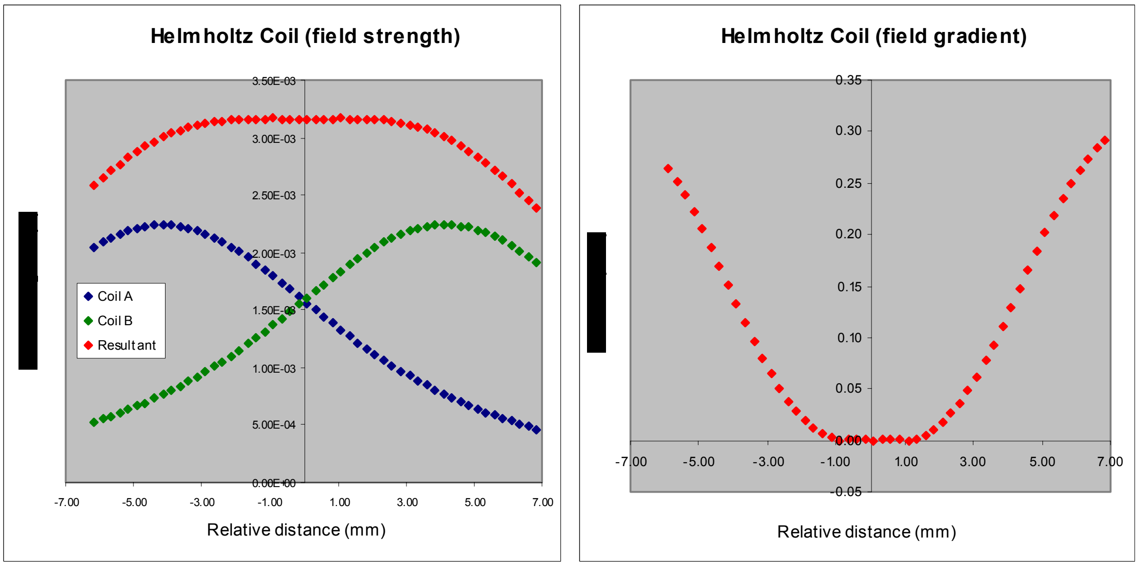

Figure 5. Graphs showing the theoretical field strength (left) and field gradient (right) relative to the distance between a permanent magnet and the physical centre of a Helmholtz coil at optimum separation

5. FINAL DESIGN

Using the above equation, parameters were determined for a pair of coils that would give the most suitable characteristics for the required purpose and comply with the design constraints described in section 3. The parameters are shown in Figure 6.

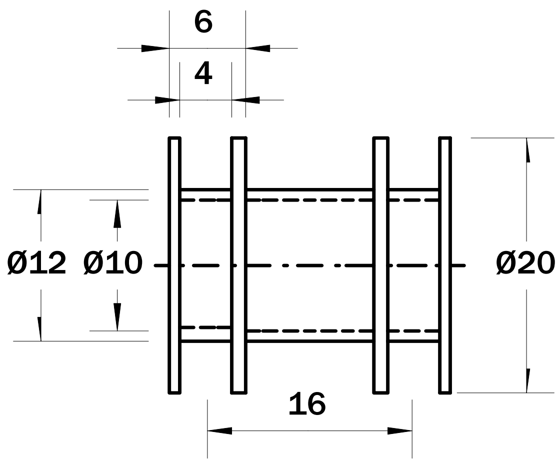

Figure 6. Dimensions of coil former for an ideal Maxwell pair, all dimensions are in millimetres

Several coil assemblies were made and tested before it was established that the optimum coil separation required to give the flattest field gradient was between 9 mm and 11 mm (the ideal Maxwell pair separation of 16 mm is calculated assuming only one turn). A current of 30 mA was used for the initial tests, which gave a maximum balance reading of 1.024 g with a 9.5 mm coil separation. The next task was to obtain enough force to counterbalance the 6 g mass of the probe. A major problem encountered was that when the current was increased to provide enough force (around 200 mA), the balance reading became very unstable. Tests using a thermometer positioned within the coil showed that there was a significant heating effect – an increase of 6.8 ºC within 30 minutes was recorded. Even when the coil was energised for a substantial time the balance reading did not become stable.

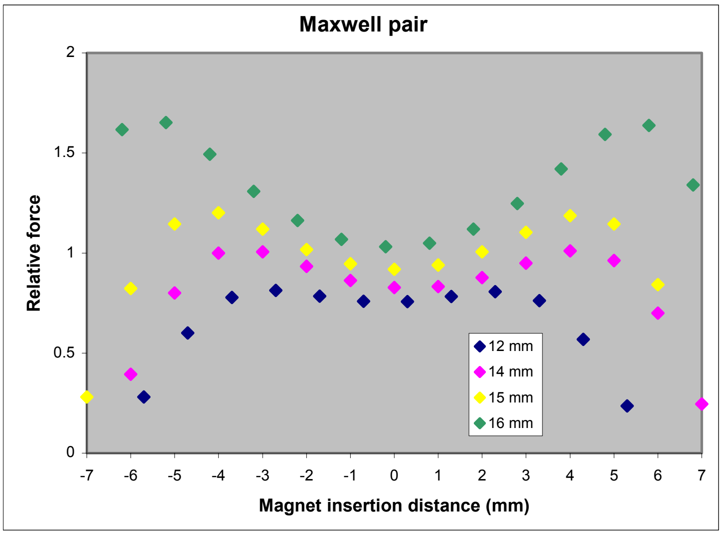

Figure 7. Relative force variation with insertion distance of magnet for coil separations of 12 mm, 14 mm, 15 mm and 16 mm

The NPL-designed current source was known to provide a very stable constant current. Therefore, if all other parameters stayed constant, the magnitude of the force should not be influenced by the heating of the coil assembly since field strength is independent of resistance. It is believed that the instability was the result of small dimensional changes caused by temperature fluctuations in the coil/former assembly, probably due to convectional effects resulting from the temperature difference between the ambient air and the air within the coil.

Because the heating effect is dependent solely on the current and resistance of the coil ($P = I^2R$, where P is power, I is current and R is resistance), it was not possible to reduce the quantity of heat produced while keeping the coil assembly within the required dimensional constraints. The only solution was to dissipate the heat. In the final design this was achieved by using coil formers made of copper surrounded by a heat exchanger made from 4 mm diameter copper tube formed into a coil (Figure 8). Water at ambient temperature in a 15 litres reservoir tank was circulated through the coil by a peristaltic pump at a rate of 12.7 litres per hour.

Figure 8. Cooling coil surrounding Maxwell pair coil assembly.

Three formers with different coil spacing were constructed and each coil was wound with approximately 850 turns of 0.125 mm enamelled copper wire. The graph in Figure 9 shows that the coil assembly using the former with the 10.5 mm coil spacing gave the flattest field, which, with a current of 200 mA applied, generated a force sufficient to counterbalance the mass of the probe.

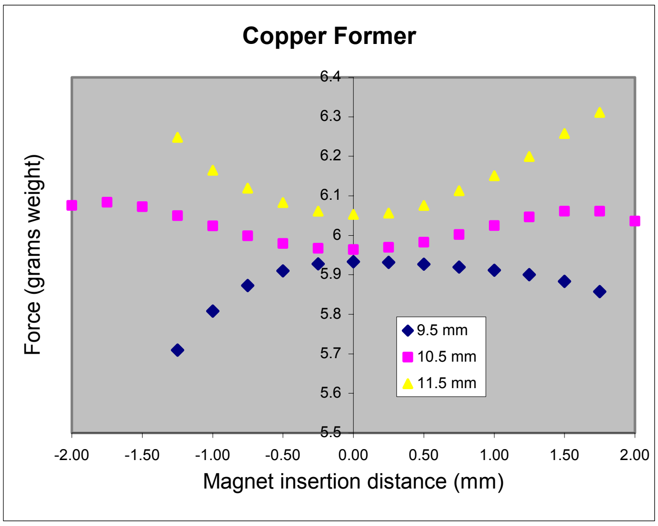

Figure 9. Graph showing variation of force with magnet insertion distance for three coil spacings.

In practice the arrangement performed well. With the cooling water circulating and sufficient current applied to support the probe, the force on the balance pan stabilised within a few minutes, and even after prolonged use, no significant temperature rise could be detected in the water in the reservoir. This assembly was, therefore, chosen for installation in the final instrument.

6. ACKNOWLEDGEMENTS

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