

Team Workshop Problem 17

The Jumping Ring

Prof. E.M. Freeman and Prof. D.A. Lowther

EMF is at the EED/CST London, UK, e-mail 10016.3130@Compuserve.com from Internet.

DAL is at the EED/McGiII, Canada, e-mail 73730.1573@Compuserve.com from Internet.

INTRODUCTION

This is a bench mark with a difference. Hitherto, the custom has been for a bench mark to be presented as a set of experimental results, together with all the details to enable calculations to be made by others. Here, we propose a rather different approach, by describing a simple experimental rig, which others can build and test. There is a further difference, in that what is proposed is a set of tests, based on a basic kit of parts. The inspiration derives from the experiment described by Laithwaite called the "jumping ring". That experiment can be regarded as the ultimate goal of this bench mark, in that it requires the solution of a coupled mechanically dynamic eddy current problem. The set of tests starts with a simple axisymmetric, linear, magnetostatic problem, and then moves through problems of increasing levels of difficulty, taking in: magnetic non-linearity; two dimensional eddy currents, static; three-dimensional eddy currents, static; then finally two- and three-dimensional eddy currents with transient dynamic conditions.

The quantities to be measured and calculated include: induced voltages, inductance self and mutual, impedance self and mutual, forces of attraction and repulsion and power flow. These can be in both two and three-dimensions. Some of the quantities can be determined analytically. This input would be most welcome.

The advantages of such an approach are seen as follows:

- The tests are of progressive levels of difficulty, so that researchers at all levels can contribute and thereby gain experience and confidence.
- The experimental conditions are completely under the control of those predicting the results. The experiments, for the static tests, require only very basic instruments.
- The very fact that a number of groups are measuring results on a variety of rigs to the same design, will give useful information on the statistical spread.

Finally, it should not be overlooked, that most TEAM bench marks so far, have been of more interest to the physics community rather than the engineering community. This is

THE KIT OF PARTS

The basic rig comprises an exciting coil plus a set of inner cores, various plates, and conducting rings. This is shown schematically in Fig. 1.

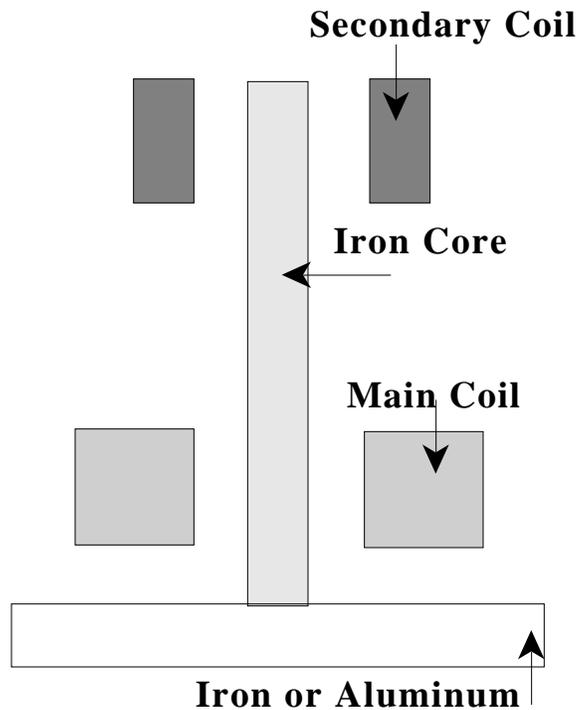


Figure 1. The Basic Jumping Ring Layout.

The Main Coil. The coil was specified 500 turns of a pair of 15 SWG (1.88mm diameter) enamelled conductors, wound closely in a parallel. The inner radius was 40 mm, the outer radius was 77.5 mm. This last is a function of the skill of the winder. The axial length was 100 mm. The coil was wound on a wooden former, between two side pieces of wood, thickness 12.5 mm. Those side pieces had a 50+ mm dia hole to take a 50 mm dia plastic pipe, of length 434 mm. This was a sliding fit, since the inner core within the pipe has to be removable. The plastic pipe, could contain: air or laminated iron. The two coils are brought out to two separate pairs of terminals. In most of the tests, one coil was used to excite the device and the second was used to measure secondary parameters.

The Search Coil. This is wound on a 200 mm dia wooden former, thickness 50 mm. It

has 50 turns, of 28 SWG enamelled wire. The coil length is 12 mm axially.

The Inner Core. For the statics experiments, the inner core, within the pipe, is air of laminated iron. For eddy current experiments, it is proposed that the core should be a 25 mm bar, length 150 mm. The core materials of interest are: solid iron; copper; and pure aluminium. The small diameter allows for the fitting of search coils to the bar.

The Plates. For some of the eddy current experiments, a 12 mm pure aluminium plate was used. This should be of the order 1000 mm square. A refinement is to cut a 300 mm square from one corner of the plate, to produce a further variation on the eddy current problem. In addition, a 1000 mm square, 12 mm thick, iron plate is useful.

The "Jumping Ring." The original device, as proposed by Laithwaite, [1], had a variety of rings. By the sudden application of an ac supply, the force on the ring could produce high levels of acceleration. This aspect should always be borne in mind from the point of view of safety. The rings used so far were made out of aluminium alloy and are detailed below.

THE INITIAL SET OF EXPERIMENTS

1. Coil in Air. This is very basic, it serves as a useful check. The coil has 500 turns, inner radius 40 mm, outer radius 77.5 mm, length 100 mm. The measured value of impedance, at 50 Hz, was 5.3 ohms. Voltage, current and power measurements were made on the main coil. These measurements gave the following results:

$$\text{Terminal resistance} = 1.29 \text{ ohms} \pm 0.02 \text{ ohms}$$

$$\text{Terminal reactance} = 5.15 \text{ ohms} \pm 0.12 \text{ ohms}$$

$$\text{Input impedance} = 5.3 \text{ ohms}$$

This is an axisymmetric magnetostatic problem. Measure voltage induced in the search coil versus vertical distance between the inner edges of the main and search coils. Determine the mutual inductance as a function of distance. Also determine the equivalent circuit parameters. This test also serves as a useful bench mark for open boundary calculation techniques, [2].

2. Coil with Laminated Iron Core. With the central core vertical, the coil edge is 12 mm above the end of the iron. The measurements gave the following results:

$$\text{Terminal resistance} = 2.48 \text{ ohms} \pm 0.32 \text{ ohms}$$

$$\text{Terminal reactance} = 20.2 \text{ ohms} \pm 0.3 \text{ ohms}$$

$$\text{Input impedance} = 20.35 \text{ ohms}$$

This is an axisymmetric magnetostatic problem. Repeat the measurements of induced search coil voltage.

3. Coil above Large Conducting Plate. The coil was positioned 12.5 mm above the centre of the large aluminium plate, i.e. it was placed directly on the plate so that the wooden end plate touched the aluminium. The applied voltage, current and input power were measured at 50 Hz. The measurements gave the following results:

$$\text{Terminal resistance} = 1.53 \text{ ohms} \pm 0.03 \text{ ohms}$$

$$\text{Terminal reactance} = 4.48 \text{ ohms} \pm 0.15 \text{ ohms}$$

$$\text{Input impedance} = 4.73 \text{ ohms}$$

The power into the plate was measured directly by measuring the "shadow" coil technique described in [3]. This is an axisymmetric eddy current problem.

$$\text{Resistance of plate (from shadow coil)} = 4.47 \text{ ohms} \pm 0.14 \text{ ohms}$$

$$\text{Reactance of plate (from shadow coil)} = 0.24 \text{ ohms} \pm 0.01 \text{ ohms}$$

4. Coil with Iron Core and One Ring. Plot the height of the ring above the upper edge of the coil against current input. This test has to be done quickly to avoid problems with the rise of temperature of the ring. This is an axisymmetric eddy current problem.

A ring with the following dimensions was used:

$$\text{inner radius} = 38.5 \text{ mm}$$

$$\text{outer radius} = 44.85 \text{ mm}$$

$$\text{height} = 25.4 \text{ mm}$$

$$\text{conductivity} = 2.08 \times 10^7 \text{ S/m}$$

With the bottom of the ring 12.5 mm above the coil, i.e. resting on the wooden end plate, the following measurements were obtained:

$$\text{Terminal resistance} = 4.87 \text{ ohms} \pm 0.19 \text{ ohms}$$

$$\text{Terminal reactance} = 12.04 \text{ ohms} \pm 0.22 \text{ ohms}$$

$$\text{Ring resistance (from shadow coil)} = 3.82 \text{ ohms} \pm 0.21 \text{ ohms}$$

$$\text{Ring reactance (from shadow coil)} = 12.15 \text{ ohms} \pm 0.24 \text{ ohms}$$

Results in other positions are available from the authors. A complete set of curves of values against position will be available shortly.

5. Coil with Conducting Inner Core. Measure the impedance and power flow into a conducting bar inside the coil. Determine the complex mutual impedance between the main coil and a search coil around the round bar. This is an axisymmetric eddy current problem, [4].

6a. Coil with the core above Edge of Plate. This is now a three-dimensional eddy current problem. The measurements were:

Terminal resistance = 3.59 ohms \pm 0.18 ohms
Terminal inductance = 18.46 ohms \pm 0.25 ohms

Plate resistance (shadow coil) = 2.35 ohms \pm 0.09 ohms
Plate reactance (shadow coil) = 18.76 ohms \pm 0.06 ohms

6b. Coil above a Corner of the Plate. Again 3-D. The measurements were:

Terminal resistance = 3.10 ohms \pm 0.11 ohms
Terminal reactance = 19.4 ohms \pm 0.1 ohms

Plate resistance (shadow coil) = 1.94 ohms \pm 0.06 ohms
Plate reactance (shadow coil) = 19.75 ohms \pm 0.15 ohms

6c. Coil above an Inner Corner. Again 3-D. The measurements were:

Terminal resistance = 3.14 ohms \pm 0.07 ohms
Terminal reactance = 19.03 ohms \pm 0.34 ohms

Plate resistance (shadow coil) = 1.94 ohms \pm 0.02 ohms
Plate reactance (shadow coil) = 19.32 ohms \pm 0.19 ohms

7. Coil axis Parallel to Plate. This is more difficult 3-D problem related to shielding losses in transformers. The coil axis is 200 mm above the plate.

Further Tests. The above are simply an introductory set, to form the basis of discussion to establish a full working set. Further tests could include: a second main coil to form an air-cored transformer; upward attraction force to an iron plate; transient dynamic tests on a conducting ring, this will require advance data acquisition techniques; and rates of temperature rise. Variation of values with frequency would be very interesting, since that opens up the possibility of trying out low and high frequency approximations. These impedance variations can be plotted as complex frequency impedance or admittance diagrams.

The above is hardly an exhaustive list, but it will serve to start the bench mark. It should not be overlooked that the tests described could form the basis of projects for a CAD magnetics course. Indeed, the tests 1 to 5 appear in [5] as standard problems for CAD magnetics students. The authors would welcome feedback, by post, phone, fax or email.

References

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