Geophys. J. R. astr. Soc. (1972) **30**, 295–303.

Magnetic Remanence Related to Slow Rotation of Ferromagnetic Material in Alternating Magnetic Fields

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(Received 1972 July 24)

Summary

The experiments described in this paper show that a permanent remanence can be induced in a ferromagnetic specimen if it is rotating even very slowly, during the slow decrease of an alternating field pervading the specimen. The remanence is antiparallel to the rotation vector, when the rotation axis is perpendicular to the alternating field axis. The result therefore seems incompatible with existing electromagnetic theories for rotating conducting paramagnetic bodies, but the solution for *ferromagnetic* bodies might still be compatible with Maxwell's equations. Precautions were taken to ensure that the remanence was neither an anhysteretic remanence, nor other spurious remanence.

From the practical point of view, the results are relevant to the design of alternating field demagnetization equipment, such as is used by palaeomagnetists to separate various components of magnetization in a single specimen. Without care in design, a spurious remanence could be induced by the 'tumbling' of the specimen.

Introduction

The experiments described in this paper show that a permanent remanence can be induced in a ferromagnetic specimen if it is rotating even very slowly, during the slow decrease of an alternating field surrounding the specimen. The remanence is not an ordinary anhysteretic remanence due to small superimposed steady fields, but is clearly related to the act of rotation in the alternating field.

Equipment

The equipment allowed us to manipulate four variables (Fig. 1); the velocity of rotating ω; the orientation θ of ω relative to the magnetic axis of the alternating field B; to a limited extent the frequency f of the field B; and the maximum value B_{max} of B. The rotation velocity could be varied between about 0·002 and 3·0 rotations per second, in either the positive or negative sense. The angle θ between the specimen rotation axis and the alternating field axis was variable from 90° to 0° (parallel). The available frequencies of the alternating field B were either 50 or 500 cycles/second. The external geomagnetic field was cancelled to $\pm 50\gamma$ by three sets of orthogonal Helmholtz coils, and was frequently checked with a fluxgate magnetometer. As described below, anhysteretic remanences induced in 50γ are considerably less than the observed rotational effects, so that 50γ was an adequately small field. Remanences were measured using at first an astatic, and later a parastatic magnetometer.

Specimens

Natural specimens of igneous rock contain titanomagnetite as their magnetic carrier. They weie so chosen as to span a very wide range of palaeomagnetic stability (S_{200} in Wilson, Haggerty & Watkins 1968). We also include three specimens investigated earlier by R. L. Wilson and J. Edwards, as well as two synthetic powder specimens kindly given to us by D. Dunlop. The rock specimens came from Iceland, Britain and America. They were cores of diameter 2·5 cm and length 2·5 cm (except for the synthetic specimens).

Avoidance of anhysteretic magnetizations, and measurement of rotational remanent magnetizations

Anhysteretic magnetizations (ARM's) were avoided in two ways simultaneously, firstly by cancelling the steady field b well and second by a process that subtracts out any ARM created. The procedure is observed to make the effects of ARM less than 10^{-2} of the rotation remanent magnetization (RRM) which is the topic of this paper. For example:

(a) Specimen D–264–3 acquired an ARM (specimen stationary) of $0{\cdot}2\times10^{-5}$ emu/g when the peak alternating field was 600 Gauss (slowly reduced to zero), the steady field b was 50γ and when there was the most favourable geometrical arrangement for ARM acquisition. The maximum RRM given to the same specimen was $3{\cdot}0\times10^{-5}$ emu/g with 600 Gauss peak alternating field. The RRM effect was in that case 15 times as great as the ARM effect. This is typical and so ARM's are not a predominant factor in our observations.

(b) The method of measuring an RRM was furthermore designed to eliminate any residual ARM effect. RRM's were usually generated with ω perpendicular to B (Fig. 1). The RRM was observed always to be induced antiparallel to ω. By measuring an RRM induced first in setting 1 (Fig. 1) and

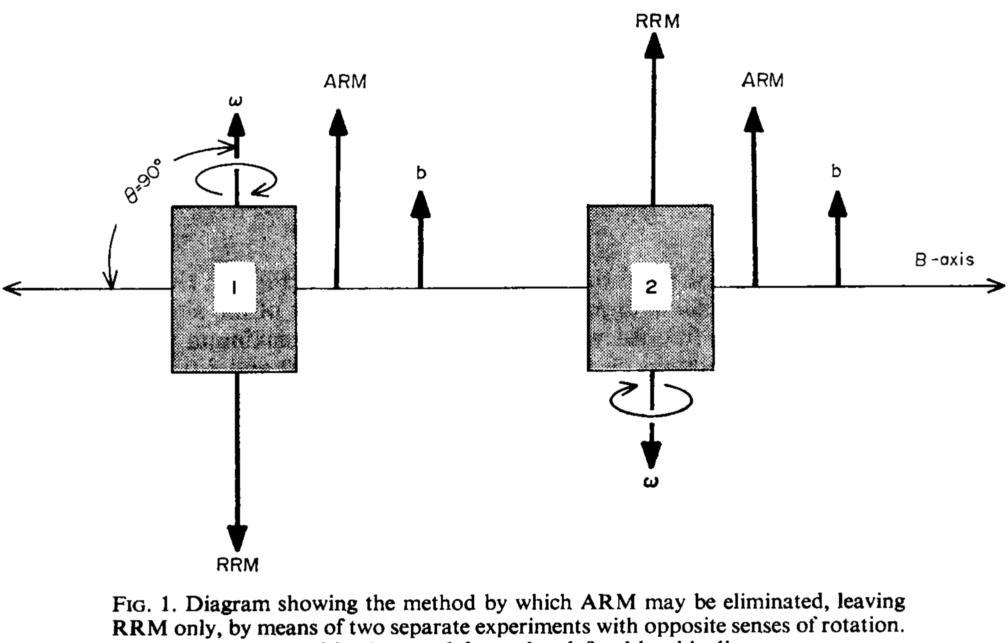

FIG. 1. Diagram showing the method by which ARM may be eliminated, leaving RRM only, by means of two separate experiments with opposite senses of rotation. The quantities B, ω and θ are also defined by this diagram.

then by reversing the sense of rotation as in setting 2, and adding the two magnetizations, we got a double value for the RRM while cancelling out any ARM, since the steady residual field (assumed constant) was not inverted when going from setting 1 to setting 2.

The combined effects of procedures (a) and (b) is to reduce an ARM to at least 10^{-2} of the maximum RRM in the same specimen. All specimens were given a standard demagnetization in 800 Gauss fields prior to use in these experiments, to minimize the natural remanent magnetization, although any NRM will be eliminated by the procedure for eliminating ARM's.

The sense of acquisition of rotational remanent magnetization

Specimen S–2–4 was rotated in zero steady field at various speeds (Table 1) and at each speed the alternating field (50 c/s) was slowly raised to 800 Gauss and slowly reduced to zero. B was perpendicular to ω. The remanence was measured along all three of the X, Y and Z axes of the specimen, although the positive Z axis was always the sense of rotation. The X and Y axes acquired small random magnetizations, but the Z (or rotation) axis acquired systematic magnetizations up to 40 times larger (Table 1). The RRM was induced perpendicular to B and in the opposite sense to the sense of rotation. This is confirmed by the further experimental fact that to change nothing except the sense of rotation, inverts the RRM acquired as in Fig. 1.

This experiment seemed to prove that a remanence was induced in specimen S–2–4 by the mere act of rotation in the demagnetizing field. We now show that RRM exists for a large variety of rock types and for synthetic magnetite, by investigating the variation of RRM with:

(a) magnitude of peak field B_{max} in which RRM is acquired;

(b) magnitude and sense of specimen rotation velocity ω;

(c) frequency f of applied alternating field B;

(d) the angle θ between ω and B.

The effect of the magnitude of peak field B_{max} on RRM

For each specimen in this series of measurements, the rotation speed was kept constant with ω perpendicular to B ($\theta = 90°$). From specimen to specimen ω varied from a minimum of 0·13 rev/s to 0·30 rev/s. Fig. 2 shows that as one repeats RRM production at higher and higher peak fields, the RRM curve is at first concave upwards but often later tends to level off at some saturation value. Specimen R–8–1 did not acquire any significant RRM at all.

Table 1

RRM on all 3 Axes of S–2–4

Peak A.C. field = 800 Oe, f = 50 Hz

Rotation speed c/s	RRM (emu/g × 10^{-5}) X-axis	Y-axis	Z-(rotation) axis
0·025	0·04	0·10	−3·4
0·17	0·066	−0·066	−31·2
0·20	−0·7	−1·1	−40·0
0·50	−0·93	0·04	−30·7
0·71	1·2	1·8	−15·0
1·7	−0·13	1·1	−12·0

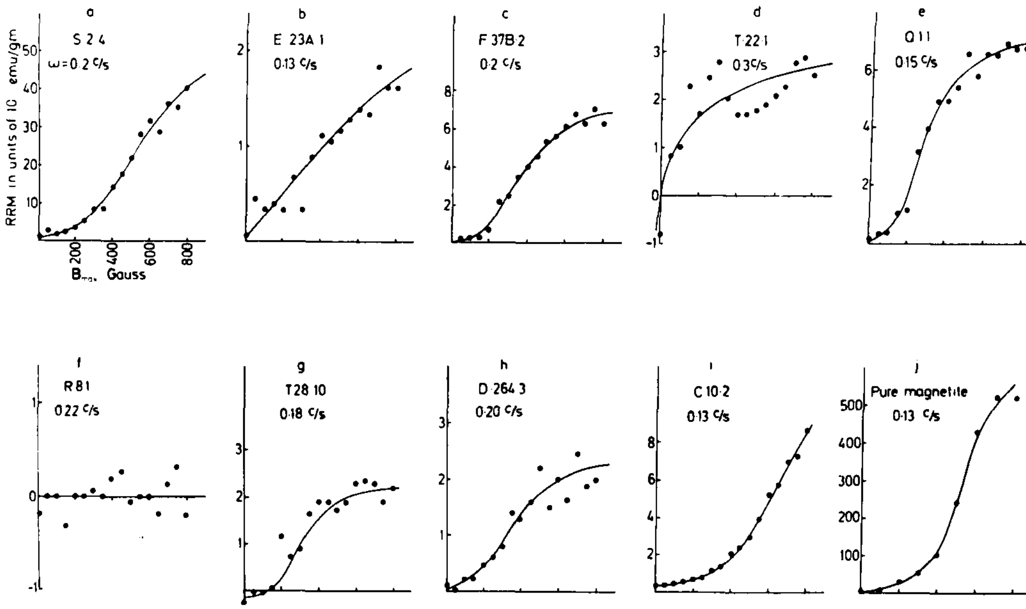

FIG. 2. The RRM acquired by several specimens as a function of B_{max}, for fixed ω (stated in each diagram), $\theta = 90°$, and $f = 50$ Hz.

The effect of rotation speed ω on RRM

For each of these experiments ω was varied, while B_{max} was always 600 Gauss, (except for L–51–2), the frequency f of B was 50 Hz, and θ was 90°. The RRM's, measured by the rotation inversion technique (Fig. 1), are shown in Fig. 3. Clearly, not only does rotation in an alternating field *produce* a remanence, but it does so for astonishingly slow rotation speeds. It is detectable even at 0·02 rev/s, yet it is absent for *zero* rotation.

For some of the specimens, particular experiments were repeated two or more times (L–51–2, NL–28–6 and C–10–2 particularly). Vertical bars in Fig. 3 connect repeated results. The repeatability of the whole experiment established a statistical error level near to $0{\cdot}3 \times 10^{-5}$ emu/g, well below the level of most observed RRM's.

An interesting feature of all the curves in Fig. 3, is that each specimen has a maximum RRM somewhere in the range 0·1 to 3·0 rev/s. Some specimens also show a minimum RRM at higher ω followed by another rise in RRM above this minimum. The curves are not all identical in shape, but have certain similarities.

Similar experiments produced no RRM in a schist containing single magnetite crystals up to several millimetres in diameter, in a specimen of extracted highly altered olivine (Riding 1959) with strongly magnetic intergrowths, and in a large sample of compacted haematite powder.

We believe that the schist (and specimen R–8–1) took on no remanence because their low coercivities prevented them holding any remanence at all (R–8–1 was 20 times less magnetically stable than any other rock specimen). The altered olivine and haematite had on the other hand very high coercive force spectra, so that the B_{max} of 600 Gauss could have little effect on them. RRM is most obvious in those ordinary basalts which are the everyday material of palaeomagnetic research.

The effect of the frequency f of the field B, on RRM

Only two frequencies, 50 and 500 Hz, were available for the alternating field current supply. Specimens S–2–4 and F–37B–2 were investigated at $f = 50$ *and*

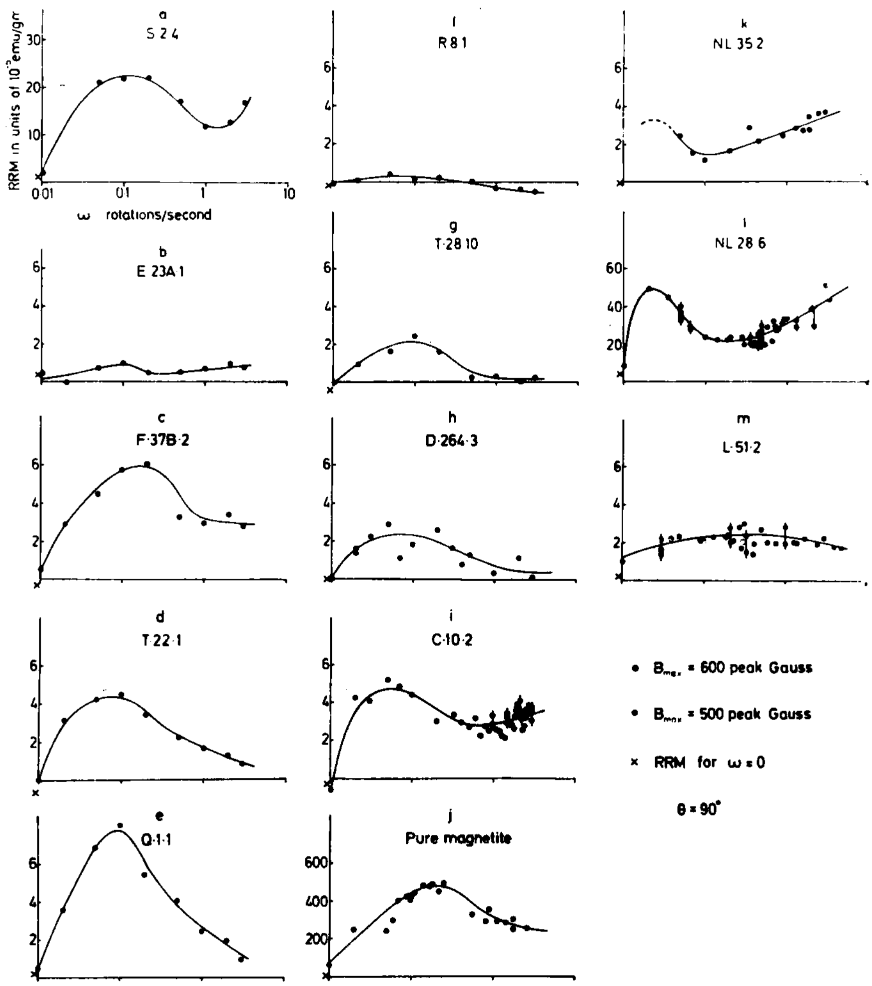

FIG. 3. The RRM acquired by several specimens as a function of ω for fixed B_{max}, $\theta = 90°$, and $f = 50$ Hz. Vertical bars join repeat results from identical experiments.

500 Hz, for variable ω and $B_{max} = 250$ Gauss, and $\theta = 90°$. It was necessary to keep B_{max} down to 250 Gauss in order to prevent arcing in the A.C. coils at 500 Hz. The 500 Hz data have been plotted as open circles on Fig. 4, *by multiplying the real rotational speed* ω *by* 10 *before plotting*. Within the errors,* the 50 and 500 rev/s curves then coincide, for a given specimen. It follows that the effect of raising f by a factor of 10 is to shift the peak (and all other features) of the RRM $-\omega$ curve, down by a factor of 10. The higher the frequency f, the slower the rotation speed ω at which a given feature is observed. At $f = 500$ Hz, the *maximum* RRM is being observed near to $\omega = 0{\cdot}02$ rev/s, a very slow speed. The RRM *magnitudes* do not seem to be modified by f. It follows that the RRM depends on the combined factor, $f\omega$, as a product only.

* The errors are large in Fig. 4 because the RRM acquired in 250 Gauss is quite weak compared with that produced by the usual 600 Gauss field.

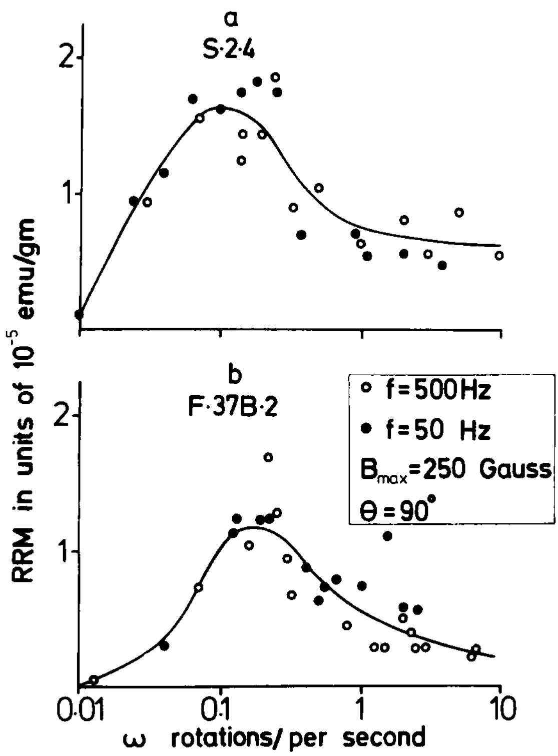

FIG. 4. RRM vs. ω for two specimens. For the $f = 500$ Hz data (open circles), ω *has been multiplied by* 10 *before plotting*. This RRM *then* coincides with the 50 Hz RRM. The implication is that f and ω must appear as a product, $f\omega$, in any theory explaining the effect.

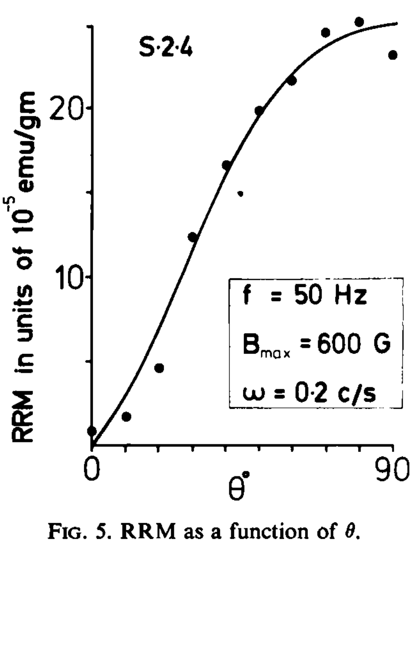

FIG. 5. RRM as a function of θ.

The effect of the angle θ on RRM

The angle θ between B and ω has been 90° in all previous experiments. Here θ is varied from 0° to 90°, while $\omega = 0{\cdot}20$ rev/s, $B_{max} = 600$ Gauss, and $f = 50$ Hz. Fig. 5 is a plot of RRM vs θ for specimen S–2–4. The RRM is zero for $\theta = 0$ and a maximum at $\theta = 90°$, which was why we chose 90° for all the earlier experiments.

Consideration of spurious sources of RRM

We do not believe that RRM can be in any way due to stray magnetic fields from the motors driving the specimen rotation. The earliest experiments were done using a D.C. motor with speed varied by the D.C. voltage, whereas later experiments involved an A.C. motor with a variable speed cone-clutch. The two experimental geometries were entirely different. Yet the results were the same for either set of experiments.

Subsidiary experiments showed that an ARM, plotted against B, has a very different character from RRM vs B curves. This is another reason for believing that the RRM is not a simple ARM in disguise due to some effective steady field which might have arisen despite earlier mentioned precautions.

There seems to be no possibility that harmonics in the power supply for B could cause the observed RRM. First, the RRM is perpendicular to B, and no B harmonic can produce an effective steady or variable field perpendicular to itself. Second, the 500 Hz generator and the 50 Hz mains are unlikely to have had the same harmonics. Third, the experiments were done in two different buildings over several years' time, and it is unlikely that the mains harmonics would remain invariable under those changes of conditions.

Anisotropy in rock specimens cannot account for RRM, both because it is too small an effect ($\sim 0{\cdot}001$ in igneous rocks) and because the RRM is *wholly* perpendicular to B (Table 1 and Fig. 5), not simply a projected component of a moment which lies along the B axis.

The possibility, that the rotation rate ω is somehow a sub-harmonic of the frequency f of B, and therefore that resonances arise, seems less likely when we consider that *raising* the frequency *lowers* the rotation rate ω required to produce a given feature (a maximum for example), as in Fig. 4.

RRM is independent of coexisting remanence

RRM's were induced into D–264–3 ($\omega = 0{\cdot}2$ rev/s, $f = 50$ Hz, $\theta = 90°$, B_{max} variable) under two circumstances:

(a) after all the natural remanence had been removed by A.F. demagnetization at 1400 peak Gauss in our normal demagnetization apparatus. The remanence was then only $0{\cdot}01 \times 10^{-5}$ emu/g and

(b) after a large partial ARM of $\cdot 21 \times 10^{-5}$ emu/g acquired between 800 and 1400 Gauss had been given to the specimen. This ARM was present and constant all during the subsequent RRM process, and coexisted with the RRM. The ARM was then subtracted out mathematically so as to compare this RRM with that acquired alongside zero remanence (a) above.

The two RRM's were experimentally identical at all B_{max}. It follows that RRM is not induced because of the influence of some pre-existing magnetization.

Making use of the results

During the enforced 10-day wait in a tent in Iceland, one of us (R.L.W.) found time to think over the implications of the earliest of the above results for the process of alternating field demagnetization. Since most palaeomagnetists use tumblers which necessarily *rotate* the specimen in an alternating field, we run the risk of inducing an RRM into the specimen systematically. Until that time then, the aim in designing a tumbler had always been to present to the alternating field axis as complete a range of specimen orientations as possible (Creer 1959). Hence the efforts to construct two, three and four-axis tumblers to achieve ever more convoluted motions. The three axis tumbler still did not eliminate spuriously induced magnetizations along the ' inner ' axis of rotation of Doell & Cox (1964). No tumbling system had been reported as having had completely successful results on all specimens. The characteristic failure is that certain rocks, above a given alternating field of a few hundred Gauss, begin to develop erratic directions of magnetization. On the other hand, Zijderveld (1967) did not tumble his specimens, which remained stationary during demagnetization, and he commonly demagnetized in 1000 Gauss fields and higher, without any erratic behaviour being evident. The results were strikingly good, but they were paid for with the extra measurement time and the care needed in zeroing the steady field.

How can we tumble our specimens and still avoid induced RRM's? The design of tumbler finally arrived at was as follows:

(1) It is a two-axis tumbler.

(2) The two axes are perpendicular and have a tumbling ratio of 2 : 1. The vertical drive is at 1 rotation per second, and the coupled horizontal one is at 2 rotations per second. The attempt to attain *very* complete angular ' coverage ' of the specimen was abandoned.

(3) Every 2 s (2 complete cycles of behaviour) the tumbling process is sharply reversed by means of a quick-reversing clutch, and the whole cycle is performed *backwards*. Since all rotatory motions are equal and opposite in alternate cycles, any RRM must average to zero, provided that the rate of reduction of B is slow enough that B reduces by a small amount over 4 s (one forward + one backward cycle).

(4) The A.C. field axis must be in the plane of the horizontal (2 r.p.s.) axis. Otherwise one of the three rock axes is always perpendicular to the field, which causes anisotropic demagnetization, and hence a slightly spurious result.

This apparatus has worked quite well and eliminates systematic RRM effects completely as far as one can test. There are still some erratic effects due, we believe, to a toc rapid rate of reduction of B, but these have not been a major problem in practice.

Discussion of possible explanations of RRM

We have not explained RRM theoretically. However, it seems clear that there are only two likely known approaches to an explanation. The first is the phenomenon of gyromagnetism, and the second is a solution to Maxwell's equations for the conditions of a rotating, conducting (?), ferromagnetic grain in an alternating magnetic field.

Gyromagnetic phenomena are well summarized by Scott (1962) and Barnett (1935). Although gyromagnetic effects do produce magnetizations antiparallel to ω, it is clear that these effects are many orders of magnitude too small to be invoked as an explanation of RRM. This also seems to offer no way to produce the ω-dependence of Fig. 3.

The approach using Maxwell's equations is typified in papers by Bullard (1949) and Rädler (1964). Bullard solved the problem of a rotating conducting sphere in a steady external magnetic field B orthogonal to the rotation axis. The net result is, for small ω, an internal current system producing a magnetic moment orthogonal to both B and ω (i.e. *not* along $-\omega$). Inspection of the solutions suggests that the inclusion of the paramagnetic property (μ) as done by Rädler, and a time-varying field dB/dt, would not change the solution so as to produce a magnetic moment along the $\pm\omega$ axis. It might be, however, that the introduction of the ferromagnetic property would produce such a result, although it is not obvious how this would produce an ω dependence like those of Fig, 3. We feel that this ω dependence might be somehow related to the coercivity spectrum of the specimens. We note that those curves in Fig. 3 which go to zero for large ω, correspond to those curves in Fig. 2 which tend to reach saturation earliest.

Despite the precautions we have taken, there is always the chance that some instrumental factor has produced these RRM effects. It therefore seems important that other workers should attempt to duplicate the results we have obtained. Minor modifications of equipment existing in most palaeomagnetic laboratories would permit this. A consensus of opinion as to the validity of the results may become important.

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