

# Iterative Method for Intrinsic Viscosity Measurements on Perpendicular Recording Media

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**Abstract**—In this paper, we introduce a new method that allows to directly measure the intrinsic viscosity ( $S_i$ ) for perpendicular media using a vibrating sample magnetometer. The measurement is carried out in a number of iterations. In each iteration, the behavior of applied field ( $H_a$ ) with time is gradually adjusted according to the change in the internal field ( $H_i$ ) calculated from the relaxation behavior measured in the previous iteration. Eventually, during the last iteration, from which the intrinsic viscosity can be extracted,  $H_i$  is kept constant by appropriately changing  $H_a$ .

**Index Terms**—Intrinsic viscosity, magnetic relaxation, magnetic viscosity, perpendicular recording media.

## I. INTRODUCTION

MAGNETIZATION of a realistic system is observed to have a logarithmic time dependence, which is known as the relaxation process [1], [2]. Magnetic viscosity can be obtained from the slope of the linear behavior of the relaxation curve  $M$  versus  $\ln(t)$ . For recording media, magnetic viscosity is a useful parameter to extract information on the thermal stability and reversal mechanisms [3]. For longitudinal media, the relaxation curve is measured in the film plane at a fixed applied field,  $H_a$  and the slope of the relaxation curve is the direct indication of the magnetic viscosity at that field. For perpendicular media, when measuring the relaxation curve in the perpendicular direction at a fixed  $H_a$ , the internal field  $H_i$  is continuously changing with time due to the change in the demagnetizing field which amounts to  $-NM$ , in which  $N$  is the demagnetizing factor in the perpendicular direction and  $M$  is the perpendicular component of magnetization. Therefore, the obtained viscosity does not reflect the correct intrinsic properties of the material, e.g., the activation volume. Lyberatos *et al.* [4] proposed an analytical formula to correct for the demagnetizing effect after a normal relaxation measurement. The intrinsic viscosity,  $S_i$ , is calculated from the extrinsic viscosity measured at a fixed  $H_a$ , the total susceptibility and the partial derivative  $\partial M_{\text{rev}}/\partial H|_{M_{\text{irr}}}$  ( $M_{\text{rev}}$  and  $M_{\text{irr}}$  are the reversible and irreversible magnetizations, respectively). The authors supposed that during relaxation, due to the change in  $H_i$ ,  $M$  changes following the major intrinsic hysteresis loop, i.e., the derivative  $\partial M/\partial H_i$  is equal to the intrinsic susceptibility,  $\chi_i$ , of the major loop. However, in fact  $M$  will follow a minor loop branch, whose susceptibility can be significantly smaller. This argument will be explained in detail in the next section. Moreover, the formula fails in principle to provide accurate results in case  $S_i$

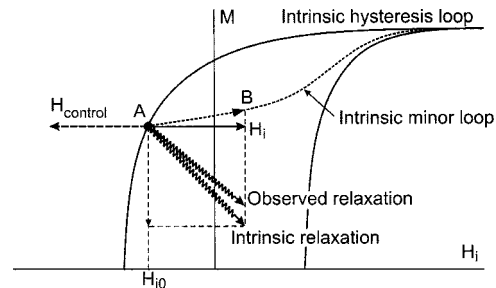


Fig. 1. Schematic illustration of a relaxation measurement at a fixed applied field. Note: the arrows are not vectors, but represent the directions of change.

varies largely with  $H_i$ , which commonly occurs near the coercivity, at which  $S_i$  exhibits a peak. During a relaxation measurement at this field region,  $H_i$  will change significantly, which leads to an uncertainty in the calculation of  $S_i$  at this point. Last but not least, in practice, it is not easy to measure correctly the derivative  $\partial M_{\text{rev}}/\partial H|_{M_{\text{irr}}}$ .

In this paper, we introduce another method that allows to measure directly the intrinsic viscosity using a vibrating sample magnetometer (VSM). By appropriately changing  $H_a$ ,  $H_i$  is kept constant during a relaxation measurement, from which  $S_i$  can be extracted.

## II. PRINCIPLE OF THE METHOD

When a relaxation curve is measured at a fixed applied field in the perpendicular direction, the observed change in magnetization is in fact contributed by the relaxation of magnetization, which is the intrinsic nature of the sample and the change in the magnetization due to the change in the internal field. Fig. 1 gives an illustration of what would happen during such a measurement. After being positively saturated, the sample is brought to a fixed applied field, at which the internal field is  $H_{i0}$  ( $H_{i0}$  is supposed to be negative). This point (A) is located on the second quadrant of the intrinsic (major) hysteresis loop. At this point, the magnetization of the sample begins to relax, which causes the demagnetizing field,  $H_d$ , to reduce in magnitude (not shown). Consequently,  $H_i$  does not remain at  $H_{i0}$  but moves to the right (more positive) with time and the intrinsic relaxation does not follow the vertical line as it would be observed if there was no demagnetizing field but goes along a diagonal line as showed in Fig. 1. On the other hand, due to the change in  $H_i$ , magnetization increases slightly, following the intrinsic minor loop (A-B). As a result, the observed relaxation, which is the superposition of the above contributions, is shifted upwards, that means the observed viscosity is smaller than the intrinsic viscosity.

In our method, the change in  $H_i$  is step by step diminished by applying a time-dependent applied field,  $H_{\text{control}}(t)$ , which changes continuously in the opposite direction to the change in

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$H_i$ . The correction is done in a number of iterations until  $H_i$  remains constant. The routine of the method is as follows:

- 1) The applied field is first set to a positive saturation value in the perpendicular direction and then it is ramped with the maximum rate to a measuring value  $H_{a0}$  which can be estimated from the relation  $H_{i0} = H_{a0} - NM$ ; in which  $H_{i0}$  is the internal field at which the intrinsic viscosity needs to be defined and  $M$  is the magnetization measured at  $H_{a0}$  obtained from the extrinsic perpendicular hysteresis loop.
- 2) Tentative measurement (or zeroth iteration): The relaxation curve is measured immediately after  $H_a$  has reached  $H_{a0}$ . During the measurement,  $H_a$  is kept constant at  $H_{a0}$ . The duration of the measurement is typically about 1000–2000 s.
- 3) After the tentative measurement, the behavior of  $H_i$  with time is calculated. As the time passes,  $H_i$  will certainly deviate from the value at beginning of the measurement due to the relaxation. Based on this knowledge, the behavior of  $H_a$  for the next iteration is calculated in such a way that  $H_i$  remains constant at any time. The behavior can finally be expressed as

$$H_{\text{control}}(t) = H_{a0} + N [M(t) - M_0] \quad (1)$$

in which  $M(t)$  and  $M_0$  are magnetization values at moment  $t$  and at the beginning of the relaxation, respectively.

- 4) The first (or  $n$ th) iteration is carried out after repeating step 1. During the measurement,  $H_a$  is varied in real time according to the behavior (1). The duration of the measurement is the same as the tentative measurement.
- 5) Steps 3 and 4 are repeated until  $H_i$  is sufficiently steady during the whole measurement. The viscosity value obtained from the last iteration will be the intrinsic viscosity  $S_i$ .

### III. EXPERIMENT AND RESULTS

An automatic measurement routine has been programmed on a VSM. The applied field is controlled to trace a predefined time-dependent behavior by discretely changing the sweep rate, while the magnetic moment signal is continuously picked up in real time. The accuracy of the time-dependent field control in our measurements is better than 0.02 kA/m.

Measurements have been tested on two perpendicular samples: a Co–Cr–Pt–B/Ti–Zr sample and a Co-filled alumite sample. Fig. 2(a) shows the behaviors of  $H_i$  with time in several iterations, with  $H_{a0} = -100$  kA/m, for the Co–Cr–Pt–B sample. In the zeroth iteration, the difference between the first value of  $H_i$  and the last one, hereinafter called the deviation of  $H_i$ , is as large as 43 kA/m. In the next successive iterations, the deviation of  $H_i$  is clearly reduced and finally almost diminishes (to about 0.16 kA/m) in the sixth iteration. In this iteration,  $H_i$  is kept almost constant at  $-167.3$  kA/m. Fig. 2(b) shows the deviation of  $H_i$  in different iterations and the corresponding values of viscosity obtained from the relaxation measurements. Whereas the deviation of  $H_i$  approaches zero, the value of viscosity asymptotes an ultimate value of 13.32 kA/m, which is the intrinsic value of the viscosity at  $H_i = -167.3$  kA/m.

In general, when measuring at other fields ( $H_{a0}$ ),  $S_i$  can be achieved after four to five iterations. Fig. 3 plots measured  $S_i$  versus internal field for the Co–Cr–Pt–B sample. The extrinsic

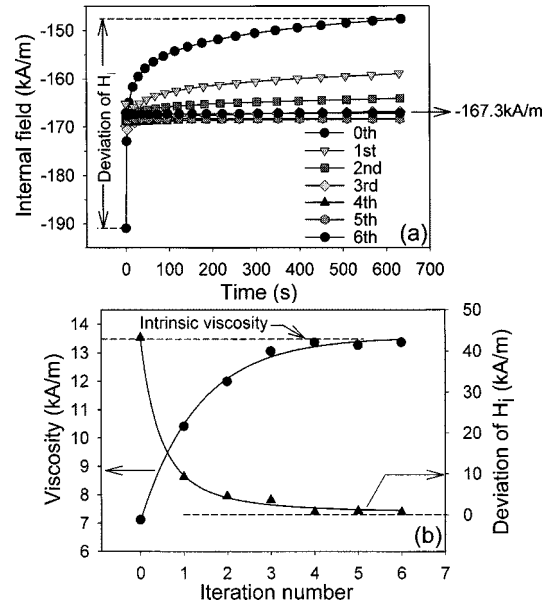


Fig. 2. Example of a measurement on the Co–Cr–Pt–B sample, measured at  $H_{a0} = -100$  kA/m. (a) Internal field as a function of time during relaxation measurements in successive iterations, in which demagnetizing factor  $N = 0.57$  was used. (b) Viscosity and deviation of  $H_i$  versus iteration number.

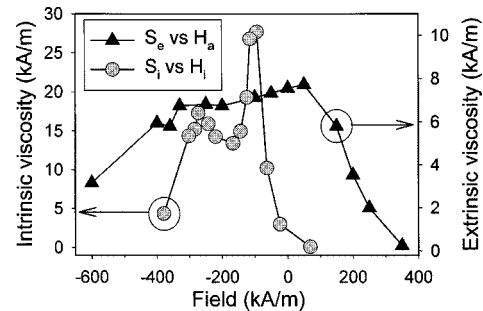


Fig. 3. The obtained intrinsic viscosity as a function of  $H_i$  and the extrinsic viscosity versus  $H_a$ , extracted from the zeroth iteration (Co–Cr–Pt–B sample).

viscosity,  $S_e$ , versus fixed  $H_a$ , obtained from the zeroth iteration, is also shown on a different scale. It can be seen that  $S_e$  is about three times smaller than  $S_i$ . The curve of  $S_i$  exhibits a peak near coercivity, which is similar to the case of longitudinal media. In addition, it has a small hump on the shoulder at a higher field ( $-273$  kA/m). This is probably due to switching of a small amount of harder phase or pinning centers. The switching is also visible as a slight kink on the hysteresis loop.

### IV. SIMULATION AND IMPROVEMENT OF MEASUREMENTS

An analytical model for the measurement has been developed. The model supposes that the observed relaxation is contributed by an intrinsic relaxation and a change in the magnetization along the minor hysteresis loop (see Fig. 1) due to the change in  $H_i$ . It also supposes that  $S_i$  is a function of  $H_i$ , thus also a function of time

$$M(t) = M_0 - S_i [H_i(t)] \ln(t) + \chi_{mr} \Delta H_i(t) \quad (2)$$

in which  $\chi_{mr}$  is the susceptibility of the minor loop branch that starts from point A (Fig. 1). The segment A–B of this branch is supposed to be linear and therefore  $\chi_{mr}$  does not change during

the measurement.  $\Delta H_i(t)$  is the difference between  $H_i(t)$  and  $H_{i0}$ . Equation (2) finally leads to

$$M(t) = \frac{M_0 - [aH_a(t) + b] \ln(t) + \chi_{mr} [H_a(t) - H_{a0} + NM_0]}{1 + \chi_{mr} N - aN \ln(t)} \quad (3)$$

in which we assume that locally around the measuring point,  $S_i$  behaves as a linear function of  $H_i$ , i.e.,  $S_i = aH_i + b$ . This equation allows to simulate any relaxation process with a given behavior of  $H_a(t)$ . With realistic parameters, by using (3) and by repeatedly replacing  $H_a(t)$  with  $H_{\text{control}}(t)$  from (1), the measurements can be simulated. The simulation reproduces very well the behaviors of  $H_i(t)$  and  $S$  in successive iterations that have been observed in experiments. Using the simulation, we were able to interpret and predict different cases that would happen in experiments. Some of the selective conclusions are as follows. 1) In case  $H_a(t) = \text{const}$ , i.e., the extrinsic relaxation measurement, (3) has a hyperbolic behavior when plotting  $M$  versus  $\ln(t)$ . The relaxation curve  $M$  versus  $\ln(t)$  bends slightly up or down depending on the sign of the factor  $a$ . 2) In the calculation of  $H_i$ , if the ratio  $N/V$  ( $V$ —the magnetic volume of the sample—appears since  $M = \text{measured magnetic moment}/V$ ) was overestimated, i.e., the hysteresis loop was overcorrected, the measurement would become divergent, that means the deviation of  $H_i$  would increase with increasing iteration number. This case has been reproduced exactly in a real experiment on the Co–Cr–Pt–B sample. Therefore, it is essential that the ratio  $N/V$  be chosen correctly. This is not always simple, especially when the sample has a complicated reversal mechanism. 3) The higher  $\chi_{mr}$  at around the measuring point, the more iterations are needed to obtain  $S_i$ . For example, measurements on the Co-filled alumite showed that after six iterations, the deviation of  $H_i$  is still rather large. It has been estimated that in order to finish the measurement, about 15 or more iterations are necessary.

To overcome such a problem, by using the simulation, we proposed a “shortcut” to accelerate the measurements. We introduced a factor  $\beta = N_{\text{control}}/N_{H_i}$ , in which  $N_{\text{control}}$  and  $N_{H_i}$  are the demagnetizing factors used in the calculation of  $H_{\text{control}}$  for the next iteration (1) and that used in the calculation of  $H_i$ , respectively. The latter is the intrinsic value of the sample, which must be properly predefined and fixed whereas the former can be set to a different value, i.e.,  $\beta$  can be different from 1. If  $\beta > 1$ , the behavior of  $H_{\text{control}}(t)$  seems to be predicted forward rather than just calculated from the previous iteration as in the case that  $\beta = 1$ . Consequently, the deviation of  $H_i$  diminishes faster (with less iterations) and may even cross zero after several iterations. Fig. 4 gives an example of a simulated measurement with  $\beta = 2$ . From the interpolated iteration number (which could be fractional) where the deviation of  $H_i$  crosses zero, the corresponding viscosity can be interpolated. This value is the intrinsic viscosity that needs to be defined. This method can be used as a “shortcut” to obtain the value of faster  $S_i$ . We have proved by simulation that this value is the same as it would be obtained with  $\beta = 1$ . There is of course a tradeoff between fast obtaining the result (using large  $\beta$ ) but poor accuracy and more time consuming measurement (using small  $\beta$ ) but more precise result. Therefore,  $\beta$  must be appro-

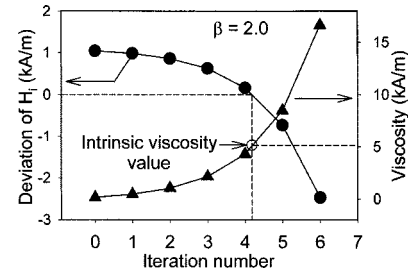


Fig. 4. Shortcut in measurements proposed by using the simulation, with  $\beta = 2$ ,  $H_{a0} = -5.0$  kA/m. The viscosity at the fractional iteration number, at which the deviation of  $H_i$  is zero, is the intrinsic viscosity value that needs to be defined.

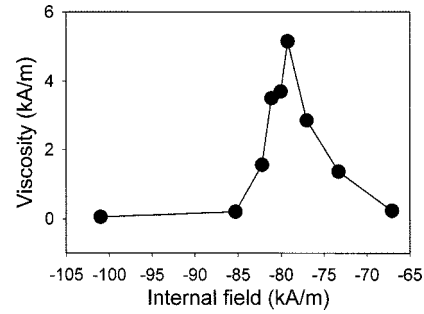


Fig. 5. Intrinsic viscosity obtained by using the shortcut, measured at different internal fields (for Co-filled alumite sample). In this sample,  $N = 1$  was used.

riately chosen. The shortcut has been applied successfully to the Co-filled alumite sample at several fields where the susceptibility is high (Fig. 5). The measured  $S_i$  also exhibits a peak near the coercivity. In these measurements,  $\beta = 2.0$  was used. The values of  $S_i$  were obtained after about five iterations.

## V. CONCLUSION

We have developed an iterative method for measuring the intrinsic viscosity of perpendicular media. The method has been demonstrated successfully on two different types of media. We believe that our method gives more accurate value of intrinsic viscosity than the existing analytical method. Besides the work reported in this paper, we have extended this ideal for measuring intrinsic relaxation of media with oblique anisotropy. The results will be published elsewhere.

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