THEORETICAL AND EXPERIMENTAL INVESTIGATION OF MAGNETIC MATERIALS FOR DC BEAM CURRENT TRANSFORMERS

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Abstract

Toroidal cores made of high-permeability magnetic materials are fundamental building blocks of DC beam current transformers (DCBT). The impact of the properties of the magnetic cores on the overall performance of DCBT was studied. The principle of the DCBT operation is based on the superposition of AC and DC electromagnetic fields in the cores. This effect was studied in detail in two magnetic materials currently used in a construction of DCBT at CERN. The simulation of the DCBT operation was made using the results of these studies and the theoretical model for description of a B-H hysteresis curve of magnetic materials. This simulation allows to evaluate the influence of various factors (a shape of the B-H curve, deviations of core parameters, presence of noise) on the performance of DCBT. A survey of available high-permeability magnetic materials suitable for DCBT is presented.
1. **Introduction.**

DC Beam Current Transformers (DCBT) are well established beam diagnostic instruments [Borer & Jung 1984, Koziol 1989, Gelato 1992]. At CERN their use was required for the first time in ISR machine [Unser 1969] where the beam was kept circulating for long periods of time and therefore traditional AC transformer techniques involving the integration of the beam current (charge) were impossible to use. Later the need to measure a DC component of a beam current lead to the use of DCBT monitors also in the PS machine and Antiproton project [Unser 1981, Koziol 1995], as well as in LEP and SPS [Unser 1989, Vos 1994]. In the future, DCBT monitors will play their role in beam instrumentation for LHC, too [Andersson 1994, Vos 1994].

Requirements of various machines in terms of the DC current resolution were summarised in [Odier & Maccarini 1997]. It was shown that in majority of cases the resolution of presently available DCBT monitors (in the range of µA) is sufficient because the intensity of the beam current is well above it. However, there are a few cases where the beam current is comparable or even lower than the resolution of DCBT. These are the cases where either a number of particles is very low (e.g. pbar), or the velocity is very low (e.g. deceleration projects), or the circumference of the machine is large (e.g. LHC). Therefore there is a need for finding ways how to improve the performance of DCBT monitors.

DCBT monitors consist of two main parts: an assembly of toroidal magnetic cores and electronics circuitry. The present state and possible further improvements of the electronics of DCBT have been described elsewhere [Odier & Maccarini 1997, Unser 1991]. It is obvious that it is desirable to have the noise level in the electronics as low as possible to improve the resolution of DCBT. On the other hand, the role of the magnetic cores in the overall performance of DCBT was not clearly established before. In fact, two quite different opinions on this subject could be found in the literature. According to the first one [Unser (1993)] "... the resolution, zero stability and temperature drift of the DCBT depend on the quality of the modulator core pair and the resolution is only limited by magnetic modulator noise (Barkhausen) ...". The second opinion [Vos (1994)] is that "... magnetic noise (Barkhausen) generated in the tori can be neglected; ... there is no sign of a requirement concerning the magnetic properties of the rings;... nevertheless, the magnetic properties of the tori are
important...”. With the situation like this there was an obvious need to find out more exactly the extent to which magnetic cores can determine the performance of DCBT. Therefore the aim of this project was to investigate the influence of various factors, such as a shape of a B-H hysteresis curve of a magnetic material, possible differences between the cores of DCBT (‘matching error’) or presence of Barkhausen noise in cores on the performance of DCBT, as compared to the influence of factors external to the cores, such as a noise in a modulator circuit. In order to achieve this aim a program simulating the operation of DCBT has been made. The program uses a mathematical model for description of a B-H hysteresis curve of magnetic materials allowing to generate hysteresis curves which are very similar to the ones found in existing materials. Another aim of this study was to make a survey of available high-permeability magnetic materials suitable for DCBT.
2. Principle of DCBT operation.

DCBT operation is based on the phenomenon which has been utilised also in magnetic amplifiers [see e.g. Say 1954 and references therein] and flux-gate magnetometers [see e.g. Scouten 1972 and references therein]. A symmetrical non-linear relationship between magnetic field intensity $H$ and magnetic flux density $B$ in magnetic materials is the physical basis of this phenomenon. If a toroidal core made from a ferromagnetic material is subjected only to a symmetrical AC magnetizing signal, both $B(t)$ and $H(t)$ wave-forms are symmetrical, as can be seen from Fig.2.1. using a simplified $B$-$H$ curve (neglecting the hysteresis of $B$-$H$).

![Fig.2.1. Symmetrical modulating signal without any DC shift.](image)

It can be shown [see e.g. Andersson 1994] that such wave-forms contain only fundamental and higher odd harmonics. If in addition to the AC modulating signal (in our case sinusoidal voltage) a DC polarizing field is present (e.g. as a result of a DC current passing through a centre of a toroidal core), situation changes. For the sake of simplicity let us suppose that the DC current $I_{DC}$, inducing the magnetic field $H_e$, ...
causes the corresponding additional DC shift of flux density, \( B_0 \), and this DC signal causes asymmetrical distortion of the field intensity wave-form \( H(t) \). In Fig. 2.2, we can see that already a small DC shift corresponding to 1 % of the amplitude of the modulating signal (almost invisible at the scale of the loop) causes observable distortion of \( H(t) \).

The higher DC shift corresponding to 10 % of the amplitude of the modulating signal would cause the disappearance of the lower leg of the loop (the saturation region) thus inducing a strong asymmetry of \( H(t) \), see Fig. 2.3. It can be again shown that such an asymmetrical wave-form contains also even harmonics of which the second is the strongest. However, it would be difficult to use this phenomenon directly to measure a DC current because of a complicated relationship between the amplitude of the second harmonic and the DC current which induced the asymmetry. Therefore the measurement device is practically arranged as a zero-flux detector using two identical toroidal cores with modulating signal applied in the opposite phase, see Fig. 2.4.
Fig. 2.3. Symmetrical modulating signal with DC shift (10% of $B_m$).

Fig. 2.4. Practical arrangement of zero-flux detector.
A detailed description of DCBT operation is given in [Gelato 1992] and description of DCBT electronics in [Odier & Maccarini 1997].

If we want to simulate the operation of DCBT by a computer program we need to use some appropriate model for description of the $B$-$H$ relation of a magnetic material of the cores. Such a model must inevitably include the hysteresis of $B$-$H$ which is always present in real magnetic materials. The model used in our study will be described in detail in Chapter 4. On the other hand, if we are to simulate the operation of a real DCBT, we are faced with another problem when we proceed from the simplified $B$-$H$ curve to a real $B$-$H$ curve. It is not self-evident what should be the DC flux density shift $B_e$ corresponding to the DC field intensity shift $H_e$, (proportional to the applied DC current $I_{DC}$); see Fig. 2.5.

In order to clarify this point it is necessary to understand the process of superposition of AC and DC magnetic fields in magnetic materials.
3. **Superposition of AC and DC magnetic fields in magnetic materials.**

The experimental results of $B$-$H$ measurements presented in [Boll 1991 p. 330] suggested that AC and DC fields were not simply summed in a manner indicated in Fig. 2.2. The applied DC field $H_a$ (higher than coercive field $H_c$) did not cause the corresponding DC shift of flux density $B_e$ close to the saturation region, as would be the case for a simplified approach, but resulted in a much smaller value of $B_e$. The theoretical explanation of this fact can be found in [Say 1954]. If the winding of the magnetic core is supplied with an AC driving voltage only then over a complete cycle of operation the mean value of the non-sinusoidal alternating current must be zero (the electric circuit cannot support a direct current):

$$\frac{2\pi}{\omega} \int_0^1 i_L \, dt = 0$$

In order to satisfy this condition the extra polarising field is necessary, see Fig. 3.1.

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**Fig. 3.1. Illustration of a difference between applied and effective field (after [Say 1954]).**
As a result of this effect the net effective polarising field, $H_e$, is smaller than the applied polarising field $H_a$ (proportional to $I_{DC}$).

In order to find out the actual dependence of $B_e$ on $I_{DC}$ in magnetic cores used in a preliminary study of DCBT prototype for LHC [Andersson 1994] we performed the $B$-$H$ measurements in presence of the DC current. The samples were tape-wound toroidal cores with dimensions $100 \times 80 \times 40$ (in mm), in a plastic box, cast in silicone rubber. The cores from two materials (produced by Vakuumschmelze GmbH) were measured: Ultraperm 10 (tape thickness 0.05 mm) and Vitrovac 6025 F (tape thickness 0.025 mm). The measurement block diagram is presented in Fig. 3.2.

![Fig.3.2. Block diagram of the measurement set-up.](image)

The experimental set up, details of which can be found elsewhere [Andersson 1994], was modified by adding an integrating $RC$ circuit which allowed to image the $B$-$H$ hysteresis curve directly on the screen of a digital storage oscilloscope Philips 3320A. Both $B(t)$ and $H(t)$ wave-forms were simultaneously recorded and stored in two channels of the scope and then transferred to a PC via a GPIB bus. The driving signal from the modulator (described in detail in [Odier & Maccarini 1997]) was a sinusoidal voltage with a frequency of 200 Hz. The DC currents up to 500 mA were supplied from a stabilised DC current source.
The results of the experiments are presented in Fig. 3.3 for Ultraperm 10 and Fig. 3.4 for Vitrovac 6025 F, respectively.

Fig. 3.3. Dependence of $B_r$ on $I_{DC}$ in Ultraperm 10.

Fig. 3.4. Dependence of $B_r$ on $I_{DC}$ in Vitrovac 6025 F.
We can see that in accordance with the above presented theory the shift of flux density, $B_e$, for a given applied $I_{DC}$ (and corresponding $H_a$) is much smaller than would be the case if a pair of values $B_e$ and $H_a$ were directly taken form the simplified $B$-$H$ curve.

This result has two important consequences on the operation of DCBT. The first is positive and concerns the upper range of currents: for a given cores even relatively high currents (~ amperes) will not cause $B_e$ to approach the value of saturation flux density, $B_s$, and therefore there is no danger that $B(t)$ would remain always in the saturation region causing disappearance of the second harmonic in the $H(t)$ signal. The second consequence is negative and concerns the lower range of currents: very low DC currents (~ microamperes) will result in very low values of $B_e$ and therefore in very small induced asymmetry in the $H(t)$ signal (and the correspondingly small second harmonic amplitude).
4. A mathematical description of the \( B-H \) hysteresis loop.

There exists a large amount of models describing the \( B-H \) relation in magnetic materials. Some of them derive the shape of the macroscopically observed hysteresis loop from a complex behaviour of individual magnetic moments or domains [see e.g. Philips 1994 and references therein]. Such models are inevitably quite complicated to work with and computation of hysteresis loops is very time consuming. In many cases (when a magnetic material is used in a given application) it is not necessary to know the exact nature of changes of magnetic properties at the level of individual magnetic moments and it is sufficient to use more simple models for a \( B-H \) loop [see e.g. Rivas 1981 and references therein]. We have found out that for a simulation of behaviour of a DC beam current transformer (DCBCT) the analytical hysteresis model proposed in [Cortial 1997] is very suitable because in spite of its relative simplicity it provides a good degree of accuracy and flexibility in generating the \( B-H \) loops of various shapes.

The main parameters of the model are: the coercive field \( H_c \), the slope of the loop at \( H_c \), \( k \); the field intensity \( H_f \), the flux density \( B_f \) and the slope of the loop \( \theta \) at the point corresponding to the end of the irreversible part of the \( B-H \) curve, and the saturation field intensity \( H_s \) and flux density \( B_s \), see Fig.4.1.

![Fig.4.1. Definition of the parameters of the model.](image-url)
The original model of Cortial et al. was given in terms of relation between the field intensity, $H$, and magnetization, $M$, instead of flux density, $B$. In our application it is more convenient to work with the flux density, $B$, therefore the original model was changed accordingly. The model was also slightly modified to enhance its flexibility; the modifications will be described below. In the model the irreversible part of the $B$-$H$ curve, i.e. in the interval $(-H_I, H_I)$, and the reversible part, i.e. $|H|>H_I$, are described by two different formulae. The relation between $B$ and $H$ is expressed in terms of the normalized field intensity $h$ and flux density $b$ defined by $h=H/H_I$ and $b=B/B_f$.

The irreversible part of the $B$-$H$ curve is expressed using the parameters $Q$, $R$ and the function $g$ defined by the following relations:

$$Q = H_c / H_I$$  \hspace{1cm} (4.1)
$$R = -k Q H_f (1-Q)^2 / B_f$$  \hspace{1cm} (4.2)
$$g(h) = \frac{1-(h/Q)}{(1-h^2)}$$  \hspace{1cm} (4.3).

The $b$-$h$ relation is then given by the sum of an hyperbolic tangent and an arctangent functions, which results in a well-known shape of the hysteresis loop. The additional linear function influences the slope of the loop at the closure point $h=1$:

$$b(h) = \{K_1 \tanh[R g(h)] + (K_2 / \pi) \arctan[(\pi / 2) R g(h)]\} (1 - \tan \theta) + h (\tan \theta)$$  \hspace{1cm} (4.4).

In the original model as given in [Cortial 1997] the parameters $K_1$ and $K_2$ were not introduced and were given as the exact values $K_1=0.5$ and $K_2=1$, respectively. However, we have found out that introducing these parameters gives more flexibility in describing mathematically the loops generally found in the common magnetic materials. In fact, these parameters function as weight factors between $f_1(-\tanh)$ and $f_2(-\arctanh)$ functions, because in the expression $K_1 f_1 + K_2 f_2$ it is possible to increase / decrease the influence of the respective functions on the final shape of the loop by a proper choice of $K_1$ and $K_2$. We can see in Fig.4.2 that the function $f_1$ gives steeper curve with sharp bending while the function $f_2$ leads to less steep curve with bending over a larger region of $x$ values. The two parameters are not independent, because in the limit
We have also found that the shape of the loop near the closure point \( H=H_f \) can be influenced by changing the power in the expression (2) and therefore we replaced the exact value of 2 by an adjustable parameter \( K_3 \).

The reversible part of the \( B-H \) curve \( (H_f < H < H_s) \) is described by the parabolic function:

\[
B(H) = A_1 H^2 + A_2 H + A_3 \tag{4.5}
\]

where the parameters \( A_1 \), \( A_2 \) and \( A_3 \) are calculated from the border conditions:

\[
B(H_f) = B_f \tag{4.6}
\]

\[
\left. \frac{dB}{dH} \right|_{H_f} = \tan \theta \tag{4.7}
\]

\[
\left. \frac{dB}{dH} \right|_{H_s} = 0 \tag{4.8}
\]

In the original model, using the magnetization \( M \), the condition (8) corresponded to a well known fact that after the saturation the magnetization remains constant, equal to \( M_s \). In our modification, using \( B \), the flux density continues to increase after the complete saturation, because \( B = \mu_0 H \) for \( H > H_s \). In order to respect this condition.
in generating the $B-H$ curve we used the field intensity $H_m < H_s$, allowing to retain a non-zero slope of the $B-H$ curve at the extreme points.

Using the described model we were able to generate hysteresis curves which were very close to those measured experimentally in materials Ultraperm and Vitrovac. The comparison of the measured and calculated curves is given in Fig.4.3. for Ultraperm and Fig.4.4. for Vitrovac, respectively.

![Fig.4.3. The comparison of the measured and calculated curves for Ultraperm.](image1)

![Fig.4.4. The comparison of the measured and calculated curves for Vitrovac.](image2)
5. Simulation of the operation of a DC beam current transformer (DCBCT): programme.

In order to study the influence of various parameters, such as a shape of a $B$-$H$ loop, magnitude of the modulation signal, differences between two magnetic cores of a DCBCT or various kinds of noise, a simulation of the operation of the DCBCT was made. The software package MATLAB was used for this simulation, due to its powerful features e.g. in a polynomial approximation of curves, calculation of special functions and FFT analysis of signals. The results of the simulation are:

- the wave-forms of the signals $B(t)$ and $H(t)$ in the two cores of the DCBCT and the signal $dH(t)=H_1(t)+H_2(t)$; optionally can be saved as an ASCII-file
- the power spectrum of $dH(t)$ and specially the 1st and the 2nd harmonic amplitude as a function of a DC current - optionally can be saved as an ASCII-file.

In the process of the simulation the model introduced in Chapter 4 was used for a description of the $B$-$H$ curve of the magnetic material of the cores. However, the model describes the flux density $B$ as a function of the field intensity $H$. During the operation of the DCBCT we generate a modulating signal which produces a sinusoidal changes of the flux density $B$ and therefore we need to know how the field intensity $H$ changes as a function of $B$. In saturation regions of the $B$-$H$ curve this fact poses no problems because we simply find the inverse function to the parabolic function (4.8). In the irreversible part we used the following procedure: in the first step we generated the $B(H)$ curve using the defined set of parameters, then having a set of corresponding $B$ and $H$ values we made a polynomial approximation of $H$ as a function of $B$. The calculated polynomial coefficients were then used in the process of the simulation of the DCBCT.

The simulation program consists of the following parts:

1. definition of parameters of the model for a description of the $B$-$H$ loop in the core No.1 and possible differences in the core No.2; there are 3 default sets of parameters: for the $B$-$H$ loop of a general shape and for the loops corresponding to the Ultraperm 10 and Vitrovac 6025F materials, respectively.

2. generation of the $B$-$H$ loop and finding the polynomial approximation for $H(B)$ in the cores No.1 and No.2, respectively.
3. adding a noise with a possibility to add several components of noise of various kinds: sinusoidal (e.g. 50 Hz), random, Barkhausen-type noise; the amplitude of the noise can be defined as a percentage of the amplitude of the modulation signal \( B_m \).

4. input for a DC current with a possibility to define the interval \(< I_{Dcmin}, I_{Dcmax} >\).

5. calculation of the shift \( B_0 \) corresponding to the shift \( H_0 \sim I_{DC} \).

6. generation of the modulation signal (including the noise).

7. calculation of the signals \( H_1(t) \), \( H_2(t) \) and \( dH(t) \) with a graphical output on the screen.

8. the FFT analysis of the \( dH(t) \) signal.

The results of the MATLAB command ‘fft(y)’, where \( y \) is the function to be subjected to the FFT spectral analysis (\( y \) is defined by a set of \( N \) discrete points), are given as a complex Fourier coefficients, from which the amplitude (magnitude) of the respective spectral components can be obtained by calculating the sum of squares of the real and imaginary parts of coefficients. The results obtained by this procedure depend on the number of discrete samples \( N \) and therefore it makes no sense to try to interpret the amplitude in terms of real physical units. The arbitrary units will be used when presenting the influence of the shape of the \( B-H \) curve on the 2\(^{nd} \) harmonic component. When the influence of presence of noise and differences between the cores is studied, the results will be presented as the ratio between the FFT amplitude of spectral components of the \( dH(t) \) signal and the FFT amplitude of the fundamental frequency of the modulating signal.

6.1. The influence of a loop shape.

The possible influence of a shape of the $B$-$H$ curve on the overall performance of DCBT was studied by generating various loops and comparing the 2$^{nd}$ harmonic amplitude obtained as a result of a simulation programme described in Chapter 5. For this purpose a kind of a ‘catalogue’ of $B$-$H$ loops was made using a default set of loop parameters as a starting point and then gradually changing the parameters to generate loops of various shapes. The sets of parameters are presented in Tab.6.1. (bold numbers indicate a different parameter as compared to the default set).

<table>
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<tr>
<th>Loop No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<td>30</td>
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<td>1.8</td>
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<tr>
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<tr>
<td>$K_2$</td>
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</tr>
</tbody>
</table>

Tab.6.1. The parameter sets for various $B$-$H$ loop shapes.

The corresponding loops are presented in Fig.6.1.
Fig. 6.1. Various $B$-$H$ loop shapes.
The 2\textsuperscript{nd} harmonic amplitude as the output of the simulation program described in Chapter 5 was calculated for pairs of identical cores with all \( B-H \) loop shapes given above. The simulations were run for a fixed \( I_{dc} = 1 \) \( \mu A \) and sinusoidal voltage-driven modulating signal with \( B_m = 0.71 \) T. The comparison of the 2\textsuperscript{nd} harmonic amplitude for various loop shapes is presented in Fig.6.2.

**Fig.6.2.** The comparison of the 2\textsuperscript{nd} harmonic amplitude for various loop shapes.

Based on the results presented in Fig.6.2, we can make the following conclusions:

- for a fixed slope of the central part of the loop, the 2\textsuperscript{nd} harmonic amplitude is strongly dependent on the flatness of the saturation region of the hysteresis curve, characterised by the angle \( \theta \); if this angle is lower then the signal goes further into saturation and the same DC shift caused by the presence of a DC current results in larger asymmetry of the field intensity wave-form and therefore in the larger 2\textsuperscript{nd} harmonic amplitude of the resulting signal from the two cores of DCBT;
- for a fixed value of the angle $\theta$, the 2nd harmonic amplitude increases with the increase of a slope of the central part of the loop characterised by the parameter $k$ (corresponds to the increase of permeability of the magnetic material);

- for the fixed values of both $k$ and $\theta$, the 2nd harmonic amplitude is slightly higher for a lower value of the coercive field, $H_c$, i.e. for a more narrow loop; although this dependence is not very pronounced, in AC applications it is generally desirable to use materials with narrow loops in order to decrease hysteresis losses (proportional to the area of the loop);

- the 2nd harmonic amplitude is slightly dependent also on the minor details of the loop shape, such as a rounding close to the closure point of the loop - differences in the rounding are characterised by the different sets of the parameters $K_1$ and $K_2$ with the fixed values of both $k$ and $\theta$. 
6.2. The influence of differences between the two cores of DCBT (matching error).

Ideally the two cores of DCBT should be identical (to have an identical $B-H$ loop) and this identity should be preserved under all conditions (e.g. when temperature is changed). In reality it is difficult (if not impossible) to find two absolutely identical cores, because even the cores from the same production batch slightly differ in one or more parameters. Not all parameters of a magnetic material are equally likely to differ from one core to another. Parameters such as saturation flux density $B_s$, Curie temperature $t_c$ or electrical resistivity $\rho$ depend only upon the composition of an alloy (which can be well controlled) and do not change substantially in the process of manufacturing a component from the alloy. On the other hand, parameters such as permeability $\mu$, coercive field $H_c$ or remanent flux density $B_r$ are drastically affected by small amounts of certain impurities, heat treatment, residual strain, grain size or plastic deformation. Therefore the latter group of parameters is much more likely to exhibit differences from core to core.

In order to evaluate the influence of the matching error on the performance of DCBT the simulation program enables to introduce a defined difference between the two cores of DCBT. The simulations were run for a difference in the slope of a loop $k$ at $H_c$ (corresponding to differences in permeability), a difference in $H_c$ and for a difference in a loop closing point $B_k$. In the following the results obtained with a loop shape corresponding to the experimentally measured loop of Ultraperm 10 material are presented. The results for Vitrovac 6025F were qualitatively practically identical. The simulations were run for direct current $I_{DC}$ defined in the interval from $-100 \, \mu A$ to $100 \, \mu A$ with a step of $1 \, \mu A$ apart from the region from $-1 \, \mu A$ to $1 \, \mu A$ where the step of $0.1 \, \mu A$ was used in order to see whether the sub-µA resolution is in principle possible to achieve with DCBT.

The loops for a default Ultraperm set of parameters (core #1) and for a difference in $k$ of 1% and 10% (core #2) are presented in Fig.6.3. The difference of 1% is practically invisible and 10% causes only a small difference in the rounding region of the loop. However, these differences have serious influence on the harmonics amplitudes as a function of $I_{DC}$ as can be seen from Fig.6.4. Although the difference of 1% does not change $2^{nd}$ harm $- f (I_{DC})$ significantly, it leads to appearance of a relatively strong $1^{st}$
Fig.6.3. $B$-$H$ curves for two cores with different $k$.

Fig.6.4. The amplitude of harmonics as a function of $I_{DC}$ for two cores with different $k$. 
Fig. 6.5. *B*-*H* curves for two cores with different *Hₐ*.

Fig. 6.6. The amplitude of harmonics as a function of *Iᵥc* for two cores with different *Hₐ*.
Fig. 6.7. B-H curves for two cores with different $B_k$.

Fig. 6.8. The amplitude of harmonics as a function of $I_{DC}$ for two cores with different $B_k$. 
harm. component of $dH$ signal (in the identical cores 1st harm. is well below -120 dB level). The difference of 10 % causes a flattening of 2nd harm $\sim f (I_{DC})$ (i.e. worse resolution of the system) as well as observable offset. Also the 1st harmonic further increases. Similar behaviour can be observed also in the case when the cores differ in the value of a coercive field $H_c$, see Fig.6.5 and Fig.6.6.

The situation with different loop closing point $B_k$ is presented in Fig. 6.7. and 6.8. We can see that harmonics amplitudes are extremely sensitive even to the slightest deviations in this region - for example the difference in $B_k$ of only 0.1% has an effect on 2nd harm $\sim f (I_{DC})$ comparable to that of the difference of 10% in $H_c$. On the other hand, if we slightly adjust the amplitude of the modulation signal in the core #2 it is possible to restore almost completely the resolution of the pair. In fact, such an adjustment has been successfully used in practical DCBT systems [Gelato 1992].
6.3. The influence of noise.

In DCBT systems various types of noise may be present. In our simulation program we examined the influence of sinusoidal line frequency noise, random noise and Barkhausen-like noise. The last type is a noise specific to magnetic materials and is caused by discontinuities of the magnetization processes in the steep part of the $B$-$H$ loop (irreversible domain displacements = Barkhausen jumps). In the saturation region a dominant magnetization process is a rotation of magnetization vectors in domains and such a continuous process does not contribute to noise. Therefore in the simulation program Barkhausen noise is modelled simply as random noise with amplitude modulation such that the maximum amplitude occurs close to the coercive field $H_c$ and then the amplitude decreases to zero in the saturation region. Barkhausen noise of this character was experimentally observed [Swartzendruber 1990]. (Note: Barkhausen jumps were observed also in saturation region [Scouten 1970] but the amplitude of the corresponding noise was of the order of nT, therefore many orders of magnitude lower than the modulating flux density - in the following it will be shown that much higher levels of noise of this type do not have a strong influence on the DCBT operation).

In order not to mix various influences on performance of DCBT a pair of identical cores was used in the simulation studies of noise influence.

Sinusoidal line frequency noise even with relatively high amplitude equal to 0.1% $B_m$ does not cause serious degradation of DCBT performance, as can be seen in Fig.6.9. Dependence $2^{nd}$ harm ~ $f(I_{DC})$ is very close to that in absence of noise. Situation is similar with a sinusoidal noise of higher frequencies. On the other hand, the influence of random noise with amplitudes orders of magnitude lower is very serious. The results of the simulations with a random noise of amplitude equal to 0.01% $B_m$ and 0.001% $B_m$ are presented in Fig.6.10. and Fig.6.11., respectively. In the case of 0.01% the resolution is practically lost at the level of tens of µA; apart from this relatively high and very noisy $1^{st}$ harm. is present. The situation is obviously better with 0.001%, but still it seems that it would be difficult to achieve sub-µA resolution at this conditions. The reason why the signal is so sensitive to the random noise is that even the slightest disturbances in the peaks of modulating (=flux density) signals are transformed to large
Fig. 6.9. The amplitude of the 2\textsuperscript{nd} harmonic as a function of $I_{DC}$ in presence of sinusoidal noise 50 Hz, amplitude 0.1\% $B_m$.

Fig. 6.10. The amplitude of the harmonics as a function of $I_{DC}$ in presence of random noise, amplitude 0.01\% $B_m$. 
Fig. 6.11. The amplitude of the harmonics as a function of $I_{DC}$ in presence of random noise, amplitude 0.001% $B_m$.

Fig. 6.12. Wave-form of $dH$ signal in presence of random noise (0.01% $B_m$, $I_{DC} = -0.1$ mA).
Fig. 6.13. The amplitude of the 2\textsuperscript{nd} harmonic as a function of $I_{DC}$ in presence of Barkhausen-like noise, amplitude 0.01\% $B_m$.

Fig. 6.14. Wave-form of $dH$ signal in presence of Barkhausen-like noise (0.1\% $B_m$, $I_{DC}$ = -0.1 mA).
disturbances of the field intensity wave-form when the material is driven far into the saturation; and, of course, by adding two signals from the two cores of DCBT this effect is even enhanced if the disturbances are uncorrelated in the two cores. An example of a $dH$ wave-form in the presence of random noise is presented in Fig.6.12. Contrary to this behaviour, the influence of Barkhausen-like noise is much less serious as can be seen from Fig.6.13 It is simply because this type of noise is maximum between the peaks of the resulting $dH$ signal and in the regions of peaks of $dH$ it is practically negligible. An example of a $dH$ wave-form in the presence of Barkhausen-like noise is presented in Fig.6.14.
7. Magnetic materials for toroidal cores for DCBT.
This chapter is intended as an introductory information about the most important properties of the magnetic materials for DCBT as well as a survey of the commercially available materials. More detailed information about magnetic materials can be found in a specialised literature [see e.g. Boll 1990, McCurrie 1994 and references therein].

General requirements in AC applications are:
- low hysteresis losses due to cyclic magnetization changes; hysteresis losses are proportional to the area of the hysteresis curve:

\[ W_h = \frac{1}{2} H dB \]

therefore magnetic materials with narrow loops are preferable;
- low eddy current losses due to the induction of electric currents by the changing magnetic flux; eddy current losses are inversely proportional to the electrical resistivity of the material:

\[ P_e \sim \frac{f}{d} B_m^2 \frac{d}{\rho} \]

therefore materials with high \( \rho \) are preferable (\( f \) - frequency; \( d \) - thickness).
- relative permeability \( \mu \) should be as high as possible;
- preferably linear dependence of \( \mu \) on temperature;
- possibility of special shapes of a \( B-H \) loop, e.g. rectangular, flat.

If the specific application (such as DCBT) requires very high permeability a material must possess the following properties:

1. Very low crystalline anisotropy constant \( K_1 \), preferably with many easy directions (e.g. in Ni-Fe alloys there are 8 easy directions \(<111>\)). Low \( K_1 \) leads to low domain wall energy \( \gamma \)

\[ \gamma = 4\sqrt{A K_1} \]

where \( A \approx kT_c / a_0 \) (\( a_0 \) - the crystal lattice constant). Low domain wall energy facilitates the nucleation and displacement of walls in the lowest possible fields. Low \( K_1 \) also results in domain walls with relatively high thickness \( \delta \) :

\[ \delta = \pi \sqrt{A/K_1} \]

which means that the interaction of walls with grain boundaries, inclusions, defects (with dimensions much smaller than the wall width) is not very strong and therefore...
magnetization changes are not hindered. Low $K_1$ also leads to low coercive field $H_c$ and high initial permeability $\mu_i$ because $H_c \sim K$ and $\mu_i \sim 1/K$, respectively.

2. High homogeneity: if the magnetic material is single phase material, free from inclusions, impurities, defects and stresses then in the presence of an applied field the domains should move easily.

3. Low magnetostriction: the presence of stress produces an effective additional anisotropy and further impedes the motion of domain walls because of an interaction between mechanical stress and magnetization (magnetoelastic interaction).

Additional requirements are:
- high Curie temperature
- good temperature stability
- good corrosive resistance
- mechanical strength
- low cost.

High-$\mu$ materials can be found in the following groups of materials:

1. Ni-Fe alloys. These materials are well established in all applications requiring magnetic materials therefore they will be only briefly mentioned here. A range of compositions over which good magnetic properties can be obtained exists. The highest $\mu$ can be found in 79-80 % Ni materials such as Permalloy (with added Mo), Supermalloy (79 % Ni, 15 % Fe, 5 % Mo); Mumetal (77 % Ni, 5 % Cu). Various grades of these alloys are commercially available from producers such as Vacuumschmelze GmbH (material with the highest $\mu \sim 400 000$ - Ultraperm™ 200) or Imphy S.A. (material with the highest $\mu \sim 350 000$ - Superimphy™ TLS).

2. Amorphous alloys. These materials are usually based on the composition $T_{80}M_{20}$ where $T$ is one or more of the transition metals (Fe, Co, Ni, Mo...) and $M$ is one or more of the metalloids or glass forming elements (B, C, Si, P). The alloys are quenched from the melt which means that there is no regular crystalline structure and consequently no magnetocrystalline anisotropy energy. Small induced anisotropy can exist in thin ribbons, but it is very low. As a result $\gamma$ is low and $\delta$ high which means that domain walls move easily and very high $\mu$ can be achieved. Further increase of $\mu$ can
be achieved by annealing in order to remove residual stress (via magnetoelastic effects it impedes domain wall motion). The first commercial alloys were produced by Allied Signal Corp. - Metglas™, and by Vacuumschmelze GmbH - Vitrovac™. There exist several groups of these alloys:

1. Fe-based: they have high saturation flux density $B_s \sim 1.4 - 1.8$ T;
2. Fe-Ni-based: with $B_s \sim 0.75 - 0.85$ T;
3. Co-based: with $B_s \sim 0.4 - 1.2$ T, magnetostriction $\lambda_1 \to 0$, the highest $\mu$ (500 000 for Vitrovac 6025Z; 1 000 000 quoted for Metglas 2714A), the lowest losses.

From this it is clear that $B_s$ is very sensitive to the exact composition!

The amorphous alloys are prepared by rapid cooling ($10^5 - 10^6$ K/s) process in which the melt is injected into (onto) 2 (1) cylinders. Due to the nature of this process only limited thickness (0.02 - 0.05 mm) of the final material (usually in a form of ribbons or tapes) is available. These materials have very high mechanical hardness (high yielding point limit) due to the absence of the long range ordering. The mechanical properties of amorphous magnetic materials allow to use them in the form of flexible foils for the applications such as magnetic shielding.

3. Nanocrystalline materials. In composition they resemble the amorphous Fe-based alloys (roughly $T_{70-80} M_{30-20}$, where T and M are explained above). Their special properties are set after a crystallization heat treatment. The structure obtained consists of crystal grains with diameter of cca 10-15 nm surrounded by an amorphous residual phase. Contrary to amorphous alloys described above the nanocrystalline ribbons are extremely brittle, therefore only the end product (e.g. a toroidal core) can be heat treated. Magnetic properties such as permeability, coercivity and core losses are comparable to amorphous Co-based alloys and thin strip 80%NiFe alloys. As compared to these materials, nanocrystalline materials have very low magnetostriction, higher saturation flux density $B_s \sim 1.2$ T and better temperature and temporal stability (especially when compared with amorphous alloys) - the possible permanent application temperature is up to 150 C. A high value of the Curie temperature $t_c \sim 580$ C could reduce temperature effects around 20 C and reduce ageing effects. The alloy contents are also less expensive (compared to Co-based amorphous alloys). A possibility of very small magnetic domains size (although grain size does not
necessarily correlate with the size of domains) leads to low level of magnetic noise and good high frequency performance. The present structural phases lead to low or vanishing saturation magnetostriction which minimises magneto-elastic anisotropy. Nanocrystalline alloys have relatively high electrical resistivity $\rho \approx 115 \, \mu\Omega\text{cm}$ (comparable to amorphous alloys) which together with a low ribbon thickness $\sim 20 \, \mu\text{m}$ yields a favourable frequency dependence of $\mu$ and low eddy current losses up to 100 kHz (values such as $\mu_1 > 80000$ at 1 kHz, $\mu_1 > 10000$ at 200 kHz can be found in technical literature).

The main problems of nanocrystalline materials are:
- brittleness as-cast and especially after annealing - it is a consequence of the relatively low glass-forming ability of the alloy;
- the stress-sensitivity of the magnetic properties which arose from the fact that the magnetostriction approaches zero only as a result of an internal average (in contrast, Co-based amorphous alloys are truly non-magnetostrictive almost down to an atomic scale), as a result nanocrystalline alloys are unsuited to applications such as flexible shielding.

Commercially available nanocrystalline materials:
- Vitroperm™ - produced by Vaccumschmelze GmbH, products:
  - Vitroperm 500F: $\mu$ (at $H=0.3\,\text{A/m}$, 10 kHz) $\approx 80000$; $B_s\sim 1.2\,\text{T}$, $H_c\sim 0.5\,\text{A/m}$, $t_c\sim 600\,\text{C}$,
  - Vitroperm 800F: $\mu$ (at $H=0.3\,\text{A/m}$, 10 kHz) $\sim 100000$
- Finemet™ - produced by Hitachi Metals, products:
  - Finemet FT-1: with balanced magnetic characteristics, $B_s \sim 1.35\,\text{T}$, $H_c \sim 1.3\,\text{A/m}$, $\mu_1 (1kHz)=70000$
  - Finemet FT-2: with high $B_s$, $B_s \sim 1.45\,\text{T}$, $H_c \sim 1.8\,\text{A/m}$, $\mu_1 (1kHz)=50000$
  - Finemet FT-3: with zero magnetostriction, $B_s \sim 1.23\,\text{T}$, $H_c \sim 2.5\,\text{A/m}$, $\mu_1 (1kHz)=70000$
  - each available with 3 types of the loop: with a high remanence ratio ($B_r/B_s$); with a midrange ratio and low ratio (the above data are for midrange).

4. Ferrites. A general formula for the composition of these materials is $\text{MO}_x\text{Fe}_2\text{O}_3$ where $M$ is bivalent metal ion (Mn, Fe, Co, Ni, Cu, Zn ...). Most ferrites are oxide magnetic materials with mechanical properties similar to insulating ceramics. Maximum permeability and saturation flux density $B_s$ are lower as compared to those in the above
mentioned materials. The important property of ferrites is very high resistivity which leads to very low eddy current losses. This property makes these materials especially suitable for high frequency applications.

5. **Powder materials.** These materials consist of fine powder (Fe or NiFe) insulated and bounded by binding material. Such a procedure ensures that eddy currents are reduced in all 3 dimensions (when compared with sheets and foils). The important property is high isotropic electrical resistivity - factor $10^4 - 10^{10}$ more than metallic alloys. Similarly to ferrites, these materials are suitable for high frequency applications, e.g. for cores and various forms elements for radio & TV as well as for power electronics. The problem can be a relatively high coercive field $H_c$ which results in high hysteresis losses.

Comparison of metals, ferrits and powder materials is given in Fig.7.1. ($J_s$ is saturation magnetization).

![Fig.7.1. Magnetic and electrical properties of soft magnetic materials (after Boll 1990).](image)
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References:
