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Hysteresis in an axial rotating SMB used in the ring spinning process

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Abstract

Superconducting magnetic bearings are passive stable magnetic levitating bearings which only need a material depending cryogenic temperature for their operation. The application of a rotating superconducting magnetic bearing (SMB) with high rotational speed in a ring spinning machine replaces the traditional, friction afflicted ring-traveler twist element. Ring spinning is the most common process to produce short stable yarn in textile industry. The SMB twist element significantly reduces the productivity limiting friction heat in the spinning process and thus the process speed will be increased from commonly 25000 rpm up to 50000 rpm.

In this application melt textured $YBa_2Cu_3O_{7-x}$ (YBCO) is used as superconductor and NdFeB as permanent magnet (PM). The PM ring rotates driven by the yarn and thereby imparts twist in it. The yarn force on the PM is an eccentric acting point force which leads to a tilt of the PM ring in the position to the superconductor ring. In combination with high rotational speed this tilt leads to a significant heat input in the superconductor due to hysteresis.

Keywords : superconducting magnetic bearing, hysteresis heat , axial rotating bearing, YBCO, ring spinning

1. Introduction

Superconducting magnetic bearings (SMB) enable the levitation of a magnet in an inherently stable position over a cooled superconductor. No additional positioning system is necessary but a material depending cryogenic temperature of the superconductor has to be guaranteed for their operation. These passive bearings are being investigated for applications of stationary levitation and contact free motion in all space dimensions. Linear superconducting magnetic bearings e.g. are used in the levitating transport systems e.g. Supratrans2 [1]. In energy storage applications SMBs could prove advantage compared to the conventional system [2].

The application of a rotating superconducting magnetic bearing in a ring spinning machine as a replacement of the traditional, friction afflicted ring-traveler twist element is presented in [3] [4] [5]. The continuous ring spinning process converts a loose fiber lint named roving to yarn by drawing down, twisting, and winding up on a bobbin. The ring traveler system thereby induces twist in the processed material by guiding it around the spindle. The yarn is guided through a c-shaped clip, the traveler, which is dragged along a ring surrounding the spindle. The traveler is slightly slower than the spindle, enabling the winding of the yarn onto the bobbin. The rotational speed and hence the productivity of the process is limited by the friction heat between ring and traveler. This heat damages the twisting element which causes wear and also can lead to melting of synthetic yarns at high rotational speed. Therefore the maximum rotational speed with a conventional twist element is 25000 rpm or less, depending on the raw material of the fibers. The application is shown in Figure 1. Further modeling about the bearing and yarn properties was published in [6] [7].

The SMB twist element significantly reduces the productivity limiting friction heat in the spinning process of short staple yarn and thus the process speed can be increased from commonly 25000 rpm up to 50000 rpm. In Figure 2, the components are shown. It consists of a fixed superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) ring which is cooled on 77 K. Levitating above it is a rotating permanent magnetic (PM) ring with a fixed eyelet as yarn guide. The YBCO ring is cooled by a continuous flow cryostat using liquid nitrogen (LN_2) [8]. The special design cools down the superconductor (SC) by solid state conduction and hence allows the free positioning of the YBCO ring in the vacuum chamber. This is important to assure a small initial cooling distance (field cooling height) between PM ring and SC ring of 5 mm and hence good bearing properties like bearing force and stiffness.
The PM ring rotates driven by the yarn and thereby imparts twist in it [3] [4]. The yarn force on the eyelet is an eccentric acting point force $F_Y(\omega)$ (components $F_Y^z, F_Y^\varphi, F_Y^r$) which leads to a tilt (angle α) of the PM ring in the position to the YBCO ring. In combination with high rotational speed this tilt leads to a hysteretic heat input in the superconductor.
At high rotational speed, this hysteresis heat becomes an important factor on the bearing reliability. It was estimated to be 13.4 W at 25000 rpm for the maximum tilt in the resonance case during rotation [8]. This is significantly higher than the heat input due to convection, radiation and conduction of ~ 2.3 W. The real amount of displacement and heat input has to be measured as well as its influence on the cooling effort of the SC.

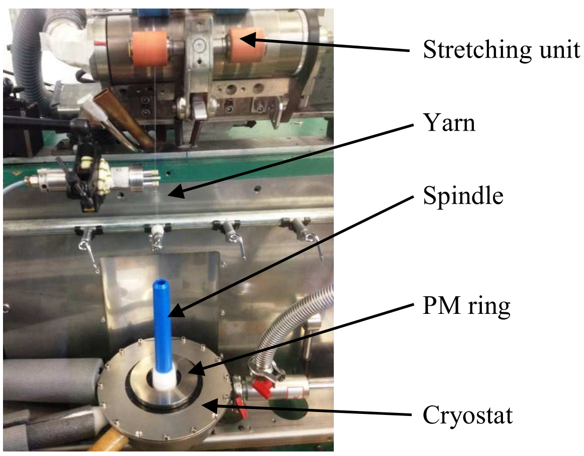

Fig. 1 SMB twist element in the ring spinning tester

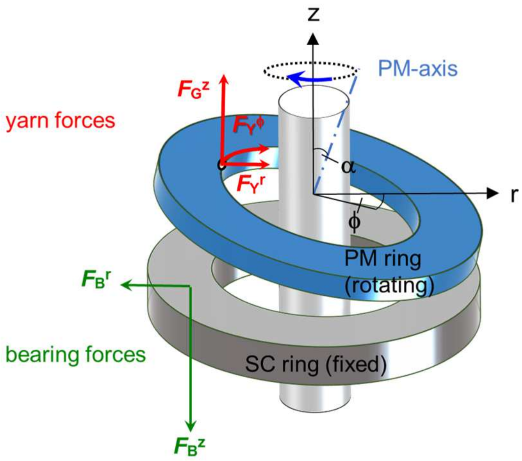

Fig. 2 Configuration of the SMB twist element

2. Calculation

The heat input due to hysteresis $\dot{Q}_{Hyst}$ mainly depends on the change of the magnetic field dB seen by the SC and the rotational speed f_i. It is described by:

$$\dot{Q}_{Hyst} = V_{SC} \cdot dB \cdot j_c \cdot f_i \cdot w \qquad (1)$$

V_{SC} is the superconductor volume affected by the hysteresis, j_c the critical current density and w the length of the current loop in the SC.
The change of the magnetic field seen by the SC during spinning depends on the yarn force induced displacement of the PM ring from its initial cooling position. Figure 3 gives an overview of the estimated values for dB (medium value over the PM ring area) vs. displacement. A movement from the PM to the SC surface causes a higher change of the magnetic field then the movement away from the SC. This is due to the inhomogeneous distribution of the magnetic field. The displacement of the PM ring during rotation under an external force is determined by the properties of the SMB which are defined by the quality of the superconductor at a given temperature, the bearing area and the field cooling distance.
The calculation of the dynamic oscillation amplitude $A(\omega)$ as a function of the frequency was done by Sparing *et al.* [7]. It can be described as a function of the yarn force $F_Y(\omega)$, the mass of the PM ring m_{PM}, the rotational speed ω, the eigenfrequency ω_0 and the damping constant δ.

$$A(\omega) = \frac{F_Y}{m_{PM}} \frac{1}{\sqrt{(\omega^2 - \omega_0^2)^2 + 4\delta^2\omega^2}} \quad (2)$$

In [7] the dynamic displacement of the PM ring was calculated with experimentally obtained values for ω_0 and δ as a function of the field cooling height and initial displacement. These results show, for a field cooling height of 5 mm and the yarn force $F_Y(\omega)$ measured by Hossain *et al.* [6], an oscillation amplitude of max. 0.6 mm at the resonance frequency of the bearing at around 1000 rpm and an oscillation amplitude of only a few micrometer in the high frequency range intended for the operation of the twist element.

For a YBCO ring out of 10 melt textured YBCO bulk segments with a total surface of 16 cm² and a critical current density j_c of 10^4 A/cm², the heat input shown in Table 1 was estimated.

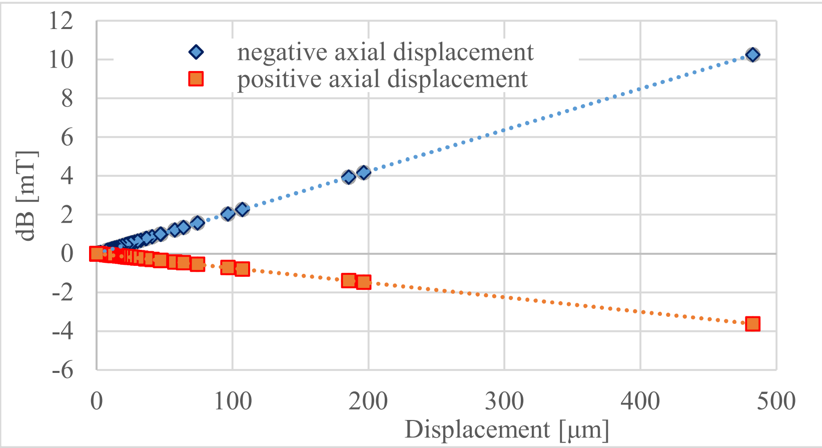

Fig. 3 Medium change of magnetic field seen by the SC ring over the displacement of the PM ring for a field cooling height of 5 mm

Table 1 Hysteretic heat in W

	f [rpm]		
B [T]	5000	25000	50000
0.002	0.13	0.66	1.33
0.004	0.27	1.33	2.65
0.03	1.99	9.95	19.90

3. Experimental setup

3.1 Measurement of the displacement

First, the calculated data for the oscillation amplitude needs to be verified. This is done by an optical measurement of the displacement of the PM ring $A(\omega)$ during the actual ring spinning process. The knowledge of the real dynamic displacement of the PM ring is important in order to realistically estimate the change of the magnetic field seen by the superconductor during the process and with this to calculate the heat input due to hysteresis.

The system consists out of four optical distance sensors which measure the position of four given surface points of the PM ring and two sensors to measure spindle speed and PM ring speed. Out of the position measurement the displacement of the PM ring to the initial position (field cooling position) can be calculated.

3.2 Measurement of the hysteretic heat

To validate the calculated heat input due to this displacement, a calorimetric test facility shown in Figure 4 is set up. The YBCO ring therein is fixed to the inner vessel in the liquid nitrogen bath. The outer vessel guarantees a minimized heat input into the inner vessel due to the temperature difference between liquid nitrogen and vapor. The PM ring is connected to a motor and placed over the liquid nitrogen bath. It is adjustable in height and tilt to its initial position. The hysteresis heat is measured by the amount of nitrogen vapor evaporating in the inner vessel for a rotational speed of 1000 – 5000 rpm, a field cooling height of 3 - 6 mm, and a tilt angle around the tilt point of the PM of 1 – 4°.

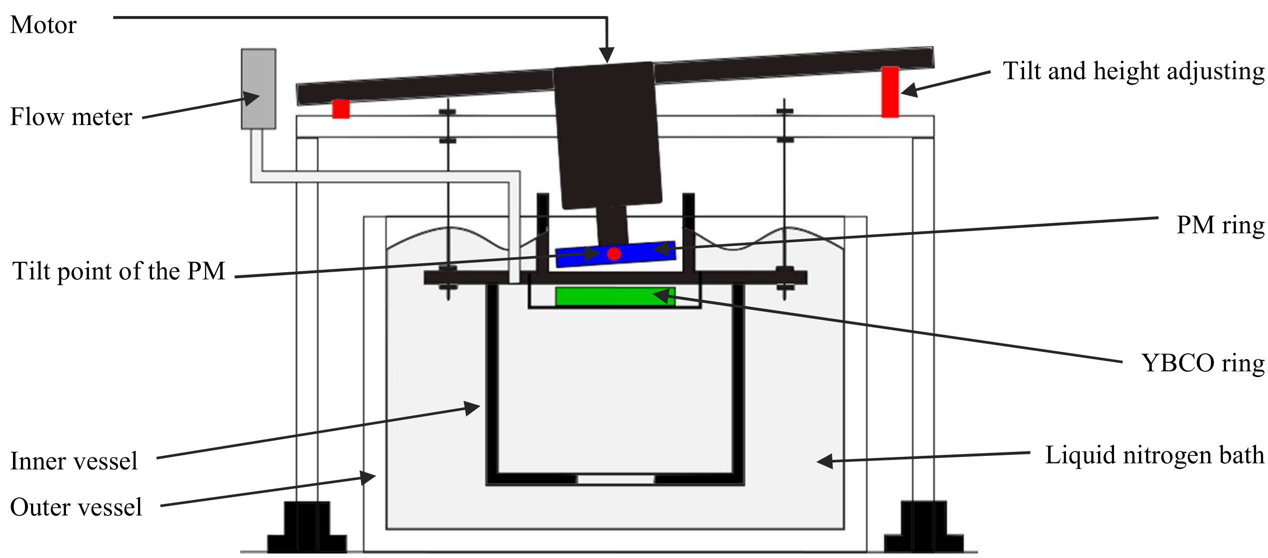

Fig. 4 Calorimetric test facility to measure the heat input due to hysteresis

4. Results

The setup of the measurement facilities has been delayed and only preliminary measurements have been done so far. The measurement results and discussion will be presented at the 15th International Symposium on Magnetic Bearings in Kitakyushu, Japan.

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