DESIGN, CONSTRUCTION AND TESTING OF A KINETIC ENERGY STORAGE DEVICE WITH HIGH-TC SUPERCONDUCTIVE SUSPENSION

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ABSTRACT

The paper describes a small kinetic energy storage device built to demonstrate the feasibility of a flywheel system in which the rotor is supported on a five axis passive magnetic suspension based on High-Tc superconductors (HTS). The tests aimed to measure the performances of the superconductive magnetic bearing are described together with the details of the design and the analysis and the tests on the prototype. The machine has been operated satisfactorily using a hybrid bearing layout and will be tested using a complete magnetic suspension as soon as superconductors with higher characteristics will be available.

INTRODUCTION

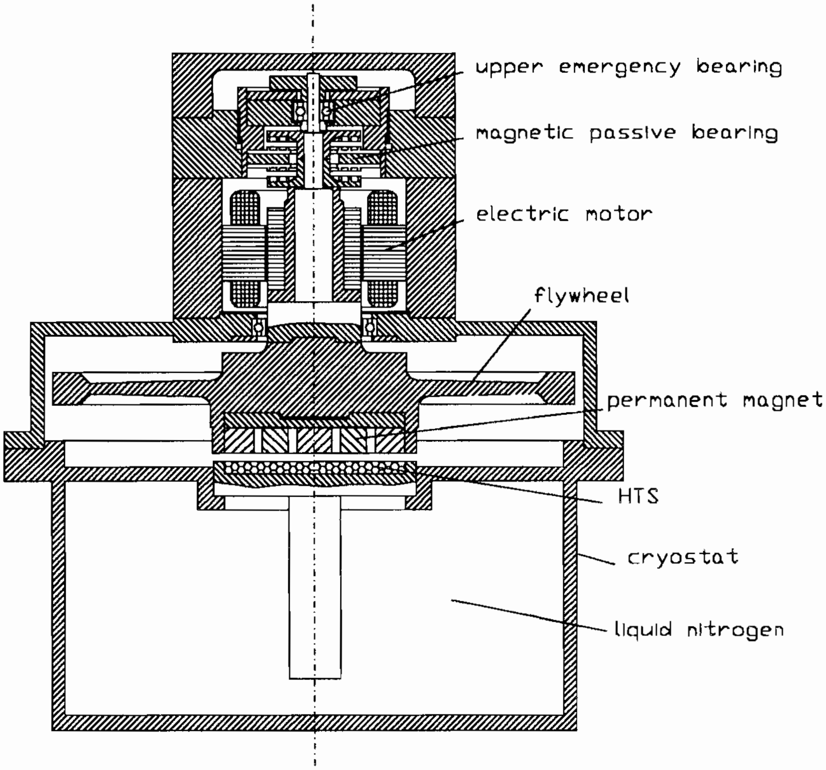
One of the most promising near term applications of high temperature superconductors (HTS) is the construction of magnetic levitation devices, both in the field of rotating machinery and of vehicles. The basic advantages over other types of magnetic suspension are the possibility of stable operation without the need of the complexities of active control and the very low drag. However, if current materials are used, the drawbacks of this solution are still overwhelming: the levitation force and, above all, the stiffness is too low for most applications and the need of a cryostat to operate at temperatures near the boiling point of nitrogen (77 K) or lower restricts the field of potential applications. It must be noted that the energy needed to maintain the system at the operating temperature well exceeds the energy used by active systems to generate the levitation forces.

The interest in superconductive magnetic bearings (SMB) is mostly due to the predictable improvements in the characteristics of HTS, both in terms of critical current and of critical temperature. The work here described is the continuation of a previous research in which a small very high speed (120000 rpm) electric motor was built and tested [1]. The aim was to demonstrate the feasibility of a machine of larger size, namely a flywheel energy accumulator, based on SMB technology.

The research and development work was subdivided between the participants, with CISE studying and manufacturing the HTS materials, Department of Mechanics of Politecnico di Torino performing the experimental characterisation (superconductors and assembled bearing) and participating to the design and structural analysis of the machine and Elettrorava being in charge of the detailed design, construction and functional testing of the system.

LAYOUT OF THE MACHINE

The machine was designed with the goal of storing about 20 Wh at 2200 rad/s (21000 rpm). As a consequence a single-disc light alloy flywheel, with outer diameter of 300 mm, having a polar moment of inertia of 0.03 kg m^2 was designed. As the energy density is 6 Wh/kg, the mass of the wheel is of about 3.3 kg. A further mass of about 3 kg for the electric motor/generator and the shaft must be added, resulting in a total mass of the rotor of 6.3 kg. To reduce windage losses the machine was designed for vacuum operation. This requirement compels to physically separate the cryostat from the vacuum chamber owing to the presence of boiling liquid nitrogen in the former. The design of a vacuum-tight cryostat was performed by CISE. The complexity of the cooling system suggested the use of a hybrid bearing system, in which the SMB acts as a stable axial and radial bearing while



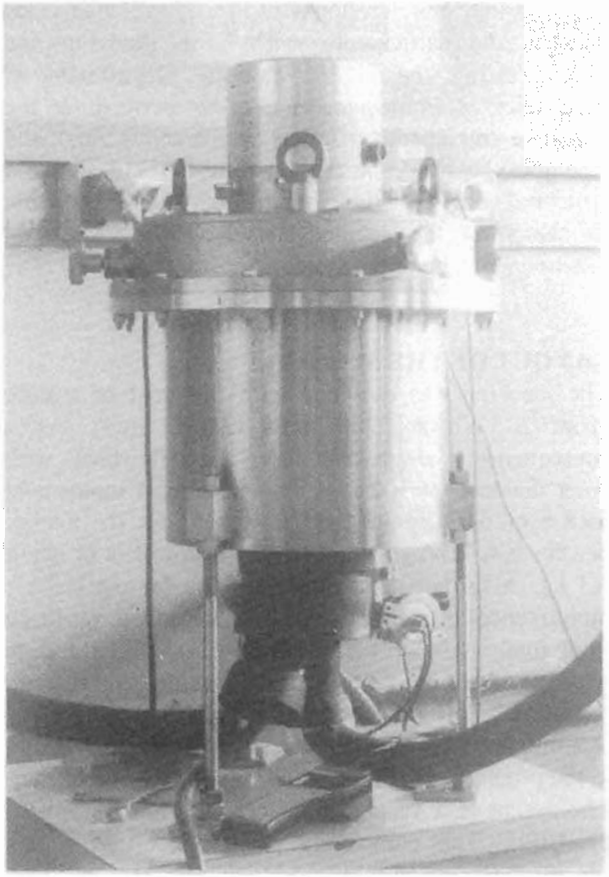


FIGURE 1: Assembled machine (sketch and picture)

the second bearing is a passive permanent magnet magnetic bearing.

As the latter is unstable in axial direction, the SMB must have an axial stiffness high enough to overcome the negative axial stiffness of the passive bearing, which was evaluated at about -36 N/m.

During the design phase several tests were conducted with the aim of evaluating the levitation force and the stiffness of the bearing. These tests showed that both the force and the stiffness obtainable from the present superconductor are not sufficient to allow a stable working of the device, but that the required values are well within the capabilities of the material. While waiting for the availability of a superconducting bearing with higher characteristics, the machine was modified to a hybrid configuration in which the upper magnetic bearing was replaced by a rolling elements bearing with ceramic balls, the same bearing which in the nominal configuration is used as upper touchdown bearing.

The superconducting surface is positioned below a fibreglass plate which constitutes the top plate of the vacuum-tight cryostat. This compels to use a value of the gap between the surface of the superconductor and the magnet which is higher than the optimum value from the magnetic viewpoint. It was stated at 2.5 mm, in such a way to allow an effective gap of 1 mm, taking into account the thickness of the fibreglass plate on the top of the cryostat. The bearing has been designed for field cooling at 2.5 mm. An iron steel disk calculated in order to close the magnetic line field and to enhance the strength of the field on the superconducting surface was adhesively bounded over the ring magnet. In order to allow to cool the system at the proper distance the flywheel container is provided of three screw-operated shoes, which clamp the flywheel during assembly. The screws enter the vacuum chamber through rubber seals. The assembly operation must be performed with the following sequence: a light alloy plate is placed on the superconductor to keep the flywheel in the proper axial and radial position; the machine is assembled and the flywheel is locked in position by the shoes by tightening the screws; the machine is disassembled and the plate is removed; the machine is assembled again and liquid nitrogen is allowed into the cryostat; after reaching the operating temperature, 14 K below the critical temperature of the material, the locking screws are untightened and the rotor is freed. This procedure can be checked visually through three viewports, covered by transparent plastic windows.

The instrumentation includes a photocell for measuring the speed, a thermocouple inlaid in the superconducting bearing and accelerometers for studying the dynamic behaviour of the machine.

A sketch of the layout of the machine, which includes the two magnetic bearings, a couple of emergency rolling-elements bearings and the electric motor (two poles, $V_n = 54$ V, $f_n = 350$ Hz, $P_n = 500$ VA) is shown in figure 1.

SMB EXPERIMENTAL CHARACTERISATION

The superconductive part of the bearing is made by a planar array of hexagonal tiles of YBCO, obtained through the melt-texturing process by CISE. A Modified Melt-Powder-Melt-Growth (MMPMG) Process was adopted to fabricate the Y-Ba-Cu-O pellets. BaO_2, CuO and Y_2O_3 powders underwent a quench treatment after a 1100°C stage in a Pt crucible. The obtained $BaCuO_2$ and $BaCu_2O_2$ lumps were ground, mixed with Y_2O_3 powder and axially pressed into cylindrical pellets having a diameter of 30 mm and thickness of 6 mm. The thermal growth treatment consisted in a 1100°C annealing and oxygenation for three days at 500°C. Further details are described in [2]. The pellets were finally cut into hexagonal tiles and placed on a block of hoxigen-free copper which is directly cooled by the liquid nitrogen. The tiles are positioned under a thin fibreglass plate which constitutes the top vacuum-tight plate of the cryostat.

The superconductors interact magnetically with a set of three concentric rare-earth ring magnets assembled in annular grooves in the lower surface of the flywheel (Table 1). A number of static tensile tests on annular magnets were performed in order to guarantee that the magnets are able to withstand centrifugal stressing. The magnetic field generated by the magnets was mapped using a computer controlled Hall probe in order to verify the axial symmetry of the field. A maximum deviation from axial symmetry of 2.5% was measured. This feature is very important if the advantages of SMB are to be fully exploited, as the drag torque of the bearing is mostly linked with the lack of axial symmetry of the field.

TABLE 1: Characteristic of the SMB

NdFeB magnets		
number of magnets	dimensions [mm] (Φ_{ext}*Φ_{int}*h)	surface field [T]
3	104*70*15 60*30*15 15*15	0.475 0.615 0.49
Y-Ba-Cu-O		
number of tiles	dimensions of tiles [mm] (Φ*h)	dimensions of array [mm] (Φ*h)
16	30*6	110*6

The experimental characterisation was performed on single tiles and on the assembled bearing using the apparatus described in detail in [1]. The experimental results were compared with the analytical prediction supplied by the mathematical model described in [3].

A first group of tests, consisting in measurements of the interaction force as function of the distance, axial and radial stiffness and magnetic creep, was performed on the complete bearing initially built by CISE.

The results are summarised in Table 2; figure 2 shows the results in the operating condition of the SMB. From the rate of the decay of the levitation force a depinning activation energy U_0= 0.1eV was calculated using

$$F = F_0\left[1-\frac{kT}{U_0}\ln(t)\right] \qquad (1)$$

were k is the Boltzmann constant, T the temperature, F_0 the initial force and t the time.

As a results of the tests performed on the bearing, the values of the levitation force, axial and radial stiffness which can be expected in the actual working conditions are respectively of 42.7 N, 45868 N/m and 15500 N/m. They are not sufficient to fulfil the requirements of the design. While the tests on the bearing where performed by Politecnico di Torino, CISE continued the development of melt textured specimens having enhanced properties and high thickness. Owing to the difficulties to obtain a significant amount of material in a short time, the characterisation tests were conducted on single tiles [4]. By extrapolating the values obtained on the single tile to the whole bearing, the values of the axial force and the axial stiffness are respectively 210 N and 91000 N/m: both are sufficient for the application [3]. They will be used in a subsequent stage of the research work.

TABLE 2: Results of the tests on the first bearing

Axial force

Fz(max) [N]	Fz(min) [N]	Cooling	Magnet d_o*d_i*t	Fza[1] [N]
16.56	-6.21	ZFC[2]	60*30*15	
15.66	-6.47	FC 5[3]	60*30*15	-4.71
18.02	-6.33	FC 2	60*30*15	-8.64
17.79	-6.66	FC 6	60*30*15	-4.37
40.88	-21.40	ZFC	3 rings[4]	
37.84	-21.78	FC 6	3 rings	-13.72
42.74	-22.15	FC 4	3 rings	-17.59

Magnetic creep

Time [s]	Cooling	Magnet	z [mm]
3600	FC 2	3 rings	2

Axial stiffness

K [N/m]	Cooling	Magnet d_o*d_i*t	z_c[5] [mm]
3410	FC 6	15*15	2
9365	FC 2	60*30*15	2
16179	FC 6	60*30*15	2
40850	FC 2	3 rings	2
45868	FC 6	3 rings	2

Radial stiffness

K [N/m]	Cooling	Magnet d_o*d_i*t	z_c [mm]	Type
6701	FC 6	60*30*15	2	$F_x(x)$
15500	FC 2	3 rings	2	$F_x(x)$
10565	FC 2	3 rings	2	$F_y(y)$

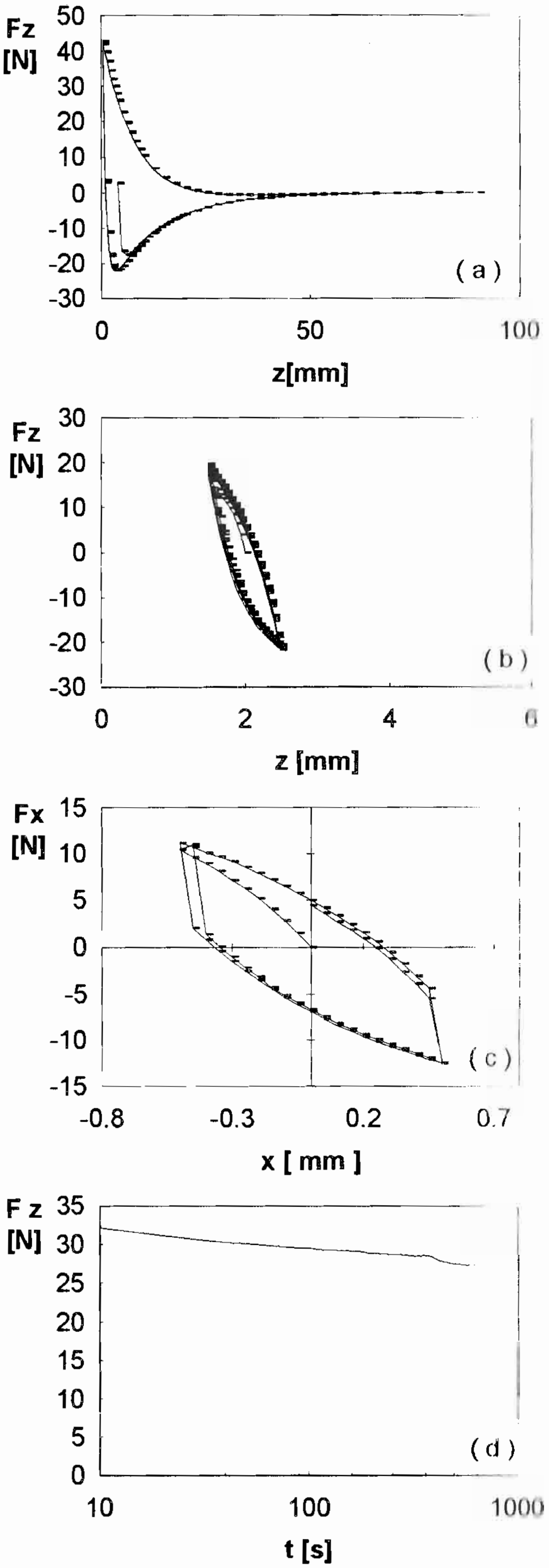


FIGURE 2: Results of the three tests performed on the SMB. a) levitation force vs. distance between magnet and superconductor; b) levitation force during a microcicle in a configuration aimed to measure the axial stiffness; c) levitation force during a microcicle in a configuration aimed to measure the radial stiffness; d) levitation force vs. time for assessing magnetic creep.

STRUCTURAL ANALYSIS OF THE FLYWHEEL AND DYNAMIC ANALYSIS OF THE ROTOR

The flywheel is shaped as a constant stress disc with constant thickness rim. A value of the moment of

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[1] maximum attractive force during the first displacement of the magnet from the HTS in field cooling conditions.

[2] Zero Field Cooling.

[3] Field Cooling with 5 mm magnet-tile displacement.

[4] dimensions 15*15+60*30*15+104*70*15.

[5] displacement offset for microloops.

inertia of 2.5 10^{-2} kg m^2 was assumed in the design, as the other components of the system would provide the remaining 0.5 kg m^2 to obtain the required energy storage capability.

The stress analysis performed using a conventional finite-difference procedure [5] yielded a maximum value of the stress equal to 125 MN/m. Owing to the low value of the stress no further stress analysis was performed.

The whole rotating system was modelled using DYNROT 4.1 rotordynamic FEM code. 17 Timoshenko beam elements, 2 mass elements and 3 spring elements were used. The latter were used to simulate the two bearings and the negative radial stiffness of the electric motor. As the damping of the SMB is quite high, no detailed numerical stability analysis was planned. As a consequence, no damping was introduced into the model. The total number of the complex degrees of freedom is 36, 18 of which were considered as master degrees of freedom in the dynamic analysis. The overall inertial properties of the model are: mass 5.81 kg, moments of inertia J_x = 0.0308 kg m^2, J_y = 0.0308 kg m^2, J_z = 0.0294 kg m^2.

The SMB was modelled as a linear spring, whose stiffness was evaluated from the above mentioned static tests. However this procedure is very likely to yield a value of the first critical speed lower than the actual one as the dynamic stiffness of the SMB is likely to be higher than the static value. To settle this matter a first experimental investigation on the whole machine was performed.

The mathematical model built using the static value of the stiffness of the superconductor (1.7 10^4 N/m) for the SMB and the value measured on a ball bearing mounted in an elastomeric hosing of the same type and size of that used in the machine (4.0 10^5 N/m) for the upper bearing, yielded the following values for the first two critical speeds: 723 rpm (12 Hz) and 18632 rpm (310 Hz). From the mode shapes it follows clearly that the first two modes are rigid-body modes, the first being a rotation about the upper bearing and the second one a rotation about the SMB. The stiffness of the latter then influences almost only the first critical speed.

The machine was assembled in the corresponding configuration and operated up to 18000 rpm, where the vibration level was high and quickly growing, indicating the approach of the second critical speed. A spin-down test was performed, finding the first critical speed at about 1700 rpm. The critical speeds were then computed, varying stiffness of the SMB, obtaining a good correspondence with the experimental results with a stiffness of 1 10^5 N/m.

Both numerical and experimental results show that the version of the machine based on a conventional rolling-element bearing has a second critical speed in a dangerous position in the operating range: its operating speed must be limited to 18000 rpm. This problem does not exist in the nominal configuration using a passive permanent magnet bearing. Using a value of 3.6 10^4 N/m for the stiffness of the upper bearing, the values of the first two critical speeds are 1458 rpm (24 Hz) and 7998 rpm (133 Hz). The second critical speed is low enough to allow to pass it without problems, while the third one, due to a flexible mode of the rotor, is well above the working range.

The presence of the electric motor reduces the values of the critical speeds owing to its intrinsic negative radial stiffness, which depends on the ratio voltage/frequency. If its value is large enough, it can even induce an unstable behaviour of the machine.

Using a value of 0.075 Vs for the mentioned ratio, the values of the first two critical speeds reduce to 1683 rpm (28 Hz) and 18765 rpm (313 Hz) for the configuration with a ball bearing at the upper support and to 1321 rpm (22 Hz) and 7781 rpm (130 Hz) if a passive magnetic bearing is used.

EXPERIMENTAL RESULTS

As there were serious doubts that the SMB initially built could be stiff enough in axial direction, provisions were made in order to operate the machine using the upper emergency bearing as working bearing instead of the passive magnetic bearing. This configuration proved to be useful also for identifying the dynamic stiffness of the SMB.

A first series of tests with both bearings replaced by ball bearings was performed: this configuration allowed to test the general layout and the power interface system and to perform a first balancing of the rotor.

After the machine proved to work in a very satisfactory way in the configuration with rolling element bearings, the superconductive bearing and the cooling system were installed and a further series of tests were performed spinning the machine to a speed close to the maximum operating speed in the hybrid configuration.

As the axial stiffness of the superconducting bearing available was too low for allowing the use of the passive magnetic bearing in the upper support, all testing was conducted in this configuration.

The machine proved to be able to accelerate up to 18000 rpm, crossing the first critical speed without problems. It was operated for several hours performing continuously acceleration-deceleration cycles and the power interface proved to be able to perform the energy input-output with good efficiency.

The SMB proved to act successfully as a radial bearing, supplying the required stiffness and damping to cross the first critical speed and to allow safe operation in the supercritical range.

Also the power interface was tested and proved to be able to work in both the power-in and power-out modes.

An interesting result of these tests was the confirmation that the stiffness of the superconductive bearing increases with increasing frequency: the dynamic stiffness computed from the value of the experimental critical speed is higher than the static stiffness obtained from the tests performed on the superconductor.

Apart from the functional tests, several spin-down curves were obtained, recording both the speed versus time and the amplitude of vibration versus speed. The tests of the first type allowed to obtain a fairly accurate evaluation of the total drag acting on the rotor. As the drag is very low, the time needed for the spontaneous decay of the speed is quite long, allowing to estimate accurately the drag with simple instrumentation.

As an example, starting from 15000 rpm, in 90 s the decay is of only 655 rpm, yielding a value of the total power losses of 34.4 W. The corresponding drag torque is about 222 mN m. It is impossible to assess separately the aerodynamic drag (the test was performed at a pressure of 0.9 mbar) and the drag to the motor, the ball bearing and the SMB.

CONCLUSIONS

The performances of the SMB used in the tests here reported are not sufficient, in terms of axial levitation force and stiffness, to operate the machine in the nominal configuration, i.e. with a passive magnetic bearing in the upper support. On the contrary, its radial stiffness and damping proved to be sufficient. This result essentially confirms the results obtained by other research groups on machines with a similar layout and similar superconducting materials [6].

The experimental tests were consequently performed using a ball bearing in the upper position and this compelled to reduce the maximum operating speed from 21000 to 18000 rpm, owing to a critical speed located at about 19000 rpm.

The tests allowed to identify the dynamic radial stiffness of the SMB, which at about 28 Hz proved to be about than five times the static value. This result was expected, at least qualitatively, as is reported in the literature.

The tests confirmed also that the critical speeds reduce when power is applied to the electric motor and that if the ratio voltage/frequency is very high the system can become unstable.

As a result of the test it is possible to note that the general layout of the machine is successful, in particular in controlling the position of the rotor during field cooling. The system was able to store energy and to restitute it with good efficiency, particularly for what the drag torque is concerned.

Operation in the supercritical range was smooth with very low vibration levels.

The tests performed on some samples of superconductor produced during the research work allowed to extrapolate values of levitation force and axial stiffness which, if confirmed for a whole bearing, will allow to operate the machine in the nominal configuration.

As a general result, the research work performed allowed to be fairly optimist on the possibility of using SMB in practical application of the type here tested. The predicted increase of the performances of high temperature superconductors can make this type of bearings a viable alternative to magnetic bearings of more conventional type and to mechanical bearings in many applications.

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REFERENCES

[1] Delprete C., Genta G., Mazzocchetti L., Rava F., Ricca A., Ripamonti G., Santini L., Tonoli A., Varesi E. and Zannella S., High Speed Asynchronous Motor with High-Tc Superconducting Bearings, Proc. of the 3rd Int. Symp. on Magnetic Bearings, Technomic Publishing Co., Virginia, 1992.

[2] Frangi F., Varesi E., Ripamonti G. and Zannella S., Y_2BaCuO_5 Excess and Quenching Influences on Melt-Textured YBCO, Supercond. Sci. Technol 7, 103, 1994.

[3] Mosolov A., Genta G. and Albanese R., High-Tc Superconductors and Perspectives of the Construction of Levitation Devices, ICMAS, France, 1993.

[4] Albanese R., Delprete C., Genta G. and Mosolov A., Experimental Characterisation and Mathematical Modelling of High-Tc Superconductors for Magnetic Bearings, Proc of the 4th Int. Symp. on Magnetic Bearings, Technomic Publishing Co., Switzerland, 1994.

[5] Manson S.S., Determination of the Elastic Stresses in Gas Turbine Discs, NACA Report 871, 1947

[6] Yagyu S., Fujishima I. and Miki M., Fundamental Test and Design of Turbomolecular Pump with Water Trap Using High-Tc Superconductor Magnetic Bearing, private communication.