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LEVITATION OF $YBa_2Cu_3O_{7-x}$ SUPERCONDUCTOR IN A VARIABLE MAGNETIC FIELD

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SUMMARY

The influence of both a linear alternating and rotational magnetic field component on the levitation behavior of a $YBa_2Cu_3O_{7-x}$ superconductor was examined. The transition from a plastic regime of levitation to an elastic one, induced by an alternating field component, was observed. An elastic regime in contrast to a plastic one is characterized by the unique position of stable levitation and field frequency dependence of relaxation time to this position. It was concluded that vibrations of a magnet levitated above the superconductor can induce a transition from a plastic regime of levitation to an elastic one. It was found that a rotational magnetic field component induces rotation of a levitated superconductor. Rotational frictional motion of flux lines is likely to be an origin of torque developed. A prototype of a motor based on a levitated superconductor rotor is proposed.

INTRODUCTION

The discovery of high Tc superconductivity stimulated a study of passive levitation phenomenon in a system consisting of a permanent magnet and high Tc superconductor. This levitation phenomenon is of great importance for passive contactless magnetic bearings. High Tc superconductors are type 2 superconductors exhibiting low values of the first critical field. These specific features of the new superconductors result in the fact that in magnetic bearings a high Tc superconductor is in the mixed state and a magnetic field penetrates inside the superconductor in the form of flux lines. Flux lines do not freely exist in a superconductor body but are pinned by lattice inhomogeneities. Strong pinning leads to hysteresis of the magnetization curve. Hysteresis of the magnetization curve due to the pinning of flux lines is the origin of two unusual levitation effects. The first effect is the possibility of stable suspension of the superconductor below a permanent magnet, first discovered with an $YBa_2Cu_3O_{7-x}$ sample doped with silver oxide (ref. 1). This effect is the consequence of large magnetic hysteresis leading to a positive superconductor magnetization after the external field decreased. The second effect is friction in levitated superconductors resulting in a continuous range of stable levitation positions and orientations (ref. 2).

ELASTIC LEVITATION

Another class of unusual magnetomechanical levitation effects was discovered by applying a variable magnetic field component to a superconductor levitated above the permanent magnet. A schematic diagram of the experiment is represented in fig. 1. The superconducting specimen was levitated above the ring-shaped permanent magnet, magnetized along the axis. In order to create an alternating field component at the sample position, an electric coil was placed inside the magnet so that the coil axis coincided with the magnet axis. The permanent magnet containing the coil was placed at the bottom of the bath with liquid nitrogen. In the case of superconductor levitation in the static magnetic field of the permanent magnet so-called dry magnetic friction is observed. There is a continuous range of levitation positions. After the displacement of the sample along Z-axis from the initial levitation position the new position is also stable for levitation. There is no visible mechanical relaxation to the original position. This is the rigid or plastic type of levitation described in (ref. 2). The superconductor levitated in this regime is similar to the load on an inclined plane rested due to friction. When alternating current is applied to the coil, a new levitation behavior appears. In this case a unique position of stable levitation having height $\mathbf{h_o}$ is observed. If the initial position of levitation is beyond $\mathbf{h_o}$, the superconductor is forced to float up off the magnet. If it is higher than $\mathbf{h_o}$ the superconducter is forced to float down. Therefore the superconductor displacement from the equilibrium position generates a restoring force and the sample returns to the original position. In this regime a levitated superconductor is similar to a spring-suspended weight. Therefore a variable magnetic field induces the transition from a plastic type of levitation to an elastic one, characterized by a single position of stable levitation. Switching off the alternating field component leads to the inverse transition from an elastic levitation to a plastic one. It was found that the time of relaxation to the unique position of levitation in the elastic levitation regime depends strongly on the variable field frequency. The experiment was the following. The superconductor levitated in a variable magnetic field was displaced by means of non-magnetic pincers 2 mm down from the equilibrium position; then the superconductor was liberated from pincers and the time of relaxation to the original position was measured. The results are represented in fig. 2. One can subdivide the field frequency dependence of the relaxation time in two parts. In the low frequency range (0–100 Hz) the relaxation time decreases with increasing field frequency. In the high frequency range, (100–5000 Hz) the relaxation time is constant. Let's consider the structure of the hysteresis loop of a high Tc superconductor. Due to the irreversibility, magnetization of the superconductor is not a simple function of the external field. Consequently, the mechanical force in the inhomogeneous magnetic field depends not only on the field intensity but also on the magnetic history of the sample. The hysteresis loop of the superconductor consists of two curves (fig. 3): the upper-curve $\mathbf{m}^+(\mathbf{H})$ corresponds to increasing the magnetic field and the down-curve $\mathbf{m}^-(\mathbf{H})$ corresponds to decreasing the magnetic field. The existence of two different curves is a consequence of the irreversible part of magnetization of superconductors with pinning. According to the Bean critical state theory (ref. 3) these curves correspond to the different directions of the critical current inside the superconductor. From this it is obvious that increasing the external magnetic field by a value exceeding **2Hp**, where **Hp** is the field value resulting in the penetration of the magnetic field to the center of the superconductor, leads to the transition of sample magnetization from the $\mathbf{m}^-(\mathbf{H})$ curve to the $\mathbf{m}^+(\mathbf{H})$ curve if initial magnetization is related to the $\mathbf{m}^-(\mathbf{H})$ curve. Decreasing the field to the same value leads to the inverse transition. These transitions between the curves form the minor loop. Due to hysteresis the superconductor magnetization can exhibit any value ranging from $\mathbf{m}^+$ to $\mathbf{m}^-$ under a given field intensity. Hysteresis of magnetization leads to the hysteresis of repulsive force acting on a superconductor so that repulsive force can exhibit any value from $\mathbf{r}^+$ to $\mathbf{r}^-$ under a given levitation height. The appearance of a unique position of levitation in the elastic regime is clearly seen when the amplitude of the alternating component is large enough to induce the cycle transitions between the $\mathbf{m}^+(\mathbf{H})$ and $\mathbf{m}^-(\mathbf{H})$ curves of the hysteresis loop. The magnetization value of the superconductor in this case is the following:

$$m = (\mathbf{m}^+ + \mathbf{m}^-)/2 + 0.5(\mathbf{m}^+ - \mathbf{m}^-)\sin 2\pi \mathrm{ft} \qquad (1)$$

where f is field frequency. One can see from (1) that after applying an alternating field the average value of magnetization equals to the reversible magnetization value $(\mathbf{m}^+ + \mathbf{m}^-)/2$ having no hysteresis. This means that the origin of the continuous range of levitation points disappeared and only the unique point of levitation occurs. However in the experiment the elastic regime of levitation is observed when the amplitude of an alternating field is low compared to the **Hp** parameter. Elastic levitation is likely to occur even when the alternating field is low compared to the **Hp** parameter and the flux lines motion is induced only in the thin surface layer of superconducting grains. Thus the microscopic origin of the transition from the plastic type of levitation to the elastic one is the flux lines motion induced by the variable field. In the elastic regime the levitation height is determined by the reversible magnetization of superconductor $(\mathbf{m}^{+}+\mathbf{m}^{-})/2$ see (1). This conclusion is of importance because the reversible magnetization is low compared to the irreversible one in high quality oxide superconductors. This means that the load capacity in the elastic regime of levitation is less than that in the plastic regime. In order to explain the field frequency dependence of relaxation time in elastic regime of levitation consider the evolution of the point representing the state of the superconductor in the plane repulsive force - levitation height plane (**r-h** plane) see fig. 4. Consider for simplicity that the alternating component has the form of rectangular pulses and the inhomogeneity of the alternating field may be neglected compared to the one of the static field. In this case the magnetic moment of a superconductor will oscillate and the representing point will be displaced instantaneously vertically up or vertically down after each change of the sign of an alternating component. This means that the value of repulsive force, acting on the superconductor, changes without any change in the levitation height. Let's suppose that the field frequency is rather low so that after each change of the sign of alternating field the superconductor occupies the new equilibrium position which we called the local equilibrium point. Therefore the point representing the state of the superconductor reaches the line $\mathbf{r}=\mathbf{mg}$ after each change of the alternating field sign. In the elastic regime the global equilibrium height $\mathbf{h_o}$ is determined as the crosspoint of the lines $\mathbf{r}=\mathbf{mg}$ and $(\mathbf{r}^{+}+\mathbf{r}^{-})/2$. Displacement of the superconductor from the global equilibrium point $\mathbf{h_o}$ induces the relaxation motion of a superconductor. During this motion alternating field pulses having different signs displace the operating point in the different directions along the line $\mathbf{r}=\mathbf{mg}$ (see fig. 4). But the contributions of the pulses of different signs are not equivalent because when the operating point is in the local equilibrium the distance between the lines $\mathbf{r}^{+}$ and $\mathbf{r}=\mathbf{mg}$ is not equal to the one between $\mathbf{r}^{-}$ and $\mathbf{r}=\mathbf{mg}$ lines. Due to these differences in the contributions of impulses of opposite signs the operating point is displaced towards the global equilibrium point $\mathbf{h_o}$ until reaching it. When the superconductor occupies the global equilibrium point the contribution of the impulses with opposite signs becomes equivalent and the superconductor oscillates near this point without the resulting displacement. From this consideration one can conclude that at low frequencies each cycle of the alternating field induces the particular displacement of a superconductor. If in order for the superconductor to reach the global equilibrium, $\mathbf{N}$ cycles is required, the relaxation time will be equal to $\mathbf{N}/\mathbf{f}$. One can see that the relaxation time is inversely proportional to the field frequency in the low frequency regime, so that at zero frequency the relaxation time is infinite. This means the transition to the plastic regime of levitation in a static field. Therefore the considerations of the relaxation process of a superconductor in a variable magnetic field presented here explain the increase of time relaxation observed in the experiment in the low frequency range.

Now let's consider the vibrations of the magnet levitated above the superconductor. The levitated magnet generates an inhomogeneous magnetic field in the surrounding space. Due to the field inhomogeneity a vibrational motion of the magnet induces a change of the magnetic field value near the magnet. Therefore the vibrating magnet generates a variable field component in surrounding space. Since the superconductor providing the levitation is placed in the vicinity of the magnet, the variable magnetic field affects it. The variable magnetic field forces the flux lines to move inside the superconductor and as a consequence induces the transition from the plastic regime of levitation to the elastic one. Therefore the transition from the plastic regime of levitation to the elastic one may be induced when the permanent magnet levitated above the superconductor is forced to vibrate relative to the superconductor. This conclusion is of great importance because in using such a bearing, for instance in aerospace applications, variations in load, attitude and speed occur. These disturbances will induce vibration of the levitated magnet, and as a consequence, change the levitation height and decrease the load capacity of the bearing. It should be noted that the inverse situation occurs when a superconductor levitated above a magnet is forced to vibrate relative to a rested magnet and is physically equivalent to the one considered above. Thus all the conclusions made in the case of the magnet levitated above the superconductor are true for a superconductor levitated above a magnet.

ROTATION OF LEVITATED SUPERCONDUCTOR

The second interesting effect is rotation of a levitated YBCO superconductor due to a rotational magnetic field. For the rotation experiment, two ceramic samples $YBa_2Cu_3O_{7-x}$ (YBCO) and $YBa_2Cu_3O_{7-x}$-Ag_2O (YBCO-Ag) prepared by means of ordinary ceramic technology were used. The first sample was a ring shape with these dimensions: outer diameter 7 mm, inner diameter 4 mm, thickness 2 mm. The second sample was a parallelepiped shape with dimensions 5.5*1.0*1.0 mm^3. A ring-shaped permanent magnet ($SmCo_5$) magnetized along the z-axis was the source of the inhomogeneous field. The Z-axis coincided with the magnet symmetry axis. The magnet had dimensions of 34 mm outer diameter, 10 mm inner diameter and 5 mm thickness. The experiment was carried out with the apparatus illustrated in fig. 5. A glass tube containing the superconductor was attached to the vacuum main. This tube was placed inside the Dewar with liquid nitrogen. The special external platform containing the ring-shaped magnet and four air coils provided the levitation of the magnet and creation of the rotational field component. An infrared beam passed through the tube and provided the registration of the rotation by infrared detector. The output of the detector was connected to the rotating-mirror oscillograph. An AC generator connected to the two equivalent power amplifiers was used to supply the current through the coils to create the rotational field.

At low rotational magnetic fields, rotation of the levitated superconductor was not observed. As the field intensity was increased, torsion oscillations of the superconductor appeared. When the rotational magnetic field intensity exceeded the critical value, the levitated superconductor began to rotate in the XY plane. In all of the experiments the superconductor rotated in the direction of field rotation. It was found that the rotation frequency increases with the increase of rotating field intensity until the rotation frequency achieves a certain value of about 10 Hz. Then the rotating frequency stops increasing and the further growing of the rotational field intensity causes considerable superconductor oscillations in the XY plane. The subsequent increase of rotating field intensity causes the rotation to be unstable. In this regime chaotic-like radial oscillations were observed. Active deceleration of the rotational superconductor (YBCO sample) and the subsequent active acceleration by the rotational field (10 Oe 50 Hz) is represented in fig. 6. One can see the rotational field develops considerable torque acting on the levitated superconductor. Superconductors' spin rate decay vs time in a static field is represented in fig. 7. Here we see a clear straight line decay. Note that the sample doped with silver oxide exhibits considerably stronger friction torque compared to the undoped sample. The torque acting on a levitated superconductor in a rotating magnetic field can arise from 1) diamagnetic geometric form effects, 2) rigid sample magnetization due to trapped flux lines, 3) anisotropy of type 2 superconductor, leading to transverse magnetization of the Abrikosov lattice, or 4) frictional rotational motion of flux lines induced by the rotating magnetic field. In cases 1) – 3) only synchronous rotation of the superconductor can occur. Only in case 4), when frictional rotational motion of flux lines drives the rotation of the superconductor, the rotational frequency of the superconductor may be less than the external field frequency and be independent of it. In this case the flux lines rotate with a frequency equal to the field frequency. Moving vortices develop a frictional torque which acts on the superconducting body inducing rotation. However, the rotational frequency of the specimen is controlled by external friction (in our case magnetic friction) and may be substantially less than the field frequency. In all our experiments the superconductor rotational frequency was less (substantially) than field frequency. From this we concluded that frictional rotational motion of flux lines inside the superconductor is an origin of superconductor rotation.

While a superconductor is rotating around a center of a homogeneously magnetized ring, no changes of the magnetic field in a superconductor occur. Consequently no flux lines motion occurs in the superconductor. Real magnets, however, have some magnetization inhomogeneity leading to the existence of the asymmetry of a magnetic field with respect to their vertical axis. In that case during rotation the magnetic field in the specimen does not remain constant causing the flux lines motion. As a result a magnet friction torque occurs (ref. 4). Moving over an atomic lattice, flux lines are acted upon by two different microscopic forces (ref. 5): 1) The pinning force, which does not depend on the motion speed of a flux line and is analogous to the dry friction force, 2) The viscous force, which is directly proportional to the flux line speed. The superconductor rotational rate decay is observed to be linear (see fig. 7); i.e. the friction torque does not depend upon the rotational frequency. This conforms with the data obtained by F. Moon et al. (ref. 4) in the experiments with the high frequency rotation of the magnet levitated above the superconductor. Thus, it may be concluded that the pinning force acting upon moving flux lines is the origin of the macroscopic rotational torque developed by the rotational magnetic field. The magnitude of the viscous force is negligible. It should be noted that different superconducting samples exhibit different friction torque during free rotation (see fig. 7). One can see that friction torque increases as pinning force decreases. The magnitude of angular acceleration of the levitated superconductor in the case of active acceleration of the superconductor by the rotational field is directly proportional to the torque acting on the superconductor. Similar to that case the magnitude of angular deceleration of the freely rotating superconductor is proportional to the magnetic friction torque. By using the slopes of this dependency (see fig. 6,7) we calculated that **rotational field torque / friction torque** =40 for YBCO sample and rotational magnetic field 10 Oe, 50 Hz. This conclusion is of great importance because it means that magnetic friction in levitated superconductors is not the factor restricting the rotational speed and in principle one can reach considerably higher speed magnitude. The instability of the rotating superconductor in a horizontal plane is likely to be the origin of low rotation rate. It was observed that the maximal rotation frequency of the levitated superconductor is approximately equal to the radial resonance frequency of the superconductor. Therefore, one can suppose that low frequency natural resonance restricts the rotational frequency.

The apparatus represented in fig. 5 may be considered as the prototype of a new motor based on a superconductor levitated rotor. We called this type of motor a superconductor hysteresis motor because the rotational field develops the torque acting on the superconductor due to the pinning of flux lines. Pinning of flux lines leads to the hysteresis of superconductor magnetization and the occurrence of a non-zero angle between the vector of magnetization and the vector of a rotational field. The occurrence of this angle results in the development of torque acting on a superconductor. This method of torque generation qualitatively differs from that used in the ordinary motor based on a magnet levitated above a superconductor as a rotor (ref. 6). In a magnet levitated motor there is an additional small magnet connected with the main magnet providing the levitation. The small magnet is acted upon by the rotational field to induce rotation. In contrast, in hysteresis, the superconductor motor rotational field acts on the levitated superconductor rotor immediately. Another important feature of the hysteresis motor is independence of the torque generated upon the relation between the superconductor rotation frequency and field frequency. It is required only that field frequency exceed the rotation frequency. This property makes initiation of rotor rotation effortless.

CONCLUSIONS

Influence of both linear alternating and rotational magnetic field components on a levitation behavior of $YBa_2Cu_3O_{7-x}$ superconductor was examined. The transition from a plastic regime of levitation to an elastic one, induced by an alternating field component was discovered. In contrast to plastic levitation, elastic levitation is characterized by a unique position of levitation and field frequency dependence of relaxation to the equilibrium position after disturbance. The elastic type of levitation exhibits low load capacity compared to the plastic one. It was concluded that vibrations of a magnet levitated above the superconductor can induce the transition from plastic levitation to an elastic one.

The rotational field component causes the levitated superconductor to rotate. Rotational frictional motion of flux lines is likely to be an origin of the torque developed. Frictional torque developed during rotation of the superconductor is low compared to the torque developed by the rotational field. Instability of the rotating superconductor in a horizontal plane restricts the maximal rotational frequency. A new type of motor based on the superconductor levitated rotor was proposed.

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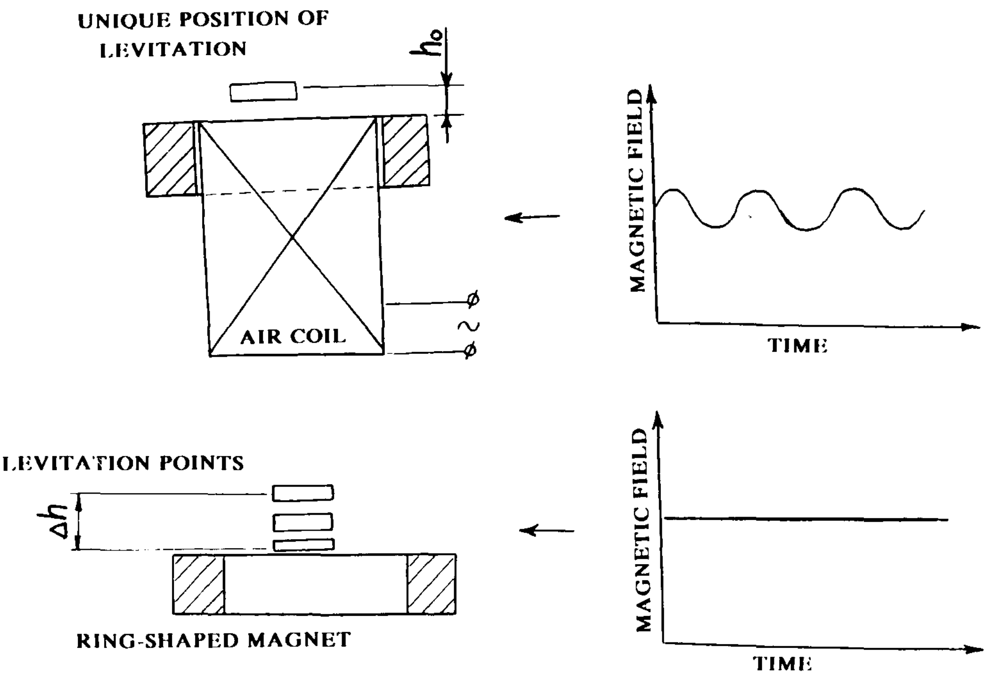
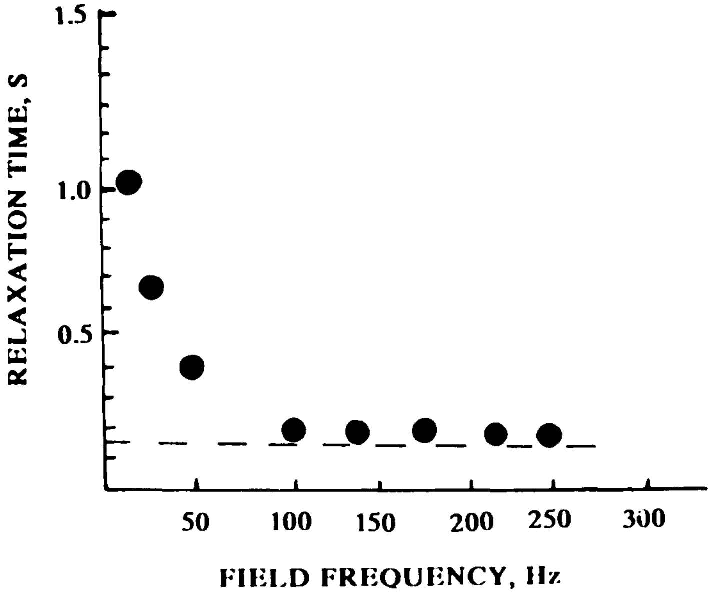
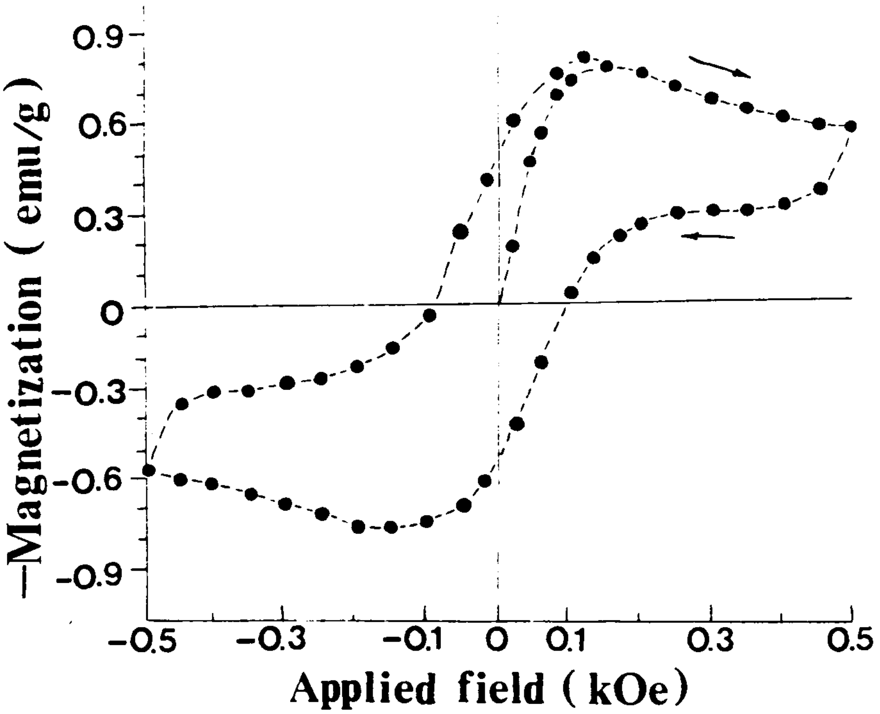


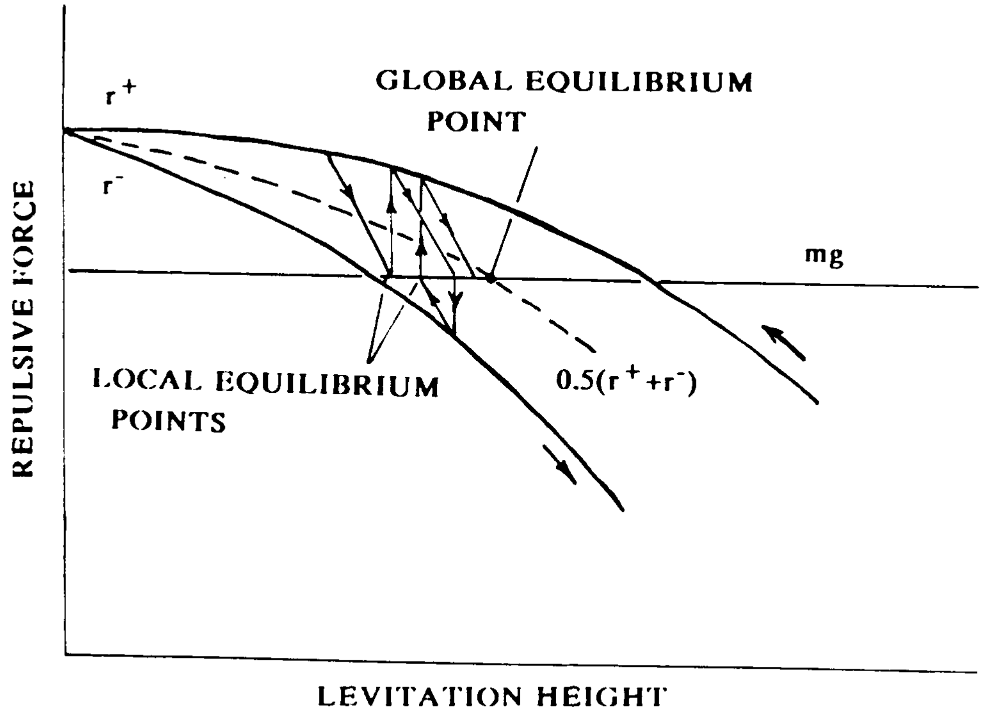
1. Apparatus for levitation experiment in the variable magnetic field



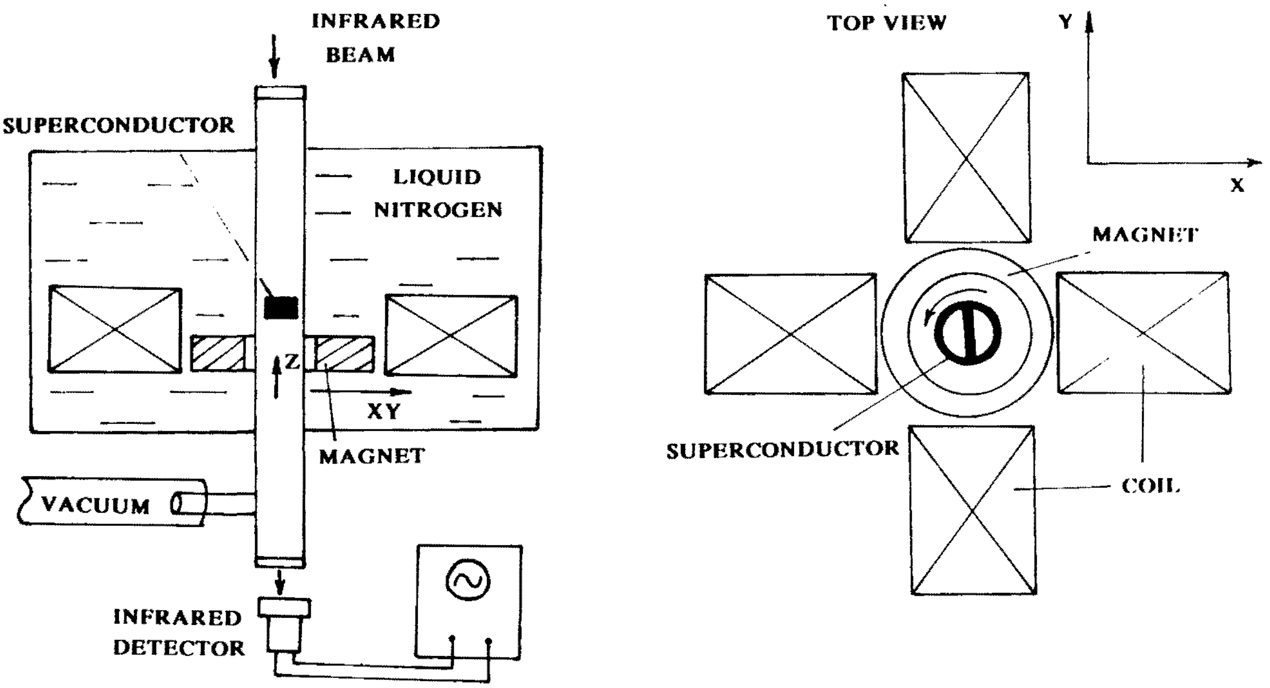
2. Field frequency dependence of the relaxation time of the superconductor to the unique position of stable levitation in elastic levitation regime.



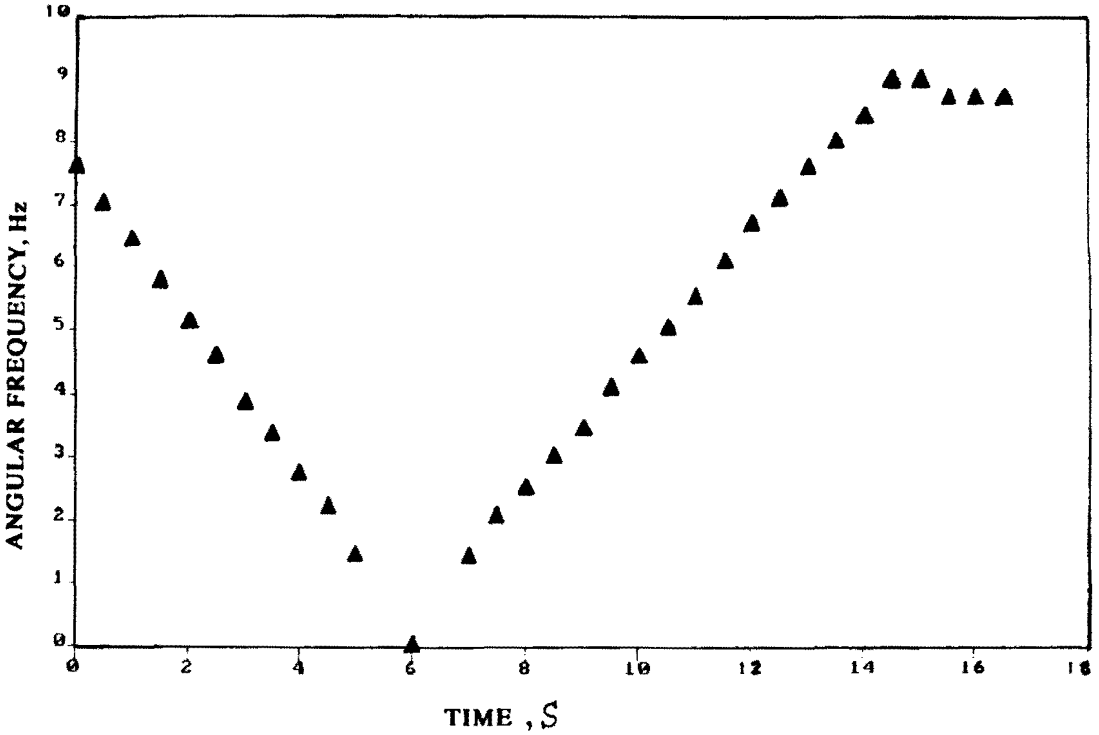
3. Hysteresis loop of YBCO superconductor used in the levitation experiment. T=77K.



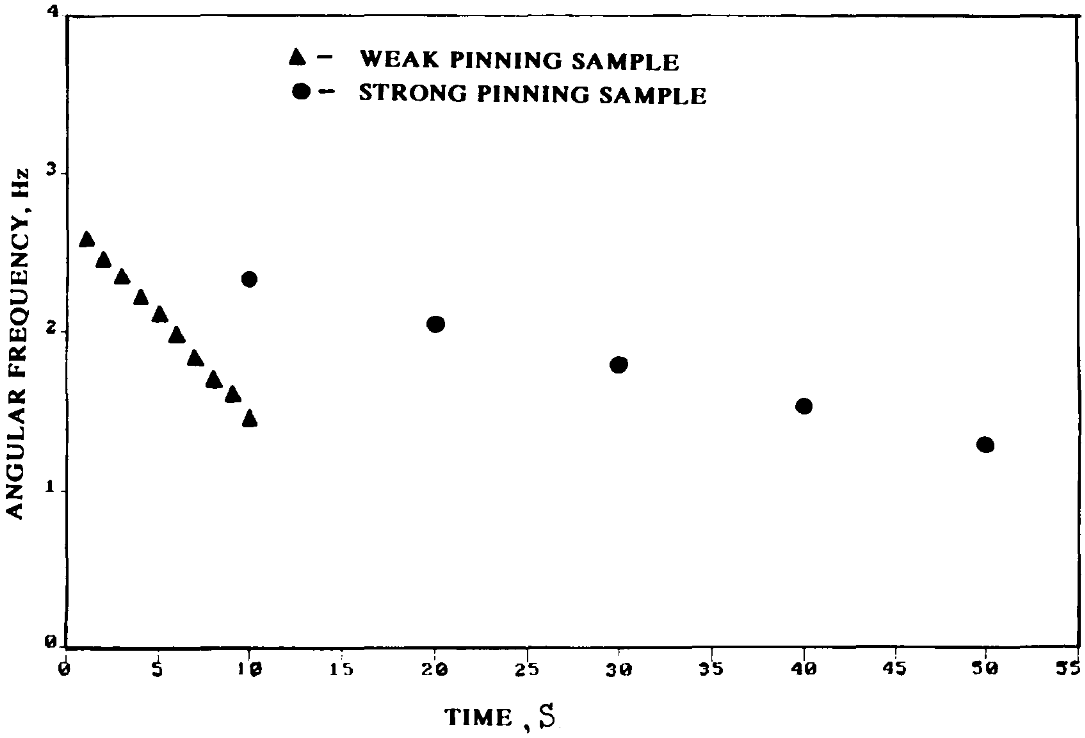
4. Relaxation of superconductor to the unique position of levitation in elastic levitation regime. Alternating field has the form of rectangular pulses.



5. Apparatus for rotation experiment.



6. Active deceleration and acceleration of rotating superconductor induced by rotational magnetic field (50 Hz, 10 Oe).



7. Superconductor rotation frequency decay in static magnetic field.