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HTSC CERAMICS RESPONSE TO ELECTROMAGNETIC SIGNAL OF FINITE AMPLITUDE

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The time dependence of electric field E on the surface of cylindrical HTSC-cermics sample irradiated by low frequency electromagnetic wave was investigated theoretically and experimentally. Several kinks observed on a curve E(t) correspond to different stages of a.c. magnetic flux penetration into a sample. The comparison between experimental data and theoretical calculation using critical state model allows to obtain values of critical parameters of superconductor and to find out the amplitude of external field when magnetic flux penetrates into the whole volume of sample.

In accordance with widely used model HTSC ceramics can be considered as a sistem which consists of superconducting grains connected by weak links. Electrodynamic properties of such medium in a low magnetic field can be described by critical state model[1]. It is necessary to take into account a strong dependence of critical current density j_c on magnetic field (see, for example,[2-3]). The model[1] was widely used to analyse the distribution of magnetic induction, to calculate a.c. losses and etc. as for the traditional low temperature hard superconductors as for the HTSC ceramics[2-4].

In the framework of critical state model it was studied a response of hard superconductor to incident electromagnetic wave of finite amplitude on its surface[5]. In this paper it was measured an electric field E on a surface of sample induced by an incident wave. The dependence of this field on time had been used in[5] to find out and to investigate such importante characteristic as surface barrier which prevents to penetrate Abricosov vortices into a volume of sample. In principle, a function E(t) containes the complete information about superconductor critical state.

In this paper we have investigated a behavior of electric field E(t) in application to HTSC ceramics. It has been shown that using a function E(t) one can study a penetration of a.c. magnetic flux into a volume of sample. In particular it has been found a simple method of determination of a.c. external magnetic field amplitude H_p at which magnetic field reaches a centre of a sample.

Experiment

We have studied a behaviour of electric field on a surface of cylindrical sample of HTSC ceramics $YBa_2Cu_3O_{7-\delta}$. An external magnetic field $H(t) = H_m \cos \omega t$ oriented along axis of sample was produced by solenoid wounded by copper wire. For registration of signal proportional to E(t) monolayer pick-up coil wounded directly onto the sample by copper wire 30 μm in diameter and contained 120 turns was used. Preliminary amplification of signal was carried out by PAR 124A amplifier working in wide-band regime.

The graphs demonstrating the behaviour of field E(t) for cylindrical sample with diameter 0.9 cm have presented on fig.1. The curves have

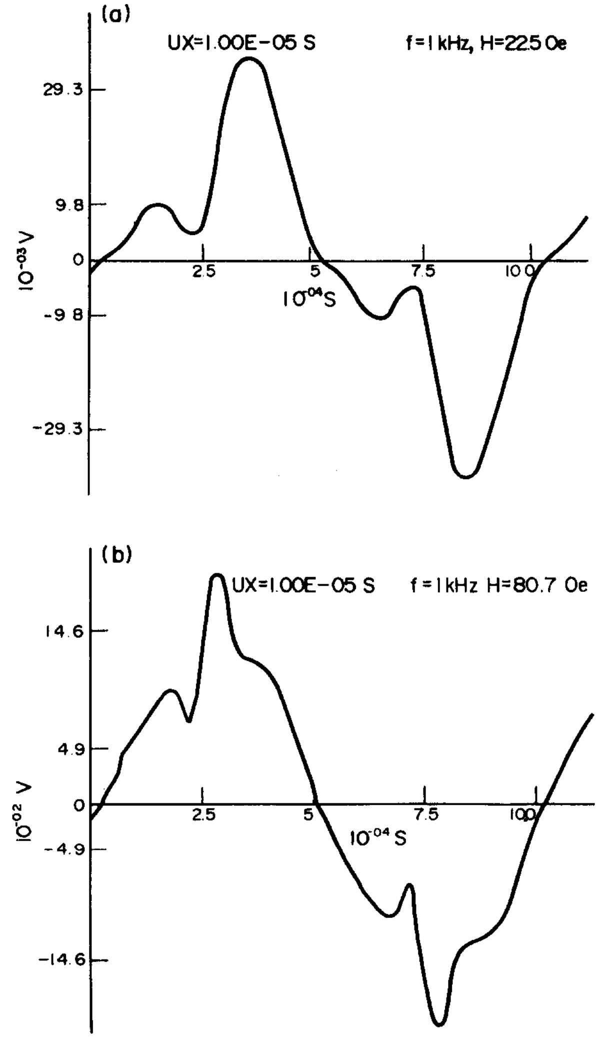

Fig.1 Electric field E(t) on the surface of cylindrical sample in a.c. magnetic field with frequency $\omega/2\pi$ = 1kHz and amplitude H_m=22,5 Oe (a), H_m=80 Oe(b).

been obtained at a frequency $f = \omega/2\pi = 1$ kHz and field amplitudes 22.5 and 80.7 Oe.

When amplitude H_m is less, then 22.5 Oe the dependense E(t) is similar to curve on fig. 1a. There are two types of features on a curve E(t). The first one takes place at moments $t_n = n/2f$ (n - integer) when external magnetic field reaches H_m. At these moments on the curve E(t) the kinks appear. The second series of features exists at moments displaced in time on 1/4f from t_n and corresponds to zero external magnetic field.

At the amplitude H_m, higher then 22.5 Oe, a new type of kinks appears on the curve E(t) (see fig 1b). When H_m encreases, the positions of these kinks are moving from $t_n = n/2f$ to $n/2f - 1/4f$. The position of another features does not depend on H_m.

Theory and Discussion

Let us consider a cylindrical sample with radius R, inserted in external a.c. magnetic field $H_o = H_m \mathrm{Cos}\,\omega t$ oriented along axis of sample (z-direction). Axially symmetric electromagnetic field in a sample depends only on radial coordinate r. Magnetic field has only z-component, and electric field - only azimuthal.

Electric field E(t) is connected with magnetic flux Φ by relation:

$$E(t) = -\,(\partial\Phi/\partial t)(\,1/2\pi Rc), \tag{1}$$

where c is light velocity. The calculation of B(r) distribution is based on critical state model[1]. In our case the magnetostatic equation for B(r) takes a form:

$$\partial B/\partial r = \pm\, 4\pi\mu j_c(B)/c. \tag{2}$$

Here μ - magnetic permeability of ceramics without Josephson links between the grains[2], j_c - critical current density and signs ± are defined by direction of electric field. Critical current density in HTSC ceramics is very sensitive to a magnitude of induction B. To take into account this dependence we employed well known Kim-Anderson relation[6-7]:

$$j_c(B) = j_o/(1+|B|/B^*) \tag{3}$$

Below we shall use dimensionless variables: $h = B/B^*$; $h_o = \mu H_o/B^*$; $h_m = \mu H_m/B^*$; $\alpha = 4\pi j_o \mu R/B^* c$; $\xi = r/R$. In this case equation (2) transforms to following:

$$dh/d\xi = \pm\,\alpha/(1 + |h|) \tag{4}$$

The boundary condition has a form: $h(1) = h_o$.

At time t = 0 when the field h_o on a sample surface has maximum value h_m a solution of equation (4) with boundary condition is described by formula:

$$h(\xi) = [(1 + h_m)^2 + 2\alpha(\xi - 1)]^{1/2} - 1. \tag{5}$$

Let the next condition be satisfied

$$\alpha < h_m + h_m^2/2, \text{ or } h_m > h_p = (2\alpha+1)^{1/2} - 1. \tag{6}$$

In this case the equality (5) is correct at arbitrary value of ξ. If $h_m < h_p$, formula (5) is true only in region

$$\xi_o < \xi < 1,\ \xi_o = 1 - h_m/\alpha - h_m^2/2\alpha \tag{7}$$

(in region $0 < \xi < \xi_o$ $h(\xi) \simeq 0$). This means, that in the case $h_m < h_p$ superconducting current shields the sample volume $r < R\xi_o$, but in the case (6) H_m is so high that field penetrates into the whole volume of sample.

Solutions of (4) may be obtained at arbitrary moments of time. Neglecting simple but enormous calculations, we write here the finished relations for electric field on a surface of sample:

$$E(t) = (R\omega\mu H_m/2c)F(\alpha, h_m, t). \tag{8}$$

The dimensionless electric field F(t) has a various form at different values of parameters α and h_m. In the case $H < H_p = h_p B^*/\mu$, function F(t) has different form at different intervals of time:

$$F(t) = \alpha^{-2}\mathrm{Sin}\,\omega t\ (h_o+1)\{-(2/3)(h_o+1)^3 - -2\alpha(h_o+1) + + [(1/2)(h_o+1)^2 + (h_m+1)^2]^{1/2} [2\alpha + (5/6)(h_o+1)^2 - (h_m+1)^2/6]\} \tag{9}$$

$$0 < \omega t < \pi/2 \tag{10}$$

$$F(t) = \alpha^{-2}\mathrm{Sin}\,\omega t\ (1-h_o)\{-2\alpha(h_o+1) + (2/3)(h_o^3-1) - -2h_o + (h_m^2/2 + h_m - h_o^2/2 + h_o + 1)^{1/2} [2\alpha - (h_m+1)^2/6 + 5/3 - (5/6)(h_o - 1)^2]\} \tag{11}$$

$$\pi/2 < \omega t < \pi \tag{12}$$

Let us note that current density in equation (3) is even function of induction B and odd function of electric field. As a result, an electromagnetic field inside a sample contains even harmonics of external signal only. This means, that we do not need in calculation E(t) in interval $\pi < \omega t < 2\pi$. Here F(t) is defined by relation

$$F(t) = -\,F(t - \pi/\omega). \tag{13}$$

So, electric field is described by formulae (8), (9), (11) and (13) at any time. Analysing these formulae, we find out that a function E(t) is continious but its derivative has jumps at points $\omega t = n\pi + \pi/2$. By other words, a plot E(t) has kinks at points where external magnetic field reaches extremum values $\pm H_m$ or becomes zero. Existence of these features is coursed by sharp change of character of magnetic field penetration into a sample in corresponding moment.

It is necessary to note that there is principal difference between features of function E(t) at points $\omega t = n\pi$ and $\omega t = n\pi + \pi/2$. The kinks of E(t) at points multiply π/ω are specific for any critical state model. They exist at any dependence of critical current j_c on induction B, even in a case j_c = Const. Contrary, the peculiarities of E(t), taking place at $\omega t = n\pi + \pi/2$ when H reaches zero occure only if there is a strong dependence of $j_c(B)$.

Let us discuss a behaviour of E(t) in more high magnetic field (6). In this case the whole interval (6) of changing of parameter α is divided onto two regions:

$$h_m^2/4 + h_m/2 < \alpha < h_m^2/2 + h_m, \tag{14}$$

$$\alpha < (h_m^2/4 + h_m/2). \tag{15}$$

In the first one an external field H at a moment $\omega t = \pi/2$ becomes zero at the boundary r = R and only then the induction B begins to change on axis of sample at the moment:

$$\omega t = \omega t_o \simeq \arccos\{-(1/h_m)[2(h_p+1)^2 - -(h_m+1)^2]^{1/2} - 1\} \tag{16}$$

In the second case (15) these occurences start in reverse sequence: decreasing of B at a point r = 0 begins at time

$$\omega t = \omega t_1 \simeq \arccos\{(1/h_m) [(h_m+1)^2 - 4\alpha]^{1/2} - 1\} < \pi/2, \tag{17}$$

and only then external field becomes zero at $\omega t = \pi/2$. As a result, expressions for F(t) differ from each other in situations (14) and (15).

In the case (14) up to ωt_o (16) the field F(t) is described by the same relations (9) and (11), as in the case $h_m < h_p$. The expressions for E(t) in other intervals take a form:

$$F(t) = (\alpha^{-2}\mathrm{Sin}\omega t)(1-h_o)[(2/3)(h_o-1)^3 - 2\alpha(h_o+1) + 2h_o^2 - 4h_o + (2/3)(1+2h_o-h_o^2+2\alpha)^{3/2}]. \qquad (18)$$

$$\omega t_o < \omega t < \omega t_2 = \arccos(-h_p/h_m), \qquad (19)$$

$$F(t) = (\alpha^{-2}\mathrm{Sin}\omega t)(1-h_o)[(2/3)(h_o-1)^3-2\alpha(h_o-1)+ (2/3)[(h_o-1)^2 - 2\alpha]^{3/2}. \qquad (20)$$

$$\omega t_2 < \omega t < \pi \qquad (21)$$

Here parameter ωt_2 defines a moment when the field on axis becomes zero.

Electric field describing by four relations (9), (11), (18) and (20) is continious function, but its derivative, as in the case $h_m < h_p$, has jumps at points $\omega t = n\pi$ and $n\pi + \pi/2$. But now there is the new kink at point $t = \omega t_2$. When h_m increases, the positions of these features are changing from point $\omega t = n\pi + \pi/2$ to point $\omega t = n\pi$.

In the region (15) we have not observed any qualitative changes on curve E(t). But the relations for F(t) have changed. At $0 < \omega t < \omega t_1$ formula (9) is correct. Then the field F(t) has a form

$$F(t) = \alpha^{-2}(\mathrm{Sin}\ \omega t)(1+h_o)\{-(2/3)(h_o+1)^3 - 2\alpha(h_o+1) + (2/3)[(h_o+1)^2 + 2\alpha]^{3/2}\}. \qquad (22)$$

$$\omega t_2 < \omega t < \pi/2 \qquad (23)$$

In a rest half of period the function F(t) is described by relations (18) and (20).

The results of calculations of magnetic field F(t) for $\alpha = 24$, $h_m = 6$ and $h_m = 24$ are demonstrated on fig. 2. For $h_m = 6$ the curve corresponds to penetration field h_p and is agree with experimental record E(t) on fig 1a qualitatively. At higher h_m the function F(t) has additional kink at a point $\omega t = \omega t_2$. This kink is observed distinctly on a curve with $h_m = 24$ (fig. 2) This curve has almost the same form as the experimental curve E(t) on fig.1b. So, we can conclude that the amplitude $H_m = 22.5$ Oe begining from which it is observed an additional kink on experimental records corresponds to the penetration field H_p.

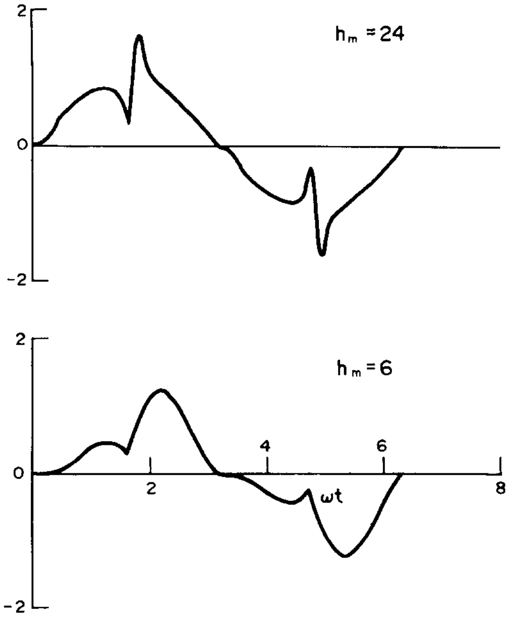

Fig.2 The results of calculation of function E(t) in dimensionless form for two values of parameter h_m: $h_m=24$ - upper curve, $h_m=6$ - lower curve.

Comparing the calculated and experimental curves, we can define the parameters of used theoretical model: $j_o = 120$ A/cm^2, $B^* \cong 2.5$ Oe, $\mu = 0.5$.

So, the study of electric field behaviour permits to get an information about critical state of HTSC ceramics. We consider that this method will be effective to investigations another magnetic and electric properties of new superconductors.

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References

1. C.P.Bean. Phys Rev. Lett., 1962, v.8, 250
2. H.Dersch, G.Blatter. Phys. Rev.B, 1988, v.38, 11391
3. V.M.Dzugutov, L.M.Fisher. FTT, 1988,v.30, 2148
4. S.I.Zakharchenko, V.B.Mitiushin, N.A.Podlevskikh, L.M.Fisher SPCE, 1989, v.2, No.10, 130
5. H.A.Ulmaier. Phys. Stat. Sol.,1966, v.17, 631
6. Y.B.Kim, C.F. Hempstead, A.R.Strnad. Phys. Rev. Lett., 1962, v.9, 306
7. P.W.Anderson. Phys. Rev. Lett.,1962, v.9. 309