AC losses and magnetic coupling in multifilamentary coated HTS conductors and tape arrays

M. Marchevsky, E. Zhang, Y-Y. Xie, V. Selvamanickam and G. Pethuraja

***Abstract*— Striation of coated HTS conductors is a promising way of reducing their ac loss. In particular, loss in the striated conductors is affected by magnetic coupling between the superconducting filaments. We experimentally study the in-field behavior of the planar arrays of superconducting tapes and deduct contribution of such coupling to the net ac loss. This contribution is largest at lowest ac field amplitudes. Dependence of the loss upon the inter-filament separation is studied and results are compared to the existing theoretical models and numerical simulations. We show that magnetization ac loss of practical multi-filamentary conductors can be reasonably fitted with the theoretical result of Mawatari et al. for infinite arrays of magnetically-coupled superconducting strips.**

***Index Terms*—AC measurements, magnetization loss, magnetic coupling, coated conductors.**

I. INTRODUCTION

Understanding ac loss in practical superconductors has recently become a subject of intense research. At present, dissipation in high-temperature superconductor (HTS) tapes under applied ac field and/or current is a major factor limiting their practical use. Minimization of the field-related losses is especially critical for the applications of coated HTS conductors in motors, generators and other machinery.

A high aspect ratio of the HTS (tape) wire conductors leads to elevated hysteretic losses when compared to the round wire of same cross-section. This is a direct consequence of the flat geometry that leads to a modification of the well-known Bean critical state, and it is worked out in a number of papers [1,2,3,4]. Most notably, Brandt et al. [1] analyzed field and current distribution in a thin superconducting strip of width *2a*, thickness d and critical current I_c in a harmonic ac field of amplitude H_m and frequency *f*, and derived an expression for the ac loss power:

$$P = 4 f \mu_0 a^2 J_c H_m g\left(\frac{H_0}{H_c}\right) \qquad (1)$$

where

$$J_c = j_c d = \frac{I_c}{2a}$$

$$H_c = J_c / \pi$$

and

$$g(x) = \frac{2}{x}\ln\cosh x - \tanh x$$

This theoretical result can be readily applied for fitting hysteretic ac loss data in practical superconducting (tape) wires, provided the ac losses due to eddy currents in the conductor substrate and surrounding copper stabilizer are small. Eq (1) suggests that dividing a superconducting tape into *N* equal “stripes” along the length reduces the net ac loss by a factor of *N*. This finding led to a development of various “striation” techniques for ac loss reduction in superconductor tapes [5,6,7]. In practice, however, losses of the finely striated tapes are noticeably larger than the sum of the losses due to all individual stripes calculated with eq. (1) and such deviation tends to increase with increasing the stripe density. The additional contribution to ac losses appears to be due to several factors, most notably an electrical coupling caused by the conductivity of non-superconducting barriers [7] and remnant superconducting “bridges” between the neighboring stripes. Using high-resistivity substrate and improving procedures used for patterning of multi-filamentary HTS conductors may eventually minimize effects of those factors.

However, an additional contribution to the ac loss exists that is independent on barrier electrical resistivity and is due to magnetic coupling. In a striated conductor, magnetic field distribution inside the superconducting filaments is influenced by the field concentration in the non-superconducting trenches that ultimately affects ac losses of the striated conductor. For an x-array (all superconducting stripes are in one plane) contribution of the magnetic coupling to the ac loss was theoretically considered in a number of papers [8,9,10,11]. Different aspects of the problem were addressed, including cases of full shielding (Meissner state) [8], pinning-free superconductor with edge barriers [9], and the modified Bean critical state [10]. When the number of stripes in the x-stack is >>1, an analytical solution for the ac loss may be sought based on a modification of the Brandt’s result and such result was first reported in the paper by Mawatari [10]:

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$$P(H_m) = -\frac{2\mu_0 L^2}{\pi a d}\int_0^{H_m} dH_a (H_m - 2H_a)\times \ln\left[1-\frac{\sin^2(2\pi a/L)}{\cosh^2(H_a/H_0)}\right] \qquad (2)$$

Here $P(H_m)$ is the ac loss power per unit volume of the array; H_m is the amplitude of the applied ac field, $2a$ is the width of the single stripe, d is the superconductor thickness, and $(L-2a)$ is the inter-stripe distance. Direct analytical calculation of the ac losses for a finite-size tape x-array with pinning presents a challenge and this problem was addressed only numerically [11,12]. It was found in [11] that coupling would increase losses due to additional field concentration in the gaps between the neighboring strips in finite-size arrays, similar to the Mawatari's result.

In this paper, we experimentally address effects of magnetic coupling to the ac losses in x-arrays and striated HTS conductors, derive experimental dependence of losses upon inter-filamentary separation and discuss applicability of different theoretical models for the data analysis. We show that the magnetic coupling effects can be rather significant at small ac field amplitudes and should be properly taken into account in design and applications of multi-filamentary conductors and tape assemblies.

II. EXPERIMENTAL

Samples were made using pieces of commercial YBCO coated conductor (tape) wires made at SuperPower, Inc. [13]. The thickness of the superconducting film is ~1 micron. The conductor is coated with an overlayer of 2.7 micron of silver at the YBCO side and ~ 1 micron of silver on the opposite, substrate side. For the 4-mm wide wires studied in this work, additional 20 micron thick copper stabilizer layers are electroplated on top of the silver layers at both sides of the tape. Critical current of all wire samples used in the experiments is measured at T = 77 K with the 1 μV/cm voltage criterion. Magnetization ac losses are measured on 4 cm long samples at 77 K using the inductive technique. In the course of the experiment, samples are placed in the compensated secondary coil that is axially centered in the middle of the larger solenoid generating a uniform ac magnetic field perpendicular to the sample surface. The ac current is applied to the solenoid using a programmable Elgar TW5210 ac power source and the in-phase and out-of-phase voltages are measured using Signal Recovery 7265 DSP lock-in amplifier. The ac loss power is found as $P = \beta B_{ac} V''$ where V'' is out-of-phase voltage, B_{ac} is the applied field and β is the calibration coefficient determined using reference samples. Our experimental setup allows for ac loss measurements at magnetic field up to 40 mT r.m.s. and frequencies up to 400 Hz.

A. Regular HTS (tape) wires

In Fig. 1, results of the ac loss measurements on the regular SuperPower® 2G HTS wire and their respective fits with the eq. (1) are shown. For the tape M3-236 MS (type SCS4050) the transport critical current is I_c = 80 A and for the tape MS-266 (type SF12100) it is 270 A. Best fits with eq. (1) were obtained using ~ 10% higher I_c values (94 and 290 A respectively) than those from the transport measurements. In general, a good agreement between the experimental data and the Brandt's model of ac losses is seen. The deviation appears at field amplitudes above ~20 mT, primarily due to the onset of the field dependence of the critical current.

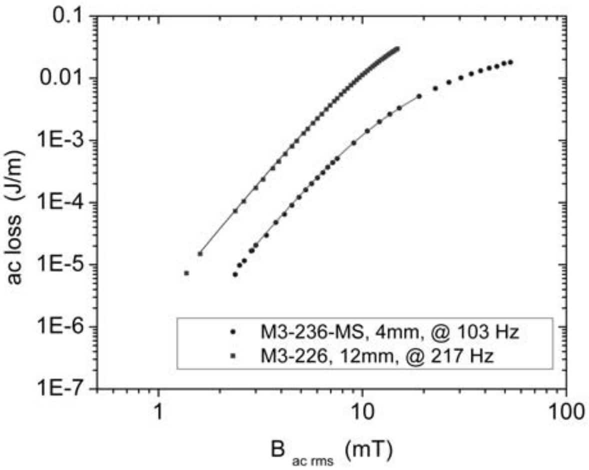

Fig. 1. Ac loss data for a 4 mm wide (l –M3-236 MS, f = 103 Hz and 12 mm wide (n – M3-226-7OAE-4, f =217 Hz) wire samples. Brandt's expression (1) is used to fit both data.

B. Tape arrays

Systematic investigation of ac losses is performed on the two-tape assemblies made from short pieces of a 4-mm wide copper-plated HTS (tape) wire (type SCS4050). The transport I_c of the original wire (before cutting) is I_c=104 A. (Tape) ire samples, 4 cm long each, are affixed edge-to-edge on a thin polyimide laminate plate with a separation d uniform along their length and the magnetization ac loss per period is measured as function of d. The measurement frequency is 173 Hz. Results are shown in Fig. 2. For all inter-stripe separations, the ac loss of the assembly is found to be larger than the sum of the losses of the individual tapes. Maximal loss is observed at the smallest separation of 0.23 mm. Surprisingly the additional ac loss seen in this experiment does not vanish up to the highest applied. field of ~40 mT Experimental results for the ac loss per period at low field amplitudes for various tape separations are shown in Fig. 2. Clearly, the magnetic coupling loss constitutes a significant portion of the total loss of the tape assembly. In fig. 2 (bottom) only the portion of the loss that is due to the coupling is plotted versus the inter-stripe separation for two arbitrary-chosen ac magnetic field amplitudes of 6.67 and 12.5 mT. The empirical fit to the data at large separations d is done using a power-law dependence $\sim d^{-\alpha(B)}$, where $\alpha(B)$ is a field-dependent exponent. Correction to value of d due to the thickness of surround copper stabilizer is made. The asymptotical behavior of the magnetic coupling losses at large separations is found to be $\sim d^{-0.8}$ and this scaling is only weakly field dependent

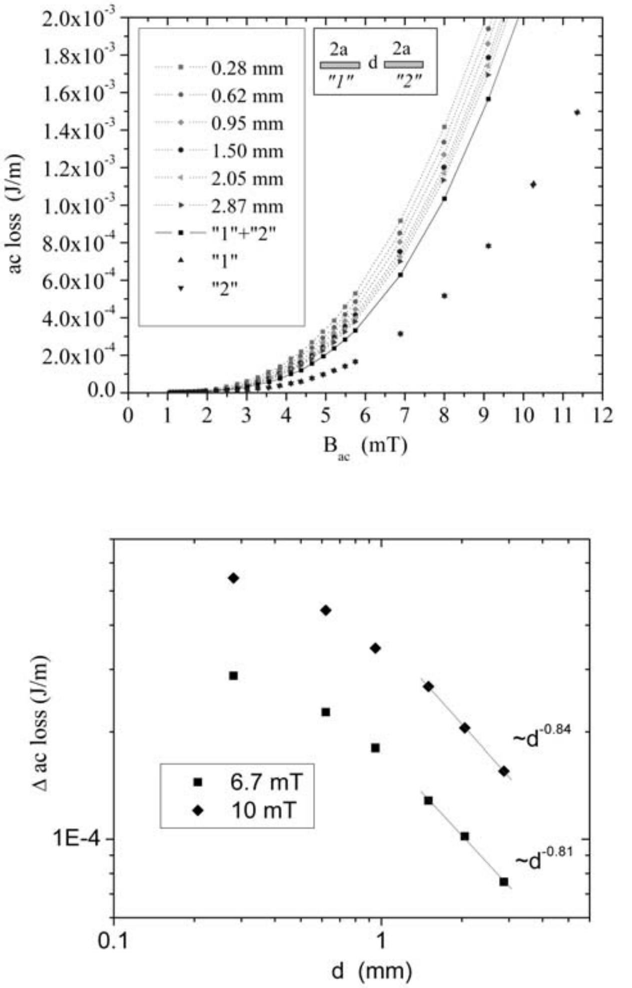

Fig 2. (top) Magnetization ac loss for a planar assembly of the two 4-mm wide superconductor tapes. Losses increase when separation between the tapes is reduced. Also shown are ac losses of the individual tapes used in the assembly and their sum. Linear scales are used at both horizontal and vertical axes for clarity. Ac field frequency is 173 Hz.
(bottom) Dependence of the net ac loss from the tape separation d, plotted for the two magnetic field inductions: B_{ac} =6.87 mT and B_{ac} =10.0 mT. The data is fitted with an asymptotical power law functional dependence in the form $d^{-\alpha}$, where d is the mutual separation of the superconducting stripes.

In the next experiment, ac loss of the x-array made of three affixed together 2-mm-wide (tape) wire samples (type SF2050) is studied. In this case, conductors are not copper-plated; only silver overlayer is present on these tapes. Transport I_c of the tape pieces are in the range of 26-27.5 A. Absence of copper plating allows to better control separation between the superconductors and probe losses at more close separations. Increasing the number of tapes is expected to produce a larger field concentration effect in the gaps and to affect losses stronger. This is indeed confirmed by the experiment. The magnetic coupling losses constitute a significant portion of the net loss at magnetic field amplitudes of ~10 mT and lower. For example, at the applied field B_{ac} = 2 mT the ac loss of the three-tape array at the smallest tape separation of 0.06 mm is 51% higher than it is for the largest tape separation of 2.5 mm studied in this experiment.

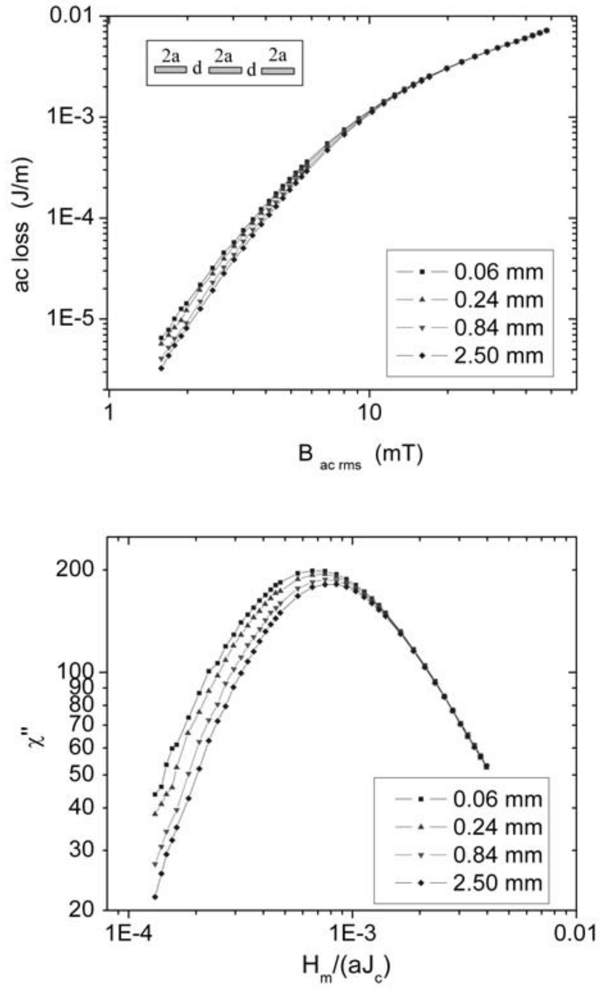

Fig 3. (top) Magnetization ac loss per cycle in the x-array made of three 2-mm wide tapes with Ic = 26-27.5 A. Losses increase when separation between tapes is reduced; at fields above ~0.01 T all the data converge to a single curve. Ac field frequency is 173 Hz
(bottom) Imaginary ac susceptibility for the 3-tape assembly as function of the normalized applied ac field amplitude Hm/a.

In Fig. 2 (bottom) the out-of-phase ac susceptibility is shown, calculated from the ac loss per cycle data as [11]:

$$\chi'' = P / 2\mu_0 \pi d a H_m^2 \qquad (3)$$

This result is qualitatively very similar to the numerical simulation results obtained in [11] (such as shown in fig 18 of [11]). In agreement with the simulation result, the χ'' peak becomes wider and shifts upwards when separation between the tapes is reduced. The experimental position of the χ'' peak is shifted towards the lower normalized ac field amplitude due to the higher transport I_c and larger width-to-thickness aspect ratio of the tapes, compared to the simulation parameters used in [11].

C. Striated conductors

A 12 mm wide SuperPower® wire (type SF1200) sample with the original transport I_c= 227 A is used in this experiment. The sample is striated using a SuperPower® proprietary dry etching process. The resulting pattern consists of 10 parallel superconducting stripes that are $2a$=840 μm wide and separated by d=400 μm wide non-superconducting gaps. A measurement of the transport critical done after the patterning yields I_{c1} = 152 A. Taking the pattern stripe-to-gap ratio into account, this result indicates a nearly 100% retention of the critical current in the striation process. Magnetization ac losses per cycle are measured at 100 and 200 Hz; the results are shown in Fig. 4. Calculations based on the Brandt's model for non-striated wire (eq. 1), striated wire (summed up contributions of 10 non-interacting stripes calculated with eq. (1)), and the Mawatari's model, eq. (2) are shown in the same plot for comparison.

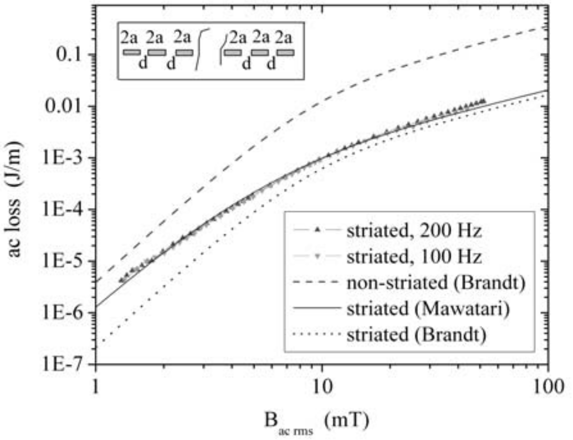

Fig. 4. Ac loss data for a 12 mm wide sample patterned with 840/400 μm SuperPower's dry etching process. Curve simulated using Mawatari's model (eq.3) and the sample original I_c and pattern dimensions provides a good fit to the data. Also shown are curves simulated using Brandt's model for the striated and non-striated (original) sample

At the high field end of the measurement range the ac loss reduction achieved with striation is close to the theoretically expected one (~11 times, compared to the losses of the non-striated tape calculated with the eq. (1). At the low field end, however, there is a significant upturn of the experimental curves relative to the simulation result for non-interacting stripes. This is clearly pointing to the coupling effects. Apparently, the Mawatari's model, eq. (2), calculated using the sample original I_c and striation period fits the data quite well in the entire field range. This type of ac loss scaling is typical for a large selection of SuperPower's dry etched multi-filamentary tapes, including the ones obtained with the reel-to-reel patterning process. It suggests that in the dry-etched samples the filaments are electrically well decoupled and only magnetic coupling remains. The latter is the major source of ac losses below 10 mT. The magnetic nature of the coupling loss is further supported by the clear absence of any significant frequency dependence, as seen in Fig. 4. Frequency-dependent contribution to the losses is commonly due to the eddy currents flowing in the inter-stripe trenches [6]. Interestingly, SEM observations of the striated samples reveal numerous sub-micron silver particles remaining in the trenches between filaments. Apparently, those particles do not contribute significantly to the coupling losses. The Mawatari's model for magnetically-coupled stripe arrays can therefore provide a useful evaluation criterion for the degree of electrical decoupling in the practical multi-filamentary conductors. Losses at low ac fields that are substantially larger than those suggested by eq. (2) are pointing to the eddy currents due to excessive electrical connectivity of the filamentary structure. Another practical use for this model can be for a non-contact evaluation of the critical currents of long striated tapes in reel-to-reel testing.

IV. CONCLUSION

We measured magnetization ac losses in various individual HTS coated conductors, (tape) wire assemblies and striated multi-filamentary conductors and compared our results with the existing theoretical models. We find that magnetic coupling contributes significantly the magnetization ac losses of superconductor tape assemblies and multi-filamentary conductors at low fields. This effect should be properly taken into account in the design of multi-conductor assemblies and superconducting devices where ultimate minimization of ac losses is critical.

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