

Novel Measurement Methods of Propagation Velocity and Direction of Normal Zone in Ac Superconducting Wire

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Abstract—A hybrid method for investigation on the propagation behavior of normal zone in an ac superconducting wire was developed by the combined use of the experimental observations and theoretical calculations. The forced quenching tests with 60 Hz ac current were carried out for a Nb-Ti/Cu-Ni superconducting wire. The local average velocity and direction of normal zone propagation were observed by the noncontact measurement method with capacity type voltage dividers. Simultaneously, the time variation of normal resistance induced in the whole sample was experimentally measured and theoretically calculated. By comparing both derived profiles and referring to the results measured by the noncontact method, we successfully estimated the quench initiation position, propagation velocity and direction of the normal zone in detail.

I. INTRODUCTION

In superconducting (SC) apparatus, the normal zone propagation process after the quench influences the over-voltage, joule heat, recovery time to superconducting state and so on. Hence, much research on the normal zone propagation has been carried out [1]–[3].

To understand propagation mechanism of the normal zone in superconducting wire or cable, it is necessary to measure the propagation velocities with high precision. The propagation velocity is usually measured using some voltage taps soldered on the sample conductor. The voltage taps, however, may disturb the propagation process, because the joule heat generated in the normal zone flows out through those voltage taps. Thus, propagation velocity may apparently be slower than that without voltage taps. To avoid such problems, we have developed the noncontact measurement method using capacity type voltage dividers [4].

In this paper, the forced quenching tests were carried out with 60 Hz ac current to investigate the propagation process of the normal zone in an ac Nb-Ti/Cu-Ni superconducting wire having electrical insulation. First, we measured the local average velocity and direction of the normal zone propagation using the noncontact method. Secondly, the time variation of the normal resistance induced in the whole sample was estimated from the terminal voltage across the sample wire monitored in the

noncontact measurement. Thirdly, taking account of the theoretical relationship between the propagation velocity and transport current, numerical calculations for the increasing behavior of normal resistance were carried out. Finally, by adjusting calculated profile of the resistance rise to fit the measured one and referring the result derived by the noncontact method, the quench initiation point, propagation velocity and direction of the normal zone were successfully estimated in detail. This hybrid method combining the experimental measurement and theoretical calculation can avoid the problem caused in the voltage tap method, because no voltage taps are connected in the sample conductor except at the terminals. Thus, our method must be useful to discuss the micro process of the normal zone propagation in ac superconducting wire.

II. NONCONTACT MEASUREMENT

A. Capacity Type Voltage Divider

Table I summarizes the specifications of the SC wire used in the experiments. This SC wire is a typical ac Nb-Ti/Cu-Ni wire having electrical insulation.

In the noncontact measurement, some capacity type voltage dividers are used. Fig. 1 illustrates the structure of the capacity type voltage divider in the noncontact method. Arranging the metal sheet around the sample, we can form capacitor C_1 . The sample conductor and metal sheet can be regarded as the inner and outer electrodes of C_1 , respectively. In this case, the electrical insulation of the sample wire functions as the dielectric of C_1 . We used C_1 of 30 mm in length, whose capacitance C_1 was measured to be 27 pF. By connecting another capacitor C_2 with C_1 in series, we obtain a capacity type voltage divider. Since the voltage v generated on the SC wire is divided by C_1 and C_2 , we can derive v by measur-

TABLE I
SPECIFICATIONS OF SUPERCONDUCTING WIRE ADOPTED.

Parameter	Value
Diameter	ϕ 0.205mm
Diameter without insulation	ϕ 0.178mm
Matrix	Cu-10%Ni
Rate of matrix	NbTi : CuNi = 1 : 2
Filament diameter	ϕ 0.67 μ m
Filament number	23 749
Twist pitch	1.76mm (S-twisted)
Electric insulation	PVDF

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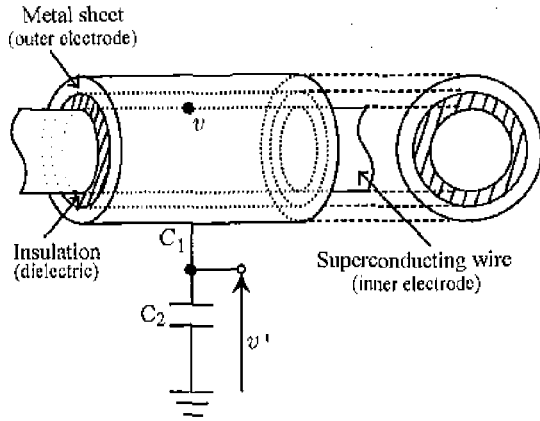


Fig. 1. Structure of capacity type voltage divider.

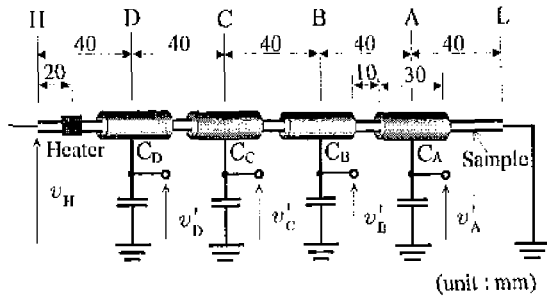


Fig. 2. Sketch of sample superconducting wire with capacity type voltage dividers and heating coil.

ing the voltage v' across C_2 . The measured voltage v' is expressed by next equation.

$$v' = \frac{C_1}{C_1 + C_2} v \quad (1)$$

where C_2 is the capacitance of C_2 . In the experiments, we used C_2 of 60 nF. From (1), v' is related to v in our experiments as

$$v' = \frac{27 \times 10^{-12}}{27 \times 10^{-12} + 60 \times 10^{-9}} v = 4.5 \times 10^{-4} v \quad (2)$$

In our previous work, we have experimentally confirmed that the outer metal electrode arranged around the sample conductor have no influence upon the propagation process [4]. The transient behavior of the normal resistance obtained for the sample with the outer electrodes agrees with actual characteristic derived for the sample without the outer electrodes, while the results for the sample with the voltage taps were slower than actual one.

B. Experimental Set-up and Procedure

Fig. 2 shows the sketch of the sample superconducting wire with the capacitance dividers and heating coil. The

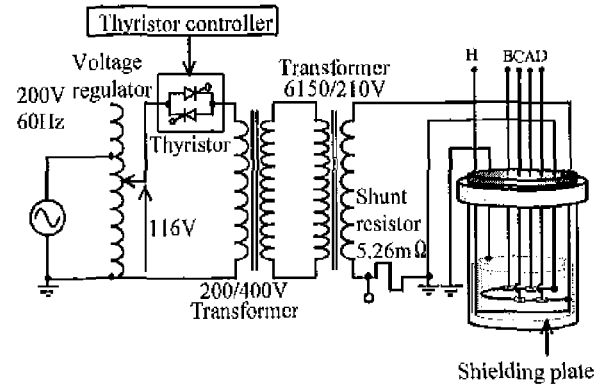


Fig. 3. Experimental circuit diagram.

sample length was 200 mm and four capacitance dividers C_A , C_B , C_C and C_D of 30 mm in length were arranged at points marked "A", "B", "C" and "D" with equal separation of 40 mm. We can obtain the actual voltages v_A , v_B , v_C and v_D at points A, B, C and D by converting the measured voltages of v'_A , v'_B , v'_C and v'_D with (2). As shown in Fig. 2, one edge of the sample marked "L" was grounded and a voltage tap was soldered at another edge "H" to measure the whole voltage v_H across the sample wire. A heater coil was located at a distance of 20 mm from H in order to always originate the quench at this point.

Fig. 3 indicates the experimental circuit diagram. The frequency of the power source is 60 Hz. The output of the voltage regulator was adjusted to 116 V and the thyristors were turned on to supply the overcurrent. The turn-on phase angle was controlled to contain no dc transient component in the overcurrent. As seen from (2), the voltage v' measured by noncontact measurement may be very small. To eliminate the noise in the measurement, we installed the shielding plate along the inner wall of the cryostat.

C. Experimental Results

Fig. 4 shows the measured waveforms of the heater current i_h , sample current i_s and whole voltage across the sample v_H . The sample current i_s began to supply at $t=0$ ms and the heater was turned on for the period from 0.10 to 1.10 ms. It was judged that the quench occurred at $t=0.30$ ms because the voltage v_H appeared at this point.

Fig. 5 shows the waveforms of the voltages v_A , v_B , v_C and v_D obtained by the noncontact measurement together with v_H . The right vertical axis of this figure indicates the magnitude of voltages v'_A , v'_B , v'_C and v'_D measured directly by the noncontact method. The voltages begin to appear in order of v_H , v_D and v_C . It suggests that the quench occurred between H and D, where the heater was installed, and the normal zone propagated toward L. The voltage v_D was appeared at $t=0.38$ ms. This means that

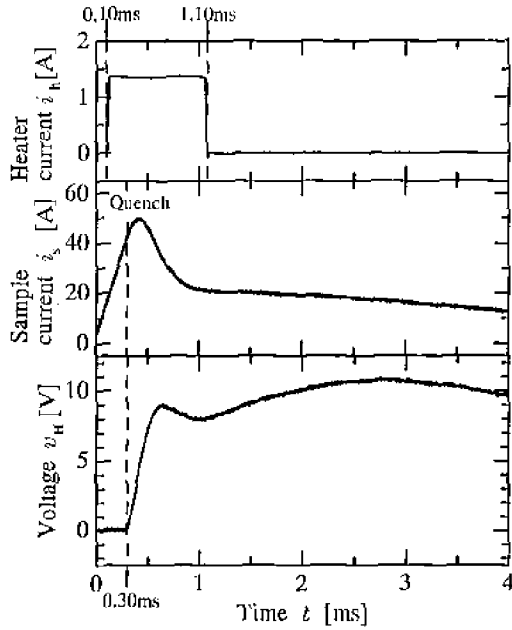


Fig. 4. Measured waveforms of heater current i_h , sample current i_s and whole voltage v_H .

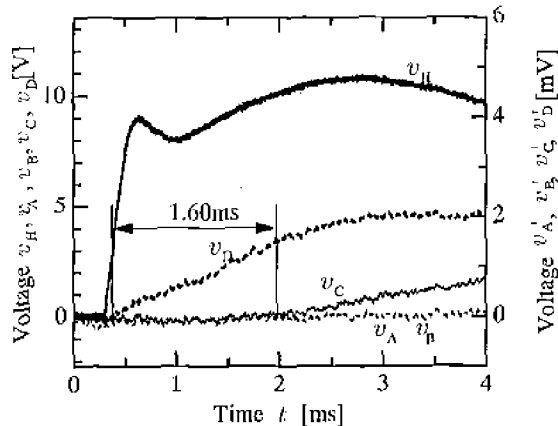


Fig. 5. Time variation of observed voltages.

the normal zone attained to the left edge of C_D at D at this time[4].

The propagation velocity v_p was obtained from the interval between onset time of voltages v_D and v_C . The voltage v_C was observed after 1.60 ms from appearance of the voltage v_D . Since the distance between the positions of left edge of C_D and C_C is 40 mm, the propagation velocity v_p was calculated as

$$v_p = \frac{40 \times 10^{-3}}{1.6 \times 10^{-3}} = 25.0 \text{ m/s} \quad (3)$$

This velocity is average value for $t=0.38$ ms to 1.98 ms, when the current changes from 50 A to 20 A.

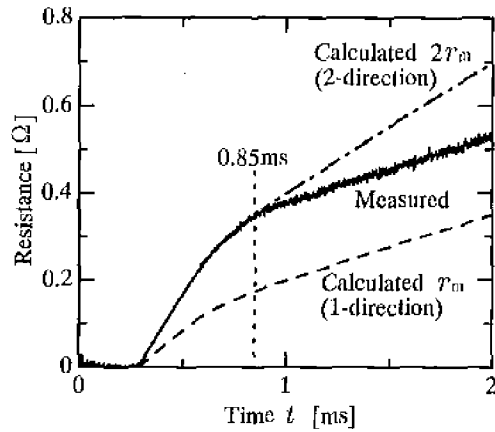


Fig. 6. Time variation of normal resistance.

III. ESTIMATION OF PROPAGATION PROCESS VIEWED FROM NORMAL RESISTANCE RISE

A. Measurement of Normal Resistance

The magnitude of the normal resistance in superconducting wire is in proportion to the length of normal region because the normal resistivity of Nb-Ti/Cu-Ni wire hardly depend on the temperature. Hence, the propagation velocity v_p may also be evaluated from the increasing rate of normal resistance. The solid curve in Fig. 6 indicates the time variation of the normal resistance. We derived the resistance by dividing the voltage v_H by the sample current i_s every moment.

It is found that the measured profile of the normal resistance rise has two main increasing rates. The normal region must spread in two directions to edge points II and L immediately after the quench occurrence. After one normal front reached to H, the normal zone propagates in only one direction toward L. This change in the propagation situation might result in the change of the increase rate of normal resistance. However, we can not determine when the normal zone propagation changes from two-direction to one-direction propagation from only measurement results, because the current also varies greatly.

B. Theoretical Calculation

We theoretically estimated the time variation of normal resistance. Neglecting the heat transfer to the liquid helium during the propagation process, v_p can be written by next equation[5].

$$v_p = \frac{i}{cA} \sqrt{\frac{\rho_n k}{T_t - T_b}} \quad (4)$$

where i is the current and T_t is the boundary temperature between superconducting and normal regions. We now assumed that T_t is expressed by

$$T_t = \frac{T_c}{2} + \frac{1}{2} \left\{ T_b + \left(1 - \frac{i}{I_c} \right) (T_c - T_b) \right\} \quad (5)$$

The meaning and value of each variable in (4) and (5) are listed in Table II. If the normal zone propagates in two

TABLE II
VALUE OF VARIABLES USED FOR CALCULATION.

Symbol	Meaning	Value
c	Specific heat	5000 [J/m ³ K]
k	Thermal conductivity	0.32 [W/mK]
A	Cross-sectional area	2.5×10^{-8} [m ²]
ρ_n	Resistivity	2.0×10^{-7} [Ω m]
T_c	Critical temperature	9.4 [K]
T_b	Temperature of LHe	4.2 [K]
I_c	Critical current	100 [A]

directions, the propagation velocity is twice as fast as v_p expressed by (4). Substituting the instantaneous value of measured current i_s shown in Fig. 4 into i in (4), we can derive the time variation of propagation velocity. Furthermore, the rise of the normal resistance r_m is obtained as a function of t by

$$r_m = \frac{\rho_n}{A} \int_{t_q}^t v_p dt \quad (6)$$

where t_q is the time at the quench occurrence.

The dashed line and dash-dotted one in Fig. 6 indicate the time variations of r_m and $2r_m$, respectively. The resistance $2r_m$ corresponds to the case of two-direction propagation. For $t < 0.85$ ms, the measured resistance agrees $2r_m$ calculated for two-direction propagation. So it is pointed out that the normal zone spreads in two directions for this period. When $t > 0.85$ ms, the slope of the measured resistance is same as that of r_m computed for one-direction propagation, i.e. the normal region propagates in one direction.

C. Propagation Velocity and Quench Initiation Point

We computed v_p for $t=0.38$ ms \sim 1.98 ms from change of the normal resistance to compare with the propagation velocity measured by the noncontact method. The normal resistance at $t=0.38$ ms is 0.07 Ω . At $t = 0.85$ ms, when the normal zone propagation switches from two-direction to one-direction, the resistance is 0.34 Ω . In the period of $0.38 \text{ ms} \leq t \leq 0.85 \text{ ms}$, the increment in the resistance is 0.27 Ω . This resistance corresponds to the normal zone of 33.8 mm in length. Since this length is for two-direction propagation, the increase of length for one direction is 16.9 mm. On the other hand, the resistance at $t = 1.98$ ms is 0.52 Ω and the change of the resistance for the period of 0.85 ms to 1.98 ms is 0.18 Ω . This magnitude of the resistance is suited to the propagation distance of 22.5 mm. Hence, the propagation velocity v_p is calculated as follows.

$$v_p = \frac{(16.9 + 22.5) \times 10^{-3}}{(1.98 - 0.38) \times 10^{-3}} = 24.6 \text{ m/s} \quad (7)$$

This v_p is in good agreement with that obtained by the noncontact measurement.

The half length of the normal region at $t=0.85$ ms is regarded as to the distance between quench initiation point and H. Since the normal resistance at $t = 0.85$ ms is

0.34 Ω and that corresponds to the length of normal zone of 42.6 mm, the quench initiation point can be estimated to be 21.3 mm from point H. This location agrees with the installed position of the heater coil.

Using this method combining the experimental measurement of normal resistance with the theoretical calculation (resistance method), we can obtain the instantaneous value of the propagation velocity as a function of the transport current although the noncontact method gives only local average value. However, if the quench occurs at more than two point, it is difficult to estimate propagation velocity only by the resistance method. Furthermore, in the measurement of quench initiation point by the resistance method, it can not be determined in which side of the sample wire the quench originates because the voltage and current in whole sample are measured. Hence, we must apply both methods to measure the propagation process.

IV. CONCLUSIONS

The novel measurement methods of the propagation characteristics were discussed. First, the quench initiation area, local average propagation velocity and direction in an ac Nb-Ti/Cu-Ni superconducting wire were measured by the noncontact measurement method proposed by us. Secondly, we tried to estimate the instantaneous propagation velocity by a new methods. In this method, the normal resistance generated in the sample was experimentally measured and theoretically calculated. By comparing both derived profiles of the normal resistance rise and referring to the results by the noncontact method, the propagation process of the normal resistance, such as quench initiation point, propagation velocity and direction, were successfully evaluated in detail.

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