Influences of Temperature Cycle on the Levitation Force Relaxation with Time in the HTS Levitation System

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***Abstract*- Levitation force relaxation phenomenon in a superconducting levitation system composed of the high temperature superconducting materials (HTSs) and permanent magnet (PM) materials (or PM guideway) is not avoidable because of the flux creep, an intrinsic feature of the HTSs. In this paper, the influences of the temperature cycle on levitation force relaxation with time were investigated. Some novel experimental results were found and these results are a benefit to the understanding of the HTSs levitation system.**

Keywords*- *Temperature Cycling; Levitation Force Relaxation with Time; High Temperature Superconducting Levitation System

I. INTRODUCTION

Since the discovery of the high-temperature superconductor (HTS), the levitated magnet or bulk superconductor has become a symbol of the new technology of superconductivity applications. The interaction between a permanent magnet (PM) and a high-temperature superconductor has become the basis of the superconducting levitating system design. The diamagnetic and flux pinning characteristics endow high temperature superconducting levitation system with an excellent loading capacity and novel passive stable characteristics. The original work of levitation force measurement was carried out by Moon et al. [1], in which they measured the hysteresis curve of levitation force versus superconductor-magnet distance. Subsequently, Moon and Chang et al. [2] measured the time effect on levitation force (relaxation). It is obvious that the flux creep, an intrinsic feature of high-temperature superconductors, is responsible for the time decay of the levitation force (relaxation) [3, 4]. In order to describe the decay characteristic of relaxation curve, a formula to calculate the logarithmic decay rate of a relaxation curve varying with time was presented by Riise et al. [3]. Magnetic relaxation phenomena in superconductors have also been studied by many researchers [5-13].

It has been recognized that the levitation force relaxation between a PM and an HTS is determined not only by the cooling height [14], but also by operating temperature [15-19]. Isaac and Jung [15] investigated the origin of logarithmic decay rate by performing the measurements: (1) the relaxation of the persistent current from its critical value, as a function of temperature T and magnetic field H; (2) the temperature dependence of the critical current at different magnetic fields. He Jiang et al. [16] found that the maximum levitation force of each levitation force-distance curve at different constant temperatures saturates with the lowering of temperature. Chiang et al. [17] have measured the hysteresis characteristics of levitation force at different constant temperatures. Tseng and Chiang et al. [18] have measured the levitation force time relaxation of bulk Y-Ba-Cu-O at different constant temperatures within 40-85 K. Suzuki et al. [19] have measured the levitation force time relaxation of bulk Y-Ba-Cu-O and Sm-Ba-Cu-O at different constant temperatures within 10-77 K, and found that the time relaxation is drastically reduced with lowering temperature. There is even no report about the influences of temperature cycling on the forces of levitation system. In our previous work [20], we have reported that the levitation force continues to decrease when continually decreasing the temperature after the relaxation at a constant temperature.

This paper will show some experimental measurements of levitation force relaxation with time under the temperature cycling that increasing after decreasing from a constant temperature.

II. EXPERIMENTAL PROCEDURE

Our experimental apparatus is an updated HTS maglev measurement system, which was developed by the Applied Superconductivity Laboratory at the Southwest Jiaotong University in China. The details of the experimental setup were described elsewhere [21]. We substituted for the liquid nitrogen vessel with a modified Gifford-McMahon (G-M) refrigerator. The cooling temperature can be held on any temperature greater than 10 K and increased on a given rate within 0.01-0.15 K/s. This measurement system including G-M refrigerator is illustrated in Fig. 1. Note that our thermometer was attached directly on the superconductor sample.

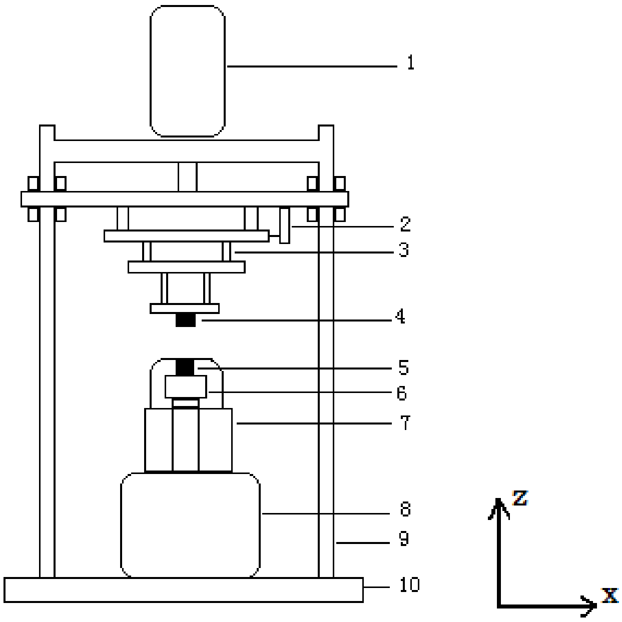

Fig. 1 The schematic illustration of updated HTS maglev measurement system. 1, servo motor; 2, horizontal force sensor; 3, vertical force sensor; 4, permanent magnet; 5, superconductor; 6, cool head; 7, vacuum chamber; 8, G-M refrigerator; 9, frame; 10, base

The cylindrical shaped HTS bulk is composed of yttrium-barium-copper-oxide ($YBa_2Cu_3O_{7-\delta}$, $0<\delta<0.7$) with a diameter of 30 mm and thickness of 18 mm, which is fabricated by the General Research Institute Metals (Beijing), and the fabricated process was described elsewhere [22]. The areal levitation force of the sample is about $12N/cm^2$, and critical temperature of it is about 90K. The cylindrical shaped sintered permanent magnet of NdFeB has dimensions of 30 mm in both diameter and thickness, and it is axially polarized in the *Z*-direction with the concentrating surface magnetic flux density of up to 0.5 T. Of course, the geometries of HTS and PM may have some effects on the experimental results, but as a fundamental research, such experiments can predict some general phenomena in the superconducting levitation system.

The increasing-after-decreasing temperature cycling is described as: firstly cool the HTS to a selected temperature (T1), then continually reduce the temperature of HTS to another lower temperature (T2), finally enhance the temperature to the third selected temperature (T3). Here we chose some temperature cycling as follows: (1) T1= 71.6 K, T2= 11.3 K, T3= 71.6 K; (2) T1= 61.9 K, T2= 11.6 K, T3= 68.6 K; (3) T1= 71.6 K, T2= 61.9 K, T3= 76.6 K; (4) T1= 61.9 K, T2= 51.9 K, T3= 66.8 K.

The detailed description of the levitation force relaxation measurements at these temperature cycling conditions is as follows. We performed the experiments by first placing the HTS on the cool head of G-M refrigerator, fixing the PM on the servo motor far away above and coaxial with the HTS to simulate the zero-field cooling and symmetrical case; and then vacuumed the vacuum chamber of G-M refrigerator, cool the HTS to the expected temperature T1 (such as 71.6 K or 61.9 K); after that the PM was moved coaxially with the HTS to the minimum gap of 12 mm between the top surface of the HTS and the bottom surface of the PM; once the minimum gap was achieved, the levitation force as a function of time was recorded; after holding on the first expected cooling temperature T1 for 600 s, we lower the temperature of HTS continually from T1 to T2 (such as from 71.6 K to 11.6 K, from 61.9 K to 11.6 K, from 71.6 K to 61.9 K and from 61.9 K to 51.9 K), then enhance the temperature from T2 to T3 (such as from 11.3 K to 71.6 K, from 11.6 K to 68.6 K, from 61.9 K to 76.6 K and from 51.9 K to 66.8 K separately). The levitation force as a function of time was recorded simultaneously and continuously with the process of holding, lowering and enhancing of temperature.

For comparison, we also carried out the measurements that directly increase the temperature from T1 to T2. Here we choose some temperature cycling as follows: (1) T1= 11.3 K, T2= 81.8 K; (2) T1= 51.9 K, T2= 61.9 K; (3) T1= 61.9 K, T2= 71.6 K. The detailed processes are that firstly cool the HTS to T1 (11.3 K, 51.9 K and 61.9 K separately) under zero-field cooling condition; then coaxially move the PM to the expected levitation height (minimum gap of 12 mm), begin to record the levitation force as a function of time; after holding on for 300 s for the cases of 11.3 K, and 600 s for the cases of 51.9 K and 61.9 K, increase the temperature from 11.3 K to 81.8 K, from 51.9 K to 61.9 K and from 61.9 K to 71.6 K with a speed of 0.01 K/s, separately. The levitation force as a function of time was recorded simultaneously and continuously with the process of holding and increasing of temperature.

III. RESULTS AND DISCUSSION

Fig. 2 shows the curves of levitation force relaxation as functions of time and the corresponding temperature cycling curves. Fig. 2a is for the process that decreases the temperature from 71.6 K to 11.3 K and then increases to 71.6 K; and Fig. 2b for the process that decreases from 61.9 K to 11.6 K and then increases to 68.6 K.

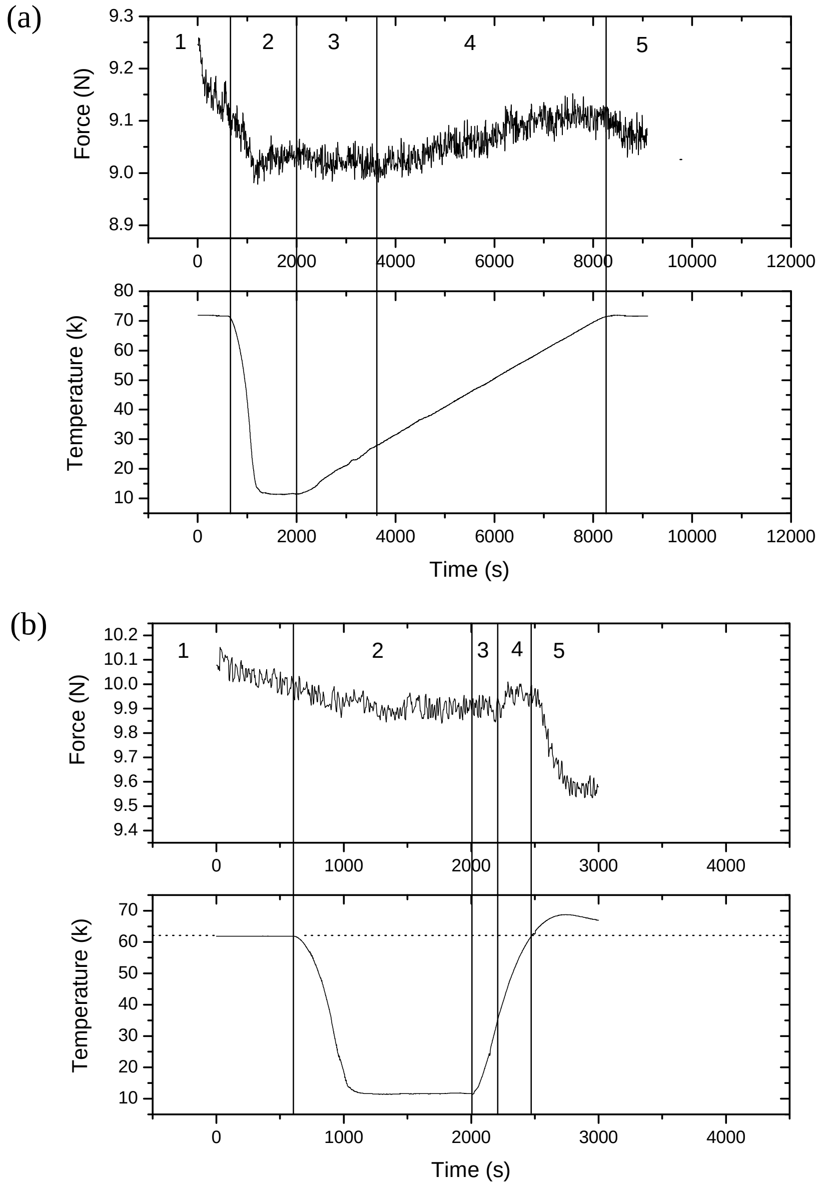

Fig. 2 Curves of levitation force relaxation and correlative varing temperature curves, temperature change (a) from 71.6 K to 11.3 K and then back to 71.6 K; (b) from 61.9 K to 11.6 K and then back to 68.6 K

From Fig. 2 one can see that the levitation force decreases with the lowering of temperature after the first 600 s constant temperature relaxation, as mentioned in [20]; and then the levitation force will keep constant after the lowering if there is no temperature change. But, after the lowering of temperature, the levitation force will increase with the increasing of temperature before exceeding the initial cooling temperature, as shown in zone 4 of Fig. 2a and Fig. 2b. This phenomenon is quite new compared with the existing results. It seems that increasing the temperature of HTS will increase the critical current density under such temperature cycling condition. As shown in Fig. 2 zone 3 and 4, the levitation force will not immediately increase with the increasing of the temperature. It should be noted that the increasing range of levitation force in zone 4 of Fig. 2 is equal to the decreasing range in zone 2. After increasing and exceeding the first selected temperature T1, the levitation force will decrease sharply, as shown in Fig. 2b zone 5.

The influences of directly increasing the temperature from the initial cooling and working temperature to another temperature during relaxation are shown in Fig. 3. During the relaxation on a constant temperature, the levitation force will decay with the logarithmic rate. And if we increase the temperature from the initial constant temperature to another temperature directly during the relaxation, the levitation force will decrease, as shown in Fig. 3. The decreasing quantity of levitation force is correlative with the increasing quantity of temperature. Such as, in Fig. 3a the levitation force is 10.1 N for 51.9 K, and 9.9 N for 61.9 K, 9.2 N for 71.6 K; in Figs. 3b and c the levitation force is also10.2 N for 51.9 K, and 9.9 N for 61.9 K, 9.2 N for 71.6 K. The final levitation force after the temperature increasing is equal to the levitation force that directly working on this final temperature under zero field cooling. That is to say that in the practical utilization of HTS, the thermal stability of HTS may be crucial for the stability of levitation system.

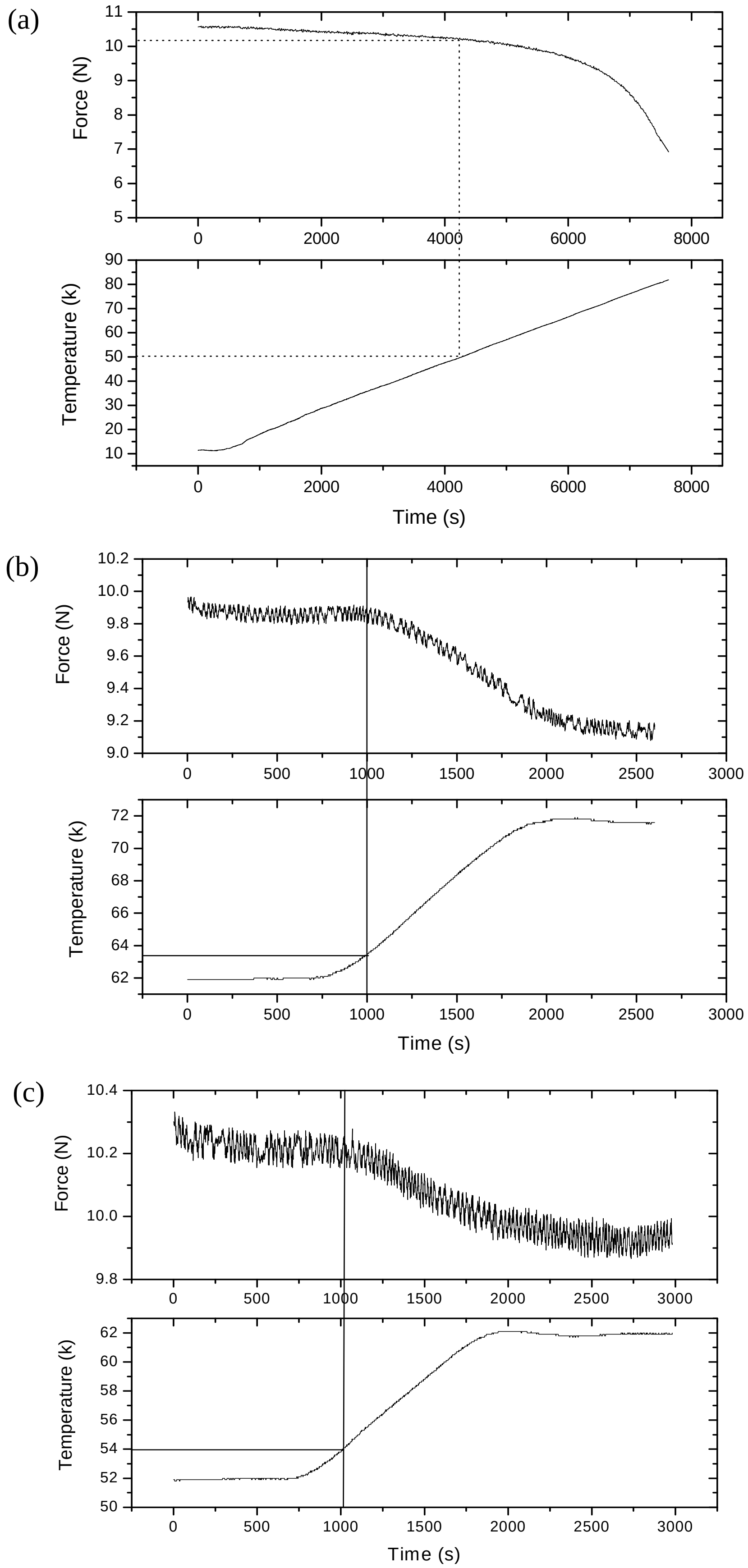

Fig. 3 Curves of levitation force relaxation and correlative varing temperature curves. Temperature directly increase (a) from 11.3 K to 81.8 K; (b) from 51.9 K to 61.9 K; (c) from 61.9 K to 71.6 K

With two samples for this pretreatment method, two tests have been conducted, as shown in Fig. 4. For the case that allows the temperature to change within about 10 K, the temperature cycling is: (1) T1= 71.6 K, T2= 61.9 K, T3= 76.6 K; (2) T1= 61.9 K, T2= 51.9 K, T3= 66.8 K. Fig. 4a is for the process that decreases the temperature from 61.9 K to 51.9 K and then increases to 66.8 K, Fig. 4b is for the process that decreases from 71.6 K to 61.9 K and then increases to 76.6 K. Form Fig. 4 one can see that during the levitation system work at 61.9 K or 51.9 K, there will arise a temperature increase less than 10 K with much less levitation force change. It should be noted that the temperature stable range is between the historical highest temperature and long time work temperature, as shown in Fig. 5. In Fig. 5, the stable temperature range is between 51.9 K and 61.9 K, in zone 4.

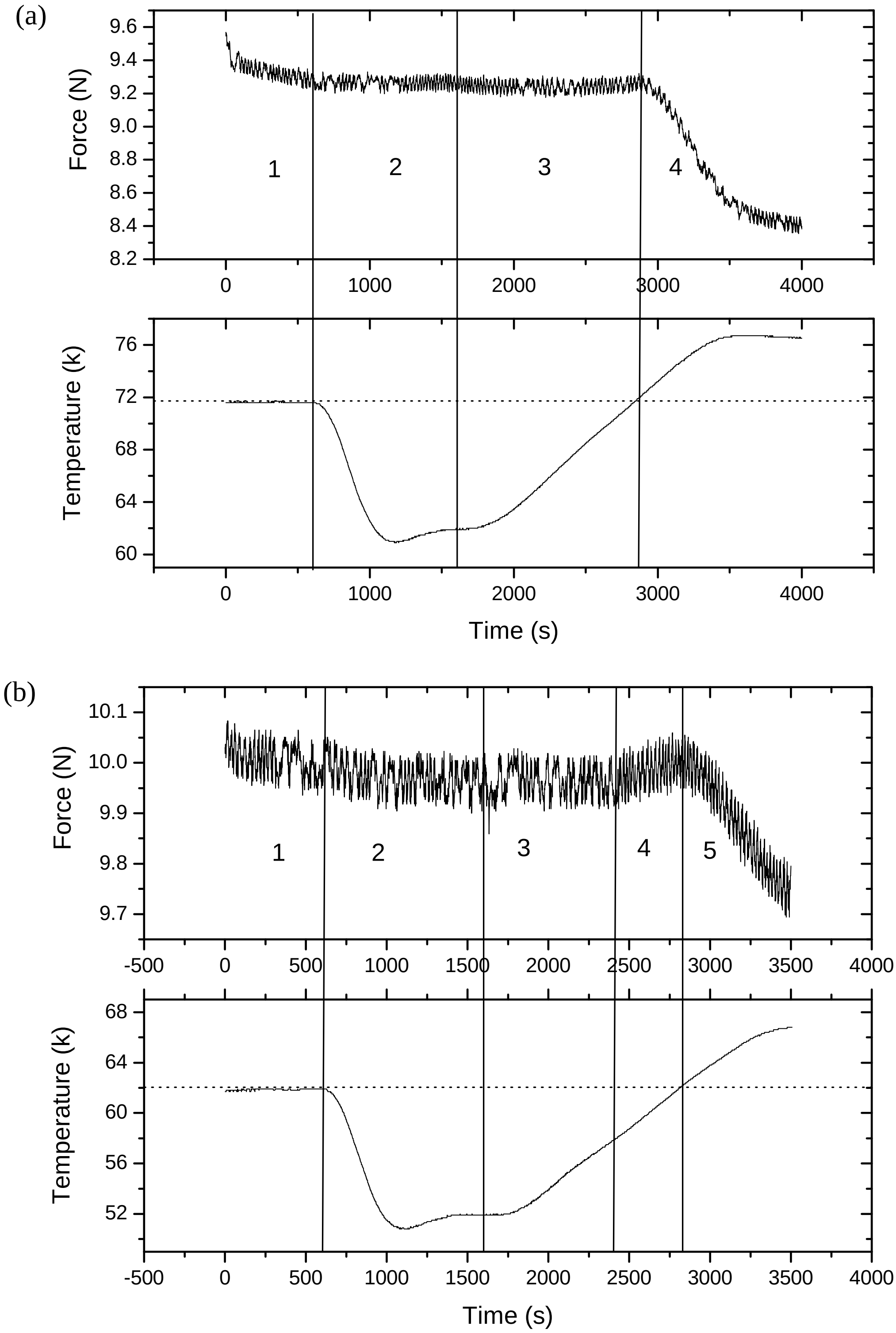

Fig. 4 Curves of levitation force relaxation and correlative varing temperature curves, (a) from 71.6 K to 61.9 K and back to 76.6 K; (b) from 61.9 K to 51.9 K and back to 66.8 K

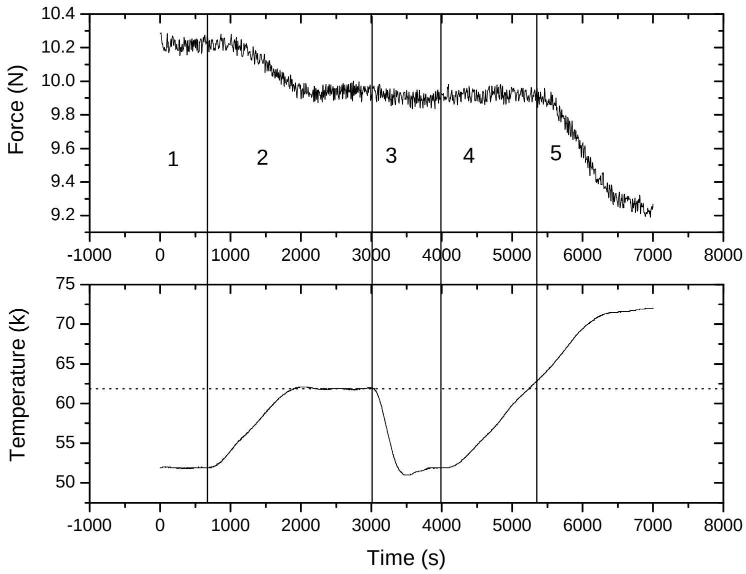

Fig. 5 Curve of levitation force relaxation and correlative varing temperature curves. The varing process is, after the relaxation at 51.9 K, increase the temperature to 61.9 K and then decrease back to 51.9 K, then secondly increase and get to 71.9 K

According to the previous researches presented in Ref [3, 4, 12, 13, 18], in the HTSs levitation system, the levitation force relaxation with time obeys,

$$F(t) = F(0)\left[1 - \frac{k_B T}{U_0}\ln(1+\frac{t}{t_0})\right] \tag{1}$$

where, U_0 denotes the pinning potential, K_B is the Boltzmann constant, T is the experimental temperature, t_0 is the characteristics time, $F(0)$ stands for the initial levitation force, t is the measurement time. When the levitation force relaxation with time reaches equilibrium at the given temperature, the probability of the attempt of fluxiods over the pinning walls does almost not change. When the temperature is decreased, according to the Equation (1), levitation force relaxation with time is increased. This agrees with our experimental observations. When the temperature went back to the initial values (a process of temperature increase), from the Equation (1), one can see that the levitation force should be decreased. But from our measurements (Figs. 2(a), (b)), levitation force relaxation with time has a little increase (or keeps almost stable) during this temperature increase process. In order to interpret these results qualitatively, a competition mechanism between temperature T and the pinning potential U_0 is introduced. Generally speaking, with the increase of the temperature, the pinning potential is decreased. In this case, the levitation force relaxation with time having a little increase during the temperature increase process is reasonable.

IV. CONCLUSIONS

This work is a continuation of our previous presentation. From these results, the following conclusions are arrived: (1) after the experimental temperature is decreased from the initial value to the expected temperature, levitation force relaxation with time has a little increase during the temperature increase process, which does not agree with the relationship between the levitation force and temperature presented previously, (2) after an increase and then decrease of temperature cycle, the influences of the temperature varying on the levitation force relaxation with time are less, and this conclusion may be beneficial to the strength stability of the HTSs levitation system.

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