Reinvestigation of the rotation effect in solid ^{4}He with a rigid torsional oscillator

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We reexamined the rotation-induced effect observed in solid ^{4}He by using a rigid two-frequency torsional oscillator (TO). The previous rotation experiments reported the rotation-induced suppression of the "nonclassical" TO response that was interpreted as evidence of irrotational bulk superfluidity in solid ^{4}He. However, the experiment employed a nonrigid TO that could amplify the elastic contribution in the TO response. Thus, it is important to clarify if the rotation-induced suppression of the TO response could be attributed to an unavoidable elastic effect. In our rigid TO, complicated nonlinear viscoelastic contributions are systematically eliminated. In addition, the TO operating at two different resonant frequencies allows us to decompose a possible superfluidlike frequency-independent contribution on period drop from that of the linear elastic overshoot effect. We found no substantial rotation-induced effect in the out-of-phase resonant mode unlike that found in the previous rotation experiments. It indicates that the previous rotation effect in the nonrigid TO cannot be attributed to the genuine supersolidity. According to the frequency analysis of the TO response, the frequency-dependent period drop, which can be attributed to the elastic overshoot effect, remains unaffected upon application of dc rotation. However, the frequency-independent superfluidlike contribution exhibits a strikingly different rotation effect that is currently inexplicable.

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I. INTRODUCTION

Superfluidity is a quantum state of matter in which a liquid sustains a dissipation-less flow. Since first discovered in liquid ^{4}He [1,2], it has been widely studied as manifestation of quantum mechanics acting on a bulk property in a macroscopic scale. The irrotational nature of superfluid ^{4}He was demonstrated through its decoupling from the container under rotation [3]. When a torsional oscillator (TO) containing liquid ^{4}He is cooled down below $T_\lambda = 2.17$ K, the superfluid density $\rho_s(T)$ does not contribute on a rotational inertia of the TO, and accordingly, leads to a reduction in its resonant period. Similarly, the reduction in a period of a TO containing solid ^{4}He, observed by Kim and Chan, was first interpreted as decoupling of the solid from oscillation due to appearance of supersolidity [4–6]. However, unlike the abovementioned TO experiment on superfluid, the resonant period of the TO containing solid ^{4}He can be changed by mechanisms other than supersolid transition, such as an elastic stiffening of solid ^{4}He [7–14] that is widely accepted as a more plausible explanation for the TO response. The increase in shear modulus of solid ^{4}He enhances an effective elastic stiffness of the TO at low temperatures and gives rise to a supersolid-mimicking resonant period drop.

Meanwhile, dc rotation was superimposed onto torsional oscillation of a TO containing solid ^{4}He to demonstrate the irrotational nature more directly. These rotation experiments revealed a strong suppression of the TO responses [15–17]. In addition, periodic staircaselike suppressions in the resonant period of TO were reported by rotation-sweep experiments. These results are inconsistent with the simple temperature-dependent elasticity model and were interpreted as strong evidence for the irrotational superfluidity in solid ^{4}He. Here, we reexamine the rotation-induced TO responses observed in solid ^{4}He with a rigid two-frequency TO to clarify the conflicting observations.

II. EXPERIMENTAL METHODS

We constructed a two-frequency rigid TO to validate previous dc rotation experiments (Fig. 1). If a TO is not sufficiently rigid, then the period changes of the TO due to the elastic stiffening of solid ^{4}He can be enormously amplified through various complicated viscoelastic coupling mechanisms between the TO structure and solid ^{4}He [18–24]. Three nonlinear coupling mechanisms have been suggested: the glue effect [18,22], the torsion rod hole effect [19], and the Maris effect [20]. The reduction in a TO period (or the period drop), proportional to the supersolid density reported in the previous rotation experiment, was unusually large [15] compared to that observed in other rigid TOs [25,26]. It implies that the TOs employed for the previous rotation experiments were not sufficiently rigid and the observed period drop might have been caused by the nonlinear viscoelastic origins. We note that nonrigid TOs are also easily affected by vibration noise

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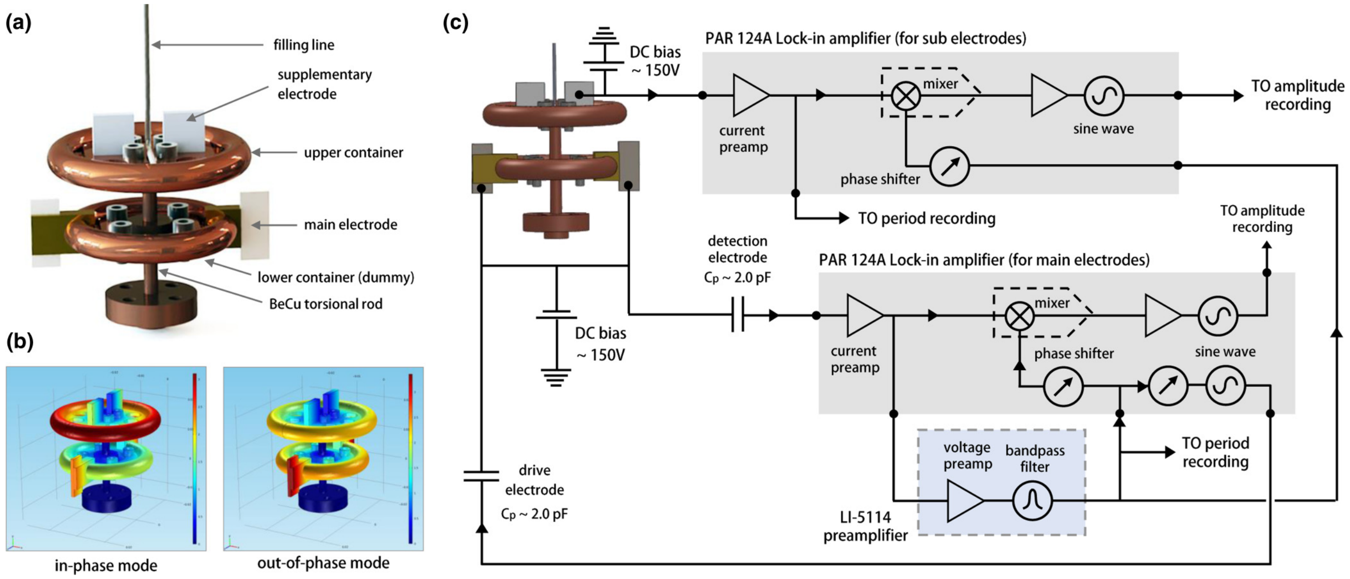

FIG. 1. KAIST rigid double-torus torsional oscillator (TO). (a) The TO consists of two torus-shaped solid ^{4}He containers and two torsional rods. A pair of main and supplementary capacitive electrodes are attached to lower and upper container, for both drive and detection of the TO responses. **(b)** Similar to a double mass-spring system, the TO has two different resonant eigenmodes. The displacement of the TO estimated by finite-element method (FEM) simulation is shown. The color on the figures shows displacement of each component. Two containers oscillate in same direction in the in-phase mode (448.65 Hz), while they oscillate in the opposite direction in the out-of-phase mode (1131.20 Hz). **(c)** The TO is driven on its self-resonance through a phase-locked measurement by using two PAR124 lock-in amplifiers.

generated during dc rotation and may show TO responses similar to the rotation-induced effect. We successfully minimized the above three nonlinear elastic coupling mechanisms by constructing the rigid TO. The details of design principle and construction of the rigid TO are summarized in our previous publication [26].

Besides, our rigid TO can be operated at two resonance frequencies [Fig. 1(b)], which allow a frequency-dependence analysis on the TO response. Even for the rigid TO, a simple and intrinsic elastic contribution called the "overshoot effect" is unavoidable. Since solid ^{4}He has a much smaller elastic modulus than a metallic container of the TO, an angular acceleration caused by torsional oscillation results in an additional displacement and deformation with respect to the wall of the container and causes a retarded back action [27,28]. This linear elastic overshoot effect gives rise to the period drop proportional to the square of frequency, whereas the superfluid-induced period drop does not change with frequency [18,27]. Therefore, the frequency-dependent analysis can distinguish the contribution of the linear elastic stiffening on the period change from that of the genuine superfluid transition. The two-frequency rigid TO used in this experiment reported a frequency-independent superfluid fraction of about 4×10^{-6} [26] that does not exceed the previously proposed upper limit of supersolid fraction [25,29].

To superimpose dc rotation on torsional oscillation, the rigid double-torus TO was attached to the mixing chamber of the rotating dilution refrigerator at RIKEN [30]. Maximum applicable rotation speed was 4 rad/s. We assessed stability in dc rotation (or rotational noise) of the RIKEN rotating cryostat by measuring maximum fluctuation of dc rotation speed, $d\Omega$, under various dc rotation speeds, Ω. The ratio between two quantities, $d\Omega/\Omega$, is approximately 0.001 from 0 to 2 rad/s, comparable to that measured on the Manchester rotating cryostat [31]. The stability of our rigid TO was not severely degraded by increased dc rotation speed; the fluctuation in the period of our TO was increased from 0.02 ns at a stationary state to 0.04 ns under 4-rad/s rotation speed. For a complementary test, we also measured spectra of both horizontal and vertical displacement on the RIKEN rotating cryostat over a frequency range of 10–1000 Hz. As a result, the displacements are too small to give influence on our TO, which is operated at approximately 450 and 1130 Hz.

We measured the period and amplitude of the TO during warming scans from 20 to 500 mK, while maintaining a uniform dc rotational speed of Ω. The empty-cell TO responses were not significantly affected by either ac oscillation or dc rotation when the TO was operated in the linear response regime. Three polycrystalline solid ^{4}He samples with pressure of 32, 36, and 47 bar were grown using the block-capillary method. Commercially available high-purity ^{4}He with the nominal ^{3}He impurity concentration of 0.3 ppm was used in the experiments.

III. RESULTS

Figure 2 shows the temperature dependence of the period drop dP divided by the mass loading $\Delta P(T)$ of solid ^{4}He, $dP(T)/\Delta P$, and the dissipation $Q^{-1}(T)$ in both in-phase and out-of-phase modes for the 32-bar solid sample. At a stationary state ($\Omega = 0$), the typical characteristics of TOs containing solid ^{4}He were successfully reproduced. In the in-phase (out-of-phase) mode, the reduction of the TO period starts to appear at about 250 mK (325 mK) and becomes saturated at approximately 50 mK (60 mK). The frequency dependence of the onset temperature is consistent with that

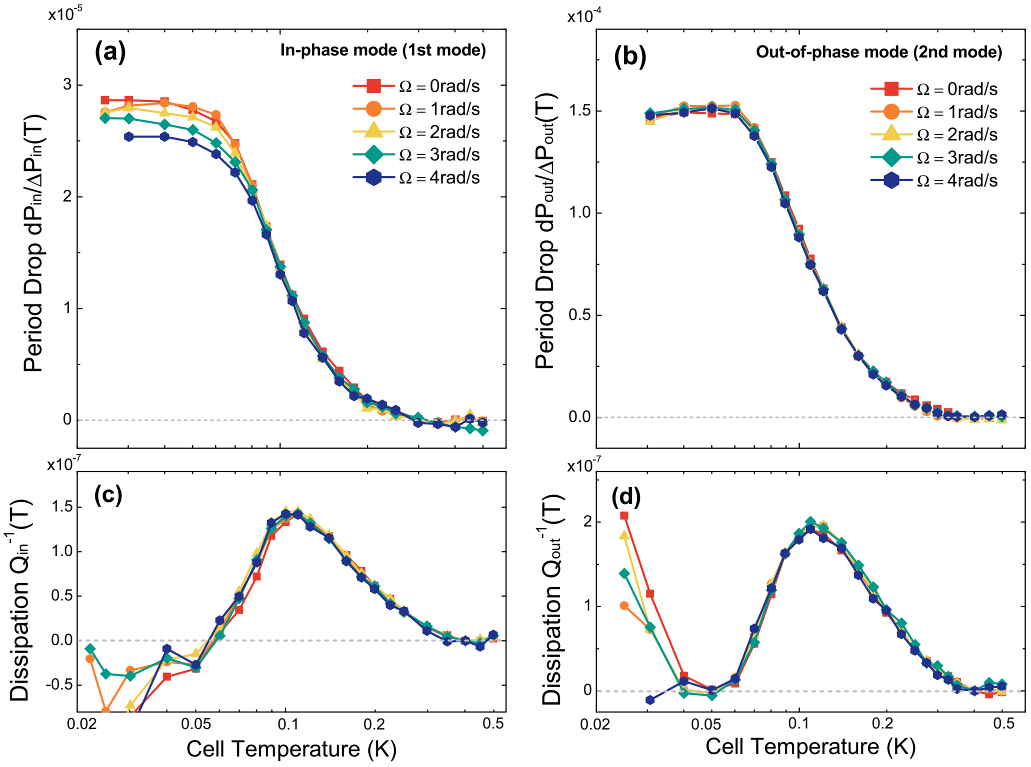

FIG. 2. Effect of dc rotation on rigid TO responses. Period drop dP of rigid TO, with respect to the mass loading of solid growth $\Delta P(T)$, in the (a) in-phase and (b) out-of-phase mode are plotted against the temperature under various dc rotation speeds in a range of 0 to 4 rad/s. Dissipation $Q^{-1}(T)$ in the (c) in-phase and (d) out-of-phase mode are also measured simultaneously.

in the other experiments using a double-frequency TO [32] and piezoelectric transducer (PZT) [9]. In the in-phase and out-of-phase modes, the TO resonant period decreased by 1.10 and 0.87 ns, respectively. After subtracting the background signal of the empty cell, the $dP/\Delta P(T)$ values of the two modes at 25 mK are $dP_{\text{in}}/\Delta P_{\text{in}} = 2.86 \times 10^{-5}$ and $dP_{\text{out}}/\Delta P_{\text{out}} = 1.48 \times 10^{-4}$, where the subscripts indicate the aspecific modes. Dissipation of the TO was also calculated by comparing the amplitude of the rigid TO containing solid ^{4}He with that of the empty TO on its resonance. The dissipation $Q^{-1}(T)$ shows local maxima where the period of TO changes most steeply. The maximum size of dissipation Q_{in}^{-1} (Q_{out}^{-1}) is approximately 1.43×10^{-7} (1.93×10^{-7}), which was much smaller than that of typical TOs.

We also examined the effect of dc rotation on the TO responses by systematically increasing rotational speed. To concentrate on the dc rotation effect, the driving voltage of ac oscillation of the TO was fixed to the minimum excitation voltage at 2 mV (3.8 mV) in the in-phase (out-of-phase) mode [15]. The ac oscillating speeds are approximately $\sim$40 μm/s for both resonant modes. As shown in Fig. 2, the TO responses measured in the in-phase [Fig. 2(a)] and out-of-phase mode [Fig. 2(a)] show a striking contrast. In the in-phase mode, the period drop is clearly suppressed as dc rotation speed increased, but no such rotation-induced effect was prominent in the out-of-phase mode. Under 4 rad/s, the magnitude of $dP_{\text{in}}/\Delta P_{\text{in}}$ at 30 mK decreased to 2.53×10^{-5}, which is about 12% smaller than the value without rotation. On the other hand, the temperature curves of $dP_{\text{out}}/\Delta P_{\text{out}}$ measured at various rotational speeds coincide well with each other. The difference in $dP_{\text{out}}/\Delta P_{\text{out}}$ at 30 mK measured at 0 and 4 rad/s rotation is smaller than 2×10^{-6}, which is less than 1.5% of the original value. It is worth noting that the absolute magnitude of suppression observed in the out-of-phase mode is approximately consistent with that observed in the in-phase mode, despite the striking difference in the relative suppression percentages. Figures 2(c) and 2(d) show the temperature dependence of dissipation $Q^{-1}(T)$ measured in the in-phase and out-of-phase modes, respectively. The dissipations measured under various dc rotational speeds seem to have similar magnitude with each other. The significant enhancement of the TO dissipation, reported in previous rotation experiments [15], is not observed in this revisited measurement in both modes with the rigid TO.

Although the rotation-induced suppression of the period shift in the in-phase mode is similar to that in the previous rotation experiment, the absence of that in the out-of-phase mode shows clear distinction. Because the elastic overshoot effect coupled to the TO is proportional to f^2, it is expected that the rotation effect is greater in the out-of-phase resonance mode. The clear discrepancy between the rotation effect in two resonant modes indicates that the suppression cannot be simply caused by the rotation-induced softening of shear modulus. Absence of rotation-induced effect in the TO dissipation also disproves the elastic models [7–14] and rotational susceptibility model [33–35], in which both period and dissipation of the TO should be affected by dc rotation concurrently.

Nevertheless, an essential clue to understand the previous rotation experiment can be associated with the rigidity of

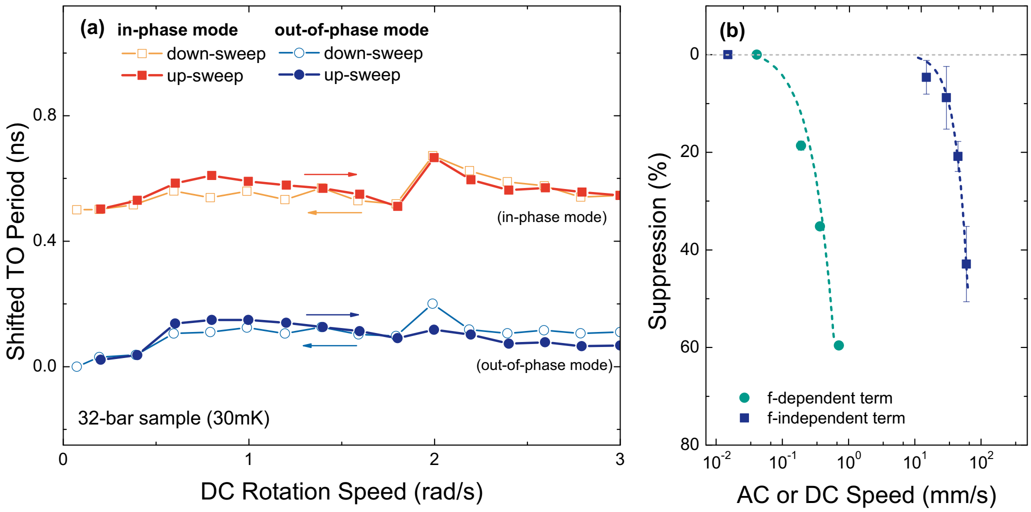

FIG. 3. Dependence of the rigid TO responses on dc rotation and ac oscillation speed. (a) Rotation velocity-sweep scans were performed at a constant temperature of 30 mK. The measured period values dP were shifted by P_0, for more clear representation; the value of P_0 is 2,267,631.549 ns (884,013.648 ns) for the in-phase (out-of-phase) mode. (b) Suppression percentage of frequency-independent term $[dP_{\rm in}/\Delta P_{\rm in}(T)]^{\rm ind}$ and -dependent term $[dP_{\rm in}/\Delta P_{\rm in}(T)]^{\rm dep}$ was plotted against a dc rotation speed and ac oscillating speed, respectively.

TO. The previous nonrigid TO was very sensitive to the shear modulus changes in solid ^{4}He because the solid ^{4}He in the TO cell links the inner and outer structures [18]. If the vibration noise due to the rotation increases the shear stress in the tangential direction $\sigma_{r\theta}$, the nonrigid TO responses may mimic the rotation-induced suppression of the period drop. As the rotation speed increases, the mechanical vibration increases accordingly, resulting in greater suppression of the TO response. However, $\sigma_{r\theta}$ from the rotation noise and the stress in the radial direction σ_{rr} due to a centrifugal force are a few orders of magnitude smaller than the critical stress required to cause elastic softening [16]. Therefore, it is necessary to find a new alternative explanation that can justify both the lack of the rotation-induced effect in the shear modulus measurements and the significant suppression in the TO response. A possible explanation is that the complicated structure of the previous TO may amplify the vibration noise effect and lead to the sizable dc-rotation-induced effect.

In the previous rotation velocity-sweep experiment, the steplike suppression of the TO period was found along with the hysteresis between the dc rotation speed decrease and consequent increase. This result had been interpreted as evidence of possible quantized vortices and Meissner state [17]. To verify this result, the rotation-sweep experiment was performed again. We first set the rotation speed to 3 rad/s at 500 mK and then cooled the TO to a target temperature (30 mK). When the TO settled down at the target temperature, the rotation speed was swept down from 3 to 0 rad/s (open marks) with a discrete step of 0.2 rad/s, then swept back up to 3 rad/s (solid marks). Both the period and amplitude of the TO were measured for 0.5 h at each point. The results are shown in Fig. 3(a). Neither staircaselike suppression nor hysteresis were found in both modes. In addition, we observed a small but reproducible jump of the TO response at around 2 rad/s, where the most pronounced rotation-induced effect was found in previous rotation experiments. This result supports the TO used in the previous experiments was very sensitive to the vibration noise that could have been amplified at the corresponding rotation speed.

To better understand the suppression of the dc rotation response in the in-phase mode, we investigated the frequency dependence in various dc rotational speeds. Unlike the experiment on superfluid ^{4}He, the period of a TO containing solid ^{4}He can also be reduced due to the change in an elastic property of the solid as we discussed above. In order to use the $dP/\Delta P$ value solely as the probe of the superfluid density, we first have to extract the contribution of genuine superfluid component from the measured value. Since the rigid double-torus TO removes all complicated viscoelastic couplings between solid ^{4}He and the TO structure, only two contributions are considered for quantitative analysis: (a) the frequency-independent contribution by the superfluid component $(dP/\Delta P)^{\rm ind}$ and (b) the frequency-dependent term $(dP/\Delta P)^{\rm dep} \sim f^2$ due to the elastic overshoot effect [18,27]. The frequency-independent term is expected to be identical in both in-phase (in) and out-of-phase (out) modes, i.e., $(dP_{\rm in}/\Delta P_{\rm in})^{\rm ind} = (dP_{\rm out}/\Delta P_{\rm out})^{\rm ind}$, while the frequency-dependent term is larger in the out-of-phase mode such that $(dP_{\rm out}/\Delta P_{\rm out})^{\rm dep}/(dP_{\rm in}/\Delta P_{\rm in})^{\rm dep} = f_{\rm out}^2/f_{\rm in}^2$.

Figure 4 shows $(dP_{\rm in}/\Delta P_{\rm in})^{\rm ind}$ and $(dP_{\rm in}/\Delta P_{\rm in})^{\rm dep}$ for the in-phase mode, measured at the lowest ac rim velocity under various rotational speeds. At 30 mK, the frequency-independent term was calculated to be about 5.01×10^{-6}, slightly larger than the range set in the current study using the same TO [26]. This increase may be associated with much higher ^{3}He concentrations of this solid sample than that used in our previous rigid-TO experiment (0.6 ppb). It is particularly surprising that the frequency-independent term is gradually suppressed as the dc rotation speed increases. Under 4-rad/s rotation, the magnitude of the frequency-independent term at 30 mK decreases to 2.86×10^{-6}. This size is consistent with the absolute magnitude of suppression in $dP/\Delta P$ observed

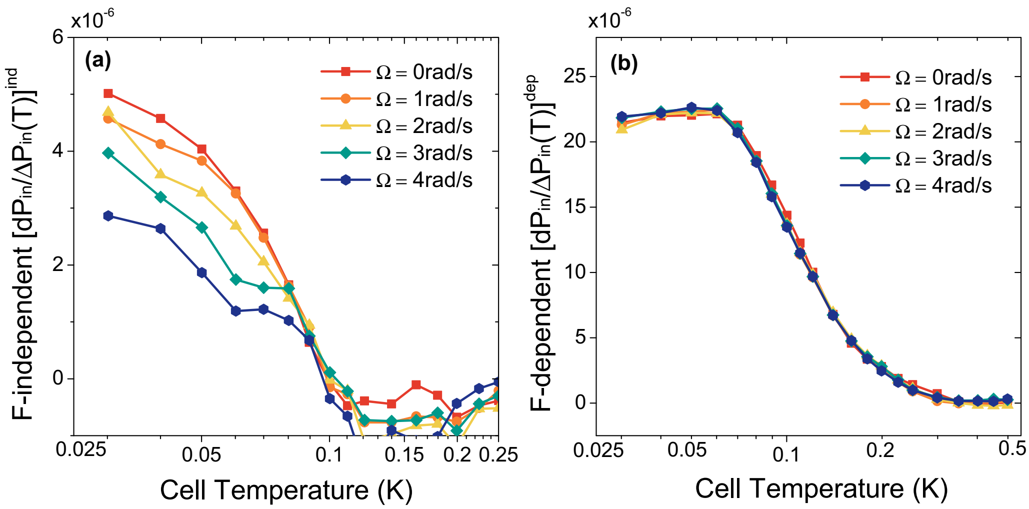

FIG. 4. Frequency-dependent analysis under various dc rotation speed. The temperature dependence of $dP/\Delta P$ in the in-phase mode are decomposed into (a) the frequency-independent term $[dP_{\rm in}/\Delta P_{\rm in}(T)]^{\rm ind}$ (superfluid contribution) and (b) the frequency-dependent term $[dP_{\rm in}/\Delta P_{\rm in}(T)]^{\rm dep}$ (elastic overshoot contribution) while maintaining the lowest ac oscillating speed.

in both the in-phase and out-of-phase mode in Figs. 2(a) and 2(b), respectively. On the other hand, the frequency-dependent term remains unchanged at around $2.15(\pm 0.04) \times 10^{-5}$ until 4 rad/s.

To investigate whether the rotation-induced suppression is related to the ac rim velocity of TO, the same frequency-dependent analysis was performed on various ac rim velocities. The effect of constant dc rotation of 3 rad/s on the TO response was compared with that of the stationary state. The ac driving voltage was carefully adjusted so that the solid sample experienced the same oscillating speed for the in-phase and out-of-phase mode at each ac oscillating speed. As shown in Figs. 5(a) and 5(b), the TO responses obtained essentially the same as that of the lowest rim velocity. The same color-coded pair for each mode indicates the data obtained at the same ac oscillation speed. The frequency-independent term is unchanged even as ac rim velocity increases. On the other hand, it shows a clear suppression as the dc rotation speed increase [Fig. 5(a)]. Under 3-rad/s rotation, $(dP_{\rm in}/\Delta P_{\rm in})^{\rm ind}$ at four different ac rim velocities is about $1.86(\pm 0.37) \times 10^{-6}$ smaller than that in the stationary state. However, the frequency-dependent term $(dP_{\rm in}/\Delta P_{\rm in})^{\rm dep}$ is strongly suppressed as ac rim velocity increases without being affected by dc rotation [Fig. 5(b)]. These experimental results demonstrate that the frequency-dependent TO response is due to the elastic change of solid ^{4}He.

The period drop due to the ac oscillation of the rigid TO is explained by an oscillating shear stress that separates the ^{3}He impurity from the dislocation and reduces the shear modulus [7]. In contrast, constant dc rotation does not cause shear stress on solid ^{4}He. Thus, it is surprising that the frequency-independent term is unchanged by torsional oscillation, but clearly reduced by increasing dc rotation speed. In addition, the suppression differs significantly from the conventional elastic effect in terms of critical temperature and velocity. The frequency-dependent term $(dP_{\rm in}/P_{\rm in})^{\rm dep}$ gradually changes from 300 mK, while the frequency-independent term $(dP_{\rm in}/\Delta P_{\rm in})^{\rm ind}$ suddenly appears at 100 mK. The threshold rotation speed for the suppression is also about two orders of magnitude greater compared with that of ac oscillation as shown in Fig. 3(b). Thus, the rotation-induced suppression on $(dP_{\rm in}/\Delta P_{\rm in})^{\rm ind}$ is clearly distinguishable from the effect of ac oscillation due to the change in shear modulus.

IV. DISCUSSION

The small but distinct frequency-independent term $(dP_{\rm in}/\Delta P_{\rm in})^{\rm ind}$ and its reduction by dc rotation were consistently observed in three solid samples with pressures of 32, 36, and 47 bar. Table I summarizes the experimental results for three solid samples. The suppression of period drops and relevant parameters show qualitatively similar values. One might note that the contribution of solid ^{4}He that fills inside a filling capillary gives rise to the frequency-independent period drop, similar to the torsion rod hole effect [19], and it can accordingly be suppressed by increased mechanical vibration under faster dc rotation speed. However, this alternative scenario cannot explain our experimental results. First, the contribution of solid ^{4}He inside the filling line on the period change $dP_{\rm el}$ is calculated to be $\sim$0.006 ns, even smaller than the detection limit ($\sim$0.02 ns) of our TO. The period drop $\Delta p_{\rm el}$, due to elastic contribution of the torsion rod hole effect, was calculated by

$$\frac{\Delta p_{\rm el}}{p_0} \sim \frac{\Delta f_{\rm el}}{f_0} = \frac{1}{2}\frac{\mu_{\rm He}}{\mu_{\rm rod}}\frac{L}{L_{\rm cap}}\left(\frac{r_i}{r_o}\right)^4, \qquad (1)$$

where $L = 9$ mm ($L_{\rm cap} = 64$ mm) is the length of the torsion rod (capillary). $r_i = 0.15$ mm ($r_o = 1.4$ mm) is the inner (outer) radius of the capillary (torsion rod). Secondly, the maximum shear stress in a tangential direction $\sigma_{r\theta}$ due to the horizontal mechanical vibration is estimated to be $\sim$0.004 Pa, which is too small to reduce shear modulus of solid ^{4}He [8]. Thirdly, if the mechanical vibration was sufficiently strong to change the elastic modulus of solid ^{4}He, the suppression in the period of the TO should have been larger in the out-of-phase

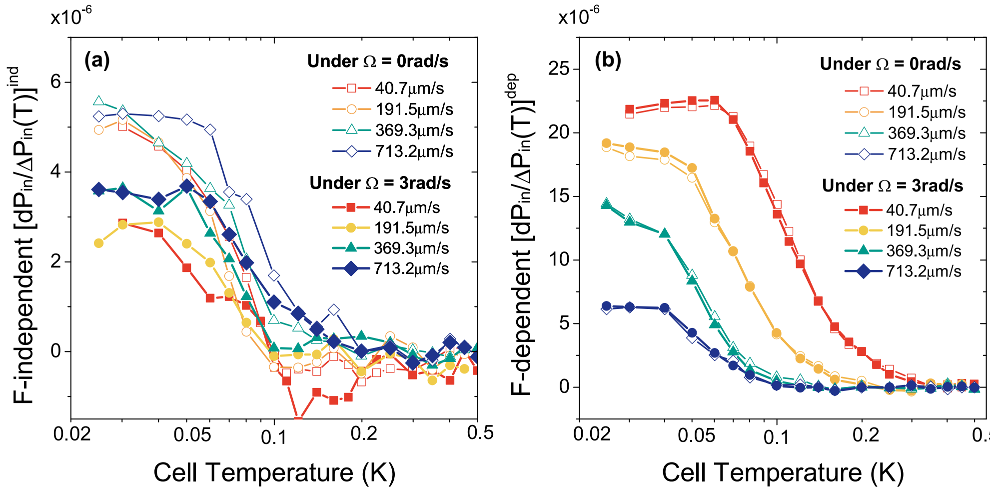

FIG. 5. Frequency-dependent analysis under various ac oscillating speed. Both (a) frequency-independent term $[dP_{\rm in}/\Delta P_{\rm in}(T)]^{\rm ind}$ and (b) frequency-dependent term $[dP_{\rm in}/\Delta P_{\rm in}(T)]^{\rm dep}$ were decomposed explicitly, under constant dc rotation speed of 0 (open marks) and 3 rad/s (solid marks). The ac driving voltage was carefully adjusted so that the solid sample experienced the same oscillating speed for the in-phase and out-of-phase mode at each ac oscillating speed. The same color-coded pair for each mode indicates the data obtained at the same ac oscillation speed.

mode. Thus, the torsion rod hole effect cannot provide a plausible explanation for the rotation-induced suppression of $dP/\Delta P$ observed here.

Polycrystalline solid ^{4}He obtained by the blocked capillary method contains numerous topological defects such as dislocations or grain boundaries that can allow superflow [36]. Thus, we investigated whether or not the presence of topological defects adequately could explain the irrotational features, the existence of $(dP_{\rm in}/\Delta P_{\rm in})^{\rm ind}$, and its suppression under rotation.

First, if the dislocation of hexagonal close-packed (hcp) solid ^{4}He can exhibit superfluidity, a network of randomly interconnected one-dimensional dislocations may account for the rigid TO response. Both screw and edge dislocations are known to have superfluid cores [36,37]. The dislocation network may also be considered as interconnected vortex tangles which may lead to the percolation of circulating supercurrent through dislocations with pinned vortex cores. This quasisuperfluid state, called the Shevchenko state [38], can be described by low-viscosity fluid-mimicking superfluid. Anderson also suggested that the superfluid flowing through the dislocation network or grain boundary can be understood as a vortex liquid model [39]. In order to examine the validity of this model, one can estimate the dislocation density n_d required to explain the apparent superfluid fraction of $n_S^{3D}/n = n_d(n_S^{1D}/n) \sim 5 \times 10^{-6}$, where n_S^{3D} and n_S^{1D} are the three- and one-dimensional superfluid density, respectively. Applying the ^{4}He number density of $n \sim 0.0287$ per $1\,\mathring{A}^3$ and the n_S^{1D} value of 1 atom per $1\,\mathring{A}$ obtained from the grand-canonical Monte Carlo simulation [37], the required n_d is about 1.4×10^9 cm^{-2}. The experimental measurements of n_d for a single crystal ^{4}He range from 3×10^5/cm^{-2} [40] to 6×10^9/cm^{-2} [41]. Thus, the quantitative estimation could support the superfluid dislocation network scenario. The drawback, however, is that the effect of dc rotation on the dissipation $Q^{-1}(T)$, which should have appeared together with the suppression in $(dP_{\rm in}/\Delta P_{\rm in})^{\rm ind}$, was not observed in our measurements.

Second, path-integral Monte Carlo studies have found the grain boundary of polycrystalline solid ^{4}He, another type of topological defects, becomes superfluid at a sufficiently low temperature around 0.5 K [42]. Similar to other polycrystals, grain-boundary premelting in hcp solid ^{4}He was observed under high-pressure condition above 1 kbar [43]. A thin premelted liquid film formed at the grain boundary can exhibit superfluidity through the two-dimensional Berezinskii-Kosterlitz-Thouless (BKT) phase transition [44]. Since the amount of ^{4}He contained in TO is fixed, the apparent superfluid density $\rho_s = n_S^{3D}/n$, and the phase-transition temperature T_{BKT}, depend on the size of R_0, the average characteristic diameter. Considering the spherical grain model [44], R_0 is given as $R_0 \cong (6m^2/\pi\rho\hbar^2)(k_B T_{BKT}/\rho_s)$, where m is the atomic mass of ^{4}He and the ^{4}He density ρ is about 214 kg/m^3. Using $\rho_s = 5 \times 10^{-6}$ and $T_{BKT} \sim 0.1$ K, one can obtain R_0 to be a realistic value of about 10 μm. Nevertheless, it is not

TABLE I. Summary of experimental results for three solid ^{4}He samples.

No.	Pressure (bar)	$[dP_{\rm in}/\Delta P_{\rm in}(T)]^{\rm ind}$	$T_{\rm onset}^{\rm ind}$ (mK)	Suppressed (%)	$[dP_{\rm in}/\Delta P_{\rm in}(T)]^{\rm dep}$	$T_{\rm onset}^{\rm dep}$ (mK)
1	32	5.01×10^{-6}	110	43	2.14×10^{-5}	320
2	36	4.54×10^{-6}	120	46	2.19×10^{-5}	300
3	47	5.63×10^{-6}	300	27	3.43×10^{-5}	300

consistent with the BKT transition model since there was no strong rounding effect to appear near the BKT phase-transition temperature due to uneven film thickness and also no additional rotation-induced dissipation peaks.

Third, a conceivable interpretation of the rotation-induced effect is a superfluidlike mass flow found in solid ^{4}He sample between two superfluid leads [45–47]. As described earlier, the superfluid density calculated from the frequency-independent term is very small, but it certainly exists. This minute size of superfluid can be screened by large shear modulus changes of solid ^{4}He at low temperatures, so it could be difficult to be detected precisely in a soft single-resonant-mode TO. Assuming that the superfluid does exist, we suggest $T_c \sim$ 90 mK, $v_c \sim 1.5$ cm/s, and $\rho_S/\rho \sim 5 \times 10^{-6}$ for a 32-bar polycrystalline solid ^{4}He. However, the supersolid density observed here is much higher than the upper limit set by the previous mass-flux experiments, $v_c \cdot (\rho_s/\rho) \sim 2.5 \times 10^{-8}$ cm/s [45]. Furthermore, the monotonically increasing temperature dependence of ρ_S/ρ found by our experiment is not consistent with that found in other mass-flux experiments. The sudden suppression of mass flow at low temperature and disappearance of the flow at high pressure were not consistent with our rigid TO experiment [46,47].

Recently, the Manchester group also performed a dc rotation experiment using a rigid TO, but unlike our experiments no rotation-induced effect was found under 2 rad/s [48]. Nevertheless, the rotation-induced effect is not substantial at the low rotational speeds of about 2 rad/s, so that it can be masked by large elastic contribution of about 10^{-4}. The stability of the TO under rotation is also important for the clarification of the very small discrepancies in the response. In addition, the recent shear modulus experiments reported an unexpected rotation-induced effect; shear modulus of solid ^{4}He was decreased by 16% at 4 rad/s, only if the shear strain applied by their PZT exceeded a critical stress [49]. However, most of our experimental results were measured at the lowest excitation, in which ac oscillation speed does not exceed the critical strain. It is also very interesting that there was no rotation-induced effect in their own Young's modulus measurement, which is not consistent with their shear modulus measurement but with our experimental results.

There have been several other attempts to find the possible superfluid density with a rigid TO. The Chan group at Pennsylvania State University (PSU) group observed a small period drop of ~4 ppm and interpreted it as the upper limit of superfluidity in solid ^{4}He. However, they could not experimentally conclude whether the residual period drop is due to superfluid-related origin or not, because the TO has only one resonant frequency. Meanwhile, both Reppy group at Cornell University [30] and Saunders group at Royal Holloway University of London [50] found frequency-independent period drop in their two-frequency TOs, respectively. However, the superfluid densities are much larger than 4 ppm, which contradicts the upper limit set by the PSU group. It is necessary to confirm the origin of frequency-independent terms by other experimental methods, for example, by application of dc rotation on their TOs.

V. CONCLUSIONS

In conclusion, most of the striking rotation-induced effects reported in the previous rotation experiments were not reproduced in this experiment using the rigid TO. This result implies that the rotation-induced effect found in the nonrigid TO cannot be interpreted as the evidence for irrotational bulk superfluidity in solid ^{4}He. The possible explanation is that the nonrigid TO amplifies the rotation-induced shear modulus change in solid ^{4}He. Nonetheless, we found rotation-induced suppression in frequency-independent period drop of the TO response which cannot be understood in a framework of simple temperature-dependent elastic models. Here, we cannot provide convincing explanation yet that explains all the experimental results clearly. Further investigation is crucial to elucidate the microscopic origin of this interesting anomaly.

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