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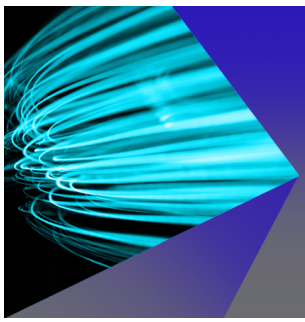
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# Measurement and analysis of magnetostriction of nanocrystalline alloy laminations under medium-frequency excitation

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## ABSTRACT

Nanocrystalline alloys, widely used as core materials of medium-frequency transformers, require accurate measurement of their magnetostriction to calculate the core vibration and noise during the transformer design phase. A synchronous measuring system consisting of a magnetizer with an optical reflector and a laser vibrometer is constructed to measure the 1D magnetic loss and magnetostriction properties under medium-frequency excitation. The annealed nanocrystalline alloy sheets are laminated and measured in this study due to their softness and brittleness. The influence of single- and double-yoke magnetic circuit structures on the measurement of magnetic properties is discussed. The hysteresis loops and magnetostriction of nanocrystalline alloy laminations with a double-yoke structure are measured from 1 kHz to 10 kHz. The results indicate that the hysteresis loops widen as the frequency increases, resulting in increased losses. Moreover, the peak-to-peak value of magnetostriction first increases and then decreases with increasing excitation frequency, and the magnetostriction curves exhibit a transition from elongation to contraction. These results can provide data support for the design of cores for medium-frequency electromagnetic devices.

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## I. INTRODUCTION

With the gradual establishment of new power systems, medium- and high-frequency transformers are becoming increasingly important in energy conversion devices. However, the issue of core vibration and noise under medium- and high-frequency excitations has also gained considerable attention.[1,2] Core vibrations are primarily induced by electromagnetic and magnetostrictive forces.[3]

Compared with other materials, nanocrystalline alloys have some advantages for medium-frequency equipment. They exhibit lower conductivity, higher magnetic permeability, and higher saturation magnetic flux density, making them suitable for high-capacity, high-power-density equipment.[4] However, research on the magnetostriction of nanocrystalline alloys remains significantly lacking at present.[5,6]

The measurement of magnetostriction is primarily conducted using single-sheet methods based on strain gauges or laser vibrometers.[7] Owing to the softness and brittleness of nanocrystalline alloy sheets, bonding multiple sheets together to form a lamination can maintain a fixed shape, facilitating easier handling and measurements of magnetostriction.[8,9]

In this study, a synchronous measurement system consisting of two yokes, an optical reflector, and a high-precision laser vibrometer is constructed. The magnetic hysteresis loops and magnetostriction of nanocrystalline alloy 1K107B ($Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$) are measured synchronously under an alternating magnetic field within medium-frequency excitation by the system.


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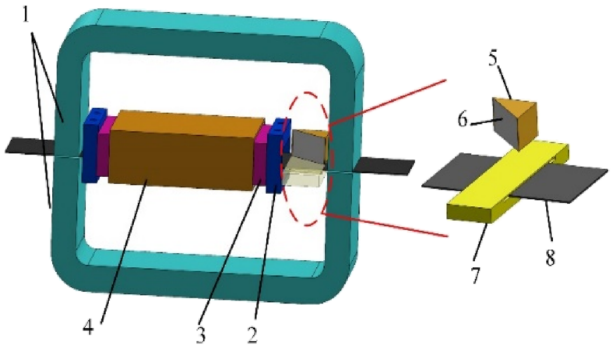



**FIG. 1.** Schematic of the yoke structure and reflection component structure. 1, yokes; 2, winding frame; 3, induction coils; 4, excitation coils; 5, mirror base; 6, mirror; 7, support plate; 8, specimen.

## II. EXPERIMENT PRINCIPAL AND SYSTEM

A novel 1D symmetrical tester is designed to measure the magnetic loss and magnetostriction properties of nanocrystalline alloy laminations ranging from 1 to 10 kHz as shown in Fig. 1. The specimen is the 1K107B nanocrystalline alloy lamination composed of 13 single sheets bonded together with the resin adhesive, with an overall dimension of 162 mm × 30 mm × 0.3 mm. The lamination factor is 0.85.

### A. Magnetizer

The magnetizer consists of two magnetic yokes and a winding frame. The yokes are made of nanocrystalline alloy strips which meet the requirements of medium-frequency tests. The winding frame is 3D printed from epoxy resin, with windings wrapped around the outside and the sample placed horizontally inside. The induction coils are wound on the inner layer, and the excitation coils are wound on the outer layer. The current transformer measures the current in the excitation coils, whereas a voltage probe measures the voltage in the induction coils. From the measured signals, the magnetic flux density and magnetic intensity of the specimen can be calculated using Eqs. (1) and (2), where $N_1$ and $N_2$ are the turns of the excitation and induction coils respectively; $u_2$ is the induced voltage in the induction coil; $A_e$ is the effective cross-sectional area; and $l_e$ is the magnetic path length.

$$H(t) = \frac{N_1 i_1(t)}{l_e} \tag{1}$$

$$B(t) = -\frac{1}{N_2 A_e}\int u_2(t)dt \tag{2}$$

### B. Laser test module

A PSV 500 laser vibrometer (Polytec, Germany) is used as the laser tester. The equipment features a very high signal sam-

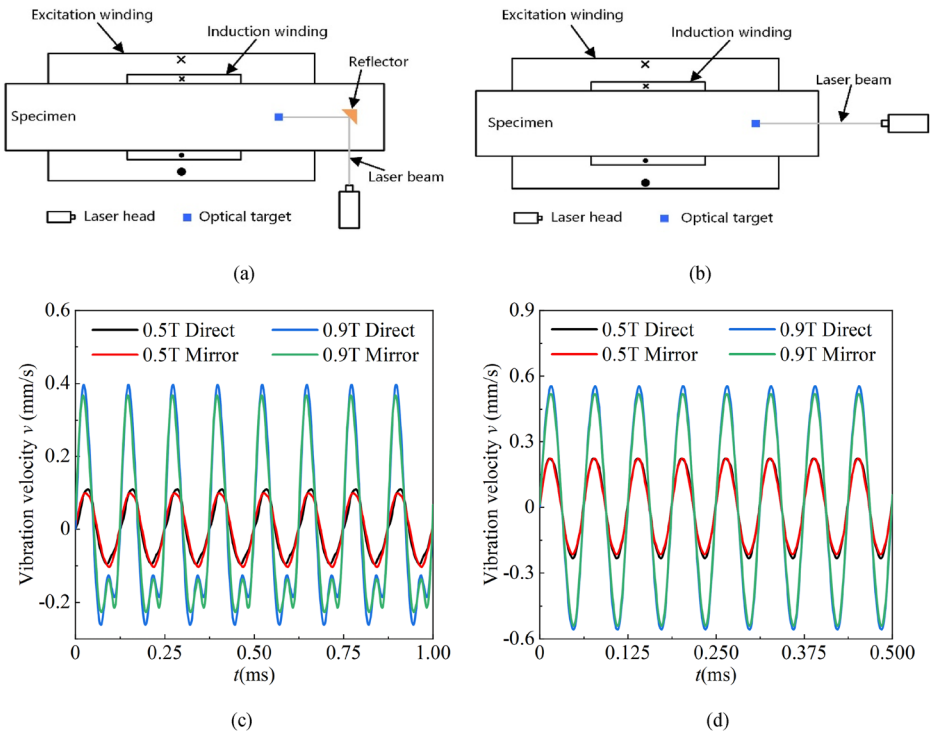



**FIG. 2.** Schematic of the optical paths and comparison of the vibration velocity measurement results using the two methods. (a) "L" shape optical path diagram; (b) Optical path diagram of the traditional measurement method; (c) results at 4 kHz; (d) results at 8 kHz.

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pling frequency, and its magnetostriction measurement resolution can reach $10^{-10}$ m/m, thereby addressing the measurement difficulties posed by the high working frequency and small magnetostriction coefficient of nanocrystalline alloys. Due to the double-yoke structure of the magnetizer, which obstructs the open light path, traditional laser-based magnetostriction measurement methods cannot be applied. Consequently, an "L" shaped optical path is constructed using an aluminum-coated mirror, as schematically shown in Fig. 2(a). The mirror is affixed to an isosceles right triangular prism, forming a 45° angle with the length direction of the specimen. It reflects the vertically incoming laser onto the optical target, which has a certain reflectivity, and sends the laser back along its original path to complete the magnetostriction measurement. To verify the effectiveness of the constructed optical path, a comparison is made between the traditional laser method and the new optical path method under a single-yoke structure, with the results shown in Figs. 2(c)–2(d). The results indicate that there is no significant deviation in the measurement results within the working magnetic flux density range when the new optical path approach is used.

### C. The measurement system

Figure 3 shows the synchronous measurement system for the magnetic loss and magnetostriction properties of the nanocrystalline alloy laminations. The magnetic field signals, collected by the voltage probe and the current transformer, are amplified by a homemade signal amplifier and then acquired by the NI PXIe 6368 DAQ. The magnetic flux density B is controlled by a frequency-domain feedback control program to maintain its waveform as a sinusoidal wave. The controlled signal is amplified by a power amplifier to drive the excitation coils for magnetizing the specimen. Once the magnetic flux density of the specimen reaches the preset value, the excitation signal is maintained to keep B constant. Then, the laser vibrometer simultaneously collects the induced voltage, excitation current, and vibration velocity signals of the specimen. After processing these signals, the synchronized B H and λ data can be obtained.

It is noted that the apparatus should be mounted and fixed on a vibration-isolation platform. Other equipment, such as the PC and DAQ, is placed on a separate table to avoid any resonance. It is important to note that the magnetostriction coefficient of nanocrystalline alloys is relatively small; therefore, the friction between the specimen and the apparatus should be minimized to avoid influencing the measurements. Therefore, except for the fixed end of the specimen, all contact surfaces between the specimen and the apparatus are lined with a smooth PTFE film. Additionally, to prevent the impact of the weight of the upper yoke, a support plate is used to hold the upper yoke, ensuring that the yoke only contacts the specimen without exerting a gravitational force on the specimen.

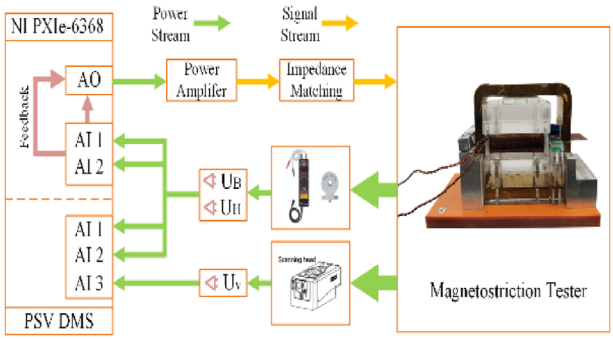



**FIG. 3.** Synchronous testing system for magnetic and magnetostriction properties of nanocrystalline alloy.

## III. MEASUREMENT RESULTS AND ANALYSIS

Figure 4 shows the magnetic properties and magnetostriction values for both the single-yoke and double-yoke magnetic circuit structures. It can be observed that the magnetic intensity is notably higher under single-yoke excitation than under double-yoke excitation at the same magnetic flux density. Additionally, the hysteresis loops measured with a single yoke are narrower than those measured with a double-yoke excitation. During high-frequency excitation, the asymmetric magnetic circuit structure induces significant eddy currents inside the specimen area contacting with magnetic yoke, which consumes extra magnetomotive force in the magnetic circuit.

In Figs. 4(c) and 4(d), the magnetostriction values under double-yoke excitation are slightly larger than those under single-yoke excitation; but the difference is minimal, indicating that the magnetic circuit structure has a relatively small impact on the magnetostriction measurement. Additionally, the peak-to-peak value of magnetostriction increases gradually with increasing magnetic flux density and becomes more pronounced in the saturation region. The magnetostriction values of nanocrystalline materials are very small, with a saturation magnetostriction peak-to-peak value of ~120 nm/m at an excitation frequency of 4 kHz, which is significantly lower than that of silicon steel and amorphous materials. The lower magnetostriction is primarily due to the reduced magnetic anisotropy and constrained domain-wall motion in the nanocrystalline structure.

Figure 5 shows the magnetic properties and magnetostriction variations of nanocrystalline alloy laminations at different frequencies. In Figs. 5(a) and 5(b), it can be observed that as the frequency increases, the magnetic intensity of the nanocrystalline alloy laminations increases, the hysteresis loops widen, and the slope decreases. The loss increases with frequency, and the loss at the saturation magnetic flux density becomes more significant with changes in frequency. This behavior can be attributed to the strengthening of eddy current effects and the limited response speed of the magnetic domains as the frequency increases, leading to an increase in the magnetic intensity.

As shown in Figs. 5(c) and 5(d), the magnetostriction loops exhibit different lagging relations between $B$ and $\lambda$ at different frequencies. As the frequency increases, the magnetostriction characteristic transitions from elongation to contraction. The transition from elongation to contraction with increasing frequency can be attributed to the interaction between magnetic and elastic properties of the material. The peak-to-peak value of the magnetostriction initially increases with frequency, reaches a maximum, and then decreases. This magnetostriction peak is likely

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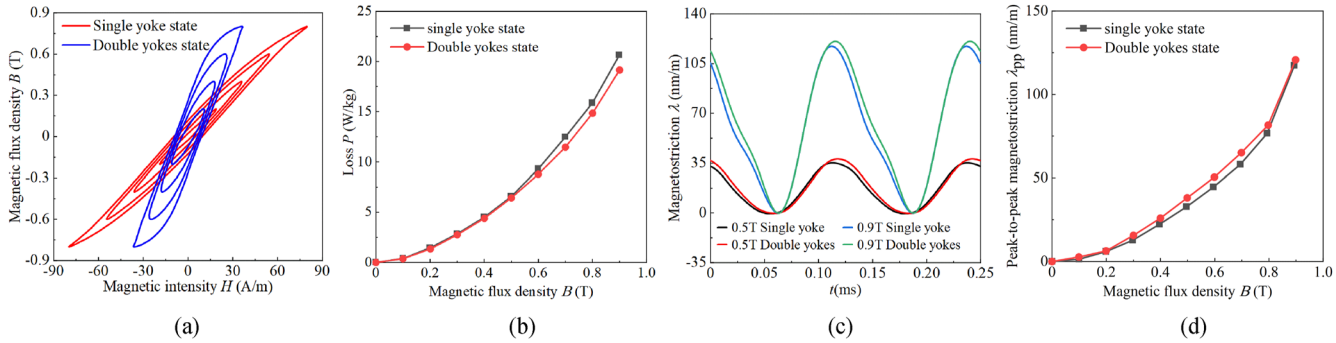



**FIG. 4.** The magnetic properties of nanocrystalline alloy laminations at 4 kHz with two magnetic circuit structures. (a) Hysteresis loops; (b) loss curves; (c) time domain curves of magnetostriction; (d) peak-to-peak values of magnetostriction.

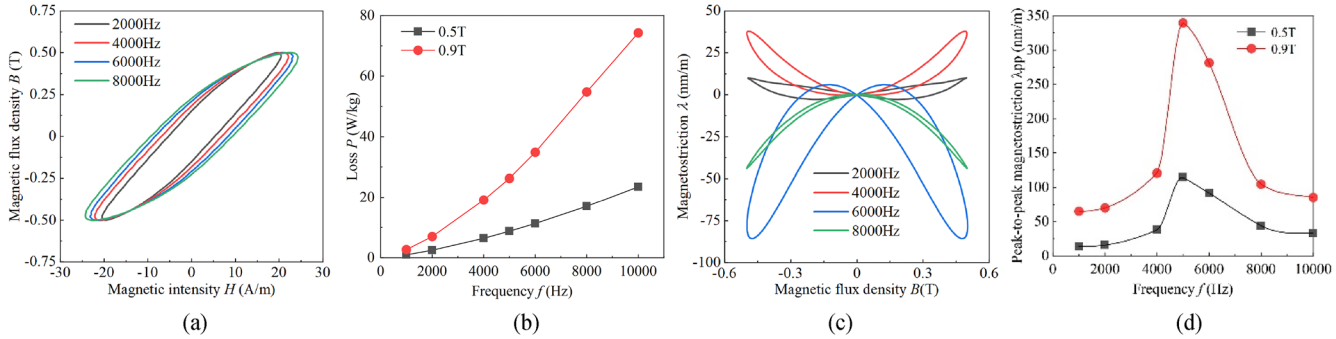



**FIG. 5.** The magnetic properties of nanocrystalline alloy laminations range from 1 to 10 kHz. (a) Hysteresis loops at 0.5T; (b) loss at 0.5T and 0.9T; (c) magnetostriction loops at 0.5T; (d) peak-to-peak values of magnetostriction.

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influenced by the resonant frequency of the laminations. The variation in magnetostriction with frequency is significantly affected by the material structure and vibration modes. These findings underscore the importance of considering the resonant frequency when analyzing the magnetostriction properties of nanocrystalline alloy laminations.

## IV. CONCLUSION

In this study, a synchronous measurement system is constructed to investigate the magnetic loss and magnetostriction properties of nanocrystalline alloy laminations. The comparison between single-yoke and double-yoke structures indicates that the double-yoke magnetic circuit structure reduces significant measurement errors in magnetic properties that occur during asymmetric magnetization. The magnetostriction values of the nanocrystalline alloy remain below 0.5 ppm under 1–10 kHz working frequency, which are significantly lower than those of silicon steel and amorphous alloy. Moreover, the peak-to-peak values of magnetostriction vary under different magnetization frequencies.

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## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

### Author Contributions

**Changgeng Zhang**: Data curation (equal); Resources (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **Haitao Zhang**: Data curation (equal); Formal analysis (equal); Methodology (equal); Software (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Tao Chen**: Investigation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yongjian Li**: Data curation (equal).


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## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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