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Study of the Effect of Harmonics and Stress on the Integrated Magnetic Properties of Oriented Silicon Steel Sheets

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Abstract—The core structure of transformers and reactors is subject to stress and high-frequency excitation during operation. The core structure is made of laminated silicon steel sheets, which are subject to magnetostrictive strain under alternating magnetic fields. To investigate the comprehensive magnetic properties of oriented silicon steel sheets under the influence of harmonics and stress, this paper builds a magnetic property measurement system for electrical steel and investigates the magnetization and magnetostriction characteristics of oriented silicon steel sheets of type 30SQGD105 under working frequency, harmonic and applied stress conditions. The results show that the effects of harmonics and stress on the hysteresis characteristics of the silicon steel sheet are small, and the effects on the magnetostriction characteristics are large.

1. INTRODUCTION

The core structure of equipment such as reactors and transformers is made of stacked silicon steel sheets, which are magnetised under the action of alternating magnetic fields [1], where the magnetisation characteristics of silicon steel can be described by two indicators: hysteresis line and magnetisation curve [2, 3]. The magnetisation of silicon steel materials is also subject to deformation during the magnetisation process, i.e., magnetostriction [4], which changes the volume of the silicon steel and is one of the main causes of vibration in core-containing power equipment. The magnetostriction and magnetisation properties of the silicon steel material vary significantly under different conditions, and because the nonlinearity of the core material and rectification equipment can lead to harmonics, and because fasteners such as clips and bolts make the silicon steel sheet subject to stress, the magnetostriction and magnetisation properties of the silicon steel material need to be measured under different conditions to ensure the accuracy of the simulations.

In recent years, research analysis for the magnetostriction measurement of silicon steel sheets can be divided into two stages: strain gauge measurement and optical measurement [5, 6]. Enokizono and other Japanese scholars conducted a study in 1990 using strain gauges to measure the magnetostriction curve variations of oriented and non-oriented silicon steel sheets under rotating magnetic flux density at different magnetization conditions [7], and later improved the measurement method and designed a two-dimensional magnetic measurement technique to obtain the magnetostriction parameters of silicon steel sheets in multiple dimensions [8]. In 1994, Moses and other British scholars conducted measurements on the hysteresis loss and magnetostriction of silicon steel sheets under stress conditions before and after annealing. They also investigated the impact of coatings on the losses of the silicon steel sheets [9]. In 2007, they further analyzed the changes in magnetization curves of oriented silicon steel sheets after applying different directional stresses [10]. Although the measurement of magnetostrictive parameters

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using strain gauges is simple, the strain gauges need to be glued to the surface of the silicon steel sheet in advance before measurement, and the effect of the gluing can seriously affect the accuracy of magnetostrictive measurements, so experienced operators are required for gluing the strain gauges. To solve this problem, Japanese scholar Nakata used laser measurement to measure the magnetostrictive properties of silicon steel sheets in 1994 [11], and the laser measurement method has gradually replaced the previous strain gauge measurement method as the most mature magnetostrictive measurement technique for silicon steel sheets in subsequent studies. In 2015, Chinese scholars including Zhang et al. utilized the MST500 laser magnetostriction equipment designed by Brockhaus Measurements to conduct research and measurements on the magnetostrictive properties of oriented and non-oriented silicon steel. They analyzed the magnetostrictive characteristics of the silicon steel sheets under various conditions, including DC biasing, harmonic excitation, and stress conditions [12]. In 2016, they further independently designed and built a three-axis strain gauge magnetostriction measurement system. This system enabled the research of vector magnetostrictive properties of individual electrical steel sheets using a three-axis strain gauge method [13]. In 2014, Chinese scholars led by Yang Qingxin designed a three-dimensional magnetic tester by comprehensively considering the three-dimensional properties of soft magnetic materials. They employed finite element methods to analyze and compute the three-dimensional magnetic flux within the magnetized structure. Furthermore, they conducted measurements on the three-dimensional magnetic properties of laminated silicon steel sheets using this system [14, 15].

Through the measurement of the magnetostrictive parameters of silicon steel sheets under different conditions, scholars have found that stress, harmonics, DC bias, rotational magnetisation, and insulating coatings all affect the magnetostrictive parameters of silicon steel sheets. In summary, most of the research on the measurement of the integrated magnetic properties of oriented silicon steel sheets has focused on the influence of a single factor on the measurement results, but less on the influence of multiple factors acting together, and less on the measurement of the integrated magnetic properties of some newer grades of high performance silicon steel sheets as silicon steel materials continue to innovate.

In this study, the TS3300 model comprehensive magnetic performance measurement system for electrical steel, designed and manufactured by TUNKIA in accordance with the IEC 60404-17 standard, was used to measure the magnetization characteristics and magnetostrictive properties of the 30SQGD105 grade oriented silicon steel sheets. The research investigated the effects of power frequency excitation, harmonic excitation, and applied stress on the comprehensive magnetic performance of the silicon steel sheets. The study also analyzed how the magnetic properties of the silicon steel sheets changed under the combined influence of different excitations and stress conditions. The analysis of hysteresis lines and magnetostriction butterfly curves is mainly included to provide a data base for calculating core vibration.

2. MAGNETOSTRICTIVE EFFECT AND INTEGRATED MAGNETIC PROPERTY MEASUREMENT SYSTEM FOR ELECTRICAL STEEL

2.1. Magnetostrictive Effect

Ferromagnetic materials all exhibit magnetostrictive effects in a magnetic field, and at the microscopic level, the phenomenon of changes in the dimensions of this material in the magnetised state can be explained by the theory of magnetic domains [16]. In the absence of an external magnetic field, the internal magnetic domains of a ferromagnetic material are equally distributed in all directions and are in a disordered state. The magnetic moments of the domains are taken in all directions. The magnetism cancels each other out, and the magnetism does not appear on a macroscopic scale. When an external magnetic field is present, the internal magnetic domains are magnetised, and the magnetic moments of the domains gradually move closer to the direction of the magnetic field. As the external magnetic field increases, more and more of the domains turn in the direction of magnetisation, resulting in a macroscopic change in length of the ferromagnetic material.

A change in the elongation of a ferromagnetic material in the direction of the magnetic field under the action of an external magnetic field is called positive magnetostriction, while a shortening is called negative magnetostriction. In either case, the change in magnetostriction is very small. In typical situations, the magnetostrictive effect is often described using the magnetostrictive coefficient λ. The magnetostrictive coefficient λ is the ratio of the dimensional change $\Delta\lambda$ along the direction of the magnetic field to the original length L of the ferromagnetic material:

$$\lambda = \frac{\Delta L}{L} = \frac{L_1 - L_0}{L} \tag{1}$$

where L is the length of the test specimen without excitation, (m). L_0 is the distance between the laser vibrometer and the retroreflector, (m). L_1 is the distance between the laser vibrometer and the retroreflector after exciting the test specimen, (m). $\Delta L = L_1 - L_0$ is the elongation (contraction) of ferromagnetic material in a magnetic field, which represents the difference between the length of the material with an applied external magnetic field and its original length, (m). λ is the magnetostrictive coefficient, which characterizes the magnetostrictive effect, (µm/m). The magnitude of λ typically ranges from several hundred nanometers per meter (nm/m) to a few micrometers per meter (µm/m).

2.2. Integrated Magnetic Property Measurement System for Electrotechnical Steel

The comprehensive magnetic performance measurement device for silicon steel used in this study is the TS3300 electrical steel magnetostriction measurement system, which conforms to the IEC 60404-17 standard. This measurement system was designed and manufactured by TUNKIA. The system employs a laser vibrometer to measure the magnetostrictive displacement of the test specimens under various conditions such as harmonic excitation and stress. The schematic diagram of the measurement system setup is illustrated in Figure 1.

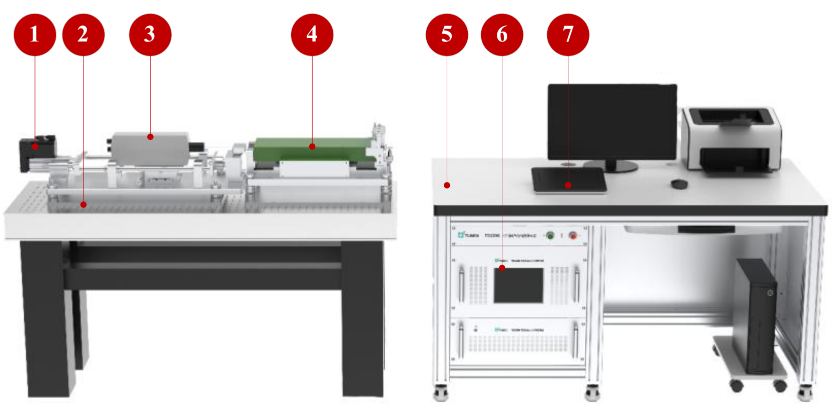


Figure 1. Magnetic property measurement systems for electrical steel.

The whole set of measuring system devices mainly includes pressure loading devices, air floating vibration damping platform, laser vibrometer, single piece magnetic permeability meter, etc. The role of each device is shown in Table 1.

The principle of magnetostrictive measurement of silicon steel sheets: During the measurement process, the sample to be measured is magnetized by the applied magnetic field, and the magnetostrictive strain occurs, causing the reflector attached to the sample to vibrate in the direction of magnetization. The strain in the direction of magnetization causes the reflector on the sample to vibrate. The laser signal is then received by the receiver and reflected by the laser emitter, and the magnetostrictive strain of the silicon steel sample can be measured by the change in laser signal.

A schematic diagram of the magnetostrictive measurement is shown in Figure 2, with the following measurement steps:

(1) The sample to be measured is placed in the magnetometer with a reflective sheet glued to it;
(2) Measure the distance L_0 between the laser vibrometer and the reflector;
(3) Excitation of the sample to be measured followed by measurement of the distance L_1 between the laser vibrometer and the reflector;
(4) Calculate the change in distance between the sample to be measured and the laser vibrometer in the direction of magnetization $\Delta L = L_1 - L_0$;
(5) Calculate the magnetostriction coefficient of the sample $\Delta L/L$.

Table 1. Overall layout of measurement system.

Serial number	Name	Description
1	Pressure loading devices	For performing pressurisation tests on silicon steel sheets
2	Air-bearing vibration damping platforms	Keeps table tops level and reduces environmental impact
3	Laser vibrometer	For testing the hysteresis coefficient
4	Monolithic magnetometer	Contains magnetic yoke, magnetising coil etc.
5	Non-magnetic table	Housing computers, mainframes, consoles, etc.
6	Magnetic measurement mainframe	For excitation and measurement
7	Measurement and Control Console	Manual adjustment of the automatic loading and unloading device is possible

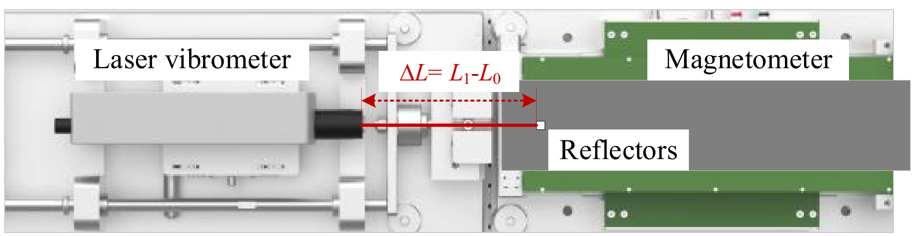


Figure 2. Magnetostrictive measurement schematic.

3. INTEGRATED MAGNETIC PROPERTIES TEST OF ORIENTED SILICON STEEL SHEETS

3.1. Integrated Magnetic Properties of Silicon Steel Sheets under Industrial Frequency Excitation

The magnetostriction and magnetization characteristics of a silicon steel sheet of type 30SQGD105 were measured in the range 1.0 T to 1.9 T at 50 Hz sinusoidal excitation with flux density starting at 1.0 T and measured in steps of 0.1 T.

(1) Hysteresis line measurement of silicon steel sheets under sinusoidal excitation at industrial frequencies.
As shown in Figure 3, the measured hysteresis lines of the silicon steel sheet are shown. From (a) it can be found that at the added flux density of less than 1.5 T, the hysteresis return area of the silicon steel sample to be measured increases with the increase in flux density and at a slower rate. When the external flux density is greater than 1.7 T, the silicon steel sheet gradually tends to saturate, and from (b) it can be seen that in the extremely saturated state of the silicon steel sheet, the overall shape of its hysteresis return becomes narrower.

(2) Measurement of magnetostrictive butterfly curves of silicon steel sheets under sinusoidal excitation at industrial frequencies.
The magnetostriction peak value λ_{pp}, calculated from the measured magnetostriction curve, can be used to set the magnetostriction material parameters for a more accurate simulation of the magnetostriction coupling when calculating the core vibration of a reactor transformer. A diagram

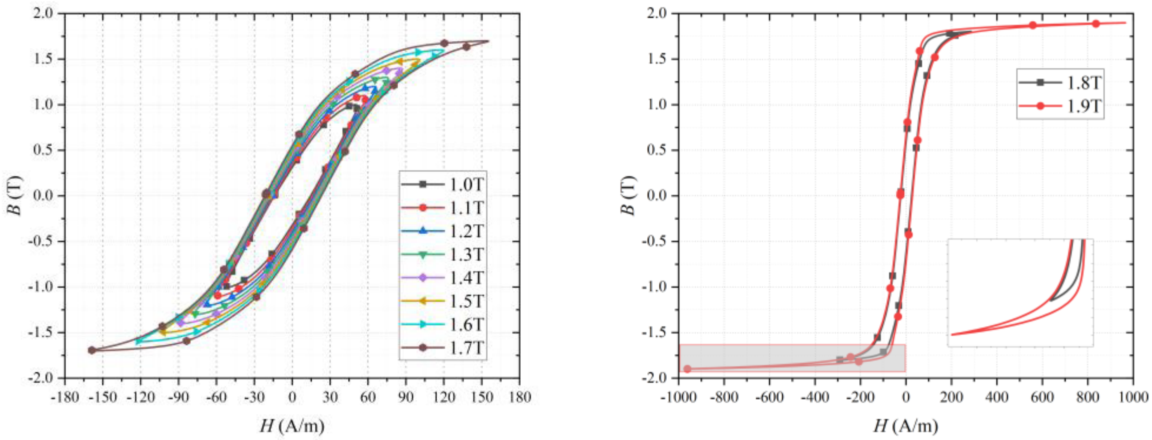


Figure 3. Hysteresis line of the silicon steel sheet to be measured in the range of magnetic flux density from 1.0 T to 1.9 T.

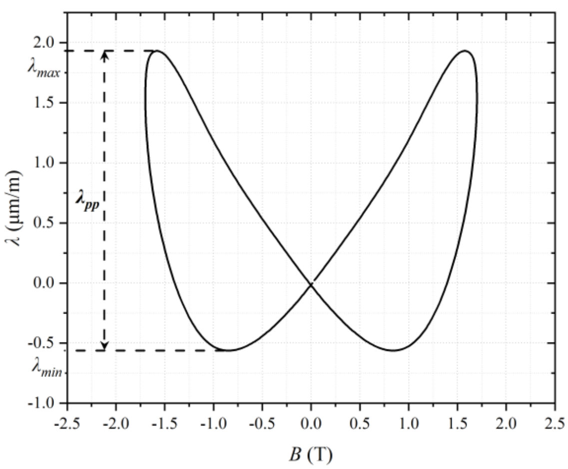


Figure 4. Magnetostriction peak-to-peak.

of the peak magnetostriction values is shown in Figure 4. The expression for the magnetostrictive peak-to-peak value is:

$$\lambda_{pp} = \lambda_{\max} - \lambda_{\min} \tag{2}$$

where $\lambda_{\max}$ and $\lambda_{\min}$ correspond to the maximum and minimum values on the magnetostrictive butterfly curve, respectively.

The variation of the magnetostrictive butterfly curve for the silicon steel wafer to be tested under 50 Hz sinusoidal excitation with increasing flux density is shown in Figure 5. Oriented silicon steel sheets exhibit both elongation and contraction strains in two directions. In this case, the magnetostrictive hysteresis curve is predominantly aligned with the elongation direction strain. It can be seen that the area of the magnetostrictive butterfly curve of the silicon steel wafer under test shows a gradual increase in the overall area of the wafer as the flux density increases within the range of less than 1.7 T, and the growth rate is faster. As with the hysteresis line, when the added flux density is greater than 1.7 T, the silicon steel sheet is gradually saturated; the magnetostriction increases rapidly; and the butterfly curve area remains the same.

The reason for this phenomenon is that the silicon steel sheet gradually enters the saturation zone at this time; the internal magnetic domains slowly rotate; and the domain walls gradually start to fuse together. When the magnetic flux density reaches 1.9 T, the area of the butterfly curve reaches

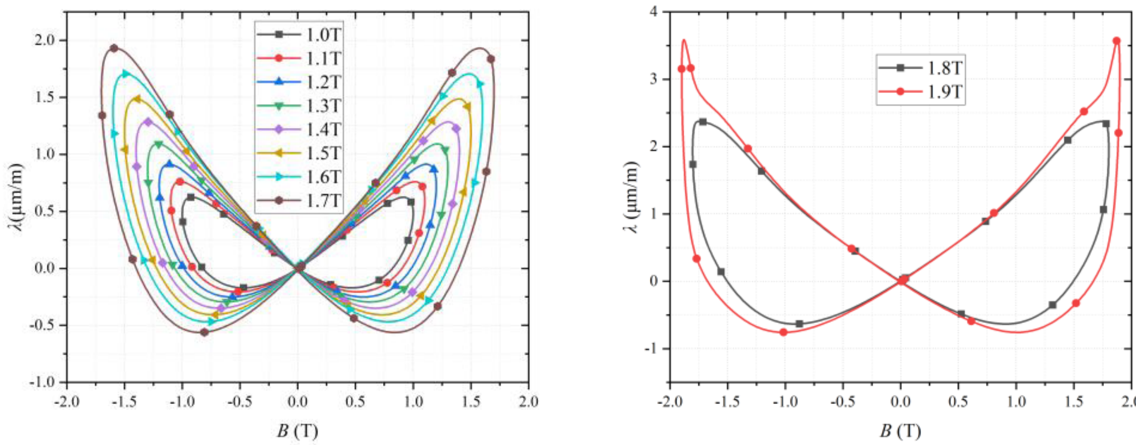


Figure 5. Magnetostrictive butterfly curves.

its maximum; the silicon steel sheet is completely saturated; the rotation of the internal domains is completed; the domain walls have completely fused; and the length of the silicon steel sheet is elongated to the maximum that at this time we can obtain. The saturation magnetostriction coefficient at the frequency excitation is 3.5868 μm/m.

The peak values of the magnetostriction of the silicon steel sheet over the range of magnetic flux density variations from 1.0 T to 1.9 T at working frequency are shown in Figure 6. The graph shows that the silicon steel sheet is fully saturated at a flux density of 1.9 T, at which point λ_{pp} is 4.3445 μm/m, approximately five times the 0.7949 μm/m at a flux density of 1.0 T.

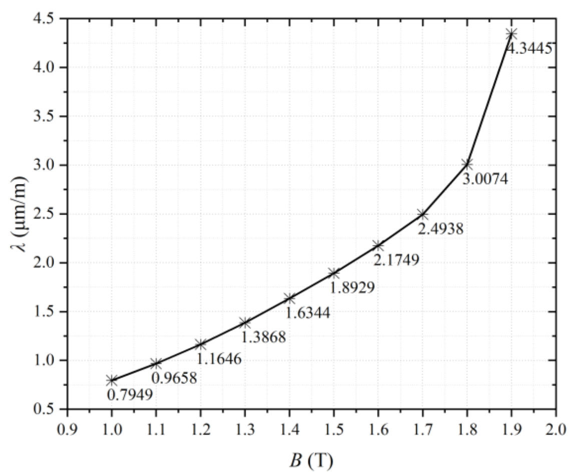


Figure 6. Magnetostrictive peak-to-peak values at industrial frequency excitation.

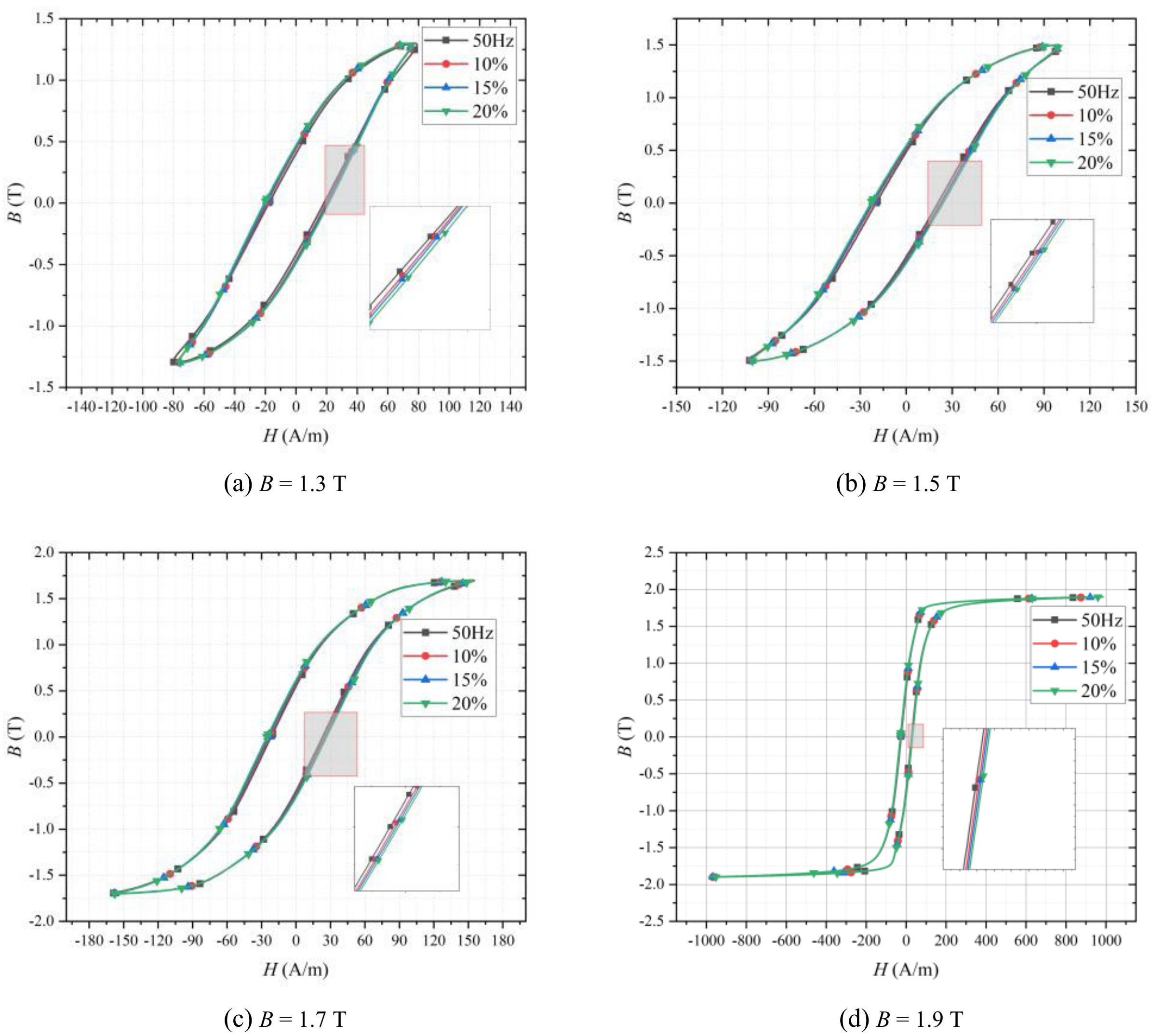
3.2. Integrated Magnetic Properties of Silicon Steel Sheets under Harmonic Excitation

During the operation of transformers and reactors, in addition to the frequency excitation, there is also the generation of harmonics due to the nonlinearity of their core materials and rectification equipment. Harmonics can affect the integrated magnetic properties of the core of the equipment and jeopardize the normal operation of the equipment. In this section, the magnetization and magnetostriction characteristics of the silicon steel sheet are measured using a 50 Hz sinusoidal excitation as the base wave, while adding the third harmonic with contents of 10%, 15%, and 20%. The applied magnetic field at this point can be expressed as:

$$B = B_0 \sin(\omega t) + B_n \sin(n\omega t) \tag{3}$$

where ω is the angular frequency, satisfying $\omega = 2\pi f$; n is the number of harmonics. The effect of the third harmonic excitation on the integrated magnetic properties of the silicon steel sheet is measured in this section, $n = 3$; B is the fundamental flux density amplitude; B_n is the flux density amplitude of the nth harmonic, $B_n = kB_0$, $k = 10\%$, 15%, 20%.

The magnetic flux densities of 1.3 T, 1.5 T, 1.7 T, and 1.9 T were selected to compare and analyze the hysteresis return and butterfly curves of the silicon steel wafer at 10%, 15%, and 20% excitation of the working frequency and third harmonic respectively as shown in Figure 7.



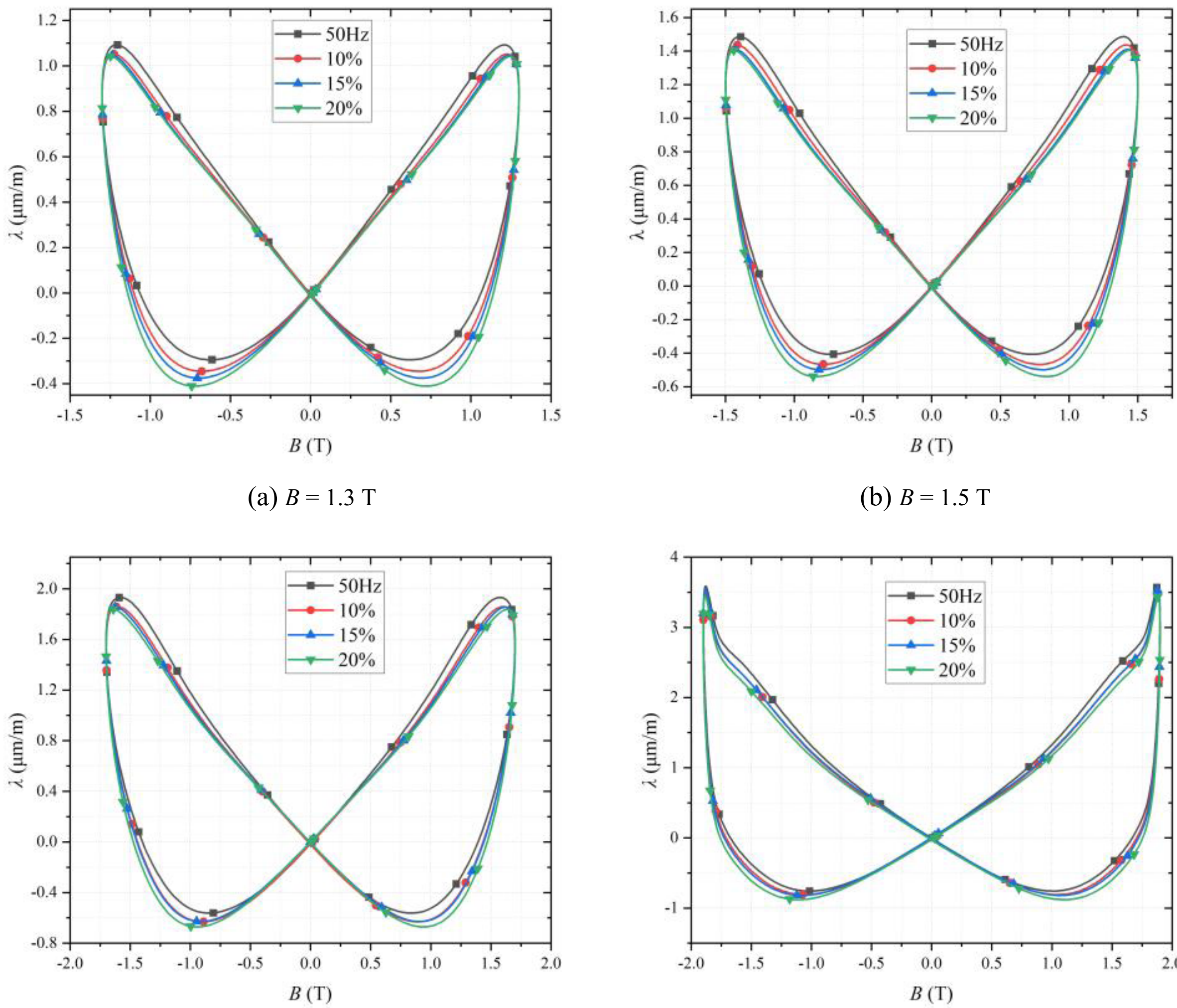
(a) $B = 1.3$ T (b) $B = 1.5$ T

(c) $B = 1.7$ T (d) $B = 1.9$ T

Figure 7. Hysteresis line comparison.

As can be seen from the measurement results in Figure 7, when different flux densities are applied to the silicon steel sheet, the overall shape of the hysteresis line does not change much as the area of the hysteresis line increases with the increasing proportion of the third harmonic component compared to the I.F. excitation.

Figure 8 shows the butterfly curve with different harmonic components. From the measurement results, it can be seen that the valley of the butterfly curve becomes sharper as the percentage of the third



(a) $B = 1.3$ T (b) $B = 1.5$ T

(c) $B = 1.7$ T (d) $B = 1.9$ T

Figure 8. Comparison of magnetostrictive butterfly curves.

harmonic component increases; the overall curve shifts downwards; and the magnetostriction amplitude gradually decreases compared to that of the I.F. excitation. Exactly, as the third harmonic component increases, the strain in the elongation direction of the silicon steel sheet decreases, while the strain in the contraction direction increases. However, the third harmonic component has less pronounced effects on the hysteresis behavior of the silicon steel sheet.

The results are shown in Figure 9, and the specific values are shown in Table 2. The magnetostrictive peak-to-peak values λ_{pp} were compared and analyzed for the cases of 10%, 15%, and 20% of the third harmonic component under industrial frequency excitation.

From the measurements compared in Figure 9 and Table 2, it can be seen that between 1.0 T and 1.7 T, λ_{pp} gradually increases as the proportion of harmonic components in the excitation gradually increases compared to the working frequency excitation, and between 1.7 T and 1.9 T, the silicon steel sheet gradually saturates, at which point the change in λ_{pp} is not significant. Therefore, between 1.0 T and 1.7 T, to achieve the same magnitude of strain, a larger third harmonic component requires a smaller peak magnetic flux density. This indicates that the influence of the third harmonic component has a certain enhancing effect on the strain magnitude of oriented silicon steel sheets.

Table 2. Magnetostrictive peaks and valleys for different harmonic component share excitations.

Incentive / B(T)	Industrial frequency	Harmonics 10%	Harmonics 15%	Harmonics 20%
1.0	0.7949	0.7975	0.8133	0.8414
1.1	0.9658	0.9725	0.9899	1.0247
1.2	1.1646	1.1737	1.1941	1.2342
1.3	1.3868	1.3972	1.4219	1.4523
1.4	1.6344	1.6424	1.6589	1.6959
1.5	1.8929	1.9039	1.9084	1.9436
1.6	2.1749	2.1791	2.1735	2.2039
1.7	2.4938	2.49	2.4849	2.509
1.8	3.0074	3.0002	3.0064	3.0594
1.9	4.3445	4.3033	4.361	4.329

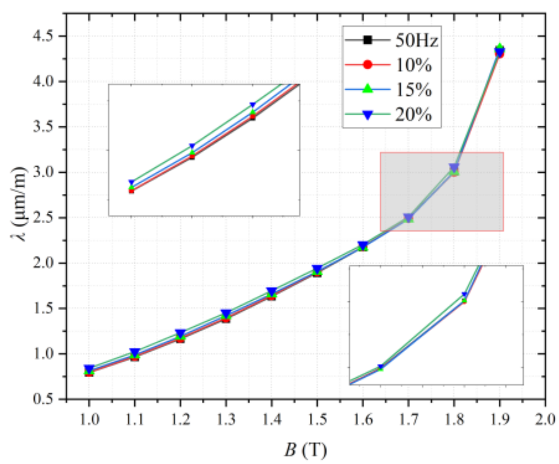


Figure 9. Comparison of magnetostrictive peak-to-peak values.

4. COMPREHENSIVE MAGNETIC PROPERTIES TESTING OF ORIENTED SILICON STEEL SHEETS UNDER STRESS CONDITIONS

During the operation of transformers and reactors, fasteners such as clips and bolts subject the core structure to stresses, which have been shown to affect the grain arrangement within the silicon steel sheet, thereby changing the magnetostriction parameters of the sheet. In this section, the effects of stress on the magnetization and magnetostrictive properties of the silicon steel material are investigated by applying different stresses to the core structure under frequency and harmonic excitation.

4.1. Effect of Stress on the Integrated Magnetic Properties of Silicon Steel Sheets under Industrial Frequency Excitation

The integrated magnetic properties of the silicon steel sheet were measured over the magnetic flux variation range from 1.0 T to 1.9 T by applying pressures of 0.5 MPa, 1 MPa, 1.5 MPa, and 2 MPa, respectively, to the sheet under sinusoidal excitation at working frequency.

(1) Effect of applied stress on the magnetisation characteristics of silicon steel sheets under industrial frequency excitation.
The measured results of the hysteresis lines of the silicon steel sheet for different stresses applied at $B = 1.3\,\mathrm{T}$, $1.5\,\mathrm{T}$, $1.7\,\mathrm{T}$ and $1.9\,\mathrm{T}$ were selected for plotting and analysis, and the results are shown in Figure 10.

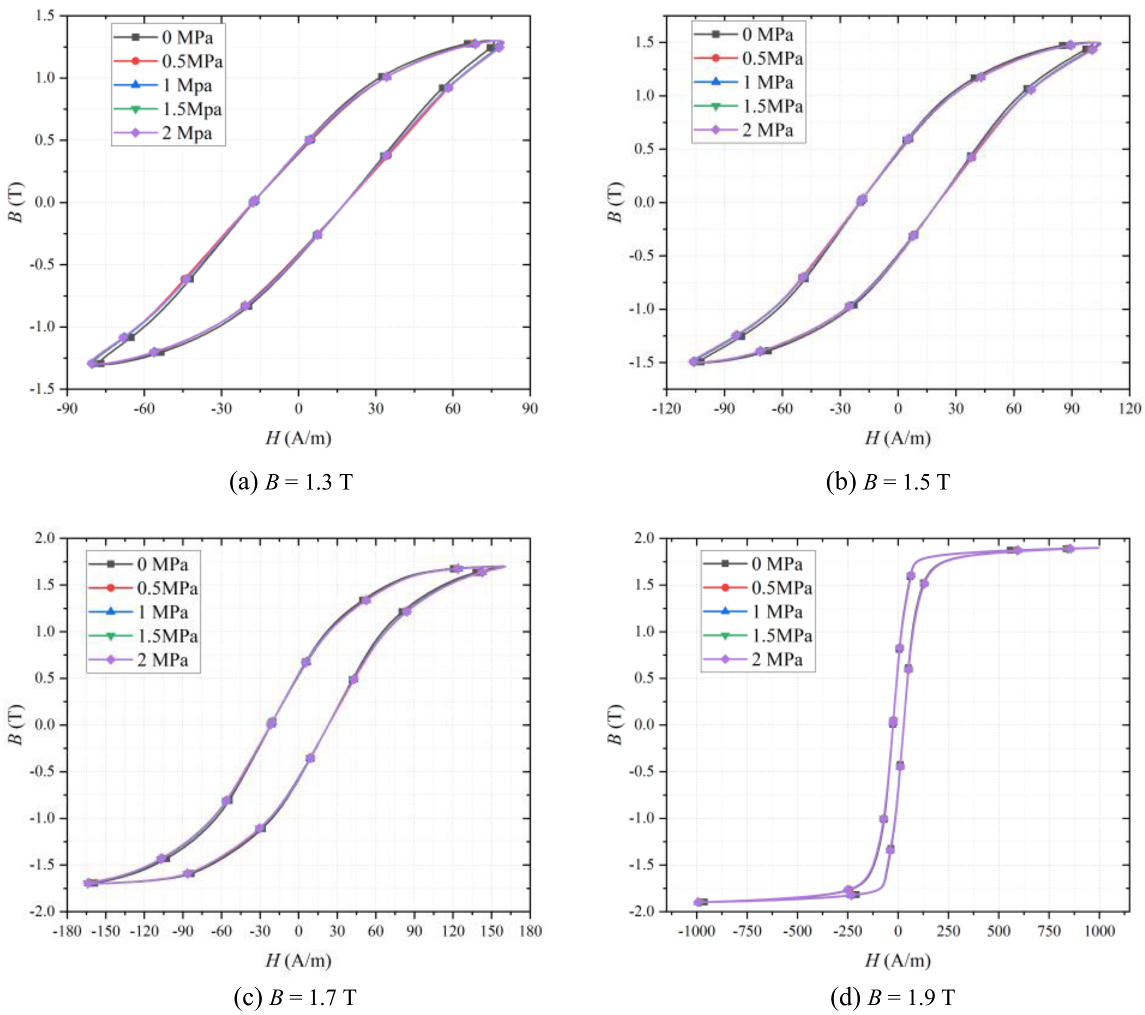


Figure 10. Hysteresis loop of silicon steel sheet under different stresses.

As can be seen from the measured hysteresis lines for the four flux densities shown in Figure 10, the effect of stress on the hysteresis lines is small. It can be seen that for the same flux density, the hysteresis tends to 'flatten' as the stress increases compared to the no-stress case, but overall, the stress has only a small effect on the hysteresis line, so the effect of stress on the B-H curve is also small. In other words, the B-H curve would be broader than when stress is not applied. However, overall, stress has only a minor impact on the hysteresis loop of the material.

(2) Effect of applied stress on the magnetostrictive properties of silicon steel sheets under industrial frequency excitation.
The measured results of the magnetostrictive butterfly curves of the silicon steel sheet for different stresses applied at $B = 1.3\,\mathrm{T}$, $1.5\,\mathrm{T}$, $1.7\,\mathrm{T}$, and $1.9\,\mathrm{T}$ were plotted and analyzed, and the results are shown in Figure 11.
As can be seen from the measurements in Figure 10, the effect of stress on the magnetostrictive butterfly curve is greater than the no-stress case. In this scenario, the two ends of the butterfly

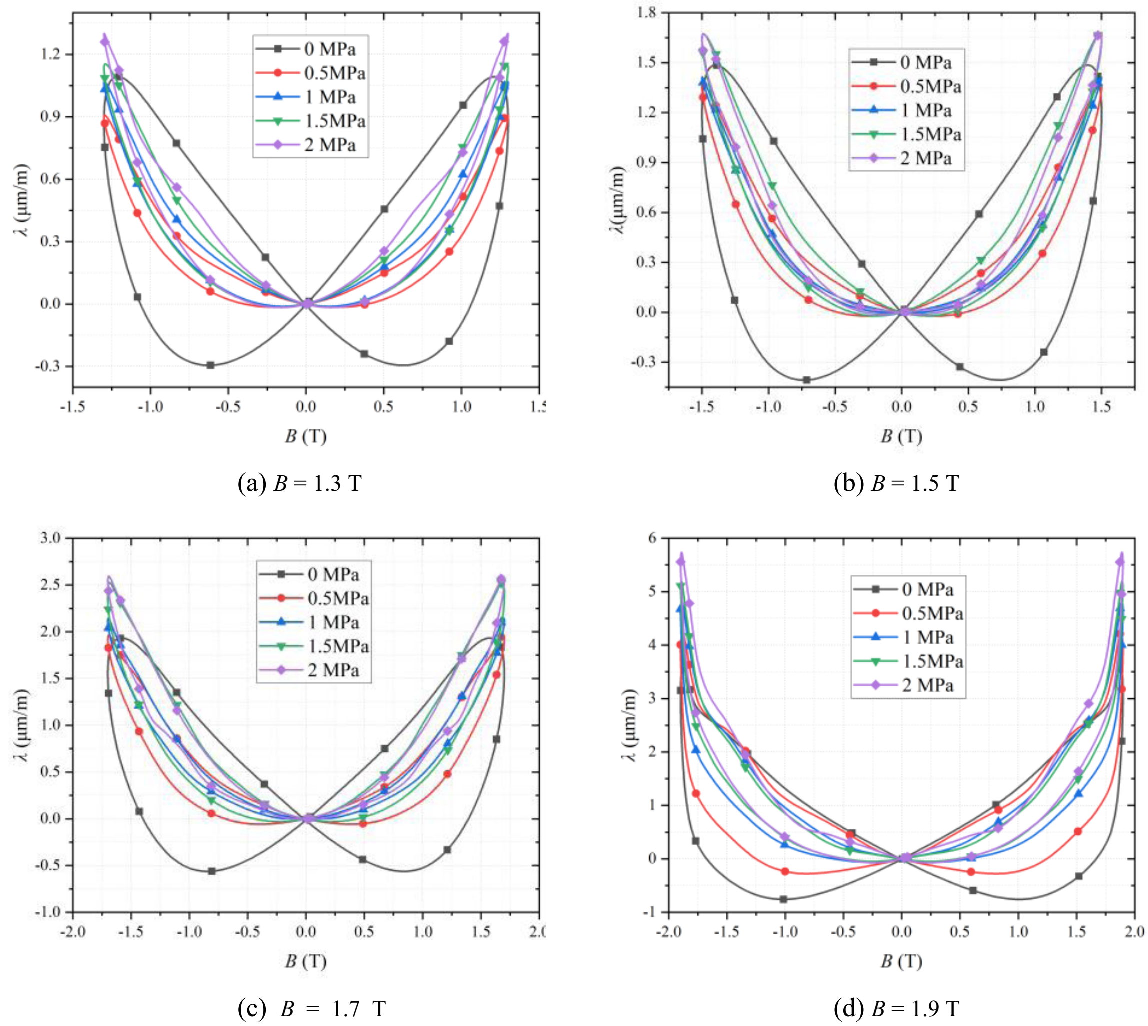


Figure 11. Butterfly curves for silicon steel sheets under different stresses.

curve's hysteresis loop contract sharply, leading to a significant reduction in the hysteresis phenomenon. Meanwhile, the left and right parts of the butterfly curve's loop elongate, causing an increase in the elongation of the oriented silicon steel sheet's deformation. As the stress increases, the butterfly curve gradually moves upwards, and the magnetostriction amplitude gradually becomes larger.

Figure 12 shows the variation curve of λ_{pp} for silicon steel sheets under different stresses in the range of $B = 1.0\,\mathrm{T}$ to $1.9\,\mathrm{T}$, and the specific values are shown in Table 3.

Figure 12 shows that at flux densities less than 1.7 T, when the peak magnetic flux density remains constant, a higher applied stress leads to a smaller magnetostrictive peak-to-peak value (λ_{pp}). To achieve the same magnitude of strain, a higher peak magnetic flux density is required. This indicates that stress has a certain inhibitory effect on the strain magnitude of oriented silicon steel sheets when the magnetic flux density is relatively low. Compared to no stress, while applied stress increases the maximum elongation in one direction, it decreases the maximum elongation in the other direction. Therefore, the λ_{pp} is smaller than in the absence of stress.

After the magnetic flux density exceeds 1.7 T, applied stress causes the increase in maximum elongation in one direction to be more significant than the decrease in maximum elongation in the other direction. This results in a noticeable increase in the magnetostrictive amplitude, and at this point, the λ_{pp} increases with higher applied stress. This suggests that when the magnetic flux density is relatively

Table 3. Magnetostriction peaks at different stresses.

B(T) \ Stress (MPa)	0.5	1.0	1.5	2.0
1.0	0.4478	0.5727	0.6559	0.6713
1.1	0.5856	0.7336	0.8112	0.8561
1.2	0.7515	0.9006	0.9612	1.1109
1.3	0.9226	1.0815	1.1699	1.3169
1.4	1.0583	1.2415	1.4121	1.3635
1.5	1.3959	1.4146	1.6924	1.6857
1.6	1.6665	1.7503	2.0006	2.1496
1.7	2.0224	2.1487	2.5573	2.6
1.8	2.8411	3.0332	3.3976	3.5875
1.9	4.4973	4.8752	5.2422	5.8086

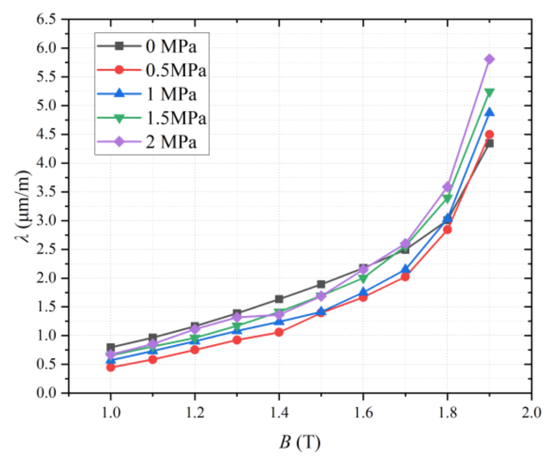


Figure 12. Magnetostriction peak-to-peak variation curves at different stresses.

high, stress has a certain enhancing effect on the strain magnitude of oriented silicon steel sheets.

4.2. Effect of Stress on the Integrated Magnetic Properties of Silicon Steel Sheets under Harmonic Excitation

In this section, the magnetization and magnetostriction characteristics of silicon steel sheets under complex operating conditions of harmonics and stress are measured and investigated. The integrated magnetic properties of the silicon steel sheet were measured at harmonic components of 10%, 15%, and 20%, respectively, and at applied stresses of 1 MPa and 2 MPa, respectively, with flux densities of 1.3 T, 1.5 T, 1.7 T, and 1.9 T, using the industrial frequency excitation as a control.

(1) Effect of applied stress on the magnetisation characteristics of silicon steel sheets under harmonic excitation.
Firstly, the effect of comparing different harmonic component ratios on the hysteresis lines at applied stresses of 1 MPa and 2 MPa and flux densities of 1.5 T and 1.7 T respectively was analyzed, and the results are shown in Figure 13, (a) for the effect of the percentage of harmonic components on the hysteresis line under an applied stress of 1 MPa; (b) for the effect of the percentage of harmonic components on the hysteresis line under an applied stress of 2 MPa.

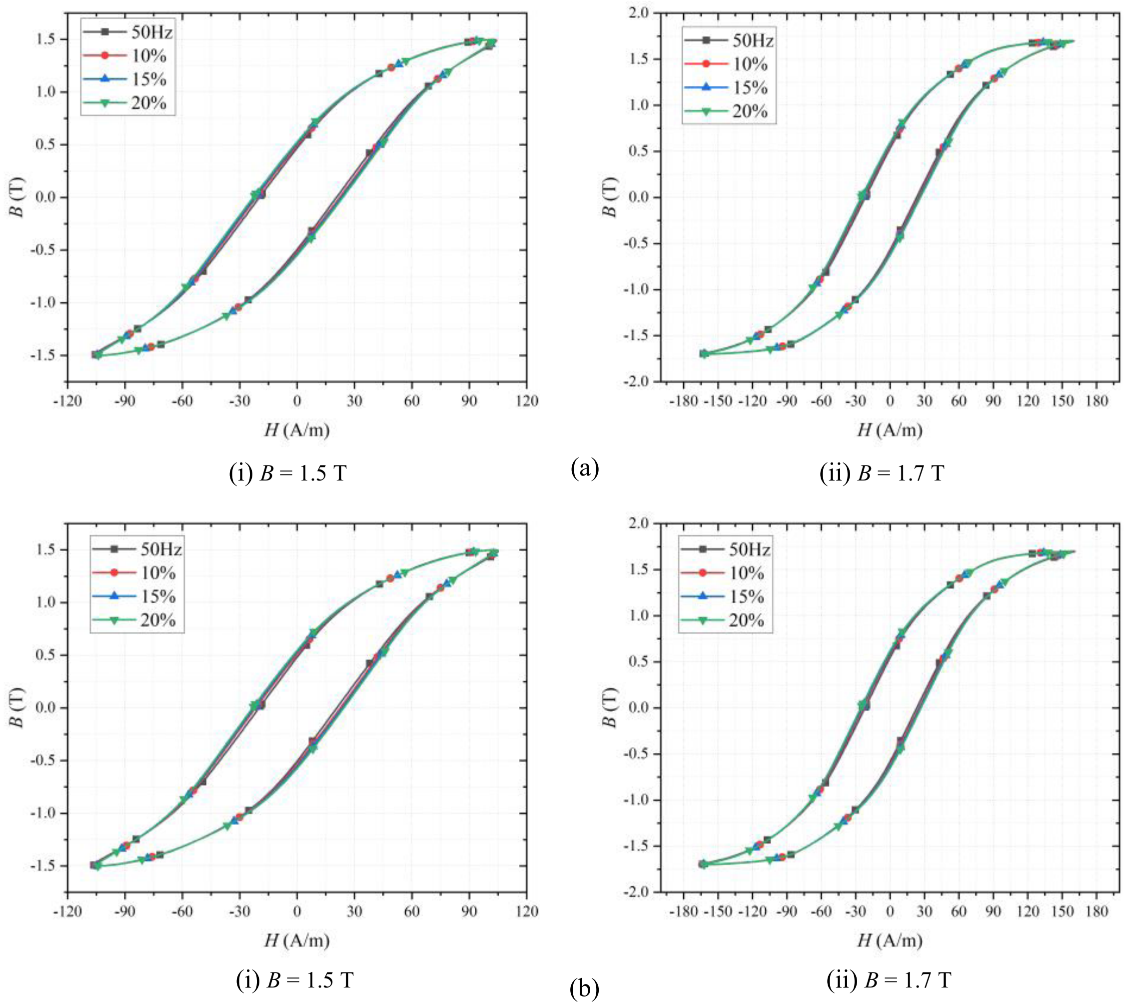


Figure 13. The effect of harmonic component proportion on hysteresis loop when the same stress is applied.

As can be seen from Figure 13, the effect on the hysteresis characteristics of the silicon steel sheet is limited under the applied stress and harmonic conditions, with a small change in the overall shape of the hysteresis return. At the same stress, the area enclosed by the hysteresis line becomes progressively larger as the proportion of harmonic components increases.

(2) Effect of applied stress on magnetostrictive properties of silicon steel sheets under harmonic excitation.

The effect of comparing different harmonic component ratios on the magnetostrictive butterfly curves was first analysed for stresses of 1 MPa and 2 MPa, and flux densities of 1.5 T and 1.7 T, respectively. The measured results are shown in Figure 14, (a) for the applied 1 MPa stress and (b) for the applied 2 MPa stress.

The effect of the harmonic component on the magnetostrictive butterfly curve becomes larger after the application of 1 MPa stress. It can be observed that at a magnetic flux density of 1.5 T and with a 10% harmonic component excitation, the magnetostrictive butterfly curve undergoes overlapping and exhibits the occurrence of minor hysteresis loops. At the same time, the area enclosed by the butterfly curve increases significantly at 20% of the harmonic component compared to when no harmonic excitation is included.

When applying a stress of 2 MPa and comparing it to power frequency excitation, in the presence

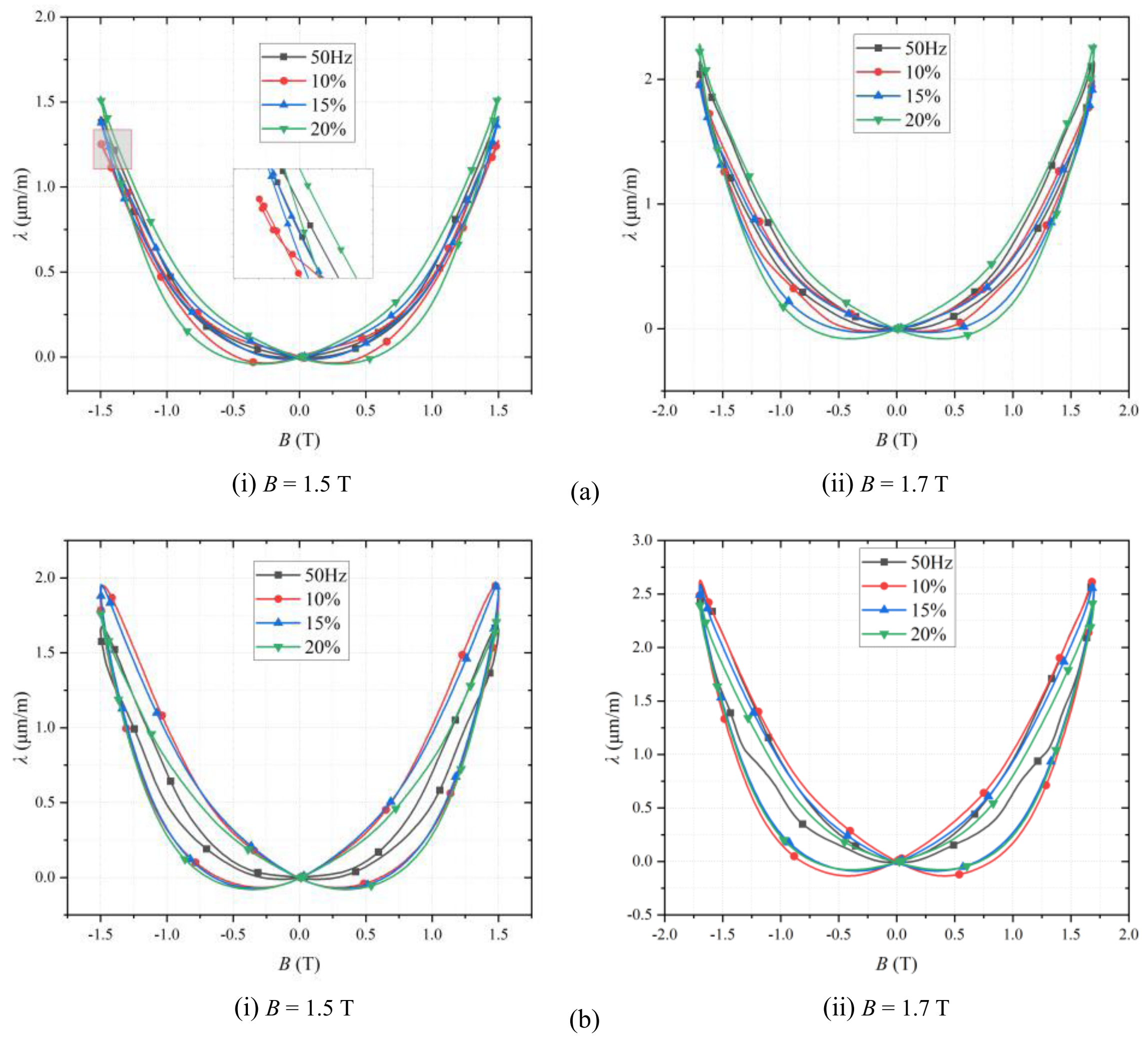


Figure 14. The effect of harmonic component proportion on butterfly curve when the same stress.

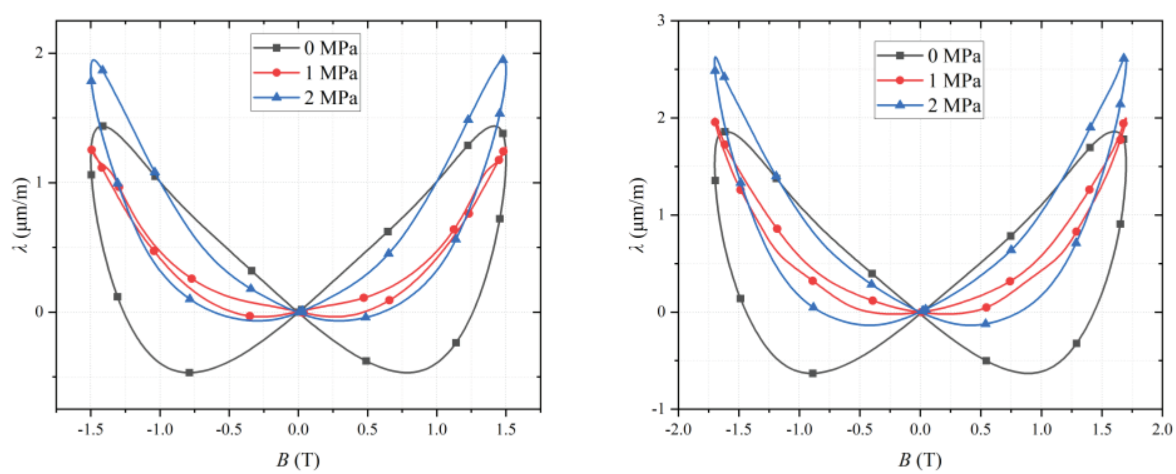
of harmonic components, the hysteresis loop area of the magnetostrictive butterfly curve will noticeably increase. At the same time, the area of the butterfly curve increases with increasing harmonics at 10% and 15% of the harmonic component. When the harmonic component reaches 20%, the tail of the butterfly curve becomes sharper, and the enclosed area compared to when the harmonic component proportions are 10% and 15% actually decreases. (a) shows the effect of the percentage of harmonic components on the butterfly curve at 1 MPa stress; (b) shows the effect of the percentage of harmonic components on the butterfly curve at 2 MPa stress.

The effect of stress variation on the magnetostrictive properties of silicon steel wafers at the same harmonic component is analyzed for flux densities of 1.5 T and 1.7 T, and for harmonic components of 10% and 20%. The results are shown in Figure 15, (a) for a harmonic component of 10%; (b) for a harmonic component of 20%.

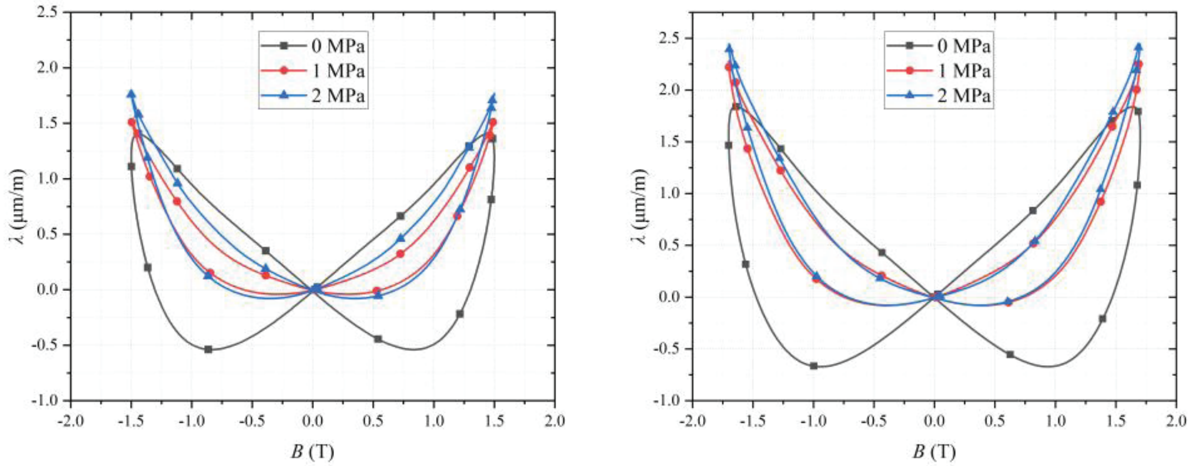
As shown in Figure 15, it can be observed that under the same harmonic component excitation, applying stress leads to a larger deformation of the magnetostrictive butterfly curve. As the applied stress increases, the tail of the butterfly curve gradually rises, resulting in an increase in the maximum elongation in the direction of elongation of the silicon steel sheet, and the magnetostrictive peak-to-peak value gradually increases. This indicates that under the influence of harmonic components, applied stress has a certain enhancing effect on the strain magnitude of the oriented silicon steel sheet. In comparison to that when no stress is applied, the area enclosed by the butterfly curve decreases, taking

Table 4. Magnetostrictive peak-to-peak values under various operating conditions.

Stress (MPa)	Harmonic percentage	B(T)	λ_{pp}
1.0	10%	1.3	0.9400
		1.5	1.3083
		1.7	2.0175
		1.9	4.6699
	15%	1.3	0.8746
		1.5	1.4087
		1.7	2.0096
		1.9	4.7480
	20%	1.3	1.0628
		1.5	1.5736
		1.7	2.3623
		1.9	5.6037
2.0	10%	1.3	1.3186
		1.5	2.0153
		1.7	2.7627
		1.9	6.5803
	15%	1.3	1.4008
		1.5	2.0292
		1.7	2.6715
		1.9	7.0534
	20%	1.3	1.3574
		1.5	1.8484
		1.7	2.5230
		1.9	5.9011



(i) $B = 1.5$ T (a) (ii) $B = 1.7$ T



(i) $B = 1.5$ T (ii) $B = 1.7$ T

(b)

Figure 15. Effect of stress on the butterfly curve under the same excitation.

on a contraction shape. The hysteresis phenomenon is significantly weakened, and the lower peaks of the curve become gradually flatter while the upper peaks become sharper. (a) shows the effect of stress on butterfly curve at 10% harmonic component; (b) shows the effect of stress on butterfly curve at 20% harmonic component. The magnetostriction peak values under various operating conditions are shown in Table 4.

5. CONCLUSION

In this paper, the hysteresis and magnetostriction characteristics of silicon steel sheets were investigated using the TS3300 electrical steel integrated magnetic property measurement system under working frequency, third harmonic, and applied stress, and the integrated magnetic properties of silicon steel sheets under different excitation and different stress were compared and analysed:

(1) The effect of harmonic excitation and stress on the hysteresis characteristics of silicon steel wafers is small. Harmonic excitation broadens the hysteresis loop, while applied stress elongates the ends of the hysteresis loop. However, overall, the changes in the hysteresis loop of the silicon steel sheet are relatively small when being subjected to different harmonic component proportions of excitation and various levels of applied stress.

(2) Under harmonic excitation, as the proportion of the third harmonic component gradually increases, the magnetostrictive butterfly curve's positive amplitude decreases while the negative amplitude increases. The strain in the elongation direction of the silicon steel sheet decreases, while the strain in the contraction direction increases. For magnetic flux densities below 1.7 T, the magnetostrictive peak-to-peak value increases with the increasing third harmonic component proportion.

(3) After applying stress, the magnetostrictive butterfly curve undergoes larger deformation, and the overall curve area rapidly decreases. With increasing stress, the positive amplitude of the magnetostrictive curve gradually increases. For magnetic flux densities below 1.7 T, the magnetostrictive peak-to-peak value (λ_{pp}) after applying stress is smaller than the λ_{pp} without stress. However, for magnetic flux densities exceeding 1.7 T, the λ_{pp} after applying stress is larger than the λ_{pp} without stress. This indicates that stress has a promoting effect on the strain magnitude of oriented silicon steel sheets when the magnetic flux density is relatively high, while stress has an inhibitory effect when the magnetic flux density is relatively low.

(4) Under the same level of applied stress, compared to power frequency excitation, harmonic excitation increases the area of the butterfly curve. When the proportion of harmonic components reaches

20%, the tail of the butterfly curve becomes very sharp, and in some cases, minor hysteresis loops might occur. Under the same harmonic excitation, the greater the applied stress is, the larger the positive amplitude of the butterfly curve is. The overall curve exhibits more pronounced changes, and the magnetostrictive peak-to-peak value increases.

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