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RESEARCH ARTICLE

Analysis of Bare Uniform Fiber Bragg Grating Sensor for Measuring Strain on the Landing Gear of the LSU-02 Unmanned Aircraft

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Abstract

This paper reports the results of testing a bare uniform FBG sensor for measuring strain occurring on the landing gear of an unmanned aircraft. The landing gear used in this research is made from carbon fiber, known for its high strength and stiffness. Fiber Bragg grating (FBG) sensor is positioned 20 cm from the center point of the landing gear, specifically at the curved section, to optimize strain detection. Static testing to measure strain was conducted by applying varying mass loads from 0 to 9 kilograms to test the sensor's response to load changes. Measurement results show a constant measurement threshold at a load of 50 grams, indicating sensor stability within that load range, with a measurement resolution of 0.1654 microstrain (με). Comparison of FBG measurement results with the BLFAB-55 strain gauge sensor revealed a measurement difference of 5.9%. Further research was conducted by introducing disturbances in the form of wind at speeds of 5 m/s and 10 m/s, and temperature disturbances of 30°C and 45°C. The results showed that the 45°C temperature disturbance had the most significant impact on the strain changes measured by the FBG, with an increase in strain value of 265% compared to when there was no disturbance.

Keywords: UAV, optic sensor, FBG, strain

1. Introduction

Unmanned aircraft have begun to be used for various applications, such as monitoring, mapping, and regional security [1]. Unmanned aircraft have several advantages over conventional or commercial aircraft, such as their more compact size, which reduces the power required for operation. Additionally, unmanned aircraft do not require long runways for takeoff and landing, making them easier to operate in various regions of Indonesia. The government agency LAPAN, now part of BRIN, has developed unmanned aircraft aimed at monitoring Indonesian territory through aerial surveillance [2]. The developed aircraft is an unmanned aerial vehicle that can be controlled remotely, named the Lapan Surveillance Aircraft (LSU). The LSU aircraft series consists of several types, depending on their use. One type of LSU aircraft is the LSU-02. This unmanned aircraft has a wingspan of 2 meters and is designed for long-distance and long-duration monitoring missions. The shape of the LSU-02 can be seen in Figure 1.1.

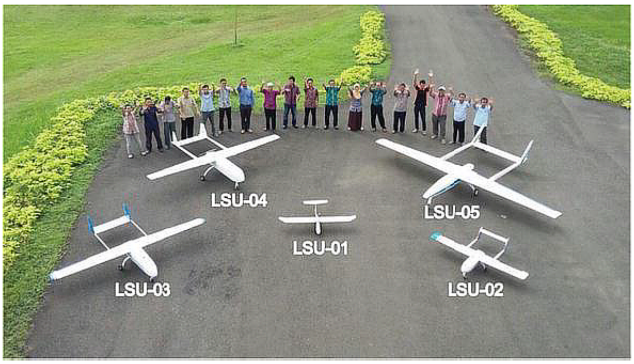

Figure 1.1 The LSU unmanned aircraft Made by LAPAN

One of the most crucial components of an aircraft is the landing gear. The landing gear is responsible for the takeoff and landing processes, acting as legs and support during takeoff and landing [3] . Additionally, the landing gear carries the aircraft's load during ground operations and flight [4]. Good landing gear is essential for ensuring flight safety, especially for unmanned aircraft that must operate on various types of terrain, such as challenging or remote environments. Therefore, monitoring and measuring strain on the landing gear is vital, as it helps identify potential failures or damage to the landing gear before an accident occurs [5].

In Indonesia, monitoring the structure of landing gear often relies solely on periodic inspection systems, which involve visually inspecting the aircraft structure for cracks. This method may not provide real-time monitoring results. The use of sensor technology can facilitate real-time monitoring of aircraft structures. One such sensor technology is the fiber Bragg grating (FBG) sensor. The fiber Bragg grating sensor operates based on the principles of optical fibers [6]. Optical fiber sensors have several advantages over traditional sensors like strain gauges, including resistance to electromagnetic interference [7], a small and lightweight design, water resistance, and the ability to multiplex many sensors within a single optical fiber [8].

Fiber Bragg grating is increasingly used due to its advantages, such as high sensitivity, good reliability, and adaptability in harsh environments [9]. Research related to the use of fiber Bragg grating on aircraft has been conducted, such as using fiber Bragg grating to monitor the condition of carbon-based aircraft structures

[10]. In this research, the structure measured was the fuselage, using bare FBG in a laboratory scale study. In the same year, a study was conducted on a different object, where the object used was a military aircraft. The aim of this study was to observe the fatigue occurring in the aircraft structure using fiber Bragg grating to measure strain [11]. Research using fiber Bragg grating sensors to monitor the landing gear structure of a passenger aircraft, specifically the Airbus A320, has also been conducted [12]. While previous studies used a single bare FBG sensor, subsequent research began using up to 20 fiber Bragg grating sensors arranged in series to monitor the wings of an unmanned aircraft [13].

In Indonesia, research related to fiber Bragg grating for monitoring aircraft structures has not yet been conducted. So far, testing on the landing gear structure of unmanned aircraft has been done by dropping the landing gear placed on a test rig called a drop test using strain gauges. This test uses loads ranging from 5 to 100 kilograms to determine the strength of the landing gear structure before it undergoes fatigue [14]. Testing with small loads has not yet been conducted, even though applying small loads can result in very small strains. These small strains are crucial for early detection of damage to the aircraft structure [15]. Therefore, in this study, FBG is used to measure strain on the landing gear of an unmanned aircraft. The landing gear used comes from the small class LSU-02 aircraft, weighing 15 kg. Testing of the FBG against high-temperature wind disturbances is also conducted to observe its effect on strain measurement results using FBG. It is hoped that the results of this research can provide a foundation for the development of FBG sensors in aircraft structure monitoring systems more broadly and in various other fields.

2. Methods

2.1 Theoretical Background

The FBG sensor is a type of optical sensor that utilizes the optical properties of glass fiber with periodic gratings along its core. The basic operating principle of FBG is based on the Bragg phenomenon, where the wavelength of light reflected by the gratings depends on physical changes around the sensor, such as strain or temperature.

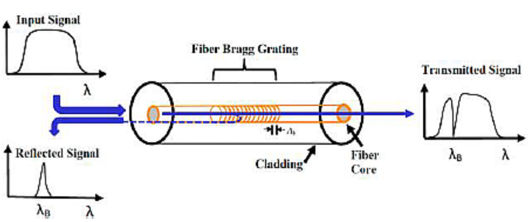

Figure 2.1 Principle Operation of FBG [16].

As shown in Figure 2.1, when broadband light (with various wavelengths) is transmitted into the optical fiber, the Bragg gratings will reflect a specific wavelength (called the Bragg wavelength), while other wavelengths will pass through [17]. FBG physically stretches and contracts on a nanometer scale in response to environmental physical changes, causing the central or Bragg wavelength to shift. The Bragg wavelength (λ_B)) is the reference point used for optical measurements. The grating period ($\wedge$) is the distance between each change in the refractive index. The Bragg wavelength ((λ_B) is defined by the following equation:

$$\lambda_B = 2n_{eff}\wedge \tag{1}$$

λ_B represents the Bragg wavelength, $2n_{eff}$ is the effective refractive index, and $\wedge$ is the grating period. When strain occurs in the optical fiber, $\wedge$ and $\wedge$ will change, causing a shift in the reflected Bragg wavelength [18]. This change can be measured and directly correlated with the magnitude of strain or temperature changes experienced by the optical fiber [19].

$$\triangle\lambda_B = \lambda_B(1 - p_\varepsilon)\varepsilon + \lambda_B\alpha \triangle T \tag{2}$$

λ_B is the Bragg wavelength, p_ε is the strain-optic coefficient, ε is strain, α is the thermal sensitivity coefficient of the optical fiber. $\triangle T$ is temperature change. In this paper, testing is conducted in a room with constant temperature, thus temperature changes are neglected, resulting in the equation:

$$\triangle\lambda_B = \lambda_B(1 - p_\varepsilon)\varepsilon \tag{3}$$

p_ε is the optical fiber's strain-optic coefficient, which depends on the material properties of the optical fiber and the configuration of the grating..

$$p_\epsilon = \frac{n_{eff}^2}{2}\left[p_{12} - \nu\left(p_{11} + p_{12}\right)\right] \tag{4}$$

p_{11} and p_{12} are components of the strain-optic tensor, and ν is the Poisson's ratio. Typically, silica-based FBGs have values of p_{11}= 0.113, p_{12}=0.252, ν =0.16, and n_{eef}=1.482, resulting in a strain-optic coefficient p_ϵ= 0.213 [20] for silica-based FBGs. To convert the change in Bragg wavelength ($\triangle\lambda B$) into strain (ϵ), the following formula is used:

$$\varepsilon = \frac{\Delta\lambda_B}{\lambda_B}(1 - 0.213) \tag{5}$$

2.2 Equipment and Materials

Here are the hardware and software used in this research

2.2.1 Landing Gear

The landing gear used is made of full carbon material, a composite material consisting of carbon fibers, with dimensions of 95 cm in length, 27 cm in height, and 58 cm spacing between the legs, 6 cm in width, and 1 cm in thickness. Carbon composite material has high strength and stiffness, allowing the landing gear to efficiently support loads without significant added weight. The shape of the landing gear used can be seen in Figure 2.2

Figure 2.2. Aircraft landing gear

2.2.2 Bare Fiber Bragg Grating (FBG)

The FBG sensor operates at a wavelength around 1550 nm. The use of uniform bare type FBG sensors in this study was chosen for their specifications: sensitivity up to 0.93 nm and accuracy of 99.1%. They are also easily integrable into composite structures like unmanned aircraft landing gear. Fiber Bragg Grating (FBG) sensors are mounted on the landing gear, 20 cm away from the midpoint. This position was chosen to obtain strain readings representative of the applied load at the midpoint. The bare FBG used can be seen in Figure 2.3

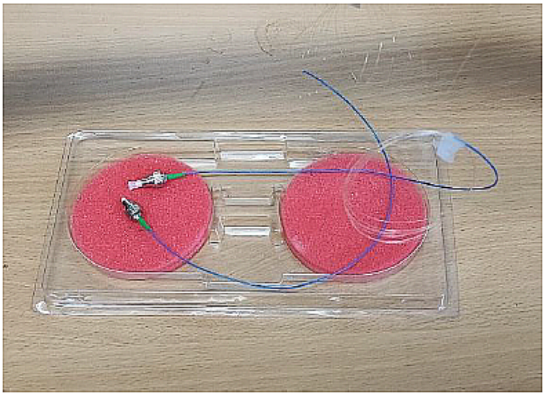

Figure 2.3. Bare uniform FBG

2.2.3 Interogator

Interrogator is a device used to read signals from Fiber Bragg Grating (FBG) sensors. The interrogator functions by sending broadband light into an optical fiber containing the FBG sensor and then analyzing the reflected light. This device can detect changes in the Bragg wavelength reflected by the sensor, which indicates changes in strain or temperature in the optical fiber

2.2.4 I-Mon USB evaluation Software

The I-Mon software is used to collect, store, and analyze data obtained from the FBG interrogator. The I-Mon software can receive and record wavelength data from the interrogator in real-time, display data in graphical form to facilitate interpretation of measurement results, and store data for further analysis and future reference.

2.2.5 Weight Block

To simulate loads on the landing gear, weight blocks are used. The weight blocks used have varying loads, ranging from 0 to 9 kilograms. These loads are applied at the midpoint of the landing gear to simulate operational conditions and measure strain responses in the structure. The 0 to 9 kilogram loads are selected to observe strain responses occurring in the landing gear when subjected to low loads. When subjected to low loads, the strain responses are usually minimal, so it allows us to assess the sensor's ability to measure strain on the smallest scale possible. Even though the strain values are very small, they are crucial in monitoring the aircraft structure.

2.3 Testing Method

In this test, a landing gear of the LSU-02 unmanned aircraft was used. The LSU-02 aircraft is a small-sized unmanned aerial vehicle. The curved landing gear has dimensions of 95 cm in length, 27 cm in height, a 58 cm distance between the two legs, 5 cm in width, and 1 cm in thickness, and is made of carbon composite. In this test, two sensors were used: a bare uniform FBG sensor and a special sensor used as a comparison, the BLFAB-5-5 strain gauge sensor. The FBG and strain gauge were alternately installed 20 cm from the midpoint of the landing gear, at the curve point. The choice of the 20 cm point was due to it being the curved position most likely to experience strain. The sensors were mounted transversely following the shape of the landing gear. The installation positions of both the FBG and strain gauge sensors are shown more clearly in Figure 2.4.

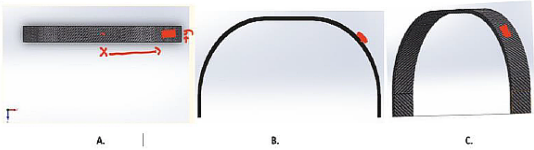

Figure 2.4. Sensor installation position on the landing gear: a) top view, b) front view, c) side view.

Figure 2.4 shows the sensor installation positions on the aircraft's landing gear. The red area represents the sensor used to measure strain. The sensor is installed at the curved part as shown in Figure 3.3b. Besides observing strain at this position, the FBG positioning also facilitates easy installation and removal of the sensor in case of problems or damage. The FBG installation points to find the best strain reading positions can be seen in Table 2.1. The x-axis distance is measured from the midpoint of the landing gear.

Table 2.1 FBG installation coordinates on the landing gear.

Position no.	X axis (cm	Y axiz (cm)
1	22	2,5
2	20	2,5
3	18	2,5

The FBG sensor is connected to the interrogator to obtain readings from the FBG. The interrogator also functions as the light transmitter to the FBG. The interrogator is then connected to a laptop via a USB cable. On the laptop, the I-MON software is installed to observe and store the measurement results obtained by the FBG. Near the FBG sensor, at the same distance of 20 cm from the center point of the landing gear. The strain gauge and FBG sensors are installed in the same position to detect the same strain as detected by the FBG. The strain gauge measurement data are then used as standard strain data for validating the measurement results from the FBG sensor.

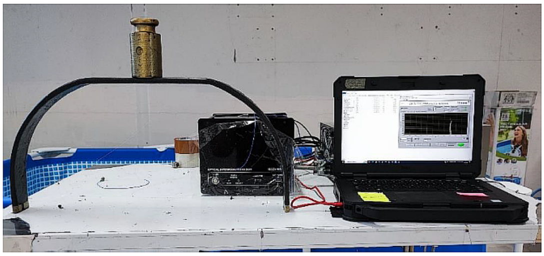

Figure 2.5. Data acquisition process

After all sensors are connected, load variations are initiated. The weighing scale is placed on top of the landing gear, at its center point, as shown in Figure 2.5. In this initial experiment, load variations ranging from 0 to 9 kilograms are used. This aims to evaluate the FBG sensor's capability in measuring strain thresholds and resolutions. Testing with small loads results in very small but still significant strains, as even minimal strains can affect the overall performance of aircraft landing gear [15].

3. Result and Analysis

The research was conducted on a laboratory scale at a temperature of 26°C. Sensors were placed at a distance of 20 cm from the center point of the landing gear

3.1 Characterization of FBG Sensor

From the strain measurement results using FBG for load variations from 0 to 9 kg, it is shown that with increasing load, there is a wavelength change as shown in Figure 3.1. The testing was conducted 5 times to assess the stability and repeatability of the FBG measurements.

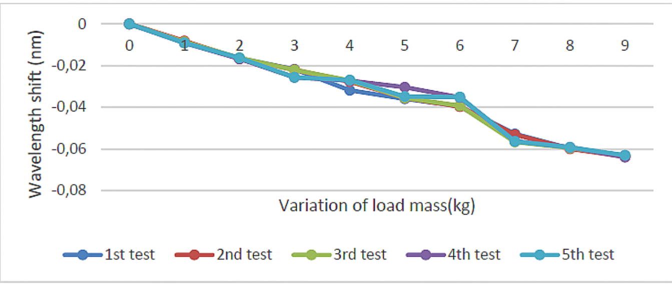

Figure 3.1. Measurement results of FBG sensor for various load mass variations

The strain measurement results using FBG sensors do not directly output strain values. The output obtained by the interrogator is wavelength. The data obtained is then input into Equation 2.5 to convert the wavelength values into strain.

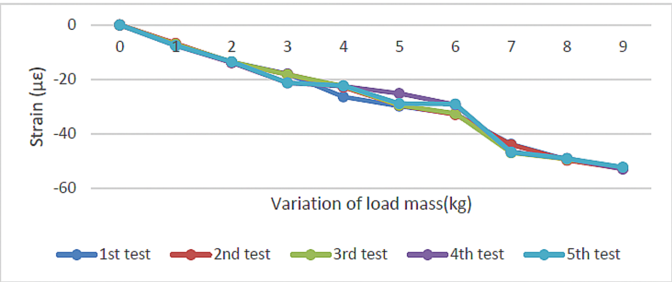

Figure 3.2. Hasil pengukuran regangan FBG untuk berbagai massa beban

Figure 3.2 shows a trend of decreasing strain values with increasing mass applied to the FBG sensor. This indicates that the FBG sensor experiences compression or negative strain. This change is consistent with the basic principle of FBG, where compression (negative strain) reduces the reflected wavelength [21]. Compression conditions under load on the aircraft landing gear will cause that part to experience further compressive force, leading to contraction. The results of the five tests conducted were averaged to obtain the strain values measured using the FBG sensor, as shown in Figure 3.3.

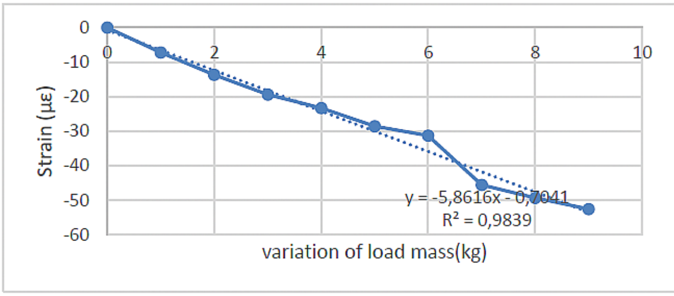

Figure 3.3. Average strain measurement results using FBG

The linear regression value obtained in the measurement is 0.98. To validate the measurement results obtained with FBG, measurements were also conducted using strain gauges positioned at the same location as the FBG. The strain gauge used is BLFAB-5-5. The BLFAB-5-5 strain gauge is commonly used to measure strain in composite material structures. The comparison of measurement results between the strain gauge and FBG can be seen in Figure 3.4. Specifications of the strain gauge used can be found in Table 4.1

Table 4.1 Specifications of BLFAB-5-5 strain gauge

No	Specifications	Value
1	Resistance	120 Ω
2	Operating Temperature	-20 ~ 200C
3	Material	Cu-Ni
4	Measurement	30000 mikrostrain

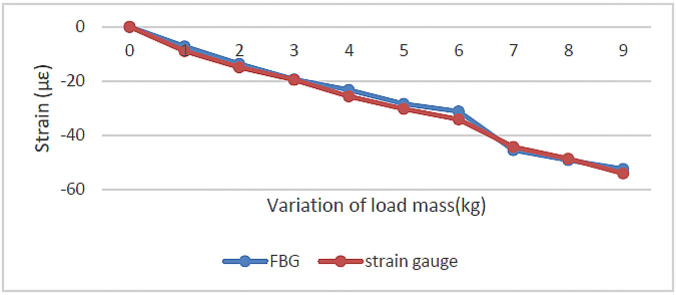

Figure 3.4. Comparison between strain measurement results using FBG sensor and strain gauge

The FBG sensor and strain gauge produced nearly identical measurement values. The average measurement difference between the strain gauge and FBG sensor was 1.37 microstrain or 5.9%. In the process of calibrating and validating strain measurements using Fiber Bragg Grating (FBG) sensors on carbon fiber landing gear, an important step is determining an accurate measurement threshold. For this purpose, testing was conducted by gradually increasing additional loads on the landing gear. Loads were applied from 0 grams to 950 grams, with increments of 50 grams. At each stage of load addition, the strain measured by the FBG sensor was recorded and analyzed. The data from these measurements were then used to determine the threshold, which is the point where the measured strain begins to show significant, reliable changes in response to increased load. This approach allows for identifying the minimum load threshold detectable by the FBG sensor with high accuracy, ensuring that the sensor functions well within the tested load range. Establishing this threshold is crucial to ensure that the FBG sensor can provide consistent and accurate strain data under actual operational conditions. Figure 3.5 shows the threshold measurement results obtained with FBG.

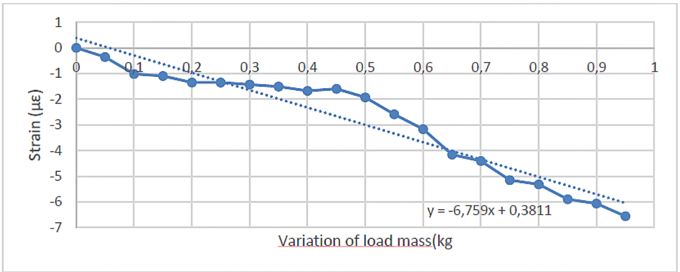

Figure 3.5. Threshold of strain measurement results for bare uniform FBG

The results of strain threshold measurement using FBG on carbon fiber landing gear in Figure 4.6 show that strain measurement can be detected with a load of 50 grams. This demonstrates that FBG is a sensor sensitive to strain changes, even very small ones. Measurement resolution is the smallest difference that can be measured by FBG. In this case, measurement resolution can be calculated as the smallest difference between two consecutive measurement values in the provided list. The smallest resolution measurable by FBG is 0.1654 με.

To validate that the measurement positions using Fiber Bragg Grating (FBG) sensors are optimal, additional measurements were taken at two different positions. Position 2 is the original position, while Position 1 is located 2 cm below the original position, and Position 3 is 2 cm above the original position. The configuration of FBG installation for the three different positions can be seen in Figure 3.6.

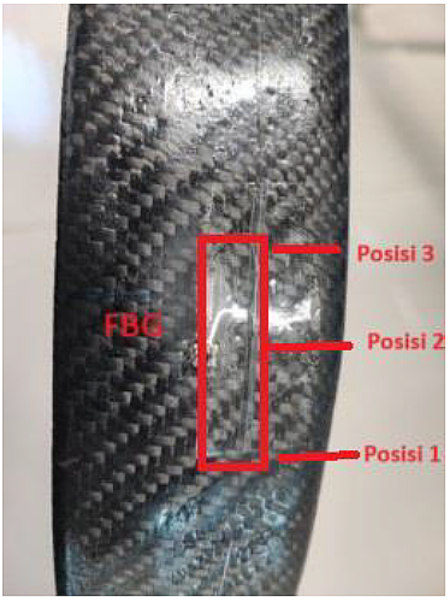

Figure 3.6. Configuration of FBG installation in 3 positions

With FBG installed in 3 different positions, FBG measurements are shown in Figure 4.8 and Figure 4.9. Position 1, located 2 cm below the original measurement position, yields linear strain readings. However, the strain values decrease slightly, resulting in a less steep slope in the graph. On the other hand, Position 3, located 2 cm above the original position, shows linear strain readings decreasing with increasing load mass, with a steeper slope. To determine the optimal position for FBG placement, the linear gradient values generated are used

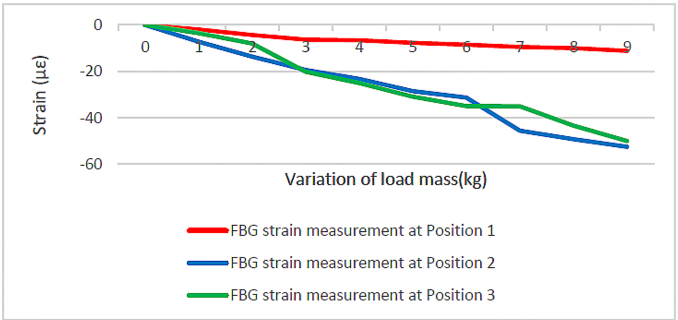

Figure 3.7. FBG measurements in 3 different positions

Based on the measurement results in Figure 3.7 obtained from these three positions, it was found that Position 2 is the best. This is based on the analysis of linear regression (R-squared), where Position 2 yielded the highest linear regression value compared to the other two positions. The linear regression values obtained for each position from 1 to 3 are 0.94, 0.98, and 0.97, respectively. High linear regression values indicate better correlation between the applied load and the measured strain, as seen in Figure 4.9, confirming that Position 2 provides the most accurate and consistent measurement results for detecting strain in carbon fiber landing gear.

3.2 Wind Disturbance Testing

Measurement of strain using Fiber Bragg Grating (FBG) sensors on carbon fiber landing gear can be influenced by various external disturbances. Wind blown by a blower at a speed of 10 m/s and a diameter of 3 inches creates forces on the surface of the landing gear. These forces induce additional stress on the carbon fiber structure, which is recorded by FBG sensors as strain changes. Wind disturbances can induce vibrations and pressure fluctuations that cause strain variations, affecting the accuracy of FBG sensor measurements. Figure 4.10 shows the strain measurement results with FBG after being disturbed by wind at wind speeds of 5 m/s and 10 m/s, shown in Figure 3.8 for load variations from 0 to 9 kg. The selection of wind speeds of 5 m/s and 10 m/s is due to the operational conditions of unmanned aerial vehicles.

In Figure 3.9, a decrease in strain values can be observed as the applied load mass increases. In this wind disturbance scenario, there is an increase in strain values compared to static testing without disturbance. This can be seen in the load mass range of 0 kg. In static testing, the strain value at 0 kg load mass is 0 microstrain. When subjected to wind disturbance, there is a slight increase to 0.1 microstrain.

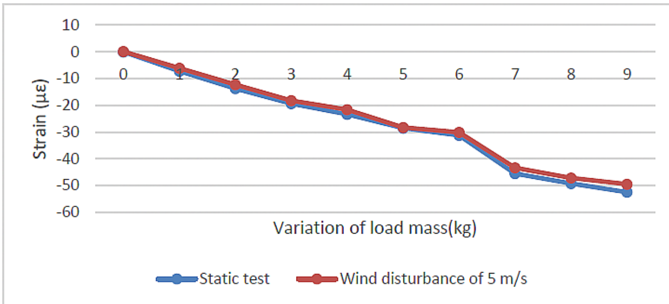

Figure 3.8. Strain when subjected to wind disturbance at 5 m/s.

This demonstrates that FBG sensors have high sensitivity, capable of detecting strain changes even when they are very small.

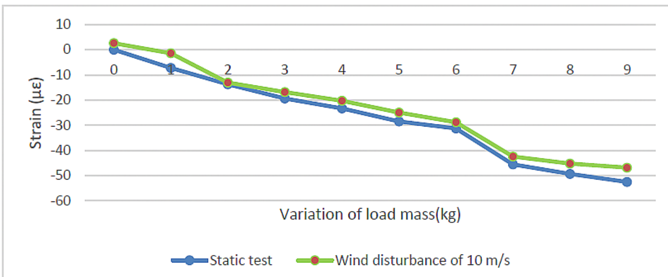

Figure 3.9. Strain when subjected to wind disturbance at 10 m/s.

Similar to the wind disturbance testing at 5 m/s, the testing at 10 m/s also shows an increasing trend in strain values compared to static testing without disturbance, as seen in Figure 3.9. The increase in strain values can be observed from the beginning of the load mass range, where at 0 kg load mass, the strain value increases from zero to a positive value. From the figure, a linear equation is derived which will be used to compare between static testing and static testing with wind disturbance. The change in strain values increases as the applied load mass increases. Wind disturbance at a speed of 10 m/s has a more significant effect, causing the strain readings to increase compared to static testing without disturbance. The strain changes occur directly from light to the heaviest load masses. The wind disturbance effect results in a strain change of 5.8% at 5 m/s wind disturbance and a strain change of 15.7% at 10 m/s wind disturbance.

3.3 Temperature Disturbance Testing

The next experiment involves measuring strain under high-temperature wind disturbance. This testing is intended to assess the performance of FBG sensors when used during flight in hot weather conditions. Two tests were conducted using high-temperature wind: the first test with wind at 30 degrees Celsius and a speed of 5 m/s, and the second test with wind at 45 degrees Celsius and a speed of 10 m/s.

The high-temperature wind was generated using a hairdryer. The temperature selection was based on aircraft operations under normal environmental conditions at 30 degrees Celsius, and under extremely hot conditions at 45 degrees Celsius. Testing was conducted only in the load mass range from 0 to 9 kilograms. To obtain strain values, Equation 2.2 needs to be used due to the influence of temperature changes. The strain changes observed after being subjected to high-temperature wind disturbance can be seen in Figure 3.10 for a temperature of 30°C.

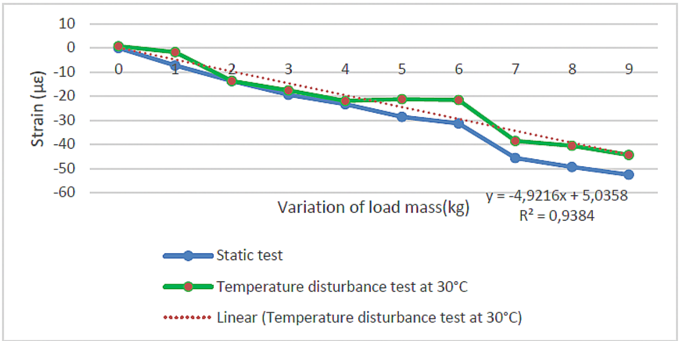

Figure 3.10. Strain at the temperature test at 30°C.

As the load mass increases, the strain resulting from temperature changes decreases. However, strain measurements with a temperature disturbance of 30°C cause the strain values to slightly increase from the initial strain values obtained from static testing. A temperature change of 4°C from the initial temperature can increase the strain values by up to 6 microstrains. Meanwhile, the strain changes observed after subjecting the system to a 45°C temperature disturbance can be seen in Figure 3.11.

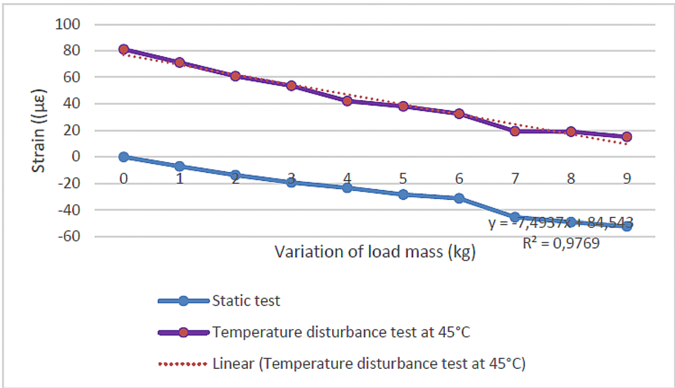

Figure 3.11. Strain at temperature test at 45°C.

Meanwhile, the temperature change from 26°C to 45°C resulted in a very drastic change in strain values. The strain value at 0 kg load mass, which initially was 0, increased drastically to 80 microstrains when subjected to a 45°C temperature disturbance. FBG is a highly sensitive sensor, particularly to temperature changes.

Temperature variations significantly affect the strain changes. When there was a temperature change of 4°C, from 26°C to 30°C, the strain change was still relatively small. The strain changes increase as the load mass increases. Larger temperature changes, such as from 26°C to 45°C, or a temperature increase of 19°C, result in more drastic changes in strain values. 4°C temperature change caused a 19% strain change, whereas a 19°C temperature change resulted in a 265% strain change.

In Figure 3.12, a comparison of all measurements can be seen, both static measurements and static measurements with disturbances. From the figure, it is clear that temperature changes have the greatest influence on the strain changes detected by FBG. The larger the temperature change, the greater the difference in strain measurements produced.

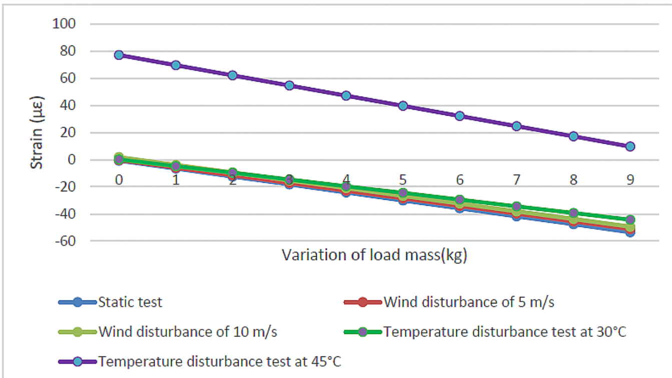

Figure 3.12. Perbandingan uji statis dengan uji gangguan keseluruhan.

Here's the differences in strain measurements caused by each static measurement with disturbance compared to static measurement without disturbance:

- In the static measurement with a 5 m/s wind disturbance, the difference in measurements is 1.4159 με or 5.8%.
- In the static measurement with a 10 m/s wind disturbance, the difference in measurements is 3.3388 με or 15.7%.
- In the static measurement with a 30°C temperature disturbance, the difference in measurements is 5.0484 με or 19.6%.
- In the static measurement with a 45°C temperature disturbance, the difference in measurements is 70.40865 με or 265%.

4. Conclusion

Testing and analysis have been conducted to assess the resolution and threshold of Fiber Bragg Grating (FBG) in measuring low strain on the landing gear of aircraft. Measurement results indicate that the FBG sensor has a resolution of 0.1654 microstrain and a threshold of 50 grams within the load range of 0 to 9 kilograms. A comparison of FBG measurements with strain gauge results showed a difference of 5.9%. Additional disturbances such as 5 m/s and 10 m/s wind disturbances, as well as 30°C and 45°C temperature disturbances, resulted in increased readings of measured strain values. Notably, the 45°C temperature disturbance had the most significant impact on the strain changes detected by FBG, with a strain value increase of 265%.

In future research, it is necessary to conduct performance tests of the FBG by testing its response time to the generated strain changes. This is to further demonstrate the advantages of the FBG sensor compared to conventional strain gauge sensors. Additionally, if possible, strain testing should also be conducted with the FBG installation configuration embedded within the landing gear material. This is to further enhance the monitoring of strain occurring on the landing gear. It is hoped that this research can contribute to the development of optical system technology for comprehensive aircraft structure monitoring, particularly for unmanned aerial vehicles

Acknowledgement

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