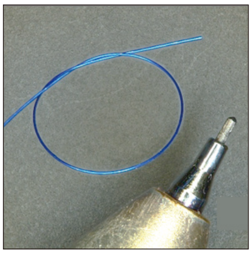

Thin Piezoelectric Wire for Sensing "Filasense"

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This paper reports on a small-diameter piezoelectric sensing wire currently in development as a product capable of physical micro-detection, with anticipated applications in fields such as industrial robotics, medical and nursing care, and automotive. This development focuses on the need to detect small displacements and contact forces that are difficult to detect with conventional image recognition or capacitive sensors. It is a wire-shaped sensor featuring flexibility and the ability to conform to complex deformations. Leveraging our wire manufacturing technology for producing metal-resin composite wires, we have achieved a filament as thin as a sewing thread. This enables easy integration into existing structures like equipment, clothing, and mechanical parts, while delivering higher signal output and faster response times compared to existing products. The effectiveness for tactile sensing and structural health monitoring is currently being recognized, and this progress also facilitates expansion into high-density sensor networks and smart material technologies, which represent anticipated future societal needs.

Keywords: sensing, line sensor, wire, stitch, monitoring

1. Introduction

In recent years, piezoelectric sensors (piezoelectric devices) have attracted attention for their potential applications in the medical and nursing care, robotics, and automotive fields due to their high sensitivity and high durability as well as self-powered voltage generation properties. For example, in the medical and nursing care fields, these sensors have been introduced to ensure continuous monitoring of the posture, body pressure, and movement of patients and elderly persons.[(1)] In the robotics field, they have been used for high-accuracy movement detection and safety monitoring.[(2)] It is required that function of body movement on robotics expand due to applying tactile sensors to robots and devices, and recently consortiums on human augmentation have been established. Thus, this field has attracted significant social attention. In the automotive field, piezoelectric sensors have drawn public interest to monitor the driver status, detect part abnormalities, and upgrade safety devices.[(3),(4)]

Image recognition (combining cameras and AI) and capacitive sensors have been widely used to detect the movement of the human body and machines. However, they have issues such as ambient light, environmental noise, power supply, and power consumption constraints. On the other hand, piezoelectric sensors can be directly installed on target objects to convert slight displacements and pressure changes into electric signals without an external power source. Thus, piezoelectric sensors offer an advantage in realizing weight reduction, low power consumption, high sensitivity and environmental resistance at the same time.[(5)] However, they present a disadvantage in terms of increased sensor cost to achieve multi-point detection in sensing areas.

Therefore, we develop the Filasense, a wire-shaped piezoelectric sensor whose diameter is smaller than that of conventional products, by using our electric wire manufacturing technologies. Traditional piezoelectric sensors have been widely used as contact "point" sensors, however we aimed to use as "line and area" sensors. This paper reports the results of applicability evaluation of this product.

2. Structure and Characteristics of the Filasense

Figure 1 shows the basic structure of a conventional piezoelectric element, which consists of a piezoelectric material sandwiched by two electrodes (one positive electrode and one negative electrode). An electric charge is induced on the material surface by applying a force to the piezoelectric device, resulting in polarization between the electrodes. This makes it possible to convert the mechanical behavior into electric signals (voltage).

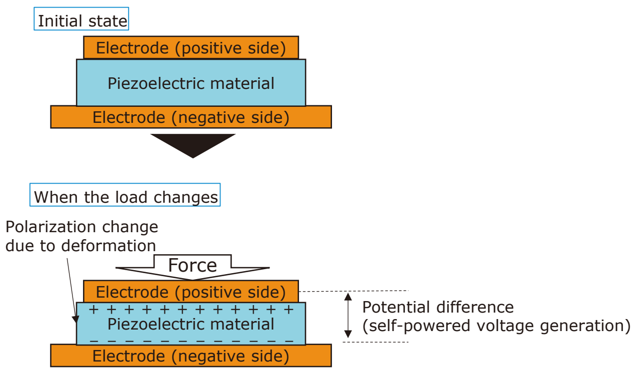

Fig. 1. Basic structure of a piezoelectric device

The product structure of the Filasense is shown in Fig. 2. Polyvinylidene fluoride (PVDF),*1 which is a piezoelectric material, is covered on the inner electrode. This is concentrically surrounded by outer electrode. Thick copper-covered wire (TCC wire),(6) which is our high-tensile strength wire product, is used for the core wire. It was decided to use the TCC wire to ensure easy handling because the high breaking load helps maintain a high tensile load of Filasense even when the sensor diameter is reduced.

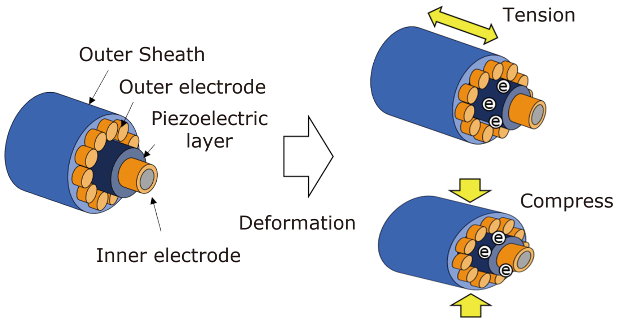

Fig. 2. Product structure of the Filasense

The mechanical properties of the Filasense are described in Table 1. The Filasense was developed with the aim of attaining a wire diameter of φ0.15 mm or less, as much as the standard No. 50 sewing thread, also a breaking load of 4 N or more, by taking into account the use as a sewing thread. A diameter of φ0.13 mm or less, including the insulating sheath, was attained.

We will also evaluate the durability test with repeated bending based on anticipated usage.

Table 1. Mechanical properties of the Filasense

Wire diameter	φ0.13 mm
Breaking load	> 4 N
Breaking elongation	> 2.0%

3. Evaluation of Piezoelectric Properties

Piezoelectric properties of the Filasense are explained in Fig. 3. The wire-shaped piezoelectric device was evaluated using the Piezo Reader LPF-03 manufactured by Lead Techno Co., Ltd. Based on the direct quasi-static method*2 (in conformity with JIS R1696), a compression force was applied from the side of a specimen, and the induced electric charge (d33) was measured using an electric charge detector.

A comparison with a typical ceramic-based piezoelectric sheet and resin-based piezoelectric sheet is presented in Table 2 based on numeric values. The output evaluation showed that the electric charge output of the Filasense is lower than that of these sheets because the volume of the piezoelectric material is small. However, we have confirmed that it is indeed detectable.

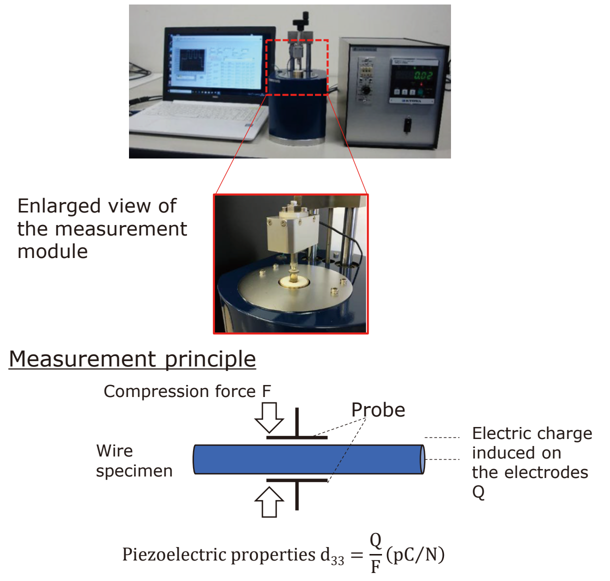

Fig. 3. Equipment for evaluating piezoelectric properties and principles of evaluation

Table 2. Comparison of piezoelectric properties

	Piezoelectric properties
This development product	1–10 pC/N
Resin-based piezoelectric sheet (PVDF)	20–40 pC/N
Ceramic-based piezoelectric sheet (PZT)*3	200–600 pC/N

As one of the responsiveness evaluations, the electric signals generated during impact load detection were measured. A 40 g weight was dropped from a height of 100 mm, and the output voltage of the Filasense was detected using an oscilloscope (Keysight EXR204A). A piezoelectric based commercially available wire (φ2.7 mm) was also evaluated under the same conditions, and the measurement results were compared. The output voltage waveforms are shown in Fig. 4.

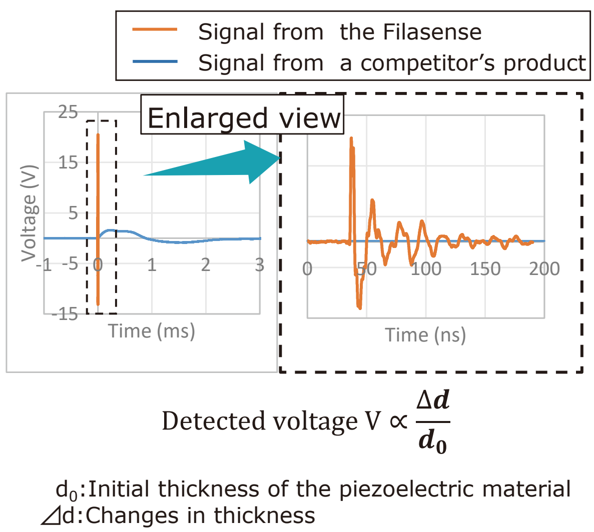

Fig. 4. Output voltage waveform

The piezoelectric layer of the Filasense is thinner than that of the φ2.7 mm sensing wire. Thus, the percentage change in deformation is high under the same load, resulting in high output voltage per unit time and realizing a high S/N ratio. Accordingly, slight pressure changes can be detected with high sensitivity.

4. Application Examples

This section introduces three application examples of sensors using Filasense. These application examples take advantage of the small diameter of the Filasense: (1) fabric with sensor - arrangement on curved surfaces by stitching, (2) wheel with sensor - detection of surface irregularities based on wheel surface deformation, and (3) mesh sensor - multi-point detection based on arrangement in a lattice pattern. A charge amplifier circuit (Fig. 5) was used to cope with short signal cycles.

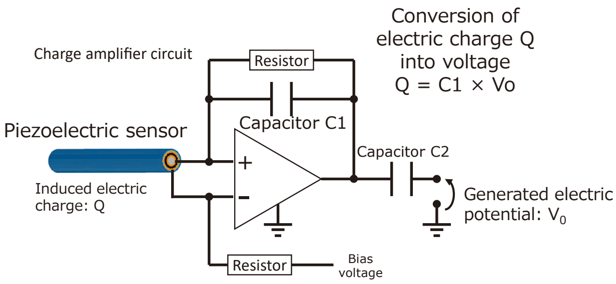

Fig. 5. Charge amplifier circuit

4-1 Fabric with sensor

Given that the Filasense is as thin as typical sewing threads, it is expected to be used for applications similar to those of threads. The Filasense was stitched onto fabric using a commercially available sewing machine. Figure 6 shows examples of stitching onto fabric using the Filasense as the upper thread and a commercially available sewing thread as the bobbin thread. In addition to straight-line stitching, the Filasense can conform to complex stitching patterns programmed into the sewing machine. It can also be used for small curved patterns. Accordingly, installation on various curved surfaces is expected to become easy.

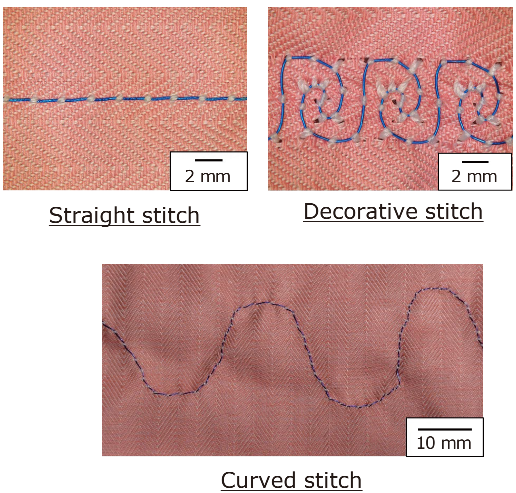

Fig. 6. Fabric with sensor

4-2 Wheel-shaped sensor

In this example, a wheel sensor was used to enable continuous sensing of the surface condition of target objects. The Filasense was installed on the periphery of the wheel. Shown in Fig. 7 is the output signal when the wheel, which was subjected to a load of 240 g, traversed a level difference of 5 mm at a travel speed of 310 to 320 m/sec. The graph shows the sensor output voltage generated when the wheel traversed a level difference.

We expected that this method is applied to inspection devices which detect surface irregularities in the manufacture of long-length products.

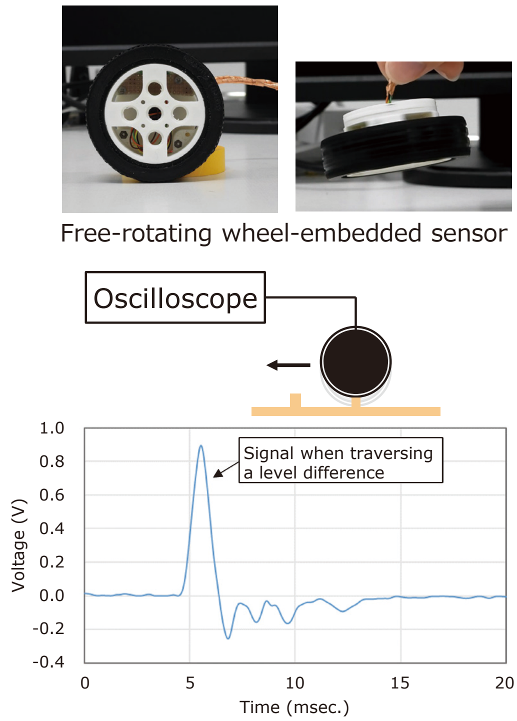

Fig. 7. Wheel embedded sensor detection of surface irregularities by sensor

4-3 Mesh sensor

Figure 8 shows an example in which multiple Filasense wires were installed in a lattice pattern to detect the impact position on the surface. Specifically, the wires were arranged in a lattice pattern (4 × 4) under top lubber sheet on a table tennis racket. When a table tennis ball impacts, the longitudinal and lateral wires which generate signals are identified to detect the impact point. Because the wire diameter is small, the resolution of position information can be enhanced by reducing the grid width and increasing the nodes. This method also offers an advantage in reducing the number of sensor connectors compared to a sensing technique in which piezoelectric device are

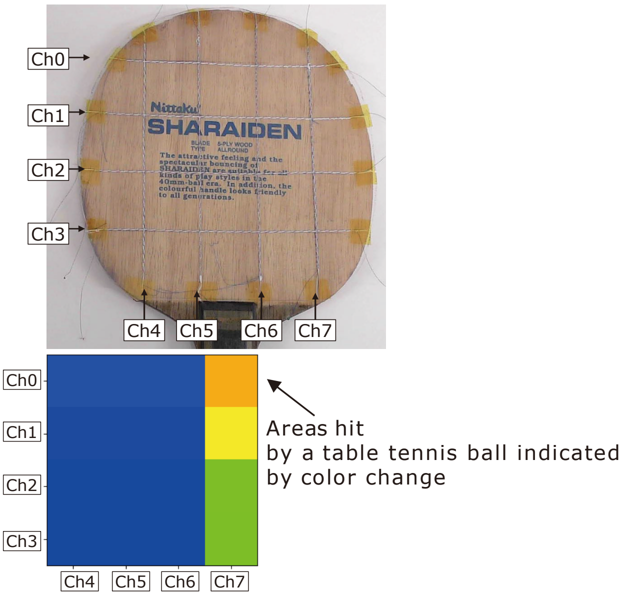

Fig. 8. A racket on which Filasense wires are embedded in a lattice pattern, and an impact point detection example

arranged at all nodes. It is expected to apply to analysis of ball impact position in ball games.

5. Conclusion

This paper has presented the characteristics of the Filasense, a small-diameter piezoelectric sensing wire, and its application examples. Unlike conventional piezoelectric sensors, this product is a small-diameter wire that makes it possible to impart sensing functionality to a wide variety of target objects. Thus, various detection capabilities can be achieved by designing new installation methods.

We will verify applicability, such as adding the detection functionality to electric home appliances, industrial machines, and vehicles, remote control in robotics, patient's condition detection in medical and nursing care, and enabling tactile detection in operation which have relied on human tactile perception, and will study the utilization across various fields.

Technical Terms

*1 PVDF: Abbreviation for "polyvinylidene fluoride." It is a resin with typical piezoelectric functions.

*2 Direct quasi-static method: A technique to evaluate piezoelectric properties as specified in JIS R1696.

*3 PZT: Abbreviation for lead zirconate titanate "$PbZr_xTi_{1-x}O_3$." It is a commonly used piezoelectric ceramic.

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