Soft Angular Displacement Sensor Theory Manual

Introduction

The patented soft angular displacement sensors developed by Bend Labs provide a unique alternative to existing sensor technologies for measuring a highly accurate and drift free angular displacement in a soft form factor while maintaining extremely low power consumption. Product highlights include:

- Sensors are made using layered medical grade silicone elastomers doped with conductive and nonconductive fillers, giving them similar mechanical properties and operating temperatures to other silicone elastomer products.
- Sensors measure angular displacement via a differential capacitance measurement, meaning common mode signals such as temperature fluctuations, strain and noise are rejected, providing a high fidelity measurement of angular displacement.
- Differential capacitance can be measured using extremely low sampling power, with less than 100 uA power consumption at 1.8V. Unlike competing technology, the signal is highly stable over time and does not drift, facilitating high reliability and accuracy.
- Sensor can be customized to include multiple channels and spatially distinct "bending pixels", can have arbitrary dimensions and varied stiffness, can be made inextensible or directly integrated into flex circuitry and can be configured to measure bending orthogonal planes.

Operating Principle

Bend soft angular displacement sensors are made from two compliant capacitors offset from a center axis and running the entire length of the sensor, with a differential capacitance being measured between the two offset capacitors (Fig 1). Because the output is differential, common mode signals such as tensile strain are rejected, thus soft angular displacement sensors can measure an accurate bending angle even if common mode tensile strain is superimposed on top of the bending strain.

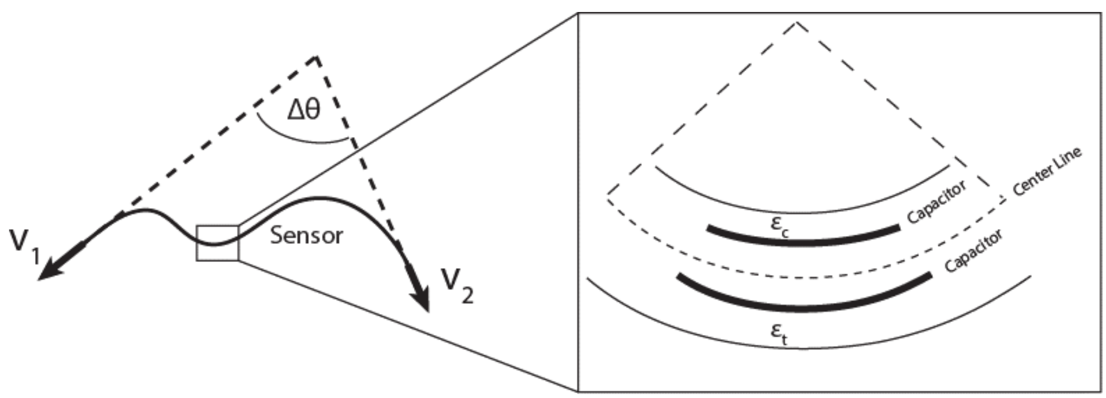

Fig 1, Operating Principle. (Left) The sensor output is the angular displacement (Δθ) as computed from the vectors defined by the ends of the sensor ($\mathbf{v}_1$ and $\mathbf{v}_2$). (Right) A cross sectional view of a bend portion of the sensor shows that there are two compliant capacitors offset from a center axis. The capacitor on the inside of the bend will experience a compressive strain (εc) while the outside will experience a tensile strain (εt). A differential capacitance measurement yields an output linearly proportional to the total angular displacement of the sensor.

Path Independence

Soft angular displacement sensors have a unique property of path independence, whereby extraneous bending has a limited effect on the sensor output (Fig 2). This property arises from the fact that the compliant capacitors run the length of the sensor, thus the total amount of bending is integrated along the length such that extraneous bending paths are cancelled. This also means that the "location of the bend" can occur anywhere along the length of the sensor.

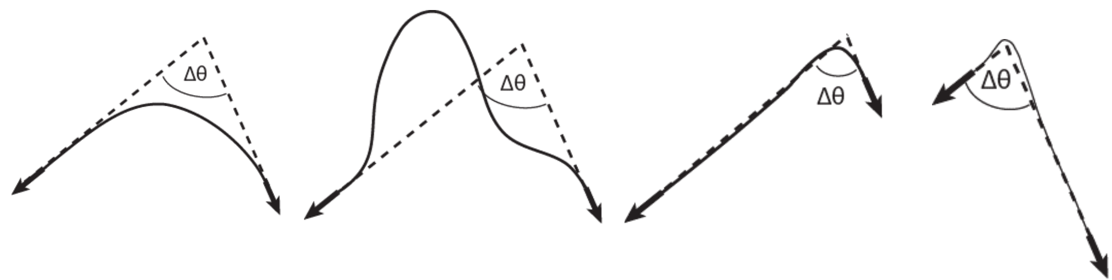

Fig 2, Path independence. The angular displacement of an ideal sensor is independent of the sensor path, thus all four shown sensor paths shown will theoretically yield the same angular displacement.

2-axis sensors and 3D output

The Bend 2-axis soft angular displacement sensor is an extension of our 1-axis sensor technology, whereby two sets of compliant capacitors are offset from a center axis instead of a single set of compliant capacitors (Fig 3, left). In this way, two angles measured in two orthogonal planes can be measured (Fig 3, right).

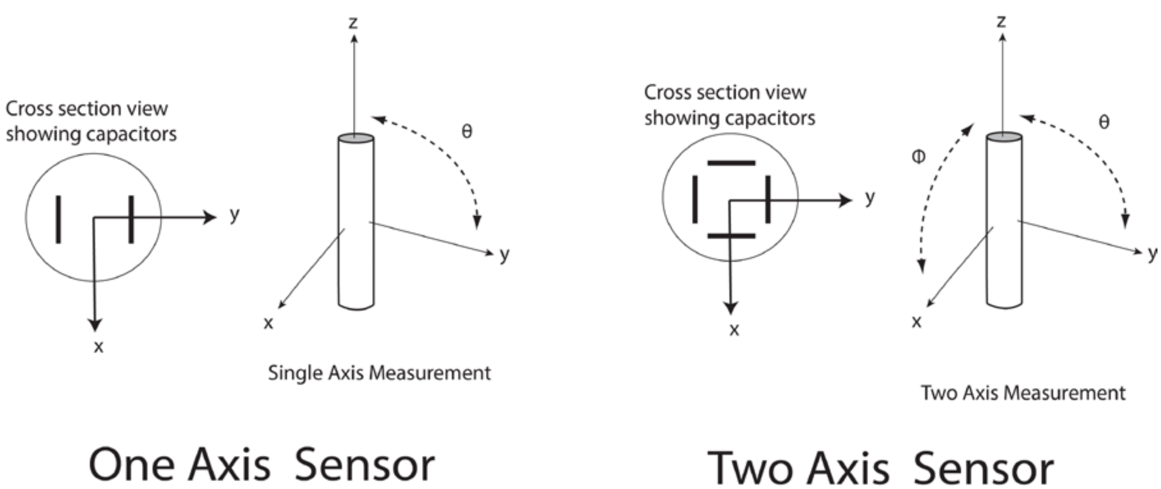

Fig 3, Two Axis Sensors. (Left) A one axis sensor is shown. (Right) By embedding an additional set of compliant capacitors, a two axis sensor can measure two orthogonal axes.

Linearity and Calibration

The sensor output is highly linear and should hold a calibration for the life of the sensors. Example plots of Differential Capacitance vs. Angular displacement are shown in Fig 4.

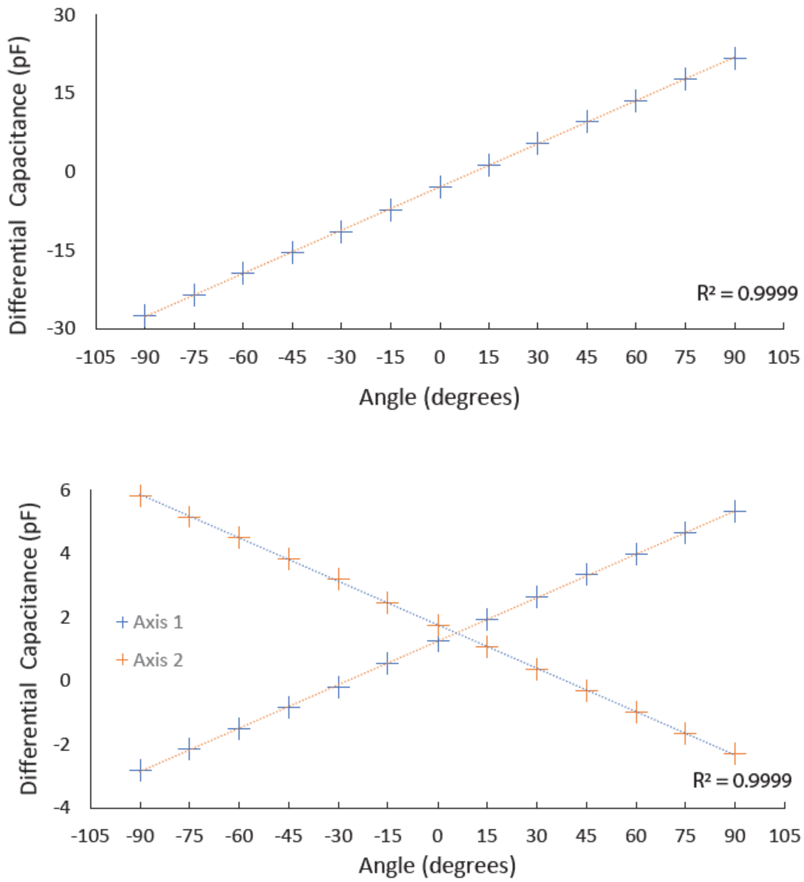

Fig 4, Sensor Linearity. (Top) A plot of differential capacitance vs. angular displacement for a one axis sensor is shown. (Bottom) A plot of differential capacitance vs. angular displacement for a both axes of a two axis sensor is shown.

Differential Capacitance to Digital Conversion

Our proprietary analog front end and embedded controller are directly integrated into the end tab of the sensor and provides a convenient I2C interface along with calibration commands and easy to use API for a clean and reliable signal. Please refer to our getting started guide for additional information.

Application Notes

While soft angular displacement sensors are a powerful and versatile tool, a number of considerations must be taken into account in order to assure proper performance:

- While sensors are soft and elastic and designed for millions of cycles of use, it is important to stay within the ranges of strain and bending outlined in the data sheet for each sensor. In general, it is recommended that stretching of angular displacement sensors does not exceed 75% strain for small durations and should not exceed 30% strain during normal use. The minimum radius of curvature should not drop below 2X the thickness of the sensor for small durations and should not drop below 4X the thickness of the sensor for normal use.

- While strain relief is provided at the electromechanical interface (where the sensor terminates at the PCB), care should be taken not to place excessive loads on this region. Furthermore, the sensor should only be gripped at the sensor end or on the strain relief itself. Never grip the sensor by the PCB or attaching wires, as this may lead to premature failure of the part.
- While ideal sensors should reject 100% of common mode signals and all extraneous bending, manufacturing tolerances are such that this is not always the case. We encourage a final calibration procedure after the sensor is in its final location, which will help eliminate any common mode signals that may arise.
- Sensors are shielded and should have a high tolerance for noise and stray capacitance from touching. However, when connected to a power source obtained from a mainline power connection, capacitive coupling to ground may occur. To avoid such issues, power sensors with a battery. If powering from mainline power, then adequate testing and electrical isolation will be needed.
- Sensors perform best when no twisting along the length of the sensor is present. For best results, prevent twisting of the sensor. In cases where twisting can not be avoided, a new calibration after installation will typically provide good performance.