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Standard Practice for Calibration of Linear Displacement Sensor Systems Used to Measure Micromotion[1]

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1. Scope

1.1 This practice covers the procedures for calibration of linear displacement sensors and their corresponding power supply, signal conditioner, and data acquisition systems (linear displacement sensor systems) for use in measuring micromotion. It covers any sensor used to measure displacement that gives an electrical voltage output that is linearly proportional to displacement. This includes, but is not limited to, linear variable differential transformers (LVDTs) and differential variable reluctance transducers (DVRTs).

1.2 This calibration procedure is used to determine the relationship between output of the linear displacement sensor system and displacement. This relationship is used to convert readings from the linear displacement sensor system into engineering units.

1.3 This calibration procedure is also used to determine the error of the linear displacement sensor system over the range of its use.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Terminology

2.1 *Definitions:*

2.1.1 *calibrated range, n*—distance over which the linear displacement sensor system is calibrated.

2.1.2 *calibration certificate, n*—certification that the sensor meets indicated specifications for its particular grade or model and whose accuracy is traceable to the National Institute of Standards and Technology or another international standard.

2.1.3 *core, n*—central rod that moves in and out of the sensor.

NOTE 1—It is preferable that the sensors prevent the core from exiting the sensor housing.

2.1.4 *data acquisition system, n*—system generally consisting of a terminal block, data acquisition card, and computer that acquire electrical signals and allows them to be captured by a computer.

2.1.5 *differential variable reluctance transducer (DVRT), n*—a linear displacement sensor made of a sensor housing and a core. The sensor housing contains a primary coil and a secondary coil. Core position is detected by measuring the coils' differential reluctance.

2.1.6 *linear displacement sensor, n*—an electrical sensor that converts linear displacement to electrical output.

2.1.7 *linear displacement sensor system, n*—a system consisting of a linear displacement sensor, power supply, signal conditioner, and data acquisition system.

2.1.8 *linear variable differential transformer (LVDT), n*—a linear displacement sensor made of a sensor housing and a core. The sensor housing contains a primary coil and two secondary coils. When an ac excitation signal is applied to the primary coil, voltages are induced in the secondary coils. The magnetic core provides the magnetic flux path linking the primary and secondary coils. Since the two voltages are of opposite polarity, the secondary coils are connected in series opposing in the center, or null position. When the core is displaced from the null position, an electromagnetic imbalance occurs. This imbalance generates a differential ac output voltage across the secondary coils, which is linearly proportional to the direction and magnitude of the displacement. When the core is moved from the null position, the induced voltage in the secondary coil, toward which the core is moved, increases while the induced voltage in the opposite secondary coil decreases.

2.1.9 *null position, n*—the core position within the sensor housing where the sensor voltage output is zero (some sensors do not have a null position).

2.1.10 *offset correction, n*—removal of any offset in a sensor's output so that at zero displacement, zero voltage is recorded.

[1] This practice is under the jurisdiction of ASTM Committee F04 on Medical and Surgical Materials and Devices and is the direct responsibility of Subcommittee F04.15 on Material Test Methods.

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2.1.11 *percent error, n*—the difference between a measurement of a reference standard and the actual length of the reference standard divided by the actual length of the reference standard and the result converted to a percent.

2.1.12 *power supply, n*—a regulated voltage source with output equal to that required by the sensor for proper operation.

2.1.13 *sensor housing, n*—central hole in a linear displacement sensor that senses movement of the core within it.

2.1.14 *signal conditioner, n*—electronic equipment that acts to convert the raw electrical output from the linear displacement sensor into a more useful signal by amplification and filtering.

3. Summary of Practice

3.1 A linear displacement sensor is mounted in a calibration fixture such that it can be subjected to a precise, known displacement.

3.2 Displacement is applied in steps over the full range of the linear displacement sensor and electrical readings (for example, voltages) are collected using the linear displacement sensor system.

3.3 Each voltage reading is taken as the average of 100 readings over 0.1 s, decreasing the error of the reading. The error in the readings is recorded as the standard deviation in the readings. This error should be constant and independent of displacement. It should be noted that the error in the readings is a summation of errors in each of the linear displacement sensor system components.

3.4 The calibration factor (S) is calculated as the slope of the voltage versus displacement curve using linear regression.

3.5 Linearity of the sensor is assessed.

3.6 The percent error is determined for each calibration point collected. This percent error is evaluated together with the tolerance of the micrometer head calibration.

4. Significance and Use

4.1 Linear displacement sensor systems play an important role in orthopedic applications to measure micromotion during simulated use of joint prostheses.

4.2 Linear displacement sensor systems must be calibrated for use in the laboratory to ensure reliable conversions of the system's electrical output to engineering units.

4.3 Linear displacement sensor systems should be calibrated before initial use, at least annually thereafter, after any change in the electronic configuration that employs the sensor, after any significant change in test conditions using the sensor that differ from conditions during the last calibration, and after any physical action on the sensor that might affect its response.

4.4 Verification of sensor performance in accordance with calibration should be performed on a per use basis both before and after testing. Such verification can be done with a less accurate standard than that used for calibration, and may be done with only a few points.

4.5 Linear displacement sensor systems generally have a working range within which voltage output is linearly proportional to displacement of the sensor. This procedure is applicable to the linear range of the sensor. Recommended practice is to use the linear displacement sensor system only within its linear working range.

5. Apparatus and Equipment

5.1 *Linear Displacement Sensor.*

5.2 *Power Supply,* with output equal to that required by the sensor.

5.3 *Signal Conditioner, Data Acquisition System, and Related Cables and Fittings.*

5.4 *Test Method—Micrometer Fixture Calibration:*

5.4.1 *Calibration Fixture,* a fixture that provides a means for fixing both a micrometer head and the linear displacement sensor along a parallel displacement axis, and is capable of applying displacement to the linear displacement sensor throughout its linear range. The alignment tolerance of the calibration fixture must be measured.

5.4.2 *Micrometer Head,* a precision instrument with known error (that is, tolerance). The spindle of the micrometer must be non-rotating and spring-loaded. The micrometer head shall be calibrated annually by the manufacturer or other qualified personnel.

6. Hazards

6.1 *Safety Hazards:*

6.1.1 This practice involves electrical equipment. Verify that all electrical wiring is connected properly and that the power supply and signal conditioner are grounded properly to prevent electrical shock to the operator. Take necessary precautions to avoid exposure to power signals.

6.2 *Safety Precautions:*

6.2.1 Examine the sensor housing for burrs or sharp edges, or both. Remove any protrusions that might cause harm.

6.2.2 The sensor can be permanently damaged if incorrectly handled. Consult the manufacturer's guidelines for handling.

6.2.3 The sensor can be permanently damaged if incorrectly connected to the power supply, or if connected to a power supply with the wrong excitation level. Consult the manufacturer's guidelines for use.

6.2.4 Follow all manufacturer's recommendations with regard to safety.

6.3 *Technical Precautions:*

6.3.1 If using a linear displacement sensor that permits the core to leave the sensor housing, do not interchange cores with other linear displacement sensor housings.

6.3.2 Replace the sensor if it, or any component of it, shows any signs of dents, bending, or other defects that may affect its performance.

6.3.3 Store all system components in dry, protective locations when not in use.

6.3.4 Do not exceed the allowable input voltage of the sensor as specified by the manufacturer.

6.3.5 Do not connect a voltage source to the output leads of the sensor.

6.3.6 Do not over-tighten the sensor within the calibration fixture.

6.3.7 The behavior of some sensors may be affected by metallic holders; this must be considered during use of the sensor.

7. Calibration and Standardization

7.1 Verify that the calibration fixture, micrometer, power supply, signal conditioner, and data acquisition system are all in good working order, and of sufficient precision and bias.

7.2 Verify that all components have been individually calibrated and are within their respective calibration cycles.

8. Procedure

8.1 Perform the calibration in an environment as close to that in which the sensor will be used as possible. All necessary equipment should be in the environment in which they are to be used for calibration for at least 1 h prior to calibration to stabilize temperature effects. Ambient temperature should be quantified and recorded. Ambient temperature during the calibration procedure should be maintained within ±2°C of the initial temperature.

8.2 Verify that the power supply is adjusted to supply the recommended voltage to the sensor.

8.3 With equipment turned off, connect all power supply, signal conditioning, and data acquisition equipment exactly as it will be used in service. Follow the manufacturer's suggested order of connecting equipment, if prescribed. Allow all electronics to warm up for at least 15 min before beginning calibration.

8.4 Verify that the sensor is working properly by changing its displacement position and watching the signal change accordingly on the chart.

8.5 Note the model number and serial number of the linear displacement sensor to be calibrated.

8.6 Note the calibration protocol to be followed.

8.7 Confirm that the micrometer head, data acquisition system, linear displacement sensor, and signal conditioner have been calibrated and are within their calibration cycles.

8.8 If any calibration is not up to date, have the proper calibration performed before calibrating the sensor within the current system.

8.9 Note the tolerance of the micrometer head calibration.

8.10 Record the name of the calibrator, date of calibration, all equipment used (model and serial numbers, if possible), calibration units, input voltage supplied, and input limits and resolution of the data acquisition system.

8.11 *Test Method—Micrometer Fixture Calibration:*

8.11.1 Secure the sensor into the mounting fixture.

8.11.2 Secure the mounting fixture into the calibration fixture.

8.11.3 Secure the micrometer head into the calibration fixture.

8.11.4 Define the zero position of the sensor. This is the position of the first calibration point and it is located at one end of the linear range of motion of the sensor. This position is found by positioning the sensor at its null position (where the voltage output of the sensor is zero) and then rotating the micrometer head in one direction until the sensor has traveled to the end of its rated linear range in that direction (that is, a distance of ½ of its total rated linear range).

8.11.5 Record the sensor system readout as Sensor Reading 1 in a table corresponding to zero displacement. Also include the error in the position reading (that is, the tolerance of the micrometer head and the combined largest error associated with the quantified misalignment of sensor and micrometer head).

8.11.6 Sample the voltage data from the sensor at a fast sampling rate for a finite time. (See Note 2.) Record the average and standard deviation of the sample in the table. It is recommended that a software program be written or used to efficiently perform these tasks.

NOTE 2—At least 1000 Hz for 0.1 s is recommended.

8.11.7 Move the micrometer to a predetermined displacement from the zero position. Move the micrometer in *only* one direction, as there may be significant backlash in the micrometer that will result in unquantified errors in displacement measurements.

8.11.8 Repeat steps 8.11.5 and 8.11.6 for the new position.

8.11.9 Repeat steps 8.11.7 and 8.11.8 for uniform intervals throughout the linear range of the sensor. At least 10 calibration points should be included.

8.11.10 Rotate the micrometer head in reverse order and record readings in the table throughout the linear range of the sensor.

8.11.11 To obtain reproducibility data, repeat these steps for a minimum of two times using the same calibration positions.

8.11.12 Calculate the calibration factor, linearity, error bounds of each data point, displacement error, and percent error as described in Section 9.

9. Calculations

9.1 *Calibration Factor*—The calibration factor (S) is calculated as the slope of the voltage versus displacement curve using linear regression.

9.2 *Linearity*—Linearity of the sensor can be assessed by calculating the coefficient of determination (R^2) of a line fit through the data points using linear regression.

9.3 *Percent Error*—The percent error is calculated for each point collected. First, the difference between the displacement value of the point calculated from the calibration equation and the actual measurement of the displacement at the point collected is calculated. The percent error of each point is 100× the resulting difference/the calibrated range.

10. Acceptability Criteria

10.1 In order for the sensor to be used, it must be calibrated within the following criteria:

10.1.1 The R^2 value must be greater than 0.95.

10.1.2 The standard deviation of the voltage measurement of any given calibration point must not be greater than 0.010 V/V full scale.

10.1.3 The percent errors at each calibration point calculated in 9.3 must be evaluated together with the tolerance of the micrometer head calibration used as the reference standard, against the error requirements for the specific application of the measurement system and be deemed acceptable.

11. Calibration Certificate

11.1 The calibration certificate should include the following:

11.1.1 Type of sensor being calibrated (linear displacement sensor).

11.1.2 Make of the sensor.

11.1.3 Model of the sensor.

11.1.4 Serial number of the sensor.

11.1.5 Date of calibration.

11.1.6 Name of calibrator.

11.1.7 Voltage excitation if applicable.

11.1.8 Input limits and resolution of data acquisition system used.

11.1.9 Acceptability criteria.

11.1.10 PASS/FAIL.

11.1.11 List of all equipment used in the calibration (make, model, serial number, calibration status).

11.1.12 Reference to the calibration protocol followed.

11.1.13 Calibration data (data points and error bounds, average and standard deviation for voltage measurements).

11.1.14 Plot of the calibration data.

11.1.15 Calibration equation and R^2 value.

11.1.16 Ambient temperature as recorded per 8.1.

11.1.17 Tolerance of the micrometer head calibration.

12. Keywords

12.1 calibration; displacement; instrumentation; measurement; micromotion; sensor; transducer

APPENDIX

(Nonmandatory Information)

X1. RATIONALE

X1.1 Calibration of linear displacement sensor systems is a critical practice that should always be performed prior to use of such a system for measurement of displacement. This step is even more critical when the value of the displacement to be measured is on the micron scale.

X1.2 This practice provides a guideline for ensuring proper calibration of such a system. This practice will ensure that product performance dependent on micromotion between orthopedic components and other medical devices will be properly evaluated.