

Capacitive Sensors in Printed Photopolymer Structures: Dielectric State, Electrode Geometry, Humidity and Calibration

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Abstract

Capacitive sensors made with printed photopolymer structures convert geometry and dielectric state into an electrical signal. Their apparent sensitivity is therefore inseparable from electrode dimensions, dielectric thickness and architecture, polymer permittivity, moisture uptake, temperature, viscoelastic deformation and the readout frequency. This review defines a qualification framework for capacitive sensors in which capacitance is treated as a state-dependent measurand rather than a fixed material property. It distinguishes geometry-driven and permittivity-driven response, explains why humidity and temperature can shift both baseline and sensitivity, and requires calibration across the declared environmental and mechanical envelope. A non-compensatory matrix links dimensional verification, dielectric characterization, electrode stability, environmental cross-sensitivity, hysteresis, drift and cyclic repeatability. The central conclusion is that calibration is valid only for the specific printed architecture and conditioned dielectric state from which it was derived.

Keywords: capacitive sensors; photopolymers; dielectric constant; electrode geometry; humidity; temperature; calibration; drift; pressure sensing; additive manufacturing

1. Significance and scope

Additive manufacturing enables capacitive sensors in which dielectric microstructure, electrode spacing and mechanical compliance are designed together. Photocurable printing can generate complex dielectric architectures that are difficult to manufacture by conventional molding, but the electrical response remains governed by ordinary electrostatics and by the time-dependent state of the polymer. This review owns capacitive sensing in printed photopolymer structures. It does not own conductive-network reliability except where electrodes interface with the capacitor, nor does it define a universal humidity, pressure or strain sensor calibration. Published photocurable and additively manufactured capacitive sensors demonstrate that measured response couples dielectric formulation, electrode architecture and mechanical deformation [1-5].

1.1 Ownership boundary

ER-262 owns capacitive-sensor qualification across dielectric state, electrode geometry, humidity and temperature cross-sensitivity, calibration and calibration transfer. ER-158 retains the broader dielectric, ferroelectric, piezoelectric and magnetic-material qualification space, including field response and device qualification; ER-21 retains electrical-insulation and dielectric-property characterization; ER-72 retains environmental conditioning and moisture-related material response; ER-157 retains electrically functional nano/micron composites; WP-27 retains the wider conductive/electronics resin application space. ER-261 owns resistive/conductive elements, and ER-263 owns dielectric breakdown and insulation ageing. ER-262 therefore treats capacitance as a calibrated measurand of a specific dielectric-and-geometry state, not as a generic dielectric-material review.

2. Capacitance contains both geometry and dielectric state

For an ideal parallel-plate capacitor, capacitance scales with electrode area and relative permittivity and inversely with dielectric spacing. Printed sensors often depart from that ideal through fringing fields, interdigitated electrodes, pores, arches, lattices and nonuniform deformation. Consequently, a calibration curve is specific to the actual electrode geometry and printed dielectric architecture. A change in layer thickness, cure shrinkage, void fraction or electrode overlap can move both baseline capacitance and sensitivity even when resin chemistry is nominally unchanged. Photocurable piezocapacitive work and architected dielectric sensors show that both material permittivity and deformation-driven geometry contribute to the measured signal [1,3,4].

3. Dielectric state depends on cure and frequency

The relative permittivity of a photopolymer composite reflects polymer network structure, fillers, residual monomer, porosity and absorbed species. Dielectric response is frequency-dependent because dipolar and interfacial polarization processes have finite relaxation times. Photocurable composites modified with conductive or polar fillers can show large permittivity changes, but those same fillers can alter cure depth and dispersion. Therefore the measurement frequency, voltage amplitude and conditioning state must accompany every dielectric constant or capacitance value used for design or calibration. SLA-resin dielectric studies likewise show that dielectric behaviour must be attached to material state and measurement conditions rather than assumed from resin identity alone [5].

4. Electrode geometry and structural amplification

Sensor sensitivity can be changed by geometry without changing material chemistry. Recent photopolymer-based pressure sensors use arches, air gaps or interwoven hollow structures to increase compliance and hence capacitance change under load. Such architectural amplification is valuable, but it also makes dimensional tolerance and mechanical fatigue part of the calibration. A 3D-printed microstructure that is thinner, denser or more compliant than intended can mimic a material-permittivity change. Dimensional metrology should therefore accompany electrical calibration.

5. Humidity and temperature cross-sensitivity

Many polymer dielectrics absorb water, and water has a high dielectric response relative to dry polymer. Moisture uptake can therefore raise baseline capacitance and can plasticize the network, changing mechanical compliance at the same time. Temperature can change permittivity, thermal dimensions, viscoelastic modulus and moisture equilibrium. Humidity and temperature should be treated as coupled

state variables rather than nuisance metadata. A pressure or strain sensor calibrated at one laboratory condition is not automatically valid over another humidity-temperature envelope. Capacitive humidity-sensor literature demonstrates that moisture can be an intended measurand in one architecture and an interfering variable in another [6].

6. Calibration, hysteresis and time dependence

Calibration should include loading and unloading, dwell time and repeat cycles because photopolymer dielectrics can be viscoelastic. Sensitivity derived from a single monotonic loading curve can hide hysteresis, creep and incomplete recovery. Baseline drift should be measured independently from applied stimulus by holding the sensor at defined zero-load conditions over time. If the intended sensor is dynamic, response and recovery times belong to the specification. If it is quasi-static, creep and dwell dependence are more important than a fast transient response. Published pressure-sensor demonstrations report sensitivity only together with particular materials, structures and test ranges, so calibration must remain device-specific [1,3,4].

7. Non-compensatory qualification matrix

No single high sensitivity value should compensate for excessive humidity dependence, hysteresis or dimensional instability.

Gate	Required evidence	Failure meaning
G1 Geometry	Electrode overlap/spacing and dielectric dimensions measured	Calibration tied to unknown geometry
G2 Dielectric state	Permittivity/capacitance at defined frequency and conditioning	Baseline not physically anchored
G3 Calibration	Stimulus-response curve with uncertainty and range	Sensitivity claim unsupported
G4 Cross-sensitivity	Humidity and temperature effects bounded	Environmental state confounds measurand
G5 Hysteresis/drift	Load-unload, dwell, zero-drift and recovery	Calibration unstable in time
G6 Cycling	Repeated mechanical/electrical cycles within acceptance	Reliability not demonstrated

8. Minimum reporting set

Report printer and process, resin and filler identity at the controlled level, build orientation, post-cure, dielectric dimensions, electrode material and geometry, surface preparation, wiring and shielding, capacitance instrument or circuit, excitation frequency and amplitude, temperature, relative humidity, preconditioning time, stimulus range, loading rate, dwell, number of cycles, number of independent specimens, sensitivity definition, regression range, hysteresis method, zero drift, response/recovery time where relevant, dimensional uncertainty and calibration acceptance limits.

9. Calibration transfer and change control

Calibration transfer requires evidence that the variables governing capacitance remain equivalent. Changes in resin lot, filler dispersion, exposure, post-cure, dielectric architecture, electrode spacing, coating thickness, adhesive, humidity conditioning or readout frequency can invalidate the previous curve. A geometrically scaled sensor should not inherit calibration simply because its topology is similar. Transfer can be supported by a bounded equivalence study that verifies geometry, dielectric state and response across the intended range.

10. Design of experiments for cross-effects

When humidity, temperature and mechanical stimulus can interact, one-factor-at-a-time testing can miss coupled effects. A compact factorial or response-surface design can estimate whether humidity changes only baseline capacitance or also alters mechanical sensitivity. The same logic applies to frequency and temperature. Replicates should include independently printed devices so manufacturing variation is represented. Calibration residuals should be inspected across the domain rather than reduced to a single coefficient of determination. The need follows directly from the coexistence of geometry-, dielectric- and humidity-sensitive mechanisms demonstrated across the cited device classes [1,3-6].

11. Knowledge boundary and limitations

Published demonstrations show that photopolymer structures can function as capacitive pressure or strain sensors and that structural design can strongly increase sensitivity. They do not establish one universal dielectric constant, humidity coefficient, linear range, minimum detectable pressure or cycle life for photopolymers as a class. Reported performance is tied to specific materials, architectures, electrodes and readout methods. Breakdown, long-term insulation ageing and high-field failure remain outside this review. The evidence base covers different materials, frequencies, structures and stimuli [1-6], precluding transfer of a single dielectric or sensitivity value across devices.

12. Conclusions

A printed capacitive sensor is a calibrated state-dependent structure. Capacitance combines dielectric properties, electrode geometry and mechanical configuration, all of which can change with cure, humidity, temperature and time. Reliable qualification therefore requires dimensional metrology, dielectric characterization at the actual readout conditions, environmental cross-sensitivity testing, hysteresis and drift analysis, and cyclic verification. Sensitivity alone is not a sufficient qualification criterion; the calibration must remain valid across the declared operating envelope.

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