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Self-test and calibration methods for micro electro-mechanical systems

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ABSTRACT

For the testing of micro electro-mechanical systems, we propose a taxonomy of built-in self-testing methods. These solutions that are non-intrusive, cost-effective and are typically non-intrusive during the testing process are being actively sought after as the cost of micro-electro-mechanical systems (MEMS) testing can account for 50% of the total cost of the end product. The selection of testing methods is analyzed extensively, and a classification table for such methods is presented according to three performance metrics: ease of application, test application, usefulness. Performance table also provides a field test domain for the method. While built-in-self-test (BIST) methods do depend on the application at hand, utilizing the inherent multimodal sensing capability of most sensors could be a promising approach for effective built-in self-test.

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1. INTRODUCTION

The crucial micro-electro-mechanical system (MEMS) frameworks risen in a long term of 1970s [1], [2] and charmed in making them has created ever since. Not in any respect like in un ordinary integrated circuits (ICs), MEMS make use of facts and texture from diverse areas of imperativeness (electrical, mechanical, warm, optical, and normal), making checking out in common, and integrated built-in self-test (BIST) for MEMS, plenty extra complex than for ICs [3]-[6]. Other than, the reasons and modes of dissatisfactions are plenty extra specific and moved, rendering on-line and offline checking out complex [7]-[11].

In contrast to IC trying out, MEMS trying out is on this manner greater exorbitant for the most part, talking to, in multiple cases, as much as 50% of the fetched of the realization product [9], [12]-[14]; integrated self-test (BIST) strategies can provide assist adjusted those cost-furnished publications of motion. All these are publicized to check over numerous areas of imperativeness and meddle [15]-[17]. Be that as it may, because of the prolonged complexity in comparison to ICs, BIST for MEMS as it have been risen in 1989 [18]-[22].

BIST permits a digital machine to be cautious of its declare condition [23]-[27]. This technique discovered ubiquitously in embedded structures licenses the extraction of parameters amplifying from an unmarried machine pass/fail statistic to a complete set of parametric statistics in regards to the prosperity of every of the machine components [28]-[33]. This article gives a genuine evaluation and type of BIST strategies for MEMS. A coordinate complete of composing is open on BIST strategies for MEMS, with all articles showing publications of motion precise to the MEMS considered [32]-[36]. A type of distinct strategies for MEMS are classified in the Figure 1 under which is in a position be visible on this paper [37].

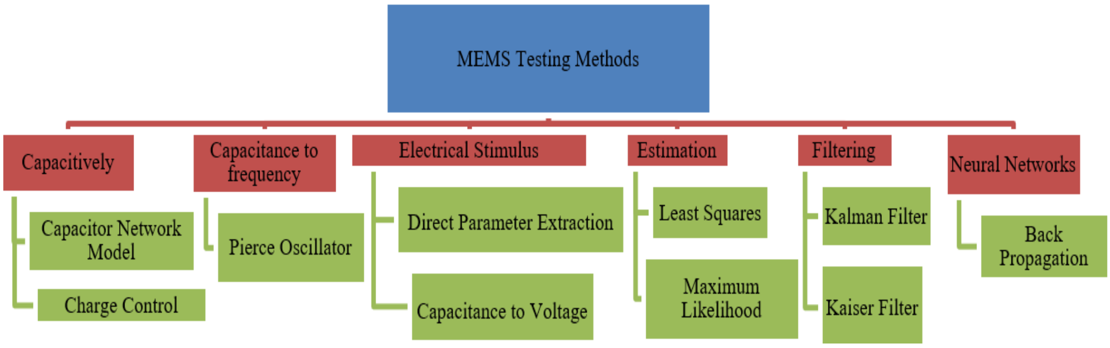


Figure 1. Classification of various MEMS testing methods

2. MEMS TESTING METHODS

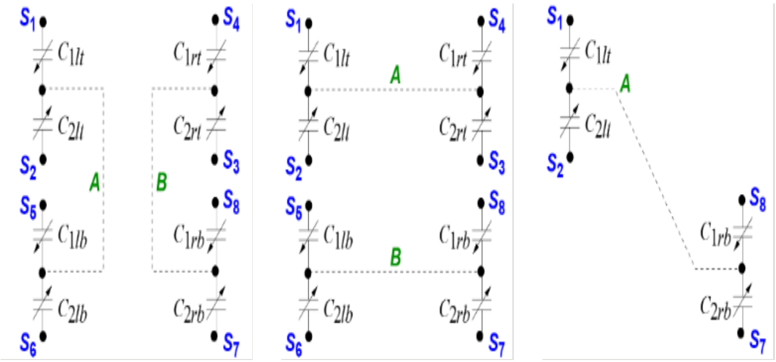
The various MEMS self-testing methods of shown are in Figure 1. All these will be explained as shown in the subsections. Each one will be described separately.

2.1. Capacitive test

The idea of this test is derived from detect the change in the capacitance. A capacitive accelerometer is actuated by electrostatic power as part of this trying out method during the duration of an electrostatic force. It makes use of electrostatic oblige to keep a strategic distance from the transferring mass [38].

2.2. Capacitor network model

A combdrive is electrically talked to as a coordinate of capacitors associated in path of action. This accelerometer sensor is strained in Figure 2(a) [38]. A key aspect of the experience operation is the totally differential spotting method which taps the experience combdrive capacitor as the source of the experience signal. The sensor has 4 unclear, symmetrically determined experience combdrives. The circuit arrange constituted with the aid of using the capacitors within the 4 experience combdrives is confirmed up in determine 3. The characters l, r, b, and t exhibit cleared out, right, foot and best, independently in Figure 2(b). The characters 1 and 2 exhibit the 2 capacitors of a differential integrate indoors a combdrive Figure 2(c). For deliver improvement in $+Y$ path, all capacitors with a subscript 1 lower whilst all capacitors with a subscript 2 increase.



(a) (b) (c)

Figure 2. Sensor topology for accelerometers: (a) in terms of the differential figuring out approach with vertical set of experience combdrive capacitors; (b) set of experience combdrive capacitors diagonal; and (c) in the modulation node group, S1 and S8 have sensing and modulatory functions, respectively [38]

2.3. Charge control

Through DC modern-day assessment, the proposed strategy for assessing a capacitive MEMS device is completed, In order to evaluate how the MEMS shape responds to increased voltage, the MEMS shape is strengthened over its entire operating range [34], [39]. The unraveled rectangular chart of the BIST set up is seemed up in Figure 3 shown. An evaluation of the response is performed by a comparator and a time-to-digital converter (TDC) [40], [41]. Using the fee pump, fee-management checks can be performed on capacitive MEMS. Checks are carried out in tiers to cover the nonlinearity effects on estimation circuitry.

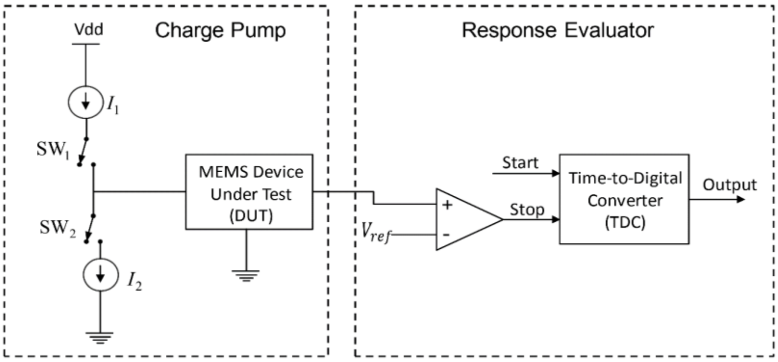


Figure 3. The block diagram of the BIST architecture in simplified form [40]

2.4. Capacitance to frequency

2.4.1. Pierce oscillator

Figure 4 appears the square chart of the proposed check setup this BIST strategy, utilized for capacitive MEMS, works with inside the recurrence locale in inclination to the time locale [39]. The auxiliary abandons causing exceptionally little capacitance deviations are claimed to be much less complex to discover out with inside the recurrence locale than with inside the time locale, particularly for thunderous structures checked closed to their thunderous frequency. Resistor inductor capacitor (RLC) tanks are used to ensure operation at the favored recurrence and provide an uncommon strength against open air disturbances. As illustrated in Figure 4, the MEMS device is connected to the oscillator by a capacitor, C1. This capacitor serves as a reference, and it's taken a toll is around to be indistinguishable to the MEMS tool's ostensible capacitance. Figure 5 may be a schematic outline of an unmistakable sort of instrument. In the modulation node group, S1 and S8 have sensing and modulatory functions, respectively [38].

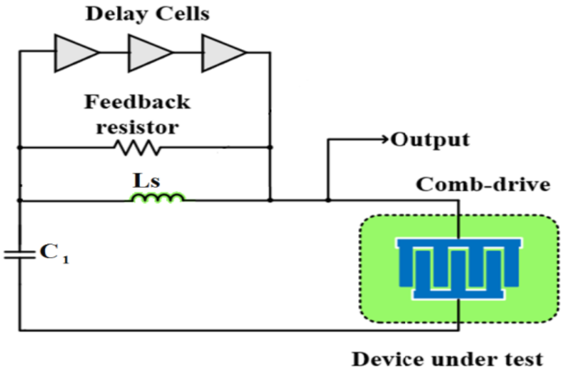


Figure 4. Chart of the proposed check setup [39]

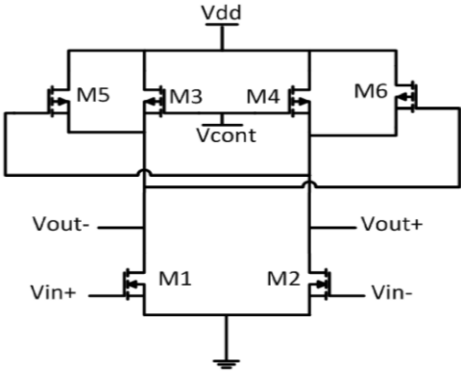


Figure 5. PMOS transistors M3 and M4 are used as variable resistor as delay control [39]

2.5. Electrical stimulus

This takes a look at technique makes use of an electrical sign to generate a bodily sign in the MEMS, together with an electrostatic force. This bodily sign is applied to cause responses from the MEMS crucial practical sub-structures. If the reaction may be translated lower back to an electrical sign, a success BIST method might rent this bodily sign to simulate the bodily forces appearing at the tool below take a look at device under test (DUT) below regular running conditions, or to extract statistics approximately the DUT's health [31].

2.6. Direct parameter extraction

Mechanical parameters (mass, damping coefficients, spring constants) closely follow electrical parameters derived from MEMS yield response estimations. To result in an oscillating movement at the capacitor plates, an excessive-frequency pulse turned into applied [40], [42]. An excessive frequency sign and capacitance detecting circuitry primarily based totally on op-amps had been applied to degree the capacitance variant brought about with the aid of using the oscillating movement. Mechanical traits of hobby are anticipated with much less than 5% mistakes from the capacitance facts the use of multivariate adaptive regression splines, which can be seen in Figure 6 [42].

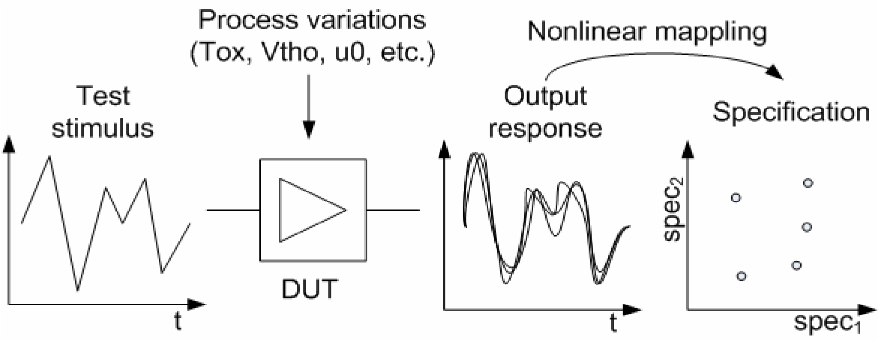


Figure 6. Reaction translated lower back to an electrical sign using response mapping [42]

2.7. Capacitance to voltage

An electric sub-gadget is hired on this approach to stimulate the MEMS and get the device's analog output voltage. The mechanical calibration coefficient can be transferred to the device's output voltage. This answer applied current readout circuitry whilst introducing much less complexity. As demonstrated in the Figure 7 [20], the circuit comprises of a digital to analog converter (DAC) to electrically fortify the MEMS gadget, a capacitive to voltage (C2V) converter, and a sigma-delta analog to digital converter (A/D) converter to convert the yield to a virtual signal.

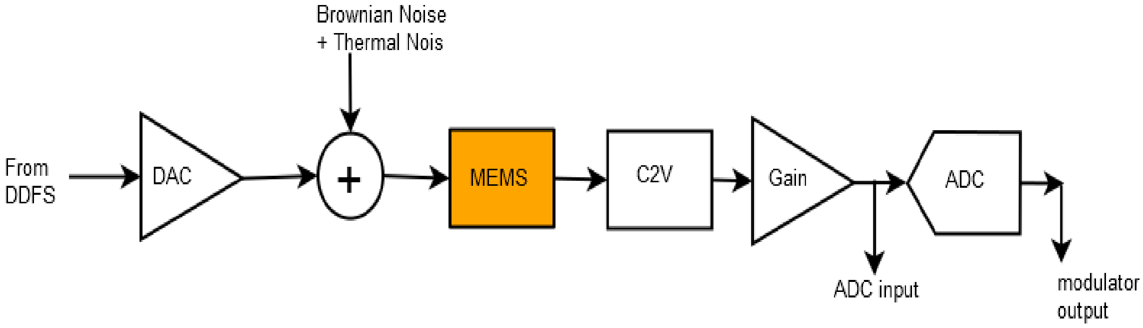


Figure 7. The proposed method (DAC) included to generate the excitation signal for (MEMS) [20]

The DAC output is applied to excite the MEMS tool, and it gives a stair-stepped signal. The plates of the MEMS tool are related to a C2V converter, and the output is digitized via way of means of an A/D converter earlier than being stored in a field programmable gate array (FPGA). The MEMS tool's excitation frequency is swept from 1 to six kHz with a 500 Hz for each step, then the output of every frequency step will be stored in the FPGA.

2.8. Estimation

The new release method is used to decide the calibration parameters, that's extra green and correct. For this reason, numerous estimating strategies were discovered, which includes the least rectangular, most probability, and least rectangular estimation approaches. There is a substantial distinction among them, for the reason that the anticipated MEMS parameters will were derived with various tiers of accuracy. This will be demonstrated in the subsuctions.

2.8.1. Least squares

The calibration scheme and the calibration set of rules are components of the calibration process. The mistakes model, sensor-to-sensor non-orthogonality mistakes, scale factor, and bias [43], is to start with defined on this section. These mistakes incorporate the package deal misalignment.

2.8.2. Maximum likelihood

Using the leading likelihood estimation approach, we show how to calibrate a MEMS triaxial accelerometer. Fabrication and set up errors with the MEMS triaxial accelerometer affect raw measurements. These mistakes include 0-bias, scale-component, non-orthogonal, among others. By [44] indicates the 0-bias error resulting from the sensor yields of the MEMS triaxial accelerometer not being zero while the suitable yields are. This method estimates calibrating parameters based on the model is built using (1) [44].

$$y_k^m = C_S C_{Sn} C_n^b y_k^n + b_a + \varepsilon \tag{1}$$

Where y_k^n reflects the acceleration of gravity in the nearby area, C_n^b C_S is the scale-factor error, C_n is the upper triangular matrix, b_a is the zero-bias error, and speaks to the Gaussian white clamor with a fluctuation of and a cruel weight of zero. The probability density function of y_k^n can be calculated using (2).

$$f(y_k^m) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[\frac{\left\|y_k^m - T_a y_k^b - b_a\right\|^2}{2\sigma^2}\right] \tag{2}$$

The likelihood function $L(\theta)$ of a persistent sort arbitrary variable, concurring to the hypothesis of maximum probability estimation strategy, is:

$$L(\theta) = \prod_{k=1}^{N} f(y_k^m) \tag{3}$$

The objective of an ML assess is to distinguish the most excellent esteem that maximizes the probability work:

$$\max L(\theta) = \prod_{k=1}^{N} f(y_k^m) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[\frac{\left\|y_k^m - T_a y_k^b - b_a\right\|^2}{2\sigma^2}\right] \tag{4}$$

Where $T_a = C_S C_n$ and $y_k^b = C_n^b\, y_k^n$.

2.9. Filtering

This technique does now no longer want the assist of outside high-precision system as compared with conventional calibration scheme. It may be done with the aid of using consumer hand rotation. In this approach, a unique clear out is designed to carry out the calibration technique and estimate thse unfairness blunders, scale element blunders and non-orthogonal blunders.

2.9.1. Kalman filter

According to [45], [46], the covariance of the states communicated through implies of a mistake state ($\Delta\hat{x}_k$) is known as the value desire of the state as in (5).

$$P_k = \varepsilon([\vec{x}_k - \hat{x}_k][\vec{x}_k - \hat{x}_k]^T) \tag{5}$$

Where: $\hat{x}_k$ is the state propagation, $\vec{x}_k$ is the system dynamics.

A highest quality remarks advantage K_k (feed back gain) may be derived with the aid of using minimizing P_k. For linear structures that is referred to as the Kalman filter. If the measure will be made available, the comment advantage K_k will be calculated, the circumstance covariance will be adjusted (decreased) appropriately.

Assume there's an unbendable outline with the outline facilitate device with the body coordinate system (OX'Y'Z') and a reference facilitate device coordinate system (OXYZ) (the Earth). Introduction points are portrayed through the points among each direction of OY, OZ and OX', OY', OZ', individually. The beginning put of the reference arrange gadget is interpreted to the beginning put of the outline facilitate gadget keeping up the rules of directions OY and OZ unaltered [46].

2.9.2. Kaiser filter

In guideline, the notorious botches of the tri-axial accelerometer are unfaltering inclinations, scale perspective botches and misalignment botches. The taking after condition (6) is broadly carried out to clarify the botches form of MEMS tri-axial accelerometer [47].

$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = \begin{bmatrix} b_{xo} \\ b_{yo} \\ b_{zo} \end{bmatrix} + \begin{pmatrix} K_{xx} & S_{xy} & S_{xz} \\ S_{yx} & K_{yy} & S_{yz} \\ S_{zx} & S_{zy} & K_{zz} \end{pmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} + \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} \tag{6}$$

Where A_x, A_y and A_z constitute the unique outputs of tri-axial accelerometer. b_{xo} b_{yo} b_{zo} are the consistent biases of accelerometer. ax, ay, and az are the real accelerations that we need. K_{xx}, K_{yy}, K_{zz} are the size factors. S_{xy}, S_{xz}, S_{yx}, S_{yz}, S_{zx} and S_{zy} constitute the effect of misalignment mistakes coefficients. ε_x, ε_y and ε_z constitute the random noises which may be removed with the aid of using averaging. The Kaiser channel numerical adaptation may be characterized through way of implies of the (7).

$$w(n) = \frac{I_o\left(\pi\alpha\sqrt{1-(\frac{2n}{N-1}-1)^2}\right)}{I_o\pi\alpha}, 0 \leq n \geq \tag{7}$$

Where N is the duration of the sequence, I_0 is the zero - order changed Bessel feature of the primary kind. The botches form condition of MEMS accelerometer in (6) may be communicated in another expression as takes after.

$$A^m = KA^e + A_o \tag{8}$$

Where A^m could be a 3×1 vector that speaks to the interesting yields of the accelerometer. K could be a 3×3 lattice which speaks to the size component and misalignment mistakes. A^0 could be a 3×1 vector that speaks to inclination. A^e may be a 3×1 vector that speaks to the right increasing speed what we require. $F(\lambda, \Theta)$ is the arithmetical separate from the information (x, y, z) measured to the comparing Figure with interior the ellipsoid floor whose condition is $F(\lambda, \Theta) = 0$.

2.10. Neural networks

The purpose of this calibration calculation is to show the non-linear relationship between MEMS sensor's null-voltage and temperature using back propagation (BP) neural arrange [3], [47]. A given work f ranging between $[0, 1]^n$ and R_m, f belongs to L2 if each of f's organize capacities is square-integrable into the unit 3d form [AA], In a n-dimensional Euclidean space, [0, 1] n is the closed unit 3d shape and R_m is the m-dimensional Euclidean space. The coming about arrangement BP neural arrange structure is appeared in Figure 8, where Wi $(i = 1, 2, \ldots, 9)$ are the weight values interfacing the input layer and the primary covered up layer, $W'ij$ $(i, j = 1, 2, \ldots, 9)$ are the weight values interfacing the primary and the moment covered up layers, Vi $(i = 1, 2, \ldots, 9)$ are the weight values interfacing the moment covered up layer and the yield layer, bi, j $(i = 1, 2;\ j = 1, 2, \ldots, 9)$ is the limit esteem, f is the transfer function tan-sigmoid and $\mathcal{F}$ is the exchange work direct sigmoid.

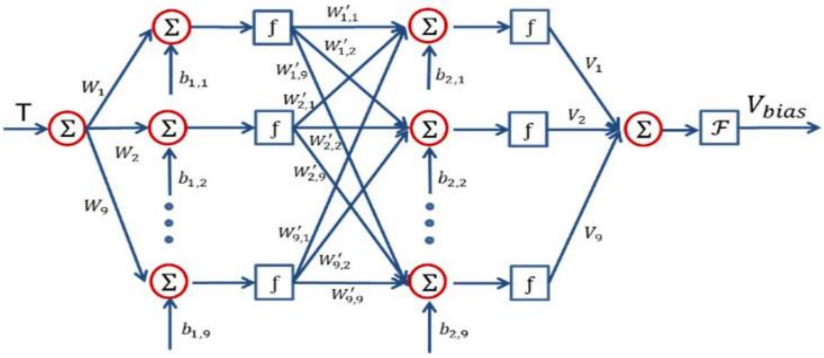


Figure 8. BP neural arrange structure [47]

3. BIST METHODS BENCHMARKING

A few execution measurements can be utilized to benchmark the different BIST strategies displayed within the past segments. Many estimations such as test length or control utilization of the test techniques, are quantifiable sums, there is a degree of disdain toward the truth that their values can be subordinated to development utilized and signal to noise ratio (SNR) inquired about. A similar estimation may be made by counseling planning bunches in any case with an ordinal regard. A value of 10 (easily achievable) to 1 (troubling) was given to the case of ease of implementation metric. Depending on the type of issues covered by the BIST procedure, and the additional functionalities that the procedure may be able to provide, a 5-point score was given for the usefulness metric. In Table 1, at the conclusion of this section, a classification table summarizes the most important findings of this article.

Table 1. Classification and summarizing the most important BIST method

Test method	Description	Ease of implementation	Test application	Usefulness
Capacitively	Testing the MEMS capacitor by charging and discharging it	4	A	2
Capacitance to frequency	Using a modified Pierce oscillator structure to analyze capacitance deviation in the frequency domain	4	A	2
Electrical stimulus	Typically, electric stimulation is used to mimic physical force, in this case acceleration	4	A	2
Estimation	Through the use of the most probability estimation method, the parameters were calibrated	4	B	2
Filtering	An innovative calibration procedure is used to assess unfairness blunders, scale element errors, and non-orthogonal errors	4	A	2
Neural networks	Use the BP Neural Arrange to visualize nonlinear relationship between null-voltage at MEMS sensor and temperature	5	A	3

4. CONCLUSION

It is obvious from this review that we cannot get the best one of BIST method. The MEMS sensing and actuation properties will specify the most appropriate test technique for implementation. In addition to that the failure modes of MEMS that to be detected, and the domain of application.

Accordingly, the first fitting MEMS test strategy will be based on identifying and enacting properties, application space. Parameter extraction comes with likely the foremost complex circuitry with respect to assessment of the yield flag. In any case, the test strategy can extricate imperative data with respect to physical parameters of the gadget. Pierce oscillator dependent technique presents one of the fastest ways of self-testing. Because it was appropriate for capacitive MEMS and hence missing for add up to system characterization, it requires additional circuitry to alter over capacitance assortments into time contrasts.

Finally, we cannot specify which test method is the best and optimum. In addition, all of the methods discussed above are intrusive and require the device’s usual functionality to be halted while the test is ongoing. Superposition test methods are a wonderful choice since they provide a solution of an on-line test with minimal overhead and they are capable of detecting catastrophic faults.

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