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ANALYSYS AND PROTOCOL FOR CHARACTERIZING INTRINSIC PROPERTIES OF THREE-AXIS MEMS ACCELEROMETERS USING A GIMBAL ROTATED IN THE GRAVITATIONAL FIELD

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Abstract: Three-axis MEMS accelerometers are typically characterized in terms of their cross-sensitivity matrix. We present an analysis and protocol to characterize them in terms of their intrinsic properties, which we define as the responsivity of each accelerometer along its axis of maximum response in a gravitational field and the angles between each of these axes. An analysis and test protocol is developed to determine these properties using a gimbal to rotate each axis of the device orthogonally to the gravitational field. We propose that this approach is better suited for laboratory inter-comparisons.

Keywords: MEMS, Microelectromechanical Systems, Accelerometer, Intrinsic, Calibration

1. INTRODUCTION

The MEMS and Sensors Industry Group (MSIG) has been engaged in the development of standards for defining sensor performance that are unique to MEMS technologies since 2009. The production of MEMS-based sensors, including accelerometers, gyroscopes, magnetometers, and pressure sensors, has been increasing dramatically since their introduction into automobiles and smart phones. The industry group recognized the inconsistency of how device manufacturers defined performance in data sheets was potentially leading to loss of efficiency, adoption by customers, and time to market as new generations of devices became available.

MISG worked with the IEEE Standards Association to publish IEEE P2700 Standard for Sensor Performance Parameter Definitions [1] in 2014. This standard defines accelerometer sensitivity, for example, as the change in acceleration input corresponding to one least significant bit change in output. MEMS-based devices typically provide digital output of the measurand, and this fundamental characteristic is what sets apart the IEEE P2700 standard for other similar standards.

With performance parameters defined, the next step is to develop testing protocols to measure them. MEMS device manufacturers typically calibrate their accelerometers by flipping them over, and often called the flip test. Three-axis accelerometers require a more refined approach as can be seen in [2]. The results are typically represented by a cross-sensitivity matrix.

$$\mathcal{P} = \begin{bmatrix} \rho_{xx} & \rho_{xy} & \rho_{xz} \\ \rho_{yx} & \rho_{yy} & \rho_{yz} \\ \rho_{zx} & \rho_{zy} & \rho_{zz} \end{bmatrix} \quad (1)$$

where R is the cross-sensitivity matrix and,

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \rho_{xx} & \rho_{xy} & \rho_{xz} \\ \rho_{yx} & \rho_{yy} & \rho_{yz} \\ \rho_{zx} & \rho_{zy} & \rho_{zz} \end{bmatrix} \begin{bmatrix} R_x - O_x \\ R_y - O_y \\ R_z - O_z \end{bmatrix} \quad (2)$$

a_x, a_y, a_z, represent the acceleration vector, R_x, R_y, R_z, represent the output of each of the accelerometers, and O_x, O_y, O_z, represent each of the offsets of the accelerometers.

This representation is useful for practical applications but may not be useful for measurement inter-comparisons. The cross-sensitivity matrix has dependence on how the device is mounted since the output of each of the axes of the three-axis accelerometer are modeled to be aligned with the coordinate system of the measurement instrument and it is further assumed that they are perfectly orthogonal to each other.

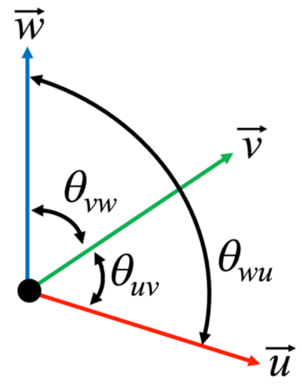

Figure 1 Model of a three-axis accelerometer with axes u, v, and w corresponding to the x, y, z coordinate system.

2. INTRINSIC PARAMETERS

We define parameters as intrinsic to signify that they are independent to the orientation in which the device is mounted in a package, device, or measurement apparatus. We model the 3-axis accelerometer as having 3 axes that each point in their direction of maximum response and are not assumed to be perfectly orthogonal, as depicted in Figure 1.

The vectors $\boldsymbol{u}$, $\boldsymbol{v}$, and $\boldsymbol{w}$ correspond to the magnitude and direction of the responsivity for each of the three accelerometers. The variables θ_{uv}, θ_{vw}, and θ_{wu} represent the angles between the vectors $\boldsymbol{u}$, $\boldsymbol{v}$, and $\boldsymbol{w}$, respectively.

Next, the three-axis accelerometer is assumed to be mounted inside of a package or, for example, a product such as a smart phone, which we will hence forth refer to as the device under test (DUT), as depicted in Figure 2.

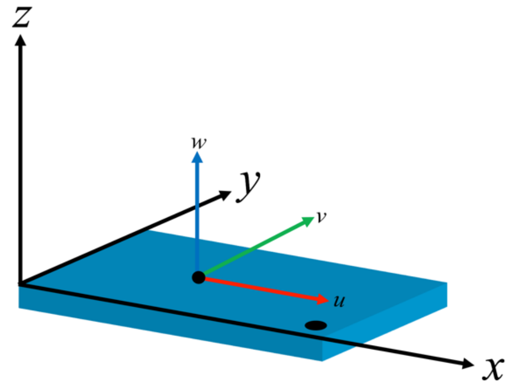

Figure 2 Model of the device under test (DUT) that incorporates the three-axis accelerometer as depicted in Figure 1.

The three-axis accelerometer is not expected to be perfectly aligned to the x, y, and z axes of the Cartesian coordinate system defined by the DUT. It follows from the diagram above that the response of the u, v, and w accelerometers can be written as:

(3)

where the unit vectors $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$ point in the direction of the x, y, z directions of the Cartesian coordinate system.

3. ANALYSIS AND PROTOCOL

We present a protocol to determine the responsivities of each of the accelerometers u, v, and w, and the angles between them, θ_{uv}, θ_{vw}, and θ_{wu}. Each axis of the DUT (x', y', z') is aligned to be perpendicular to the direction of the gravitational field while the device is rotated around that axis using a gimbal. This procedure is depicted in Figure 3 as having 3 parts: (a) rotation around the x axis, (b) rotation around the y axis, and (c) rotation around the z axis of the DUT.

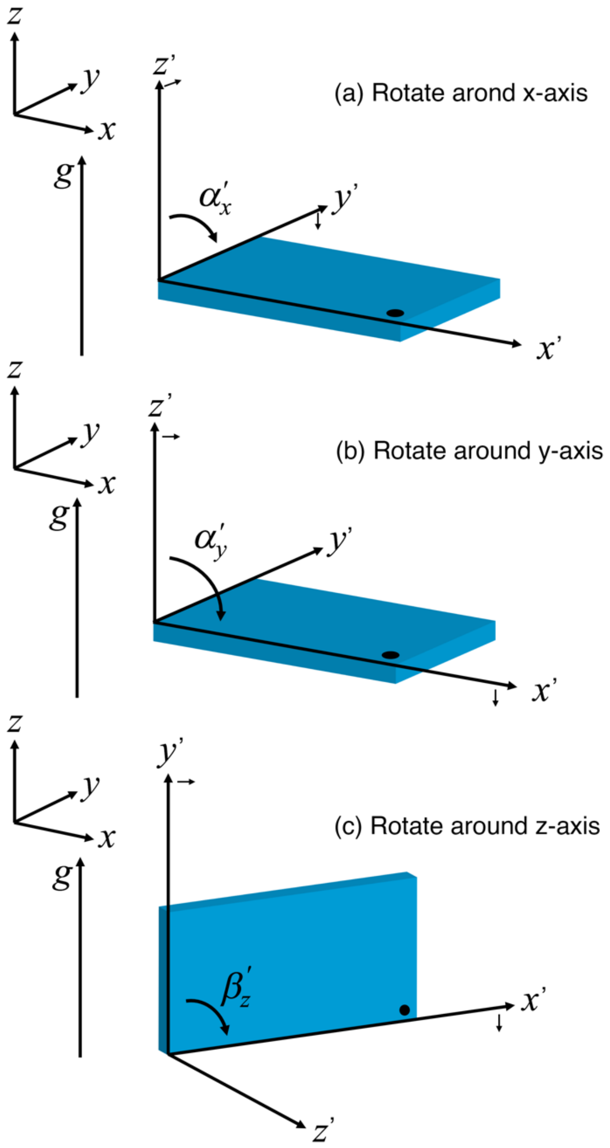

Figure 3 Protocol for rotation of the accelerometer around each axis of the device under test (DUT). The vector **g** represents the magnitude and direction of the earth's gravitational field.

$$\begin{aligned} \boldsymbol{u} &= u_x\mathbf{i} + u_y\mathbf{j} + u_z\mathbf{k} \\ \boldsymbol{v} &= v_x\mathbf{i} + v_y\mathbf{j} + v_z\mathbf{k} \\ \boldsymbol{w} &= w_x\mathbf{i} + w_y\mathbf{j} + w_z\mathbf{k} \end{aligned} \qquad (3)$$

Now, considering R_u, R_v, R_w to be the output measured from each of the accelerometers, the rotation of the DUT around each axis as described previously and the resulting measurements tabulated in increments of 360°/N for n = 1 … N results [3] in the following set of equations:

$$R_u(\alpha_{xn}) = u_y\, g \sin(\alpha_{xn}) + u_z\, g \cos(\alpha_{xn}) + O_{ux}$$
$$R_v(\alpha_{xn}) = v_y\, g \sin(\alpha_{xn}) + v_z\, g \cos(\alpha_{xn}) + O_{vx}$$
$$R_w(\alpha_{xn}) = w_y\, g \sin(\alpha_{xn}) + w_z\, g \cos(\alpha_{xn}) + O_{wx}$$

$$R_u(\alpha_{yn}) = u_x\, g \sin(\alpha_{yn}) + u_z\, g \cos(\alpha_{yn}) + O_{uy}$$
$$R_v(\alpha_{yn}) = v_x\, g \sin(\alpha_{yn}) + v_z\, g \cos(\alpha_{yn}) + O_{vy} \quad (4)$$
$$R_w(\alpha_{yn}) = w_x\, g \sin(\alpha_{yn}) + w_z\, g \cos(\alpha_{yn}) + O_{wy}$$

$$R_u(\beta_{zn}) = u_x\, g \sin(\beta_{zn}) + u_y\, g \cos(\beta_{zn}) + O_{ux}$$
$$R_v(\beta_{zn}) = v_x\, g \sin(\beta_{zn}) + v_y\, g \cos(\beta_{zn}) + O_{vx}$$
$$R_w(\beta_{zn}) = w_x\, g \sin(\beta_{zn}) + w_y\, g \cos(\beta_{zn}) + O$$

where O_u, O_v, O_w are the offsets of the u, v, w accelerometers, respectively,

$$O_u = \sqrt{O_{ux}^2 + O_{uy}^2 + O_{uz}^2} \quad (5)$$

Equation (4) represents 9 sets of N equations, which can be solved for the unknowns **u**, **v**, **w**, and **O** by standard least squares methods to determine the intrinsic properties of the three-axis accelerometer.

The maximum responsivities of the three accelerometers, are determined separately by,

$$u = ||\vec{u}|| = \sqrt{u_x^2 + u_y^2 + u_z^2}$$
$$v = ||\vec{v}|| = \sqrt{v_x^2 + v_y^2 + v_z^2} \quad (6)$$
$$w = ||\vec{w}|| = \sqrt{w_x^2 + w_y^2 + w_z^2}$$

and the angles between the accelerometer axes are determined by,

$$\theta_{uv} = arccos\left(\frac{u_x v_x + u_y v_y + u_z v_z}{uv}\right)$$
$$\theta_{vw} = arccos\left(\frac{v_x w_x + v_y w_y + v_z w_z}{vw}\right) \quad (7)$$
$$\theta_{wu} = arccos\left(\frac{w_x u_x + w_y u_y + w_z u_z}{wu}\right)$$

4. CONCLUSION

An analysis and protocol was presented to determine the intrinsic properties of a three-axis accelerometer, which we define as the responsivity of each accelerometer along its axis of maximum response in a gravitational field and the angles between each of these axes. The often used cross-sensitivity matrix is dependent on how the device is mounted on the measurement instrument and, though it has been found useful in practical applications, we propose that the intrinsic properties that we present here are more useful for laboratory inter-comparisons for SI realization of acceleration units.

5. REFERENCES

[1] Standard for Sensor Performance Parameter Definitions, IEEE Standard P2700-2014.

[2] M. Pedley, "High-Precision Calibration of a Three-Axis Accelerometer", FreeScale Application Note AN4388 Rev. 2.0, (2015).

[3] J. Geist, M. Y. Afridi, C. D. McGray, and M. Gaitan, Gravity-based characterization of three-axis MEMS-accelerometers in terms of intrinsic accelerometer parameters, NIST Journal of Research, *in press*.