Using Accelerometers for Measuring Rotational Degrees-of-Freedom

Marine Dumont and **Norton Kinsley**, Kistler Instrument Corp., Amherst, New York

In many applications, such as structural testing or vehicle collision studies, rotational data are required. Modal analysis will mainly use it to identify rotational degrees of freedom (DOFs), where crash testing will mainly look into rotational inertia. Measuring rotational acceleration can be done by computing measurements from linear sensors, but this leads inevitably to an increase in measurement errors. The Kistler quartz rotational accelerometers, Types 8838 and 8840 have been developed for direct measurement of angular acceleration. In the first part of this article, we are going to compare the internal design of the rotation accelerometers Type 8838 and 8840 to solutions based on computing measurements from linear sensors. We will look into optimization of the assembly as well as a calibration procedure. In the second part, we will focus on how the rotational sensors have been used to identify and investigate shaker planar rotation. We will then look into how these undesirable planar rotations can influence linear sensor measurement.

The acceleration experienced by a rotating member or structure is often a very important parameter during system design. An automobile crash imparts tremendous energy to the occupants, typically in the form of significant rotational inertia. Mechanical structures deform dynamically at resonant frequencies, and the resulting stresses can cause tremendous damage. The fields of study referred to as impact dynamics and modal analysis investigate the characteristics of these mechanical systems or structures.

Finite-element analysis (FEA) is typically employed to form a mathematical model of the system. This analysis relates the deformation at one surface of a discrete elemental section to the surface deformation at opposing elemental surfaces using an appropriate stress/strain relationship. Surface displacements and rotations are considered in the computer model, where each of them represents a degree of freedom (DOF) of the system.

Attachments such as welds, bolted joints, etc., can introduce a significant error into the FEA model, because the required stiffness estimates are generated from engineering judgment and empirical data. The stiffness at these connections depends on many variables such as weld homogeneity, weld thickness, mounting torque, etc. A dynamic measurement or analysis must be performed when the results may have critical consequences. Correlation can be forced between the experimental and analytical study and by applying a modification or "assumption adjustments" to the computer model. Once this correlation is obtained and the model assumptions are verified, an accurate prediction can be made with confidence regarding improvements to the existing design.

Measurement techniques have been used to estimate rotational DOFs, but a sensor designed specifically for these measurements is very rare on the marketplace. Kistler quartz rotational accelerometers 8838 and 8840 employ sensing technology having the salient feature requirements to create an accurate rotational accelerometer. Also, assembly and calibration procedures have been developed to optimize the sensors for application within a specific field of study.

True Rotational vs. Linear Solutions

A dynamic experimental study is typically performed on a structure using linear accelerometers attached at appropriate measurement sites. If they are in close proximity to each other, the difference between their linear outputs can provide an estimate of the rotation present in the system. This spatially narrow array provides a means to estimate rotational acceleration, but it's still difficult to obtain an accurate measurement near interfaces such as bolted joints, etc.

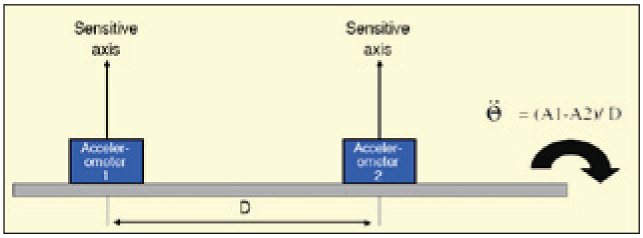

Figure 1. Rotational acceleration measurement using two linear accelerometers; rigid mount prevents any relative motion of accelerometers due to mounting compliance.

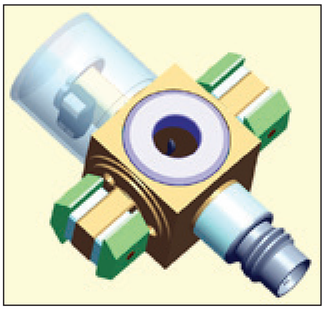

Figure 2. Internal view of quartz rotational accelerometer.

Figure 3. Rotational accelerometer with self-contained electronics.

These interfaces often have considerable relative rotation and minimal displacement. Therefore, a direct measurement of the rotation is important. Historically, measuring this dynamic rotational data has not been straightforward due to the lack of a convenient measurement device, or rotational accelerometer.[1]

There has been a variety of techniques attempted that use a pair of spatially separated, sensitivity-matched accelerometers to determine rotational acceleration. When attached to a fixture at a prescribed distance apart the output signal difference between them is proportional to rotational acceleration (see Figure 1).

If the path between them is short and rigid, so that there is no local rotation between the matched accelerometers, the rotation at the base of the fixture can be computed. This approach can be used in many situations to obtain a reasonable estimate, under favorable conditions, but not in all circumstances. "There is a major problem that is encountered, which derives from the fact that the prevailing levels of output signal generated by the translational components of the structure's movement tend to overshadow those due to the rotational motions, a fact which makes the differencing operations above liable to serious errors."[1]

This undesirable ratio places a high-precision requirement on the sensitivity-matching process. The effect of sensitivity mismatch error has been analyzed and shown that an error in sensitivity matching as small as 0.25% can contribute a 12.3% error in the computed rotational acceleration even on a simple cantilever beam structure.

This error analysis was performed with the assumption that an infinitely rigid attachment was present between the two sensors. Also, transverse influences were excluded from the study by an appropriate selection of specimen and test conditions. It is clear that producing an accurate rotational accelerometer from commercially available hardware is a very challenging task.

Manufacturers of accelerometers have better control over the

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sensitivity matching process and can incorporate technologies that have the qualities required by the design constraints of an accurate rotational accelerometer. The design of an accelerometer always involves the optimization of a “parameter compromise.”

There is not a single accelerometer that fulfills all realms of acceleration measurement. Application-specific designs are tailored for their best fit into the field of interest. As an example, experimental modal analysis (EMA) is a field of study that predominately incorporates a sensor well suited for the following conditions/characteristics:

- Low frequency range of <1000 Hz
- Moderate and controlled environmental conditions
- Excellent immunity to transverse inputs
- Lightweight package
- High output sensitivity with low noise

The next section allows us to examine such a design by investigating piezoelectric-quartz-based Kistler 8838 and 8840 rotational acceleration sensors.

Piezoelectric Quartz-Based Rotational Accelerometers

Quartz is an extremely rigid material having natural piezoelectric characteristics based on fundamental properties of its molecular structure. These characteristics are absolutely stable and do not change. Quartz can be cut into various configurations where the characteristics, or piezoelectric coefficients, depend on the resulting orientation of the crystalline lattice with respect to the physical geometry.

A common orientation, referred to as the shear cut, integrates well into an accelerometer design that is optimized for low transverse sensitivity and negligible base strain effects. This shear mode material then makes for an ideal sensing element for a rotational accelerometer. It becomes possible to create a convenient package rigidly supporting two spatially separated quartz element assemblies. An example construction is shown in Figure 2.

We then need to accommodate the required, rugged, post-processing signal conditioning. The solution lies in the fundamental design of the transducer itself. Also, a dramatic simplification to the overall sensitivity matching can be realized by appropriate management of the primary charges generated within each half of the seismic system.

Referring to Figure 2, consider the piezoelectric plates on the right side of the symmetric package to be inverted with respect to the opposite side. Also, the total mass on each side is adjusted to be exactly equal, so the output is equal and opposite when a linear acceleration is applied to the base. During a rotation, the acceleration experienced by each half will be different, and a resulting voltage will exist at the input to the impedance converter.

This voltage will be proportional to the rotational acceleration by a constant related to both the element separation and the total capacitance of the input network. The electrical arrangement of this system is very simple, and the controlling factor regarding charge generation, mass, is easily measured with extreme accuracy. This is a simple, static, weighing measurement.

The sensitivity of the device depends on the total mass and input capacitance of the seismic system. Its measurement will be detailed in the next section. A180° rotation of the unit yields a signal with the same amplitude but inverted phase as compared to the reference.

Signal processing electronics within the sensor convert the charge generated by the mechanical system into a high-voltage signal level at a low-impedance output. These accelerometers do not use standard voltage mode piezoelectric sensor couplers (IEPE types), but are powered by any commercially available (20 to 30 VDC) power supply. A picture of this optimized assembly is shown in Figure 3.

The internal orientation of the quartz elements enables the Type 8838 accelerometer to respond to oscillations occurring about the unit’s mounting axis when installed in a non-rotating test application. The element structure of the Type 8840 accelerometer is such that the unit will accurately measure the acceleration magnitude of oscillations laterally induced to its mounting base.

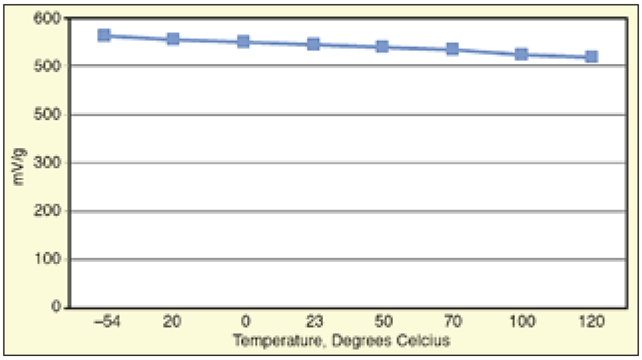

Figure 4. E00064 prototype sensitivity deviation vs. temperature.

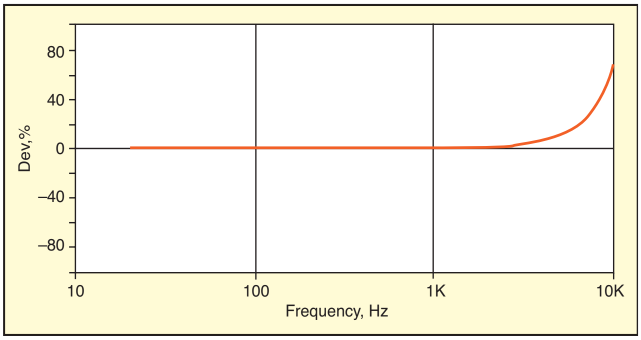

Figure 5. Prototype frequency response plot generated by using exact copy of Type 8838B accelerometer with the PiezoStar plates orientated differently to produce linear output.

For more than 10 years, Kistler has been able to manufacture in its Swiss factory its own synthetic crystal called PiezoStar®. This crystal allows for higher sensitivity and an improved temperature coefficient of sensitivity. In a continuous product improvement effort, Kistler has decided to incorporate this crystal into the next generation of rotational accelerometers, which will show a very stable sensitivity response to temperature (Figure. 4), an increased sensitivity and an extended frequency response (Figure 5).

Such a unique sensor design requires a very specific calibration method that has been patented by Kistler. This method is described in the following section.

Calibration

A typical accelerometer calibration is performed with the test accelerometer connected directly to a back-to-back reference accelerometer and excited by a calibration shaker at the common reference frequency of 100 Hz. For calibration of a rotational accelerometer, input motion from a linear shaker system drives a lever arm about a central fulcrum. Figure 6 presents a rotational test fixture driven by a shaker through a flexible attachment rod or stinger.

The oscillating bar is rigid within the measurement frequency range, and a reference accelerometer is used to determine the input acceleration. The fixture is driven at 12.5 Hz so that a significant input level is presented to the unit without distortion. A measurement of the rotational sensitivity is performed with the test unit mounted as shown in Figure 6.

Because their measurement axes are different, the Type 8838 (axial) and Type 8840 (lateral) must be mounted differently (Figures 7 and 8).

Now that we understand better the working concept of a rotational accelerometer and its calibration and resulting accuracy, we will show how such a sensor can be used for investigating shaker head rotations.

Shaker Head Rotation

Shakers are designed to ideally generate a uniaxial sinusoidal excitation movement at a given frequency. In reality, the movement generated by a shaker also contains components perpendicular to the oscillation axis, introducing what we call shaker head rotations. Depending on shaker quality/performance, these rotations can be significant, especially at some specific frequency range that could influence calibration or modal analysis results.

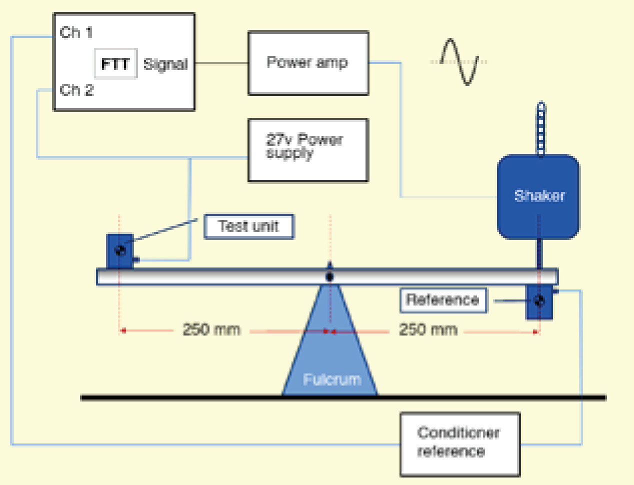

Figure 6. Rotary oscillating fixture.

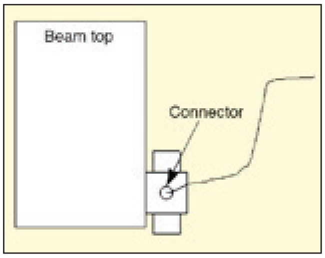

Figure 7. Mounting of Type 8838 accelerometer.

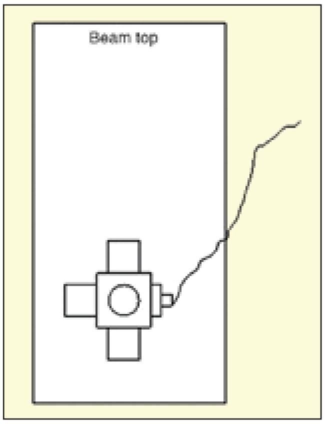

Figure 8. Mounting of Type 8840 accelerometer.

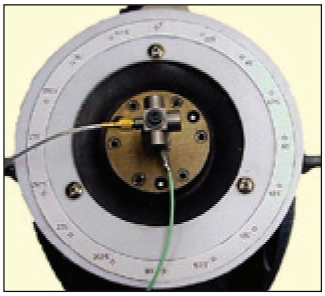

Figure 9. Measurement setup for Type 8840 sensor mounted to shaker under investigation.

A comparison between two shakers has been performed using a Type 8840 rotational accelerometer mounted at the shaker center (Figure 9). A frequency sweep has been performed between 20 and 10 kHz for different orientation of the 8840 sensors (from 0° to 180° with steps of 22.5°).

Figure 10 shows the output of the rotational accelerometer when mounted to Shaker Type A. The graph shows very low rotational acceleration output (<2.5 rad/s^2). Figure 11 shows the rotational accelerometer mounted to Shaker Type B. This graph shows much higher rotational accelerations especially between 3200 and 6000 Hz as well as toward the high-frequency limits (<40 rad/s^2). This shows that Shaker Type B is inducing 16 times more shaker head rotation than Shaker Type A. It should not be used for high-accuracy calibration or high-accuracy modal analysis investigations.

It was shown in one study how shaker head rotations can influence results on calibration data or on modal analysis results.[3] Shakers with high rotational outputs can affect accelerometer calibration results. The sensitivity of the sensor to these rotations can depend on the sensor element design.

The optimization of linear accelerometer features for specific applications has resulted in a wide selection of potential accelerometers for any application. Modal analysis sensor designs have been created with emphasis on minimizing size, weight and cost and has resulted in the use of asymmetric seismic systems within the sensor. These designs may have an inherent sensitivity to rotational inputs.[2]

When asymmetric design accelerometers are calibrated or qualified, the rotational acceleration of the shaker head causes measurement artifacts that are apparent in the transfer functions or calibration curves at the most rotationally active frequencies.[3] An understanding of their existence and influence by investigating them with rotational accelerometers is important. When measuring highly flexible structures at nodal points, special attention should be paid to the rotational susceptibility of the measuring sensor.

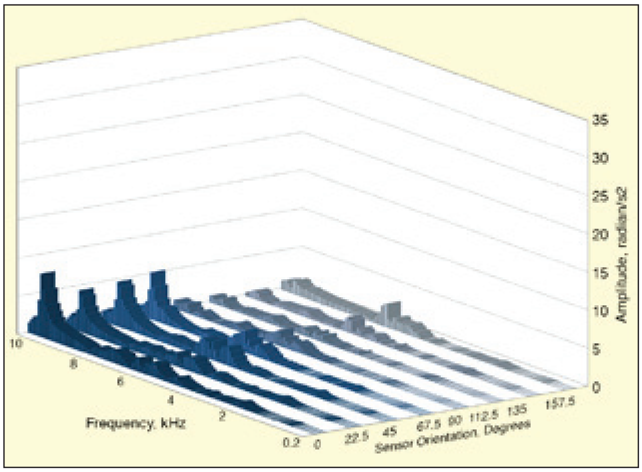

Figure 10. Shaker Type A – Rotational acceleration vs. frequency vs. Type 8840 sensor orientation.

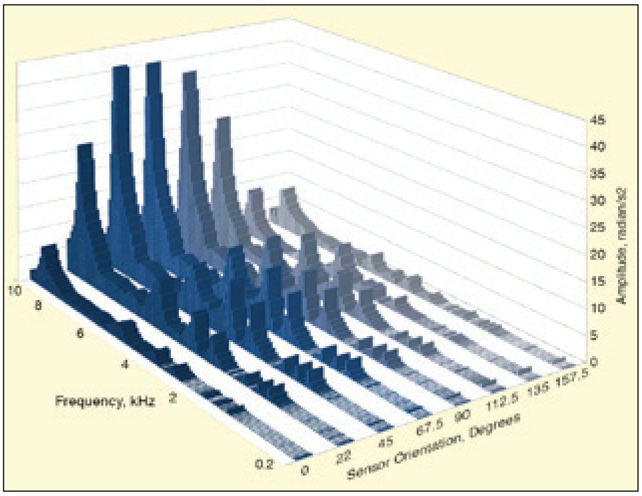

Figure 11. Shaker Type B – Rotational acceleration vs. frequency vs. Type 8840 sensor orientation.

Summary

Angular acceleration measurement and rocking motion considerations are topics not often encountered in literature. This article shows how those topics can be of high importance for modal analysis applications.

We have shown that for many years, rotational acceleration has been measured using linear accelerometers. Studies have shown that this could lead to high measurement errors where dedicated rotational sensor design was optimized for high sensitivity, high linearity and high stability. If the sensors used during modal analysis or the reference standard used during calibration have an internal design sensitive to shaker head rotations, this could influence results and accuracy.

References

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The author may be contacted at: marine.dumont@kistler.com.