The Art of Fabricating a Rotational Accelerometer

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Abstract

Measuring rotational acceleration accurately has been a significant challenge for many years. Structural testing and vehicle collision studies require rotational data and computing it from linear measurements presents unavoidable error. The difference between the outputs of spatially separated, and sensitivity matched, linear accelerometers can be used to estimate rotational acceleration. However, the inherent sensor imperfections including misalignment, transverse sensitivity, etc., contaminate the computed result. The effect of these imperfections can be minimized when an integral package design is considered and appropriate components and fabrication processes are incorporated. A description of recently developed successful designs including fabrication and test techniques is presented.

Introduction

The acceleration experienced by a rotating member or structure is often a very important parameter during system design. An automobile crash imparts tremendous energy into 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 judgement and empirical data. The stiffness at these connections is dependent 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, accurate predictions 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 has not been available in the marketplace until recently. These new designs employ sensing technologies 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.

Discussion

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 output can provide an estimate of the rotation present in the system. This spatially narrow array provides a means to estimate rotational displacement but it's still difficult to obtain an accurate measurement near interfaces such as bolted joints, etc. 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 rotational accelerometer.

There has been a variety of techniques attempted which 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. If the path between them is short and rigid, such 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 ¼ percent can contribute12.3% error in the computed rotational acceleration even on a simple cantilever beam structure.[2] 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 more control over the sensitivity matching process and can incorporate technologies which 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. Experimental Modal Analysis (EMA) is a field of study which predominately incorporates a sensor well suited for the following conditions/characteristics: low frequency range < 1000 Hz; moderate and controlled environmental conditions; excellent immunity to transverse inputs; lightweight package; and high output sensitivity with low noise. A bimorph is an ideal piezoelectric element for this set of conditions. This element is constructed from two inversely polarized piezoelectric plates that are sandwiched together and sliced to form a rectangle. The piezoelectric element also serves as the seismic mass since it is mounted in a manner allowing ‘beam’ flexure when exposed to acceleration. When packaged in a cantilever beam arrangement, the rectangular shape results in an extremely flexible seismic system in its sensitive axis as compared to the two orthogonal directions defining the transverse planes. Even though the seismic system is not extremely stiff, as is typical to most accelerometers, the obtainable frequency response is well suited for EMA. A simplified sketch of a Modal bimorph seismic element and support configuration is shown in Figure 1.

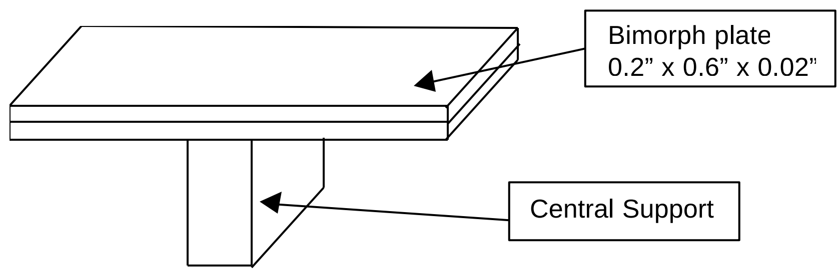

Figure 1) Symmetrically Mounted Bimorph

This arrangement is symmetric about the central fulcrum. Any rotation about this center point generates equal magnitude but inverted charges from each of the symmetric beam halves. A self-cancellation occurs when rotations are presented. Linear acceleration creates similar bending in each beam half and the charges then sum resulting in an output proportional to the imposed linear acceleration. Figure 2 presents an exaggeration of the resulting effect when linear and rotational accelerations are imposed at the fulcrum.

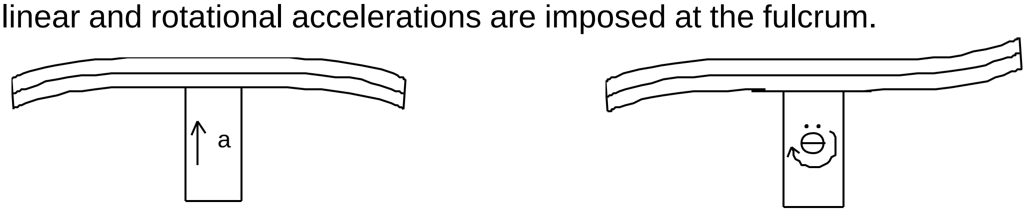

Figure 2a) Linear Input

Figure 2b) Rotational Input

Figure 2) Exaggeration of a Bimorph Element Exposed to Acceleration

When this dual cantilever beam arrangement is stressed, a voltage (V) is produced across the element. It is related to the charge (Q) generated at the surface of the piezoelectric material by the relationship Q=V/C where C is the capacitance of the element itself. A high insulation resistance (R) characteristic is present at the element stage of all piezoelectric sensors. Otherwise, the energy developed within the system will dissipate rapidly since a system time constant is formed by the relationship τ = RC. These high impedance signals are very susceptible to any adverse environmental influences (ie., EMI, triboelectric, etc.) and therefore electronic devices and circuits have been developed to transform the high impedance signals into manageable, low impedance voltages. Hence, the high impedance voltage generated within the seismic system can be converted into a low impedance voltage using a simple unity gain operational amplifier. Other techniques incorporate a feedback loop and process the high impedance charge signal into a low impedance voltage. This electronic circuit is called a charge amplifier. Either an impedance converter (voltage amplifier) or charge amplifier can be integrated with any piezoelectric system. Each method has application specific advantages. When a bimorph is integrated into a package with an internal charge amplifier, an extremely lightweight sensor is realized and a very high voltage sensitivity can be achieved.

Referring to Figure 2, it is apparent that if the output from separate halves of the bimorph can be acquired independently, both rotational and linear acceleration can be determined. These separate beams act as independent seismic systems with their centroids at a prescribed distance apart. The rectangular shaped beam element provides an inherent insensitivity to transverse acceleration. Incorporating creative assembly and process techniques such as epoxy mounting a single, long, rectangular beam across the fulcrum as shown in Figure 1 and then cutting the assembled beam in half as shown in Figure 3 provides for an extremely well aligned system.

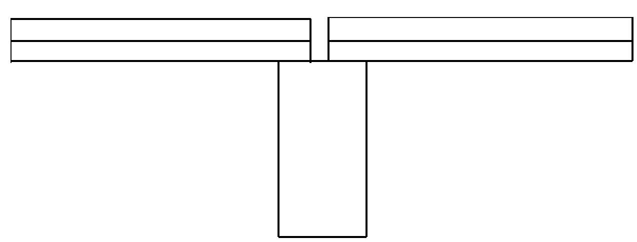

Figure 3) Independent Bimorph Cantilever Beams

Each independent system is made from the same piezoelectric material therefore each has exactly the same material dependent characteristics. Any inherent flaws such as poling alignment, temperature variations, etc. tend to be self-canceling. However, there is still one remaining critical design requirement that must be met to create an accurate rotational accelerometer. The sensitivity from each channel must be identical. Even minor variations in the epoxy fillet from side to side can have excessive influence on sensitivity matching. To avoid the unusual degree of precision necessary for perfect construction matching, an electrical matching technique can be incorporated. With the recent miniaturization of hybrid charge amplifiers, an additional internal charge amplifier can be included into the housing without adding excessive weight to the mountable package. The low impedance voltage outputs from each of the independent channels are connected to a remote signal conditioner. This remote processor has provision to power the sensor's internal electronics and process the independent channel signals. Precision potentiometers are available for adjustment of the sensitivity from each channel with the goal of an exact match to its counterpart. Sum and difference electronic circuits then further process the independent channels and provide as output both a linear and rotational acceleration channel. This overall system, the Kistler TAP® system, appears somewhat complex but in comparison to a typical low impedance measuring chain it is not all that different. Low impedance accelerometers require an external power supply typically referred to as a coupler. The TAP's 'coupler' does a little more work but both linear and rotational data are now available from a coincident measurement point on a structure. A picture of the construction is shown in Figure 4.

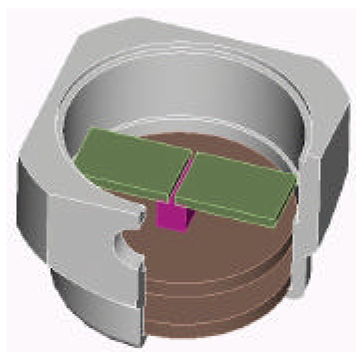

Figure 4) Internal view of Kistler TAP system

It is now possible to incorporate a 'well matched' accelerometer set into a structural test and the sensor footprint has been minimized thereby yielding negligible influence on the test conditions. However, the 'well matched' criterion still requires further improvement. With the external post processing electronic package containing provision for fine-tuning of the independent channel signals, it would appear straightforward to achieve a matched condition. Typically an 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). This is a dynamic measurement and all electromagnetic shakers exhibit some rotational motion. Since the centroid of the internal beams are offset from the shaker centerline, an associated error exists which is related to twice the rotation. Adjusting each channel sensitivity for an exact match, at a frequency where the shaker exhibits minimal rotational motion, provides reasonable accuracy. An improvement is readily achievable using an iterative test method on a rotational member. Figure

5 presents a rotational test fixture driven by a shaker through the flexible attachment rod or stinger.

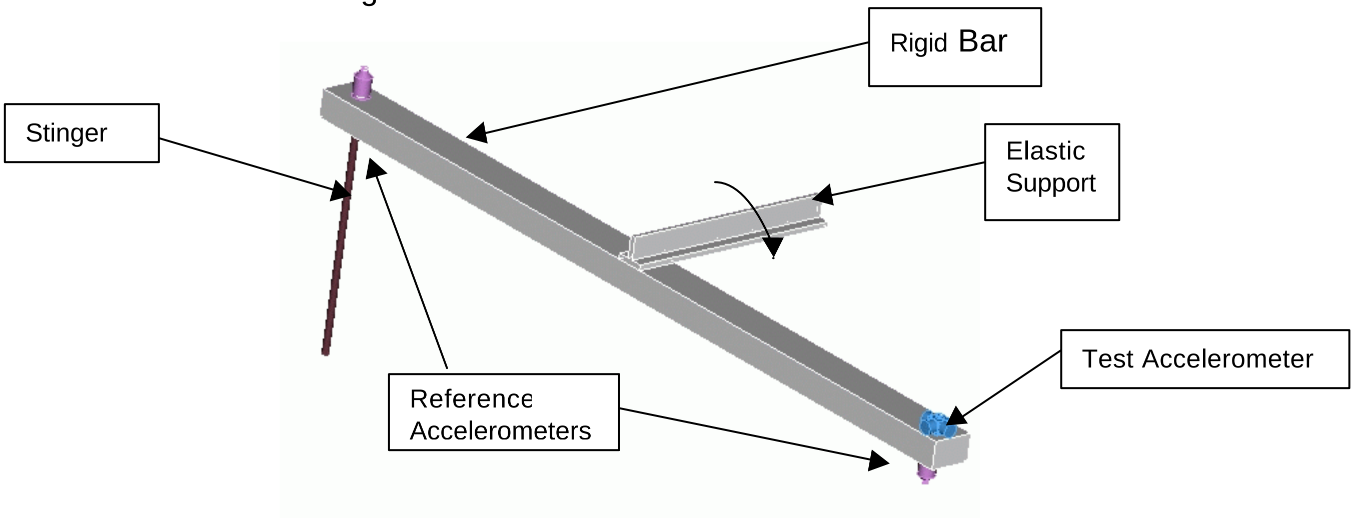

Figure 5) Rotary Oscillating Fixture

The oscillating bar is rigid, within the measurement frequency range, and reference accelerometers are used to determine the input acceleration. The central, tee shaped, supporting member is attached to a rigid base and the heavy bar twists the tee which rotates without any bearing noise or lost motion. The fixture is driven at its resonant frequency so that a significant input level is presented to the unit under test. A measurement of the rotational sensitivity is performed with the test unit mounted as shown in Figure 5. The unit is then rotated 180 degrees and the sensitivity is again measured. The output should have the same amplitude but opposite phase as the previous measurement. An ultra precision tuning is performed on the independent channel gain control and the process is repeated until convergence is achieved. This technique provides the best matching possible, from an overall system standpoint, and has proven to provide the accuracy required for reasonable rotational data extraction during EMA studies.

Rotational accelerometers are needed in other areas than structural testing. Automotive crash studies have identified rotational acceleration as a tremendous influence regarding the damage to humans during a vehicle collision. Unfortunately, the remote electronic system approach incorporated in the Modal sensor solution is not well suited for the types of tests employed in typical automobile studies. The post processing electronic requires a substantial quantity of components and is a bench top or laboratory type device. A rugged version of the electronics package can be designed specifically for installation into the crash vehicle with proper consideration towards adequate isolation from the major impact. However, this arrangement is not ideal and other more robust integral piezoelectric system solutions are better suited for these applications.

Also, a bimorph is not the ideal piezoelectric material for a crash test sensor. The qualities of quartz are unsurpassed in this type of environment.

Quartz is an extremely rigid material having natural piezoelectric characteristics based on fundamental properties of its molecular structure. These characteristics are absolutely stable. They do not change. Quartz can be cut into various configurations where the characteristics, or piezoelectric coefficients, are dependent 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 which is optimized for low transverse sensitivity and negligible base strain effects. These are the same important parameters typical to those of an EMA accelerometer. However, compared to a bimorph construction with equivalent package size and weight, a relatively low voltage sensitivity is realized. Fortunately, the accelerometers required in the crash study industry require low sensitivities thereby providing capability to measure the large accelerations common to these events. A candidate for a rotational accelerometer with high acceleration measuring capabilities is found in a quartz shear mode design. It is possible to create a convenient package rigidly supporting two spatially separated quartz element assemblies. An example construction is shown in Figure 6.

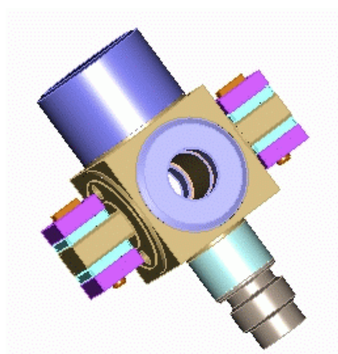

Figure 6) Internal View of Quartz Rotational Accelerometer

There is still the problem 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. The piezoelectric coefficient of quartz is defined as a ratio of the output charge (pC) resulting from an applied force (N). The applied force in the accelerometer is dependent on the seismic mass, m, by the equation F=ma. It is important to note here that the charge, Q, generated by the crystal is a function of a single variable, the seismic system’s mass. All geometry parameters (plate thickness, width, height) have no influence on the generated charges but do effect the capacitance of the system to a significant amount. A shear quartz based seismic system arranged similar to Figure 6 above, and with each leg of the symmetric system considered as half of the total seismic system, has an electrical equivalent circuit as represented in Figure 7.

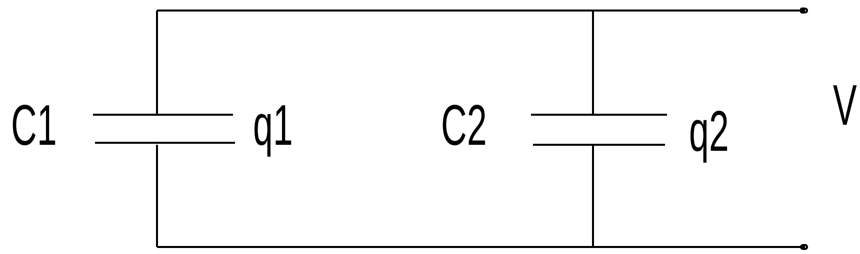

Figure 7) Parallel Capacitor Circuit

The voltage, V, across the parallel capacitor network results from the generated charges created on the surfaces of the crystals and their interaction with the capacitance of each leg of the system. The equation describing the relationship is:

$V=Q/C$ where $Q = q1 + q2$ and $C = c1 + c2$

or $V = (q1 + q2) / (c1 + c2)$;

V is the output voltage from the seismic system or potential input to an impedance converter; q and c are the crystal charge and capacitance respectively. Review of this equation shows that, for the case where q2 = -q1, the resulting voltage is zero. Refer to Figure 6 above and consider the quartz 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 selected to be exactly equal therefore the charges depicted in Figure 7 are exactly 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. An inherent benefit from this approach is a significant increase in the measurable rotational acceleration amplitude range. Since the linear acceleration components are cancelled by the parallel charge connection, prior to entering the range limiting impedance converter, the angular range of measurement is significantly increased.

The sensitivity of the device is dependent on the total mass and input capacitance of the seismic system. It is measured as described previously using the rigid rotating test fixture. 180 degree rotation of the unit yields a signal with same amplitude but inverted phase as compared to the reference.

Overall system simplification is provided by this design. The industry prevalent two-wire Piezotron® signal conditioning approach is utilized offering all its associated cost and convenience advantages. Another variation of the design incorporates the Piezotron coupling electronics with constant current diode internal to the transducer itself. This yields an extremely rugged assembly well adapted to vehicle crash studies without the need for additional external electronics. It is powered by a simple 20 VDC supply. A picture of this optimized assembly is shown in Figure 8.

Figure 8) Rotational Accelerometer With Self Contained Electronics

Conclusion

Rotational acceleration data is important in many experimental studies. Sensors have recently been developed with the capability to accurately measure this parameter. The various sensor technologies that have been used to create devices suitable for a particular application have been presented. Bimorph and quartz based piezoelectric sensors, together with the required system configurations, were discussed. A configuration using a bimorph is tailored for high sensitivity within a small, lightweight, sensor. It is coupled to a remote signal processor to accommodate long term changes, an inherent characteristic of the bimorph sensing element. This system provides both linear and rotational acceleration signals from a single measurement site. It is not robust enough for crash type studies. A shear quartz approach is used for a more rugged design configuration and is well suited for impact or crash study environments. All electronics are miniaturized and are integral to the transducer itself.

The assembly and calibration techniques presented have been optimized to achieve the demanding precision necessary to resolve small differences between slightly separated linear acceleration signals. This low level signal difference is proportional to rotational acceleration but is susceptible to minute design flaws such as transverse influences or component alignment. For the bimorph design, a satisfactory component alignment technique was described where a single beam is assembled then sliced into two independent segments. This assures alignment and also provides part homogeneity between the two beams so they tend to change in a similar fashion. Processing the independent signals externally allows for future adjustment if needed. The rugged shear quartz design is fabricated using a static weighing process to achieve an exact charge output from separate halves of the seismic system. This static process is extremely accurate and post processing of independent signals is not necessary due to the stability of the natural crystal. This assembly technique permits internal connection of the separate seismic halves thus a single seismic system is formed with a single output proportional to rotational acceleration. A charge due to linear acceleration is self-canceling and does not exist at the input to the internal electronics. This provides a single output related to the rotational acceleration only but with a very large dynamic range. The method of calibration using a rigid member excited into rotational resonance has proven to provide the accuracy necessary for accurate sensitivity matching on the time varying bimorph design. It also provides confirmation of accuracy for the shear quartz approach. These assembly and calibration techniques have evolved over the past few years and have been found to be necessary for the accuracy required for these difficult sensors.

References

1) Ewens, D. J., "Modal Testing: Theory and Practice", Research Studies Press Ltd., 1984

2) Shumin Li, David L. Brown, Armin Seitz, Mike Lally, "The development of Six-Axis Arrayed Transducer", IMAC 12 1994