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CROSS SENSITIVITY OF EXTENDED RING (ER) TRANSDUCERS DUE TO TANGENTIAL MISALIGNMENT OF STRAIN GAGES

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Abstract

The extended octagonal ring (EOR) and plain extended ring (ER) transducers are popular devices for force and moment measurement in agricultural engineering research. Much effort has been devoted to determining the optimal location of strain gages to minimize cross sensitivity. A theoretical analysis was conducted on analytical equations derived for the plain extended ring transducer to determine the effect of tangential strain gage misalignment on cross sensitivity.

The analysis showed that a tangential misalignment of one degree for one strain gage in a four arm bridge would result in a cross sensitivity of approximately 0.4% for the horizontal bridge. Except for a discontinuity near the horizontal strain node, the cross sensitivity was relatively independent of nominal angular location of the strain gages on the ring section. For the vertical bridge, the resulting cross sensitivity was approximately 1.2% in the region about ± 25 degrees on either side of the transducer center line. Discontinuities occurred at the vertical strain nodes, and the cross sensitivity dropped to zero at 90 degrees from the transducer center line.

The analysis demonstrates the importance of careful alignment of strain gages on extended ring transducers to minimize cross sensitivity.

Key Words: Extended Octagonal Ring, Extended Ring, Cross Sensitivity, Strain Gage Misalignment.

Introduction

The extended octagonal ring (EOR) is a popular device for measurement of forces and moments in agricultural engineering research. The EOR is a variation of the extended ring transducer which itself is a variation of the proving ring. As the name implies, a proving ring is a ring shaped device fabricated from an elastic material, usually steel or aluminium. It has a pair of thickened bosses on diametrically opposite sides to which loading fixtures can be attached. Applied force causes the ring to deform to an oval shape, and the deformation is measured with a dial gage. Alternatively, deformation can be measured with strain gages mounted at points of maximum strain on the surface of the rings.

In the extended ring transducer, the thickened sections are both elongated and protrude almost touching at the centre (Fig. 1). The massive central section offers a number of options for attaching the transducer to loading devices. Deformation in the thin ring sections at either end is measured with strain gages strategically placed in regions of high tangential strain on the rings to maximize sensitivity. The extended octagonal ring (EOR) transducer is a variation of the ER transducer. The plane outside surfaces of the ring sections EOR are easier to machine than the circular outside surface of the ER transducer.

Load cells usually exhibit a certain amount of cross sensitivity where extraneous forces and moments result in a small signal on the primary axis. In many load cell installations, it is feasible to minimize extraneous loads by using spherical rod end bearings to accommodate misalignment and produce a uniaxial force on the load cell, or by using spherical load buttons when only compression forces are present. In many agricultural applications, multi-dimensional force and moment measurement is required. The EOR is a popular measurement device as it is both very robust, and has capability for simultaneous measurement of forces in two dimensions, and one moment.

Much effort has been devoted to determining the optimum locations for strain gages on the ring sections of an EOR to both maximize sensitivity on the primary axis, and minimize cross sensitivity from the secondary axis, or from extraneous forces and moments. The bending moment and resulting strain distribution on the ring sections is non-uniform, and for both *Fx*, *Fy,* and *Mxy*, it varies between positive and negative, depending on the angular position. McLaughlin (1996) presented diagrams to illustrate this concept. The point zero strain where the strain is crosses from positive to negative, or vice versa, is commonly called a strain node. It is generally accepted that strain gages for measurement of the primary force should be placed at the strain nodes for the secondary force to minimize cross sensitivity. If tangential strain from a horizontal force is zero at the strain node, then placing the strain gages for vertical force at these nodes should result in zero influence of the horizontal force on the vertical force measurement.

Different methods have been utilized to locate the strain nodes on an EOR. Early work used photoelastic methods to examine strain distribution (Loewen and Cook 1956; Pang et al. 1988). Godwin (1975) used strain gages at several points on the ring section. More recently, the Finite Element Method (FEM) has been used to study strain distribution under different loading scenarios (Majumdar et al. 1994). Each of these methods have both advantages and disadvantages.

The quest for locating strain nodes seems to be based on the assumption that locating strain gages at or near the nodes will result in minimum cross sensitivity. Little attention has been paid to the importance of accurately locating all four strain gages of a bridge to maintain symmetry. Many EOR's are "home made" for special applications, and gages are often installed by people with little or no experience in strain gage installation, and no specialized equipment. Accurate alignment of gages on the inside surface of the rings is particularly difficult to achieve as the rings obstruct access and visibility. Consequently, a certain amount of misalignment is inevitable resulting in lack of symmetry of the four gages in a bridge.

Even though the strain for vertical and horizontal loading is zero at the respective strain nodes, the strain gradient is quite high at these points. A small tangential misalignment (ie $\phi \neq \phi_n$ where ϕ_n is the nominal or target angle for the gages) for one of the four strain gages in the bridge, means that the gage is not experiencing the zero strain that was expected at the strain node.

The objective of this paper is to quantify the effect strain gage misalignment on cross sensitivity of an extended ring (ER) transducer.

Analytical Analysis

Hoag and Yoerger (1975) presented an elegant analytical analysis of bending moment distribution in the ring sections of a plain extended ring transducer. McLaughlin (1996) noted some typographical errors and presented the corrected equations (Eq. 1, 2 and 3). Subsequent reference to these equations will be by the original authors, Hoag and Yoerger, but the reader is reminded to refer to McLaughlin (1996) for the corrected equations. Equations 1, 2 and 3 have been transformed from their original form to that for a right hand coordinate system as shown in Fig. 1.

$$M_\phi = -\frac{F_x R}{2}\sin\phi + \frac{F_y R}{2}\left(\cos\phi - \frac{2}{\pi}\right) + \frac{M_{xy}\left[\left(2+\frac{R\pi}{2L}\right)+\left(\frac{2R}{L}+\pi\right)\cos\phi\right]}{\left(8+\frac{R\pi}{L}+\frac{2L\pi}{R}\right)} \quad -\frac{\pi}{2}<\phi<\frac{\pi}{2} \quad (1)$$

$$M_\phi = \frac{F_x R}{2}\sin\phi - \frac{F_y R}{2}\left(\frac{2}{\pi} + \cos\phi\right) - \frac{M_{xy}\left[\left(2+\frac{R\pi}{2L}\right)+\left(\frac{2R}{L}+\pi\right)\cos\phi\right]}{\left(8+\frac{R\pi}{L}+\frac{2L\pi}{R}\right)} \quad \frac{\pi}{2}<\phi<\frac{3\pi}{2} \quad (2)$$

$$\varepsilon = \frac{6M_\phi}{Ebt^2} \qquad (3)$$

The Hoag and Yoerger equations are based on the assumption that the central part of the ring section is infinitely stiff. Under this assumption, the slope of the upper half of the ring sections at $\phi = 90^\circ$ is the same for both the right and left rings. Similarly, the slope of lower half of the ring sections is the same at $\phi = -90^\circ$ and $\phi = 270^\circ$ for the right and left hand rings respectively. In the absence of an analytical solution for the EOR with rings of varying cross section, many researchers have used the Hoag and Yoerger equations as a first approximation in estimating strain distribution in an EOR.

The strain nodes for the extended ring transducer can be found by setting the bending moment in Eq. 1 and 2 equal to zero and solving for the angle ϕ for different one-dimensional loading scenarios. For horizontal force, *Fx*, the nodes are at $\phi = 0^\circ$ and 180º in the right and left hand rings respectively. Similarly, the nodes for vertical loading, *Fy* are at $\phi = \pm 50.5^\circ$ in the right hand ring, and $\phi = 129.5^\circ$ and 230.5º in the left hand ring. For applied moment, *Mxy*, the position of the nodes depends on the ratio of the ring dimensions, R and L. The angle ϕ for strain node in the first quadrant for applied moment *Mxy* is given by Eq. 4.

$$\phi = \sin^{-1}\left[\left(2 + \frac{R\pi}{2L}\right) \div \left(\frac{2R}{L} + \pi\right)\right] \qquad (4)$$

The tangential strain gradient can be calculated by substituting Eq. 3 into Eq. 1 and 2, and differentiating with respect to angle ϕ. The maximum strain gradient can be found by setting the second derivative of equations 1 and 2 equal to zero. The first and second derivatives for of Eq. 1 for the right hand ring are given in Eq. 5 and 6 respectively. Similar equations can be derived for the left hand ring by differentiating equation (2). For simplicity, equations for the left hand ring are not given here.

$$\frac{\partial \varepsilon}{\partial \phi} = \frac{6}{Ebt^2}\left\{ -\frac{F_x R}{2}\cos\phi - \frac{F_y R}{2}\sin\phi - \frac{M_{xy}\left(\frac{2R}{L} + \pi\right)\sin\phi}{\left(8 + \frac{R\pi}{L} + \frac{2L\pi}{R}\right)} \right\} \quad -\frac{\pi}{2} < \phi < \frac{\pi}{2} \qquad (5)$$

$$\frac{\partial^2 \varepsilon}{\partial \phi^2} = \frac{6}{Ebt^2}\left\{\frac{F_x R}{2}\sin\phi - \frac{F_y R}{2}\cos\phi - \frac{M_{xy}\left(\frac{2R}{L}+\pi\right)\cos\phi}{\left(8+\frac{R\pi}{L}+\frac{2L\pi}{R}\right)}\right\} \quad -\frac{\pi}{2} < \phi < \frac{\pi}{2} \qquad (6)$$

The locations of the maximum strain gradient for horizontal loading are at $\phi = 0$ º and $\phi = 180$ º in the right and left hand rings respectively. These are the exact locations of the strain nodes for horizontal loading. The location for maximum strain gradient for vertical loading is at $\phi = \pm 90$ º. While the gradient is not maximum at the vertical strain nodes, it is 77 % of its maximum value at the strain nodes at ±50.5 º. This reveals an interesting paradox. Most researchers try to locate strain gages at strain nodes to minimize cross sensitivity. However, the strain node for *Fx* precisely the point where the gradient in the strain resulting from *Fx* is at its maximum value, and 77% of its maximum value for *Fy*. Thus these strain nodes are the points where cross sensitivity due to strain gage misalignment may be near or at its maximum value.

Strain Gage Misalignment

There are three degrees of freedom in locating strain gages on the ring sections, 1) axial, 2) tangential, and 3) angular. Each type of misalignment has a different effect on cross sensitivity.

Axial misalignment: Ideally, strain gages are located at the centre of the EOR in the z-direction. This is the neutral axis for bending resulting from external moment *Myz* and external force *Fz*. Extraneous force, *Fz*, and moment *Myz*, will produce strains in the ring sections on either side (in the z-direction) of the neutral axis, and gages placed off the neutral axis will be sensitive to these strains. Analysis of strains on either side of the neutral axis at z = 0 is beyond the scope of this paper. When only loading in two dimensions in the x-y plane is considered (ie *Fx*, *Fy* and *Mxy*), axial misalignment in the z-direction has no effect on EOR sensitivity or cross sensitivity.

Angular misalignment: In angular misalignment, the gage is located in the centre of the EOR in the z-direction, i.e. on the neutral axis, and is located at the desired angle ϕ in the x-y plane. However, it is rotated so that the gage grid is not parallel to the x-y plane. Consequently, the gage is sensitive to Poisson strain in the z-direction, and is slightly less sensitive to normal strain in the x-y plane. For small values of angular misalignment, the sensitivity to Poisson strain in the z-direction is likely more significant than the loss of sensitivity to strain in the x-y plane. The former varies with the sine of the misalignment angle while the latter varies with the cosine of the misalignment angle. Although angular misalignment is recognized as a potential source of cross sensitivity, it is not analyzed in this paper.

Tangential misalignment: Tangential misalignment means that the strain gage is not located precisely at the desired angle ϕ in the x-y plane. The ER and EOR both have a high degree of symmetry, and the ability to isolate and measure one-dimensional forces and moments from a multi-dimensional loading scenario stems from the symmetry of the device. Symmetry is both geometric, and electrical. Gages must be placed at the same angle on either side of the x-axis to achieve this symmetry. If three gages in a bridge are placed at the same angle, and one is misaligned tangentially by an amount $\Delta\phi$, then the symmetry of the bridge is violated.

Analysis

The following analysis is based on the Hoag and Yoerger (1975) equations, and provides an analytical expression of the expected cross sensitivity when three gages in a bridge are symmetrical about the x-axis and y-axis, but one gage is misaligned tangentially by an angle $\Delta\phi$. It is recognized that the Hoag and Yoerger equations are based on assumption that the centre section of the ER transducer is infinitely stiff, and consequently, the analysis of cross sensitivity based on these equations may not be exact. However, it does illustrate the concept.

The change in bridge voltage, ΔV, due to tangential misalignment of one gage by an angle $\Delta\phi$, can be approximated with the first term of a Taylor Series expression of the bridge voltage:

$$\Delta V = \frac{\partial V}{\partial \phi}\Delta\phi = \frac{\partial V}{\partial \varepsilon}\frac{\partial \varepsilon}{\partial \phi}\Delta\phi \qquad (7)$$

The first term in Eq. 7 can be found by differentiating the well known equation for a four arm strain gage bridge with respect to ε.

$$V = \frac{V_o GF(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)}{4} \qquad (8)$$

$$\frac{\partial V}{\partial \varepsilon} = \frac{V_0 GF}{4} \qquad (9)$$

Where V is the bridge output voltage, V_o is the bridge excitation voltage, GF is the gage factor ($\Delta R \bullet R^{-1} \bullet \varepsilon^{-1}$) and ε_i is the mean strain at strain gage i. The derivation from this point on will be confined to the right hand ring. Extension to the left hand ring follows the same general procedure.

The strain gradient around the right hand ring is given by Eq. 5. Substituting Eq. 9 and 5 into 7 yields an expression for a change in bridge voltage due to tangential misalignment of one of the four gages in a strain gage bridge.

$$\Delta V = V_o \frac{GF}{4} \frac{6}{Ebt^2} \left\{ -\frac{F_x R}{2}\cos\phi - \frac{F_y R}{2}\sin\phi - \frac{M_{xy}\left(\frac{2R}{L}+\pi\right)\sin\phi}{\left(8+\frac{R\pi}{L}+\frac{2L\pi}{R}\right)} \right\} \Delta\phi \qquad (10)$$

Equation 10 represents the change in bridge voltage for tangential misalignment of one gage in the bridge by an angle $\Delta\phi$. It is assumed that perfect symmetry is achieved for the other three gages in the bridge, ie located at $\pm\phi$ and $180^\circ \pm \phi$ in the right and left hand rings respectively.

The location of maximum error, or maximum ΔV can be found by differentiating Eq. 10 with respect to ϕ and setting it equal to zero.

$$\frac{\partial \Delta V}{\partial \phi} = V_o \frac{GF}{4} \frac{6}{Ebt^2} \left\{ \frac{F_x R}{2}\sin\phi - \frac{F_y R}{2}\cos\phi - \frac{M_{xy}\left(\frac{2R}{L}+\pi\right)\cos\phi}{\left(8+\frac{R\pi}{L}+\frac{2L\pi}{R}\right)} \right\} \Delta\phi \quad = 0 \qquad (11)$$

Eq. 11 is a general equation, and is applicable to bridges for horizontal and vertical forces, *Fx* and *Fy*, and moment *Mxy*. To use it for a particular bridge, simply substitute in the angle in the first quadrant for the particular bridge.

Solving Eq. 11 reveals that the change in bridge voltage for tangential misalignment of a strain gage is at its maximum value for $\phi = 0^\circ$ and $\pm 90^\circ$ for horizontal and vertical loading respectively. Recall that the strain node for horizontal loading is at $\phi = 0^\circ$. The reason for placing gages at strain nodes is to eliminate sensitivity due to strain from extraneous forces and moments. However, the strain node for horizontal loading is precisely the same point where cross sensitivity due to tangential strain gage misalignment is at its maximum. Similarly, the cross sensitivity for vertical is at 77% of its maximum value at the vertical strain nodes at $\phi = \pm 50.5^\circ$.

In theory, if both the ER and the strain gages are perfectly symmetrical (Fig. 1), it is evident from equations 1, 2, 3 and 7 that the bridges for horizontal and vertical forces, *Fx* and *Fy*, and external moment *Mxy* will be insensitive to extraneous forces and moments regardless of whether or not they are located at the strain nodes. From equation 7, equal strain in adjacent arms of a bridge cancel, and equal strain in opposite arms add.

The foregoing analysis suggests that cross sensitivity should not be an issue regardless of the value of ϕ since the gages in a four arm bridge cancel out strain resulting from extraneous loads. This statement is based on the key assumption of perfect symmetry. Minor imperfections in machining the EOR can result in slightly different ring thickness at symmetrical locations, and these result in different strains at symmetrical angular locations. In addition, differences in gage factors for the four gages in a bridge will favour one gage over another. In equation 7, it was assumed that the gage factor was identical for all four gages in a bridge. Modern strain gages from the same lot have nearly identical gage factors, usually within ± 0.5 %.

The analysis is based on three gages in perfect alignment, and one gage misaligned. In a real life situation, all four gages in the bridge will likely have some degree of misalignment. In this case, cross sensitivity can be calculated by substituting the actual installed angle for all four gages into equations 7 to 11 and calculating the actual resulting bridge voltages. Depending on which gages are misaligned and in which direction, the resulting errors will either accumulate, or cancel.

Numerical Evaluation

To quantify the effect of strain gage misalignment on cross sensitivity, an installation was assumed with all four gages in perfect symmetry. One gage on the right hand ring was then misaligned tangentially by plus one degree. Bridge voltage for the horizontal bridge was calculated for the same load in both the horizontal and vertical directions using Eq. 1, 2, 3 and 8. Cross sensitivity was then calculated by taking the ratio of the secondary to the primary sensitivity using Eq. 12 and 13. The primary and secondary sensitivity in Eq. 12 is the sensitivity of the strain gage bridge for measuring horizontal force to horizontal and vertical force respectively. It is important to note that the primary and secondary sensitivities are for the same bridge. Ideally, the secondary sensitivity would be zero in which case the cross sensitivity would be zero. Figs. 4 and 5 present the relative cross sensitivity for the horizontal and vertical bridges as a function of nominal gage location on the ring sections.

$$Horizontal\ Cross\ Sensitivity = \frac{Secondary\ Sensitivity}{Primary\ Sensitivity} = \frac{Vertical\ Sensitivity}{Horizontal\ Sensitivity} \quad (12)$$

$$Vertical\ Cross\ Sensitivity = \frac{Secondary\ Sensitivity}{Primary\ Sensitivity} = \frac{Horizontal\ Sensitivity}{Vertical\ Sensitivity} \quad (13)$$

When expressed as a ratio of bridge voltages, the cross sensitivity between horizontal and vertical bridges is independent of the dimensions of the ER, and is only a function of angular position of the gages, and the magnitude of tangential misalignment. Equations 12 and 13 assume that equal loads were applied in both horizontal and vertical directions. The same ER dimensions appear in both the numerator and denominator of the Eq. 12, and therefore cancel out.

Horizontal Cross Sensitivity

The horizontal cross sensitivity is nearly constant at about 0.435% for over the range of angle of nominal gage locations in the right ring from ϕ = - 90 º to + 90 º (Fig. 4). The exception is in the region of ϕ = 0 º. The strain node for horizontal loading is at ϕ = 0 º, and consequently, the primary sensitivity is zero at $\phi = 0$ º. The primary sensitivity is in the denominator of Eq. 12, and division by a near zero number gives rise to a very large cross sensitivity. At some point in this region, the primary sensitivity is zero, and the resulting cross sensitivity is undefined. Since the gages are misaligned (i.e. three gages at the angle ϕ and one gage misaligned by one degree), the infinite cross sensitivity would occur at an angle slightly different from $\phi = 0$ º. The data for cross sensitivity for ϕ within four degrees on either side of $\phi = 0$ º were omitted from Fig. 4.

Strain from horizontal loading is in the opposite direction on either side of the strain node. Thus the cross sensitivity tends to minus infinity for ϕ approaching 0 º from negative values, and tends to plus infinity for ϕ approaching 0 º from positive values.

The discussion of cross sensitivity in the region of the strain node is interesting but is some what academic and would be of little consequence in a real life situation. Strain gages for horizontal loading would not normally be placed near the strain node for horizontal loading as this is the location of minimum sensitivity to horizontal loading. It is desirable to place the gages near the region of maximum sensitivity.

It is somewhat surprising that the strain gradient (Eq. 5) for horizontal loading is a sine function, but the cross sensitivity which is caused by the combination of a strain gradient and misaligned strain gages is nearly constant for the entire ring section except the region around the strain node at $\phi = 0$ º. The reason for this is that the cross sensitivity is the quotient of the sensitivity of the bridge to vertical and horizontal loads. Both of these are sine functions (the cosine function for horizontal loading can be expressed as a sine function), and the quotient is nearly a constant.

Vertical Cross Sensitivity

The vertical cross sensitivity is also nearly constant for the region between about $\phi = \pm 25$º, and similar to the horizontal cross sensitivity, it is undefined at the strain nodes of ± 50.5 º (Fig. 5). Again, the reason is that the primary sensitivity is zero at the strain node, and division by zero in Eq. 13 is undefined. The direction of strain changes at the strain node, and similar to the horizontal cross sensitivity, the vertical cross sensitivity approaches plus infinity on one side, and approaches minus infinity on the other side of the node. As with the horizontal cross sensitivity, the behaviour of the vertical cross sensitivity in the region of the strain nodes is of no practical consequence since it would be defeating the purpose to locate strain gages in a region where the primary sensitivity was near zero.

The minimum vertical cross sensitivity is at $\phi = \pm 90$ º. This is the region of minimum strain gradient for horizontal loading, and consequently, the region for minimum effect of tangential strain gage misalignment. However, it is a region of high strain from horizontal loading which would have a large effect on cross sensitivity if the gages were miss matched with one gage in the vertical bridge having a larger gage factor, and therefore more sensitivity than the other three. Also, if one gage was misaligned angularly, it would be sensitive to Poisson strain which would also lead to cross sensitivity. A comprehensive analysis is required on the effects of all types of misalignment, the effects of unmatched gages, and the effects of geometric non-symmetry of the ER resulting from machining errors.

Vertical cross sensitivity near $\phi = 0$ º is about 1.2% for one degree tangential misalignment of one gage in the bridge. This is nearly three times the minimum cross sensitivity for the horizontal bridge. The reason is that the maximum horizontal sensitivity is much larger than the maximum vertical sensitivity (Fig. 2). Most researchers place the vertical gages at the horizontal strain node at $\phi = 0$ º, but as shown in Fig. 4, this is the region where tangential strain gage misalignment will result in nearly the maximum cross sensitivity (except for the regions near the vertical strain nodes). Without a comprehensive analysis, it seems like the conventional location of the vertical gages at $\phi = 0$ º is the best choice, but it must be recognized that cross sensitivity due to tangential strain gage misalignment is significant in this region.

There is a slight non-symmetry in the horizontal and vertical cross sensitivity, particularly near the strain nodes. This non-symmetry arises from the assumed misalignment of the gages. The angle for the x-axis in Figs. 4 and 5 is the nominal angle of three gages in the bridge, and the fourth is misaligned by plus one degree for all nominal gage locations. Thus, the cross sensitivity is distorted slightly and is not symmetrical for gage locations on either side of the ER centreline.

The foregoing analysis is based on an assumed tangential misalignment of only one degree. This is rather optimistic, particularly for gages on the inside of the ring sections where visibility and access is restricted. Most researchers do not have sophisticated installation equipment, and strain gage installation is usually done by hand. The magnitude of strain gage misalignment is highly dependent on the skill of the installer, but even with a high level of skill, some misalignment is inevitable. Authors have reported cross sensitivity measured experimentally of up to 12% (Gu et al. 1993). The foregoing analysis suggests that misalignment of a single gage would have to be severe to cause this level of cross sensitivity. However, if more than one gage in the bridge were misaligned, and the direction of misalignment was such that the effects were additive, it is conceivable that a moderate misalignment could yield a 12% cross sensitivity. There are many other factors not included in the analysis that could also contribute to the measured cross sensitivity.

Conclusions

Equations derived for the distribution of strain in the ring sections of a plain extended ring transducer were used to estimate the effect of tangential strain gage misalignment on cross sensitivity of an extended ring transducer. Strain gradients were shown to be maximum at the strain nodes for horizontal and vertical loading suggesting that the effect of strain gage misalignment might be maximum at these locations.

The cross sensitivity, defined as the ratio of secondary to primary sensitivity was independent of ER dimensions, and was a function of only the nominal angular position of the gages on the ring, and the magnitude of misalignment. For one gage in the horizontal bridge misaligned by one degree, the cross sensitivity for the horizontal bridge was nearly constant at about 0.43% for nearly all locations on the ring. The exception was in a narrow region on either side of the strain node at 0 º (the ER centreline) where the primary sensitivity was zero, and the resulting cross sensitivity approached infinity. Gages for the horizontal bridge would not normally be located near the horizontal strain node as this is the region of minimum primary sensitivity.

The cross sensitivity for the vertical bridge with one gage misaligned by one degree was nearly constant at about 1.2% in the region of about 25 º on either side of the ER centre line. As the angle for the gage location from the ER centre line increased beyond ± 25 º, the vertical cross sensitivity increased substantially, was undefined (infinite) at the vertical strain nodes at $\phi = \pm 50.5^{\circ}$, and then switched direction and decreased in absolute value to zero at $\phi = \pm 90^{\circ}$.

The analysis is for only one of many parameters affecting cross sensitivity of an extended ring transducer but it demonstrates the importance of careful attention to proper alignment of strain gages to maintain symmetry in the bridge configuration.

References

Godwin, R.J. 1975. An extended octagonal ring transducer for use in tillage studies. Journal of Agricultural Engineering Research. 20: 347-352.

Gu, Y., R.L. Kushwaha and G.C. Zoerb. 1993. Cross-sensitivity analysis of extended octagonal ring transducer. Transactions of the ASAE. 36(6): 1967-1972.

Hoag, D.L. and R.R. Yoerger. 1975. Design and analysis of load rings. Transactions of the ASAE. 19(4): 995-1000.

Loewen, E.G. and N.H. Cook. 1956. Metal cutting measurements and their interpretation. In eds. Mahlmann, C.V. and W.M. Murray. Proceedings of the society for experimental stress analysis. 2(3): 57-62.

Majumdar, S., E.V. Thomas and D.S. Jayas. 1994. Optimization of parameters in the design of an extended octagonal-ring transducer. Agricultural Engineering Journal. 3(4): 152-165.

McLaughlin, N.B. 1996. Correction of an error in equations for extended ring transducers. Transactions of the ASAE. 39(2): 443-444.

Pang, S.N., G.C. Zoerb and B.A. Rostad. 1988. Application of photoelastic analysis of an extended octagonal Ring. ASAE/CSAE Paper #NCR 88-105. St. Joseph, MI:ASAE.

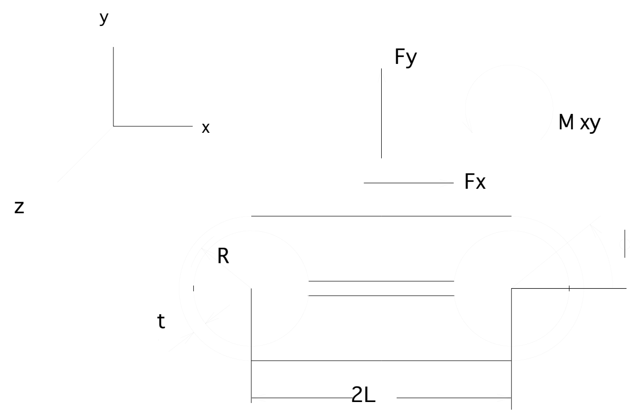

Fig. 1. Diagram of Extended Ring (ER) with dimensions, coordinate system and sign conventions.

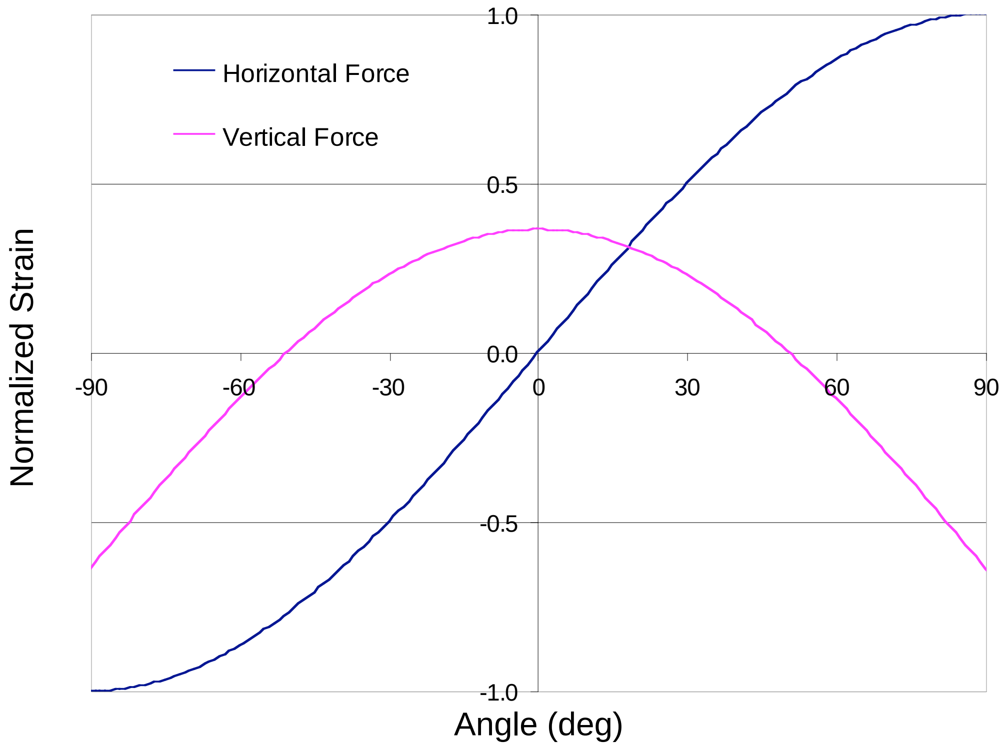

Fig. 2. Normalized strain distribution in right hand ring of an Extended Ring (ER) transducer for horizontal and vertical loading.

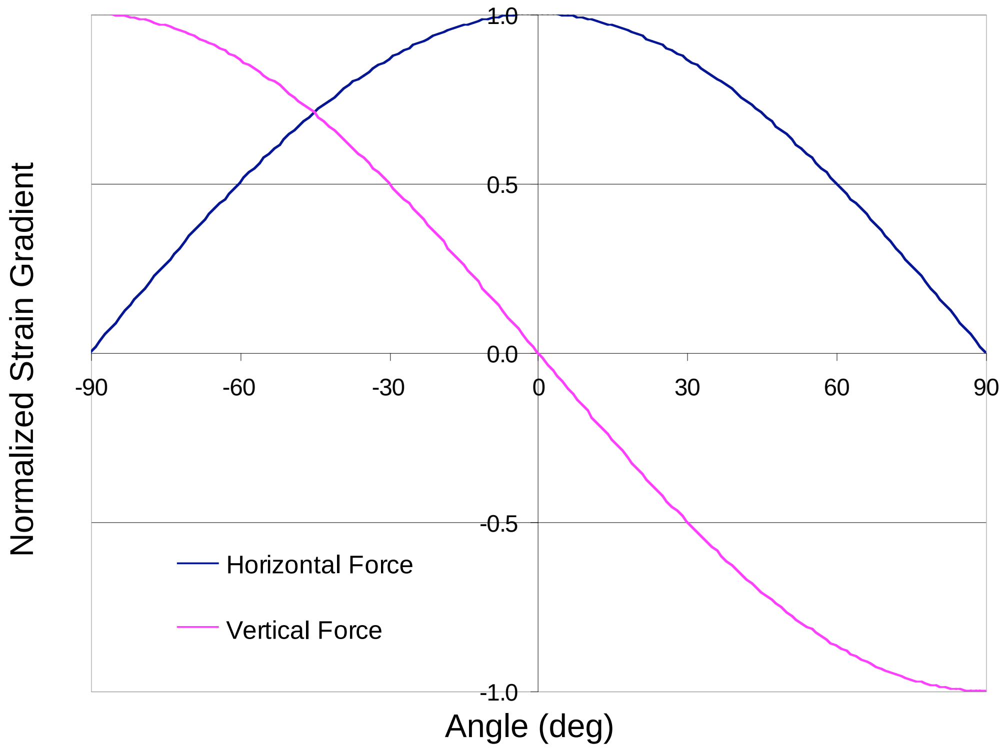

Fig. 3. Normalized strain gradient for right hand ring section of an Extended Ring (ER) transducer for horizontal and vertical loading.

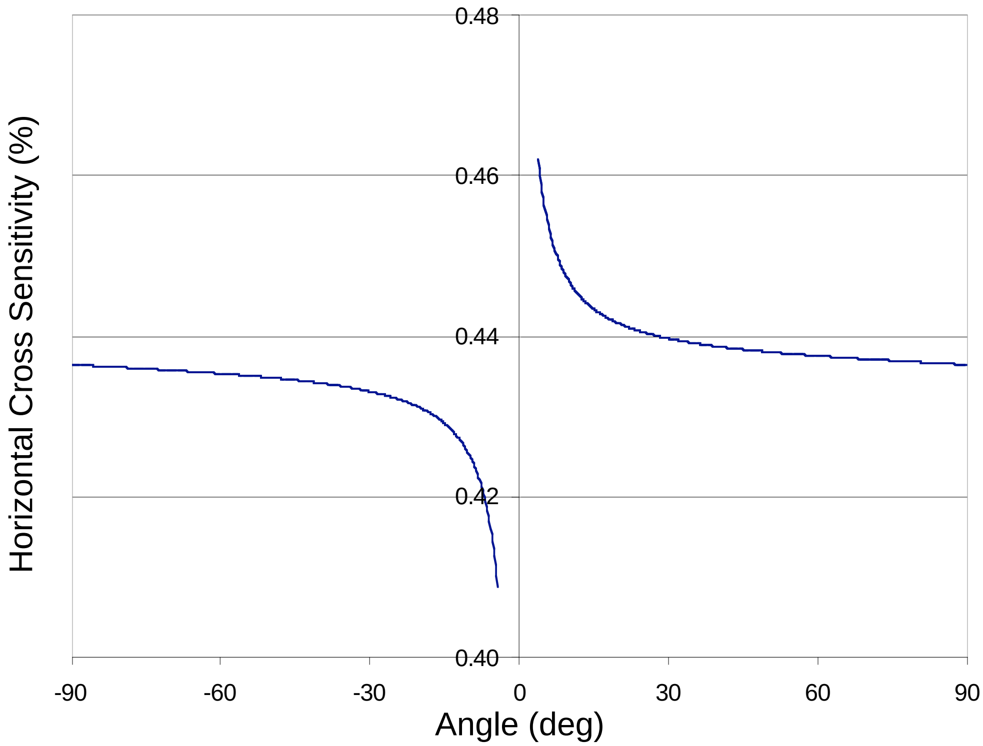

Fig. 4. Horizontal cross sensitivity as a function of strain gage location on an Extended Ring (ER) transducer with one gage in the horizontal bridge misaligned tangentially by one degree. Data for four degrees on either side of the discontinuity at strain node at 0 º have been omitted.

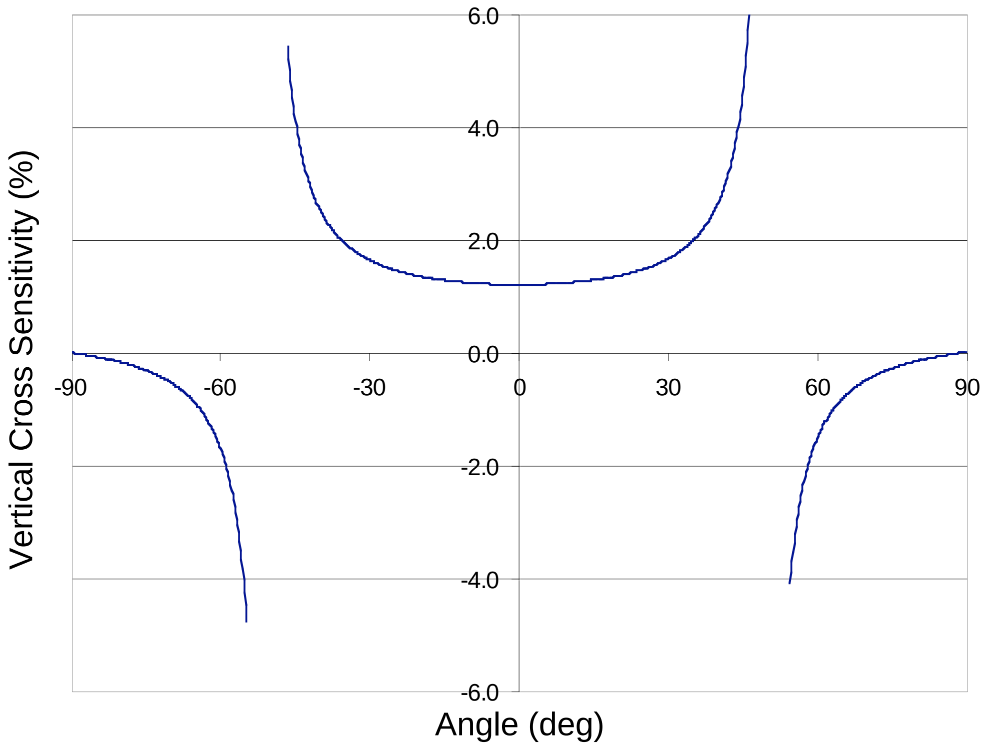

Fig. 5. Vertical cross sensitivity as a function of strain gage location on an Extended Ring (ER) transducer with one gage in the vertical bridge misaligned tangentially by one degree. Data for four degrees on either side of the discontinuities at the strain nodes at ± 50.5 ° have been omitted.