Acceleration Sensitivity of SAW and STW Devices

John A. Kosinski*

US Army CECOM RDEC
Intelligence and Electronic Warfare Directorate
ATTN: AMSEL-RD-IEW-TAE-M
Fort Monmouth, New Jersey 07703

Abstract - An analysis of the normal acceleration sensitivity of rotated Y-cut quartz SAW and STW resonators simply supported along rectangular edges is presented. The analysis is based upon the perturbation integral formulation of Tiersten, and makes use of the previously known analytic representation of the substrate deformation for the case considered. An approximate acoustic mode shape which accounts for spatial variations along all three axes is employed in the perturbation integral, allowing the derivation of analytic expressions relating the normal acceleration sensitivity to such parameters as substrate length, width, thickness, and orientation, mode center offset, mode shape spatial variations, etc. While the case considered represents something of an overestimate as compared to support configurations typically employed in production, questions regarding aspect-ratio compensation, optimum choice of substrate parameters, etc. are clarified by the case considered. The results of the analysis compare favorably with measurements of oscillators employing two-port SAW and STW resonators.

INTRODUCTION

Surface transverse wave (STW) resonators have a number of potential performance advantages over their Rayleigh wave (SAW) counterparts. Firstly, STW resonators feature higher wave velocities leading to either higher frequency operation for a given feature size or less rigorous feature sizes for a given frequency of operation. Secondly, STW resonators feature much higher power handling capability leading to superior noise floor performance. Thirdly, the STW mode features a higher intrinsic Q-f product, with a value $2 \times 10^{14} (\tau_i = 4.88 \text{ fs})$ for the AT-cut.

In light of the substantial performance advantages of STW over SAW in these various areas, theoretical and experimental studies of the acceleration sensitivity of STW resonators have been undertaken. The purpose of the studies has been to understand the nature of STW acceleration sensitivity, and to determine whether the performance advantages seen in other areas extend to the case of acceleration sensitivity.

In this paper, an analysis of the normal acceleration sensitivity of rotated Y-cut quartz SAW and STW resonators simply supported along rectangular edges is presented. The analysis is based upon the perturbation integral formulation of Tiersten, and makes use of the previously known [1] analytic representation of the substrate deformation for the case considered. An approximate acoustic mode shape which accounts for spatial variations along all three axes is employed in the perturbation integral, allowing the derivation of analytic expressions relating the normal acceleration sensitivity to such parameters as substrate length, width, thickness, and orientation, mode center offset, mode shape spatial variations, etc. While the case considered represents something of an overestimate as compared to support configurations typically employed in production, questions regarding aspect-ratio compensation, optimum choice of substrate parameters, etc. are clarified by the case considered. The results of the analysis compare favorably with measurements of oscillators employing two-port SAW and STW resonators.
The analysis of the acceleration sensitivities of SAW and STW resonators is conveniently accomplished using the perturbation integral formulation of Tiersten [2], which we reproduce here for completeness:

$$\omega = \omega_0 - \Delta \mu,$$  \hspace{1cm} (1)

$$\Delta \mu = \frac{H_\mu}{2 \omega_0},$$  \hspace{1cm} (2)

and

$$H_\mu = -\int g_{\alpha, M}^\mu \hat{v} L_\mu^\alpha \delta_{\gamma, \iota} dV,$$  \hspace{1cm} (3)

where

$$g_{\gamma, \iota}^\mu = \frac{u_{\gamma, \iota}^\mu}{N_{\mu}},$$  \hspace{1cm} (4)

and

$$N_{\mu}^2 = \int g_{\gamma, \iota}^\mu u_{\gamma, \iota}^\mu dV.$$  \hspace{1cm} (5)

Equation (1) teaches that the frequency under acceleration, $\omega$, is shifted from the unperturbed frequency, $\omega_0$, by a small amount $\Delta \mu$ which can be calculated using equation (2) and "the perturbation integral" of equation (3). The perturbation integral given by equation (3) looks quite complicated but actually has a rather simple interpretation: it is essentially a weighted average of the acceleration induced biasing state throughout the volume of the quartz plate, where the weighting factor for the averaging is determined by the acoustic mode shape. Equations (4) and (5) provide the necessary normalization of the acoustic mode shape.

The acceleration-induced biasing state is most conveniently written using the material cofactor representation [3]

$$\hat{v}_{L_\mu^\alpha} = k_{L_\mu^\alpha KN} w_{N, K},$$  \hspace{1cm} (6)

where

$$k_{L_\mu^\alpha KN} = c_{L_\mu^\alpha KN} + c_{LMKN} \delta_{\gamma^\alpha} + c_{LKM} \delta_{\gamma N}.$$  \hspace{1cm} (7)

The $w_{N, K}$ term in equation (6) represents the nine acceleration-induced biasing deformation gradients (N and K take values 1, 2, 3), and contains all of the required information on how the shape of the crystal plate is deformed by the acceleration. Which c-hat terms are required is determined by the mode of operation, and each c-hat term is the sum of the deformation gradients, each multiplied by the relevant material cofactors as defined in equation (7). Besides being computationally convenient, equations (6) and (7) clarify two fundamentally important concepts, namely 1) the frequency shifts because the plate is deformed and 2) the response to the deformation involves both linear and nonlinear elastic constants [3]. As applied to the calculation of the normal acceleration sensitivity, equations (1) through (3) readily yield

$$\Gamma_2 = \frac{1}{8\pi^2 \nu^2 a_2} \int g_{\alpha, M}^\mu \hat{v} L_\mu^\alpha \delta_{\gamma, \iota} dV.$$  \hspace{1cm} (8)

Equation (8) is typically evaluated numerically, often using finite element techniques to determine the acceleration-induced biasing state. While this approach has advantages in the analysis of complicated support structures and resonator geometries, it does not provide the designer with insight into the basic nature of the problem. As a consequence, the problems at hand have been analyzed from an analytical standpoint. The goal of this work has been not simply to calculate the SAW and STW acceleration sensitivities, but to do so in such a fashion as to obtain an understanding of the functional dependencies of the acceleration sensitivities upon real-world design and fabrication parameters.

**SAMPLE GEOMETRY**

The sample geometries for the cases considered here are shown in Figures 1 and 2. The substrate is a rotated Y-cut quartz plate with width 2a along the crystallographic X-axis, thickness 2h along the rotated Y-axis, and length 2b along the rotated Z-axis, with the axes denoted $X_1$, $X_2$, and $X_3$ respectively in the coordinate system of the plate. The substrate is considered to be simply supported along the edges, and an acceleration $a_3$ is applied parallel to the $X_3$ axis.

The SAW device is confined to the portion of the substrate denoted by regions I, II, and III in Figure 1a. The SAW metallization is considered to be on the face of
the plate located at $X_3 = -h$. The center of the SAW region is displaced from the center of the substrate by some small amounts denoted as $(\delta, \epsilon)$ along $(X_1, X_3)$.

The STW device is confined to the portion of the substrate denoted by regions I, II, and III in Figure 2a. The STW metallization is considered to be on the face of the plate located at $X_3 = -h$. The center of the STW region is displaced from the center of the substrate by some small amounts denoted as $(\delta, \epsilon)$ along $(X_1, X_3)$.

**SAW Acoustic Mode Shape**

The SAW mode considered here is a Rayleigh wave propagating along the $X_1$ direction with components of particle displacement along the $X_1, X_2,$ and $X_3$ directions. The amplitude of the SAW in the transducer region is taken to be uniform along the propagation direction, cosine along the transverse direction, and exponentially decaying into the substrate. The amplitude in the reflector regions is taken to include an exponential decay beginning at the transducer/reflector boundary, and is taken to be zero at the ends of the reflectors. The particle displacements may be succintly written using the general form [4-8]

$$u_j = \left[ \sum_{p=1}^{4} X_j^{(p)}(x_1) Y_j^{(p)}(x_2) \right] Z(x_3), \quad (9)$$

provided that we account for the different forms of $X_j^{(p)}(x_1)$ in the various regions:
Region I (transducers):

\[ X_j^{(p)}(x_1) = A_j^{(p)} \cos[\beta(x_1 - \delta)] + B_j^{(p)} \sin[\beta(x_1 - \delta)], \]
\[ \delta - s \leq x_1 \leq \delta + s, -h \leq x_2 \leq h, \varepsilon - w \leq x_3 \leq \varepsilon + w. \] (10)

Region II (r.h. reflector):

\[ X_j^{(p)}(x_1) = \left[ A_j^{(p)} e^{-\zeta_1(x_1 - (\delta + s))} + C_j^{(p)} e^{-\zeta_2(x_1 - (\delta + s))} \right] \]
\[ \times \cos[\beta(x_1 - (\delta + s))] \]
\[ + \left[ B_j^{(p)} e^{-\zeta_1(x_1 - (\delta + s))} + D_j^{(p)} e^{-\zeta_2(x_1 - (\delta + s))} \right] \]
\[ \times \sin[\beta(x_1 - (\delta + s))], \]
\[ \delta + s \leq x_1 \leq \delta + 1, -h \leq x_2 \leq h, \varepsilon - w \leq x_3 \leq \varepsilon + w. \] (11)

Region III (l.h. reflector):

\[ X_j^{(p)}(x_1) = \left[ A_j^{(p)} e^{\zeta_1(x_1 - (\delta - s))} + C_j^{(p)} e^{\zeta_2(x_1 - (\delta - s))} \right] \]
\[ \times \cos[\beta(x_1 - (\delta - s))] \]
\[ + \left[ B_j^{(p)} e^{\zeta_1(x_1 - (\delta - s))} + D_j^{(p)} e^{\zeta_2(x_1 - (\delta - s))} \right] \]
\[ \times \sin[\beta(x_1 - (\delta - s))], \]
\[ \delta - 1 \leq x_1 \leq \delta - s, -h \leq x_2 \leq h, \varepsilon - w \leq x_3 \leq \varepsilon + w \] (12)

Region IV:

\[ X_j^{(p)}(x_1) = 0, \text{ elsewhere.} \] (13)

In addition, we take

\[ Y_j^{(p)}(x_2) = \exp[-\xi p(x_2 + h)] \] (14)

and

\[ Z(x_3) = \cos[\chi(x_3 - \varepsilon)]. \] (15)

everywhere. In practice, the \( C_j^{(p)} = D_j^{(p)} = 0 \), and the forms of \( X_j^{(p)}(x_1) \) in regions II and III simplify accordingly.

**STW Acoustic Mode Shape**

The STW mode considered here is a horizontal shear wave propagating along the \( X_1 \) direction with particle displacements polarized along the \( X_1 \) direction. The amplitude of the STW in the transducer region is taken to be uniform along the propagation direction, cosine along the transverse direction, and exponentially decaying into the substrate. The amplitude in the reflector regions is taken to include an exponential decay beginning at the transducer/reflecter boundary, and is taken to be zero at the ends of the reflectors. For the \( u_1 \) particle displacement, we thus consider four regions:

Region I (transducers):

\[ u_1^I = M \cos[\chi(x_1 - \delta)] \exp[-\xi(x_2 + h)] \cos[\beta(x_3 - \varepsilon)], \]
\[ \delta - w \leq x_1 \leq \delta + w, -h \leq x_2 \leq h, \varepsilon - s \leq x_3 \leq \varepsilon + s. \] (16)

Region II (r.h. reflector):

\[ u_1^{II} = u_1^I \exp[-\xi(x_3 - (\varepsilon + s))]. \]
\[ \delta - w \leq x_1 \leq \delta + w, -h \leq x_2 \leq h, \varepsilon + s \leq x_3 \leq \varepsilon + 1. \] (17)

Region III (l.h. reflector):

\[ u_1^{III} = u_1^I \exp[+\xi(x_3 - (\varepsilon - s))]. \]
\[ \delta - w \leq x_1 \leq \delta + w, -h \leq x_2 \leq h, \varepsilon - l \leq x_3 \leq \varepsilon - s \] (18)

Region IV:

\[ u_1^{IV} = 0, \text{ elsewhere.} \] (19)

In addition, we take \( u_1^1 = u_1^3 = 0 \) everywhere.
FLEXURAL BIASING STATE IN THE ROTATED Y-CUT QUARTZ PLATE SIMPLY SUPPORTED ALONG RECTANGULAR EDGES

The flexural biasing state in the rotated Y-cut quartz plate simply supported along rectangular edges has been determined by Shick and Tiersten [1]. The zeroth order, \( X_2 \)-component of the flexural deformation is given by a Fourier series expansion:

\[
 w^{(0)}_2 = \sum_{\text{odd } m} \sum_{\text{odd } n} A_{mn} \cos(\alpha_m x_1) \cos(\kappa_n x_3),
\]

where

\[
 \alpha_m = \frac{m \pi}{2a},
\]

\[
 \kappa_n = \frac{n \pi}{2b},
\]

\[
 A_{mn} = -\frac{48 \rho_a}{h^2 \kappa_n^2 R_{mn}},
\]

and

\[
 R_{mn} = \gamma_{11}\alpha_m^4 + \gamma_{33}\kappa_n^4 + (2\gamma_{13} + 4\gamma_{55})\alpha_m^2\kappa_n^2,
\]

where

\[
 \gamma_{RS} = c_{RS} - c_{RW}\frac{1}{c_{WW}} c_{VS}.
\]

Note that equation (25) is a matrix equation, with \( R,S=1,3,5 \) and \( W,V=2,4,6 \). Analytic expressions for all of the biasing deformation gradients are then obtained from the zeroth order \( X_2 \) deformation as:

\[
 w_{1,1} = \begin{bmatrix} w^{(0)}_{2,11} \end{bmatrix} \cdot x_2,
\]

\[
 w_{1,2} = -w^{(0)}_{2,1} - 2\left[ P_{31} w^{(0)}_{2,11} + P_{32} w^{(0)}_{2,233} + P_{33} w^{(0)}_{2,13} \right] \cdot x_2,
\]

\[
 w_{1,3} = \begin{bmatrix} w^{(0)}_{2,13} \end{bmatrix} \cdot x_2,
\]

\[
 w_{2,1} = w^{(0)}_{2,1},
\]

\[
 w_{2,2} = \left[ P_{11} w^{(0)}_{2,11} + P_{12} w^{(0)}_{2,33} + P_{13} w^{(0)}_{2,13} \right] \cdot x_2,
\]

\[
 w_{2,3} = w^{(0)}_{2,3},
\]

\[
 w_{3,1} = \begin{bmatrix} w^{(0)}_{2,13} \end{bmatrix} \cdot x_2,
\]

\[
 w_{3,2} = -w^{(0)}_{2,23} - 2\left[ P_{21} w^{(0)}_{2,11} + P_{22} w^{(0)}_{2,233} + P_{23} w^{(0)}_{2,13} \right] \cdot x_2.
\]

NET BIASING TERMS (C-HAT'S)

In order to compare the acceleration sensitivities of the SAW and STW modes, it is convenient to develop a general expression for the c-hat terms to be evaluated. Equations (20) through (35) are substituted into equation (6), and after a few algebraic manipulations yield

\[
 \hat{c}_{LY,M} = \sum_{\text{odd } m} \sum_{\text{odd } n} A_{mn} \left[ E_{LY,M} \alpha_m^2 + F_{LY,M} \kappa_n^2 \right] \cos(\alpha_m x_1) \cos(\kappa_n x_3) \\
 - A_{mn} \left[ G_{LY,M} \sin(\alpha_m x_1) \cos(\kappa_n x_3) \right] \\
 - A_{mn} \left[ H_{LY,M} \alpha_m \sin(\alpha_m x_1) \sin(\kappa_n x_3) \right] \\
 - A_{mn} \left[ I_{LY,M} \kappa_n \cos(\alpha_m x_1) \sin(\kappa_n x_3) \right]
\]

1995 IEEE ULTRASONICS SYMPOSIUM — 191
where we have defined the quantities

\[ E_{LYMa} = k_{LYMa11} + P_{11} k_{LYMa22} + 2P_{21} k_{LYMa23} + 2P_{31} k_{LYMa21} \]

\[ F_{LYMa} = k_{LYMa33} + P_{12} k_{LYMa22} + 2P_{22} k_{LYMa23} + 2P_{32} k_{LYMa21} \]

\[ G_{LYMa} = k_{LYMa12} - k_{LYMa21} \]

\[ H_{LYMa} = k_{LYMa13} + k_{LYMa31} + P_{13} k_{LYMa22} + 2P_{23} k_{LYMa23} + 2P_{33} k_{LYMa21} \]

and

\[ I_{LYMa} = k_{LYMa32} - k_{LYMa23} \]

**NET NORMAL ACCELERATION SENSITIVITY**

The c-hat terms given by equations (36) through (41), along with the relevant normalized mode shape displacement gradients calculated using equations (4), (5), and (9) through (19), are substituted into equation (8) in order to obtain expressions for the normal acceleration sensitivities. After some tedious but tractable integral calculus, followed by some algebraic manipulations, equation (8) yields a relatively simple expression for the STW case,

\[ \Gamma_2 = \sum_{m \text{ odd}} \sum_{n \text{ odd}} \eta_{mn} \]

where

\[ \eta_{mn} = \frac{1}{2\pi^2} \frac{\cos(\alpha_m \xi) \cos(\kappa_n \xi)}{\gamma_{13}^2 \nu_4 b^2 + (\nu_m \nu_{13}^2 / \gamma_{11}) b^2} \]

\[ + \left[ \frac{2\sin(\alpha_m \xi) + \sin(2\alpha_m \xi) \sin(2\xi - \alpha_m \xi)}{(\alpha_m \xi)} \right] \]

\[ + \left( \frac{1}{h} \frac{1 - 2g \cdot \coth(2g \xi)}{2g \xi} \right) \]

\[ + \left[ \frac{2\sin(\kappa_n \xi) + \sin(2\beta + \kappa_n \xi) \sin(2\xi - \beta - \kappa_n \xi)}{\kappa_n \xi} \right] \]

\[ + \left( \frac{2\cos((2\beta + \kappa_n \xi) - (2\xi - \beta - \kappa_n \xi)) \sin((2\beta + \kappa_n \xi) - (2\xi - \beta - \kappa_n \xi))}{4\xi^2 + (2\beta + \kappa_n \xi)^2} \right) \]

\[ + \left[ \frac{1 + \frac{1}{2\xi^2} + \frac{\beta \xi}{(\beta^2 + \xi^2)} \cos(2\beta s) + \frac{\xi^2}{(\beta^2 + \xi^2)} \sin(2\beta s)}{2\beta s} \right]^{-1} \]

+ 12 other smaller terms.

A similar but somewhat more lengthy expression is obtained for the SAW case, with, of course, the propagation and transverse direction variables interchanged, and with summations extending over the full range of partial waves and particle displacement components.

**DEPENDENCIES OF \( \Gamma_2 \) UPON SUBSTRATE PARAMETERS**

The functional forms given, for example, by equation (43), clarify the dependencies of the normal acceleration sensitivity on various quantities of importance in the design and fabrication of SAW and STW resonators. Two distinct design paradigms are found which lead to low normal acceleration sensitivity: 1) the aspect-ratio compensation paradigm in which control of the substrate length to width ratio is used to obtain low normal acceleration sensitivity, and 2) a non-
aspect-ratio compensation paradigm wherein the plate area is minimized and plate thickness is maximized to obtain low normal acceleration sensitivity.

**Substrate Material Properties**

The acceleration sensitivities of both SAW and STW resonators are determined in part by the choice of substrate material through the values of various material constants.

\[ \Gamma_2 \] is directly proportional to a sum of linear and nonlinear stiffnesses, which essentially govern the sensitivities to effective cavity length and wave velocity changes respectively.

\[ \Gamma_2 \] is directly proportional to material mass density, as this contributes to the magnitude of the body force developed in response to the acceleration.

As expected, \[ \Gamma_2 \] is inversely proportional to the linear stiffnesses controlling the flexure of the plate.

**Substrate Orientation**

\[ \Gamma_2 \] reflects the angular dependence of the linear and nonlinear elastic stiffnesses involved. As a consequence, the optimum design for low acceleration sensitivity varies slightly with cut angle.

**Substrate Length**

For non-optimum aspect ratio, \[ \Gamma_2 \] has a net proportionality to the square of the lateral dimensions (essentially, proportional to substrate area).

**Substrate Width**

Similar to substrate length.

**Substrate Thickness**

As expected, \[ \Gamma_2 \] is inversely proportional to substrate thickness. Note that this is essentially the same effect seen in, for example, Figure 7 of [9].

**Aspect Ratio (a/b)**

Aspect ratio compensation arises from the fact that certain cofactor combinations have opposite signs. For example, the required aspect ratio for an STW resonator is dominated by the first term of equation (43) and may be estimated using

\[
\sum_{m \text{ odd}} \sum_{n \text{ odd}} \left( \frac{m}{n} \right) E_{311}^2 b^2 + \left( \frac{n}{m} \right) F_{311}^2 a^2 \right) \approx 0.
\]

The exact value of the optimum aspect ratio for a given substrate orientation, substrate thickness, etc. depends in detail upon the other smaller terms (several pages worth) whose functional dependencies are not the same as those of the first term.

The net normal acceleration sensitivity achievable using aspect ratio compensation is directly proportional to the dimensional tolerances achievable in production.

**DEPENDENCIES OF \( \Gamma_2 \) UPON MODE SHAPE PARAMETERS**

It is by now well known that the acceleration sensitivity has an important dependence upon the offset of the mode shape center with respect to the center of the plate [10]. The functional forms given, for example, by equation (43) provide important insights into this and other dependencies. In particular, the acceleration sensitivity of an acoustic resonator is determined in part by the type of acoustic mode chosen, as the choice of mode type determines the relevant material constants.

**Wave Velocity**

\[ \Gamma_2 \] is inversely proportional to the square of the wave velocity. For a given substrate with all other factors being equal, higher velocity modes have inherently superior acceleration sensitivity.

**Mode Shape Envelope**

The acoustic standing waves of the SAW and STW resonators exist within amplitude envelopes as described in equations (9) through (19). The functional forms given, for example, by equation (43) indicate that spatial variations of the mode shape envelope do not dominate and hence cannot be used to minimize the net normal acceleration sensitivity.

\[ \Gamma_2 \] has a moderately strong (factor of 1/3) but complicated dependence upon the propagation direction cross-section of the mode shape envelope, which in turn depends upon the details of transducer, cavity, and reflector design.
\( \Gamma_2 \) is independent of the transverse cross-section of the mode shape envelope (transverse cosine order).

\( \Gamma_2 \) has a slight dependence on the ratio of acoustic aperture to substrate width.

\( \Gamma_2 \) has a weak dependence on the penetration depth into the bulk of the substrate.

**Mode Center Offset**

The dominant term given, for example, in equation (43) is proportional to the cosines of the in-plane offsets along both \( X_1 \) and \( X_2 \) axes. In the design paradigm where aspect-ratio compensation is not used, the largest SAW or STW acceleration sensitivities occur for the mode shape exactly on center.

The other smaller terms noted, for example, in equation (43) have various combinations of sine and cosine proportionalities to the in-plane offsets. As a consequence, when aspect-ratio compensation is employed, the net normal acceleration sensitivity is minimized for the mode shape exactly on center.

In the aspect-ratio compensation paradigm, the residual sensitivities to offsets along the \( X_1 \) and \( X_2 \) axes are of different signs and of different magnitudes, leading to an X-shaped locus of allowed mode shape centers for minimum normal acceleration sensitivity. For a given non-zero \( \Gamma_2 \), the direction in which the mode shape center needs to be moved to minimize \( \Gamma_2 \) is readily determined from the sign of the vector component.

**COMPARISON TO RECENT EXPERIMENTAL RESULTS**

A comparative study of the acceleration sensitivities of 360 MHz SAW and STW two-port resonators fabricated using the same rotated Y-cut quartz substrate has been reported recently by Huynh, et al. [11]. Figures 3 and 4 present a comparison for SAW and STW respectively of the measured acceleration sensitivities reported in [11] and values calculated using, for example, equation (43).

Huynh, et al., reported that a quasi-uniform mounting configuration yielded the lowest normal acceleration sensitivities for both SAW and STW resonators. This finding is consistent with the fundamental nature of the problem; a uniform, rigid
mount admits no flexural deformation and hence allows only a negligible acceleration sensitivity due to thickness compression and Poisson's ratio effects. For both SAW and STW, the net normal acceleration sensitivity where flexure is allowed varies strongly with aspect ratio.

Using a 14 mm support frame with a 1:1 aspect-ratio, Huynh, et al. found that the STW resonators performed only marginally better than the SAW resonators. The calculated acceleration sensitivities are both on the order of $1 \times 10^{-9}$ per $g$ for this case.

**CONCLUSIONS**

Closed-form expressions for the normal acceleration sensitivities of SAW and STW resonators using thin, rotated Y-cut quartz plates simply supported along rectangular edges has been derived. From the closed-form expressions, the functional dependencies of the normal acceleration sensitivities of SAW and STW resonators have been determined. It has been shown that the functional dependencies of both SAW and STW acceleration sensitivities are of essentially the same form, differing only in details such as specific material constants of interest, etc. The most important parameters for obtaining low acceleration sensitivity are found to be the substrate dimensions and dimensional tolerances.

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