

TECHNIQUE FOR MEASURING THE ACCELERATION  
SENSITIVITY OF QUARTZ RESONATORS

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SUMMARY

We present a simple method for measuring the acceleration sensitivity of quartz resonators. This method utilizes readily available electronic components and the voltage-frequency effect in doubly-rotated cuts, or a simple VCO for singly-rotated cuts, to determine both phase and magnitude information. The method is based on monitoring vibration-induced FM sidebands of an oscillator with a spectrum analyzer while applying acceleration compensation. An op amp circuit with reversible polarity is used to supply a compensation signal which is proportional to an accelerometer output. Since the goal is to observe a reduction or increase in FM sideband magnitude, the phase and magnitude requirements of the compensation circuit are less than that required for high level compensation.

Examples will be given of the method. Typical reductions or enhancements of 6 to 20db can be seen easily and are sufficient to establish the absolute phase (sign) of each gamma vector component. Data is presented to show that acceleration sensitivities of  $1E-10/g$  can be measured with confidence.

INTRODUCTION

The acceleration sensitivity of quartz resonators arises from the stresses caused by the mass of the resonator blank reacting against the resonator mounting structure during acceleration. A common method of representing the acceleration sensitivity is by the gamma vector, made up of the frequency shifts observed for unit acceleration in three orthogonal axes[1]. Typical numbers for the components of the gamma vector range from low  $E-9/g$  to mid- $E-10/g$ . The acceleration-induced frequency response of a resonator is then the dot product of the gamma vector and the applied acceleration. In research and development, a measurement technique for the gamma vector is required for a wide range of frequencies, resonator configurations, and overtone operation. Often measurements must be done on unsealed devices: the Q will typically be lower, and the resistance higher, than under ideal, sealed conditions. Many situations require knowing both the magnitude and the direction of the gamma vector. These include anticipation of using various compensation techniques such as opposed-pair compensation, accelerometer feedback compensation, and spring/mass compensating systems[1]. Also, when applying theories regarding the acceleration performance of a device, a full description of the gamma vector is needed.

Measurement techniques commonly used have a number of disadvantages which make them less than ideal in R & D environments. A method commonly used is observing, with a spectrum analyzer, the FM sidebands generated by sinusoidal acceleration of the crystal under test[2]. With this method, one is able to obtain the magnitude, but not the phase, of the gamma vector. Another common method is FM demodulation[3]. This technique requires virtually noise free demodulation circuitry to detect sensitivities as low as  $1E-10/g$ . The voltage controlled oscillators used in such circuitry usually have a small frequency range over which they are useful. Retooling for crystals of varying frequencies can become time consuming and expensive. Another method which is used is the 2-g tip-over test. Because of the small frequency shifts involved, an extremely stable temperature environment and a high resolution counter is necessary to obtain useful results for crystals with low sensitivities. However, the 2-g tip-over test does provide the sign (phase) of the gamma vector. The reader is referred to Filler's tutorial on acceleration effects on crystals[1] for more details.

Errors can occur in the measurement of small gamma components in the low  $E-10/g$  to high  $E-11/g$  range. The errors are related to cable reactance modulation due to vibration of power cables and signal cables passing to and from the shaker table. The problem was observed in varying degrees for all the different methods tried in this work.

Presented here is a versatile method of determining both the magnitude and direction of the gamma vector for crystals with a broad range of frequencies. The equipment used is readily available laboratory equipment. Cable modulation effects are addressed.

#### THEORETICAL BASIS

When a crystal is under vibration, its resonant frequency is shifted due to stresses induced by the interaction of the resonator blank and its mounting structure. The frequency shift  $df_a$  is proportional to the acceleration. The frequency/voltage effect of an SC cut crystal (or other doubly rotated crystals) also results in a shift of the resonant frequency ( $df_v$ )[4]. If the applied voltage and the acceleration are correlated such that  $df_v$  and  $df_a$  are equal in magnitude but opposite in sign, an apparent decrease in the g-sensitivity of the device can be observed. This effect has been used previously by Rosatti and Filler as a compensation technique[5].

In the case of singly-rotated quartz cuts, such as the AT-cut, that do not have a voltage-frequency effect, a voltage controlled phase shift network may be used to modulate the frequency of oscillation.

As discussed recently[6], the phase relationship between the acceleration and the applied compensation signal must be accurately controlled near  $180^\circ$  to achieve compensation. Figure 9 shows a theoretical plot of how much sideband suppression can be accomplished for phases approaching  $180^\circ$  as the ratio  $df_v/df_a$  is varied. In order to observe a significant decrease in g-sensitivity, the amplitude and phase of the compensating signal must match the amplitude and phase of the acceleration effect of the device quite closely. Assuming precise amplitude control, the phase of the compensating signal must match the phase of the acceleration effect to within  $+/-5$  degrees to achieve 20db sideband reduction. We have found that 10-20 db is adequate to identify the phase of  $df_v$  that reduces the acceleration-induced  $df_a$  sideband.

Logically, if the quartz crystal is turned upside down, the gamma vector component should be equal in magnitude and opposite in sign for the two orientations. This has never occurred in any experiment we have tried when dealing with gamma responses below 2E-10/g. We attribute this to the fact that the cables passing to and from the shaker, no matter what test configuration is used, are modulated by the vibration. The cable vibration sinusoidally detunes the oscillator, to varying degrees, depending upon the test configuration and the Q of the crystal or circuit under test. This creates an effect that adds vectorially to the gamma vector being studied, and is therefore a source of error. (In the configuration to be described this effect is repeatable, and on the order of 1E-10/g at 50 MHz. The effect is much less significant at lower frequencies. When testing the same crystal either in the setup described herein or when shaking the complete oscillator circuit, some cable effects are observed.)

The present experimental equipment and procedures are based on holding cable effects constant and measuring the crystal both right side up and upside down. Since the cable effects add primarily in-phase or out-of-phase with the acceleration effect of the crystal, the algebraic average of the two readings is approximately equal to the crystal effect, with the cable effect cancelling. In other words, if  $df_c$  is the cable effect, and assuming it is additive to the  $df_a$  in the +x direction, it will be subtractive from the  $df_a$  measured in the -x direction. The measured  $df$  is, thus

$$df(+x) = df_c + df_a \quad [1]$$

$$df(-x) = df_c - df_a \quad [2]$$

and the desired  $df_a$  is given by

$$df_a = [df(+x) - df(-x)]/2. \quad [3]$$

#### EQUIPMENT USED

A block diagram of the test system is shown in Figure 1. The test equipment used includes a LING Electronics Inc. model 203B shaker table driven by a variable frequency audio oscillator and an audio amplifier. Attached to the shaker is a fixture for mounting the crystal in any of 6 directions (+/- X,Y,Z).

Figure 2 shows the crystal fixture. Rigid wiring is used inside the cube to minimize motion during vibration. The cube can be turned over to test all six axes. The cables running to the shaker are carefully fixed so that their effects remain constant, allowing cancellation using Equation 3 above.

A Saunders & Associates 100HF CI meter was chosen as the oscillator circuit in order to drive crystals with a broad range of frequencies and impedances. It is connected to the crystal through a pair of coaxial cables clamped at both ends. Figure 2 shows a block diagram of the oscillator, cable, and filter used with SC-cuts. Figure 3 shows the phase shift network used for AT-cuts. The phase shift network can also be used with SC-cuts, but is not preferred because of its susceptibility to power supply noise. The output of the oscillator is observed on an HP3585A spectrum analyzer. High frequency crystals (greater than

40 MHz) require a mixer with a relatively low noise reference oscillator (HP3325A Frequency Synthesizer) to shift the signal to a frequency within the operating range of the spectrum analyzer.

The compensation signal is obtained from an accelerometer mounted on the fixture that holds the crystal. (The shaker table driving signal may also be used for compensation as long as the phase requirements previously mentioned are satisfied.) The signal is fed through a variable gain op-amp circuit with switch selectable polarity and an option to apply a dc voltage. This op-amp circuit is shown in Figure 5. The output of this circuit is fed back to the crystal via the filter network of Figure 3 or the phase-shift network of Figure 4.

#### MEASUREMENT PROCEDURE

The crystal under test is clamped in the cube, which provides for easy, repeatable alignment of the crystal in any of 6 directions. The polarity of the frequency shift effect of a crystal is determined by observing a slight shift in frequency when a dc voltage is applied to either the crystal (doubly rotated case) or the phase shift network. The device is then shaken at approximately  $3g_{rms}$  and the sideband amplitudes are measured using the spectrum analyzer.

The phase of the gamma vector in the axis of vibration is measured by slowly increasing the level of compensation from zero while observing the sideband amplitude. Referring to Figure 9, if the compensation signal is of the correct phase to cancel the crystal's acceleration effect, the sideband amplitude will first decrease, and then increase. The opposite phase will show only an increase in sideband amplitude as shown in Figure 9 for  $0^\circ$  phase. Switching the phase of the compensation without changing its amplitude will result in a fairly large difference in the amplitude of the sideband peaks. By correlating this information with the polarity of the accelerometer output relative to the crystal acceleration, the magnitude and direction of the gamma vector component can be uniquely determined.

The polarity of the voltage frequency effect reverses when a doubly rotated crystal is turned upside down in our fixture because the pin polarity of the crystal is reversed, while the polarity of the compensating circuit stays the same. It is important to keep track of this! By referencing everything to the dc shift test, one can keep the signs straight. If the cable capacitance effect is predominant, the compensation amplifier circuit requires a polarity reversal when the doubly rotated crystal is inverted. In contrast, when the crystal acceleration effect predominates, no polarity reversal is needed because both the acceleration effect and voltage effect in the crystal change sign. In contrast, for crystals where the phase shift network is used, no polarity reversal is needed when the cable capacitance effect predominates but polarity reversal is needed when the crystal effect predominates as the crystal is reversed.

Measurements are made for opposing directions. The true answer (if cable effects are constant and in phase with the crystal acceleration effect) is found by using Equation 3.

## RESULTS

Several shaker frequencies were used to verify that no structural resonances occur in either the experimental fixturing or the crystal package. No structural resonances are observed from 30 Hz to 200 Hz in our fixturing.

When measuring small gamma vector components, one can see some variation with shaker frequency that we attribute to standing wave acoustic resonance in the cables. Figure 6 shows results for a crystal with a low Q (in air), where the cable modulation effects are larger than the acceleration effect in the crystal. Note that one would measure an erroneously high gamma value if only one orientation of the crystal was measured (either the open circles or filled circles of Figure 6). Also, one would erroneously conclude that there was a structural resonance. In fact, the true answer (x's in Figure 6) is approximately  $-6E-11/g_{rms}$  ( $-4E-11/g$ ), as seen by using Equation 3 with the two measurements at each shaker frequency.

Figure 7 shows a histogram of the gamma vector components measured for a group of 10 MHz, 3rd overtone, SC-cut, two-point mount crystals. Included in Figure 7 are theoretical results obtained using finite element modeling to calculate the stress in the quartz and the theoretical development of Tiersten[7] to calculate the frequency shift. The theoretical methods will be published later, but the comparison between the experimental average and the theory is excellent.

As a demonstration of the present experimental techniques, the magnitude of the full gamma vector is shown in Figure 8 before and after proprietary treatment of four of the resonators of Figure 7. Note that all four devices measure tightly around  $2.7E-10/g_{rms}$  or ( $1.9E-10/g$ ). This means that the technique described herein can consistently measure components on the order of  $1E-10/g$ .

## CONCLUSIONS

The method described for measuring the gamma-vector of quartz crystal resonators is quite practical in a research and development environment, and may be applicable to production facilities as well. The method is able to detect both the magnitude and phase of g-sensitivities less than  $1E-10/g$  in crystals having a variety of frequencies and designs. The measurement procedure is rapid and uses equipment readily available in most laboratories.

## ACKNOWLEDGEMENTS

The authors wish to thank Mr. Kevin Kelly for making the measurements described herein.

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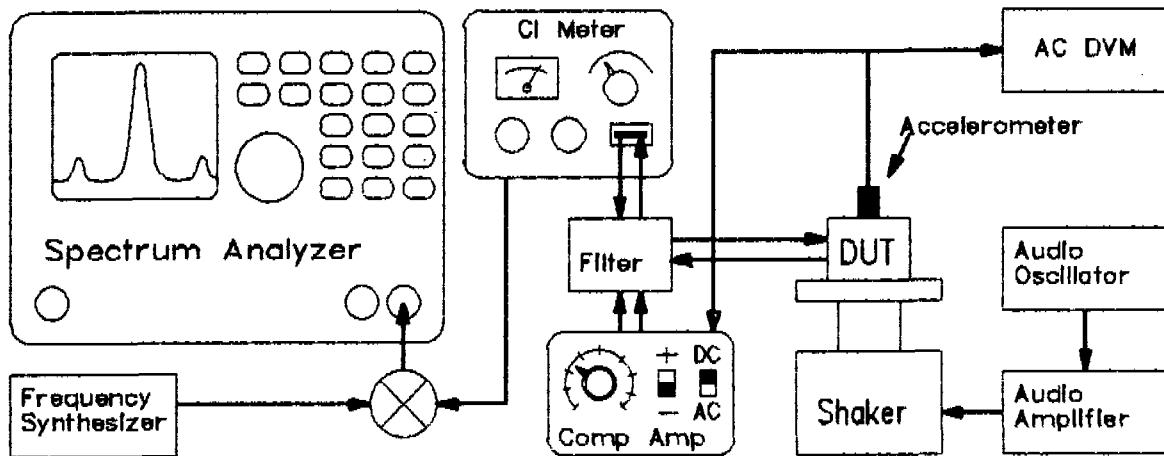


FIGURE 1. Block diagram of the test system used to determine the acceleration sensitivity of doubly-rotated quartz resonators. The spectrum analyzer is used to measure the magnitude of the sensitivity vector. Determining the polarity of compensation required for sideband suppression yields the absolute sign of the acceleration sensitivity vector.

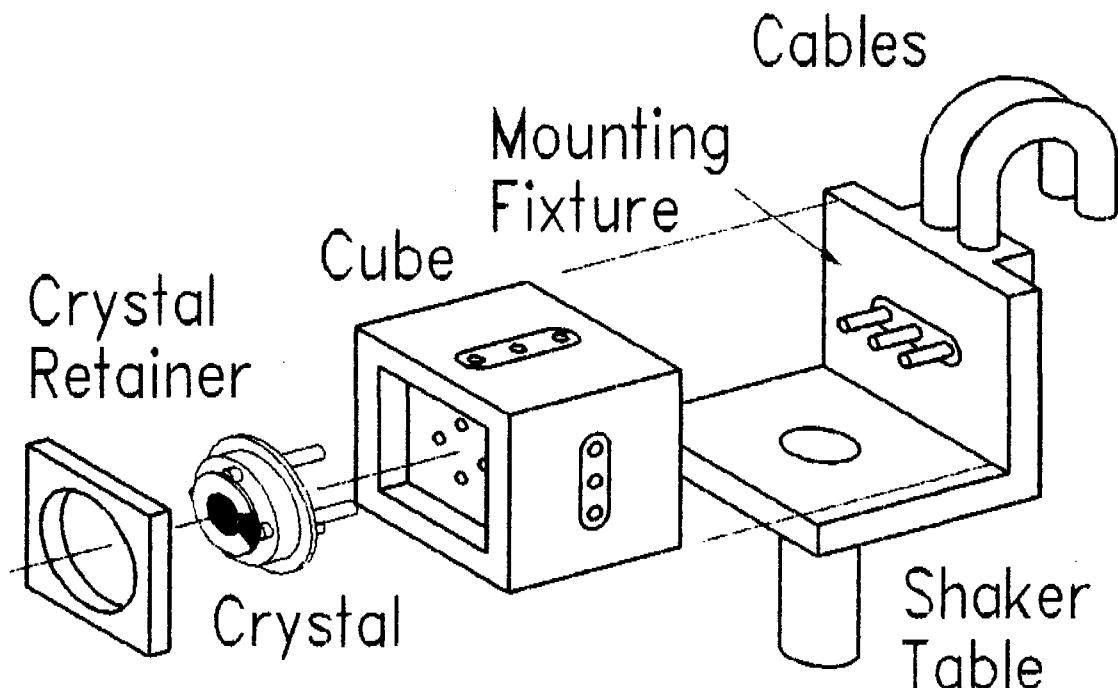


FIGURE 2. Fixture for measuring the acceleration sensitivity of quartz resonators. The crystal is secured in the cube, which can be rotated into  $+/- X, Y$ , and  $Z$  orientations. The cube is secured to the mounting fixture by a clamp (not shown). Cable effects are repeatable and do not change with cube orientation.

### ISOLATION FILTER NETWORK

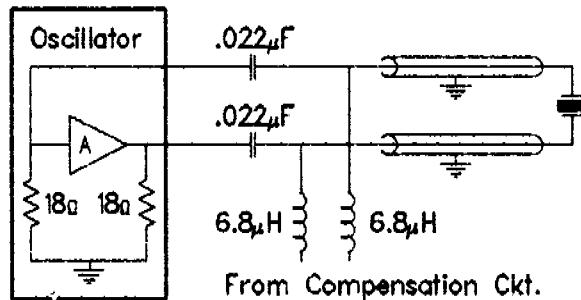


FIGURE 3. Typical filter network used with SC-cuts to isolate the oscillator from the compensation circuitry. Actual component values will vary depending on the crystal frequency and oscillator circuit used.

### PHASE SHIFT NETWORK

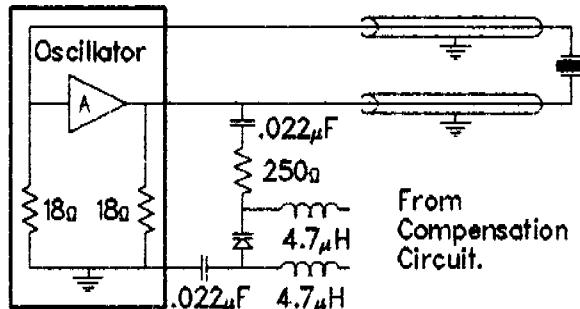


FIGURE 4. Typical phase shift network used for measuring AT-cut crystals. The varactor (SK332) reacts with the output resistance of the oscillator to modulate the phase of the circuit. The series resistor is used to reduce the sensitivity.

### COMPENSATION AMPLIFIER CIRCUIT

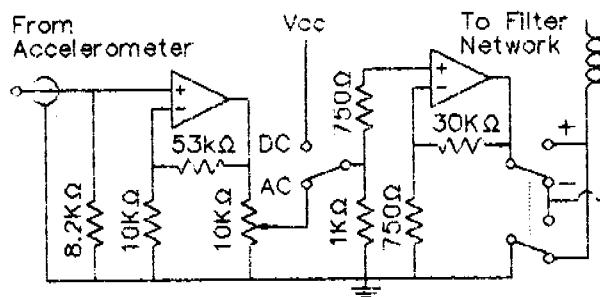


FIGURE 5. Simplified schematic of the compensation amplifier showing the buffer and gain stages, amplitude control, and switching schemes for phase reversal and D.C. voltage effect polarity checking.

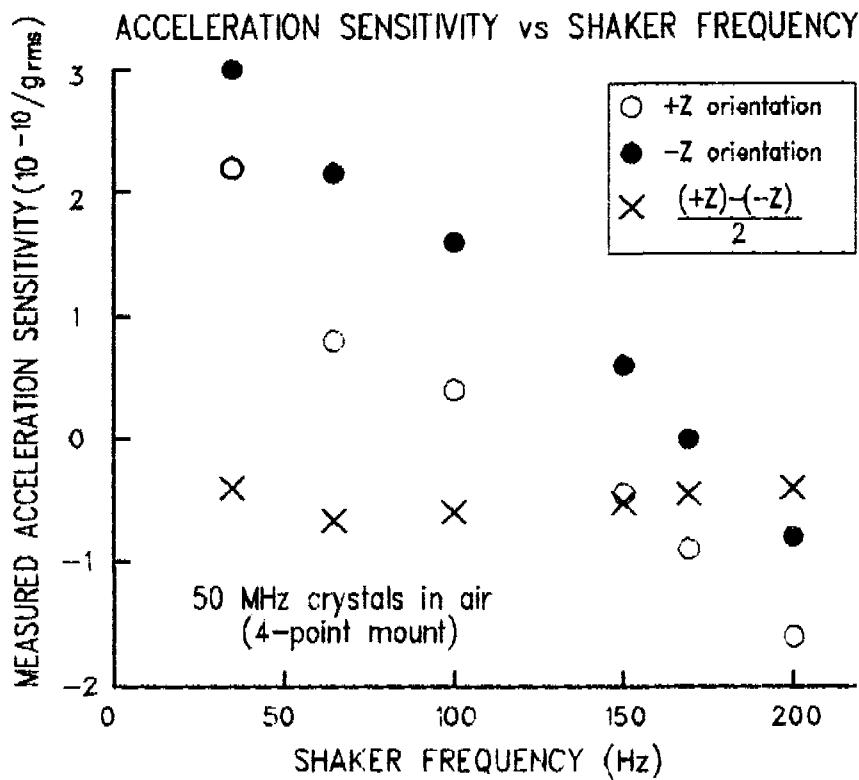


FIGURE 6. Measured acceleration sensitivity versus shaker table frequency for a 50 MHz, 4-point mount, SC-cut crystal. The effects of the cables are subtracted by measuring both + and - orientations for each axis. Note that once these cable effects are eliminated the measured acceleration sensitivity is independent of frequency.

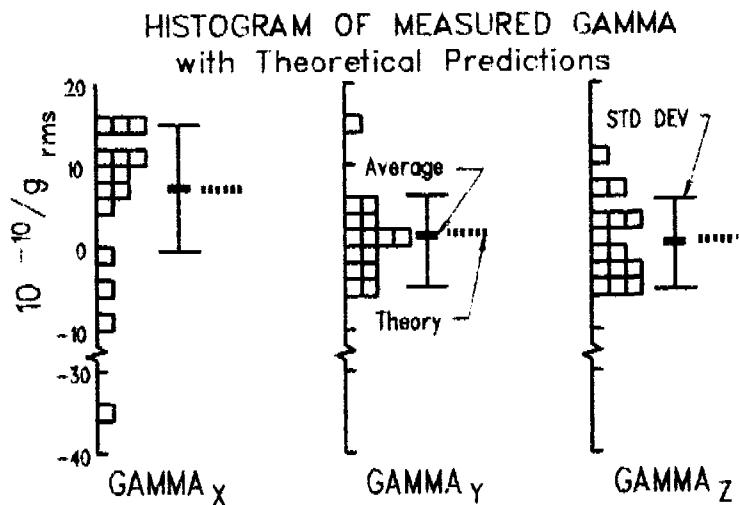


FIGURE 7. Histogram of gamma measured on each axis of 15 resonators (10 MHz, 3rd, SC-cut, 2-point mount.) Average and standard deviation of measured values are compared to analytically predicted values.

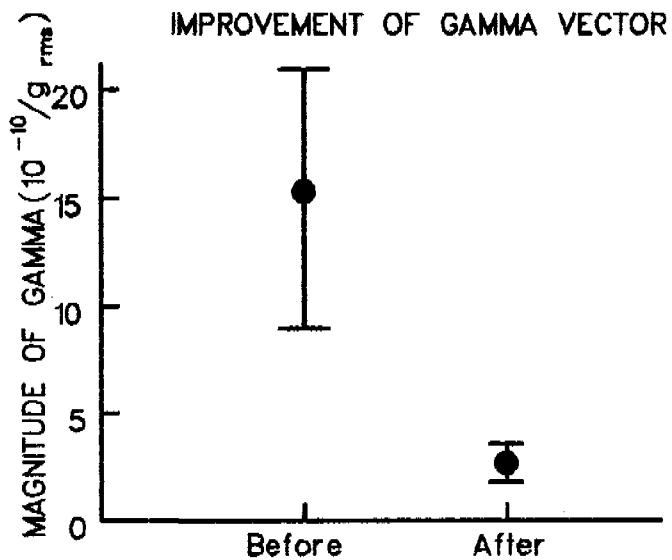


FIGURE 8. Improvement of gamma vector by proprietary processing. Mean and standard deviation of gamma vector magnitude of 4 units (10 MHz, 3rd, SC-cut, 2-point mount) before and after processing.

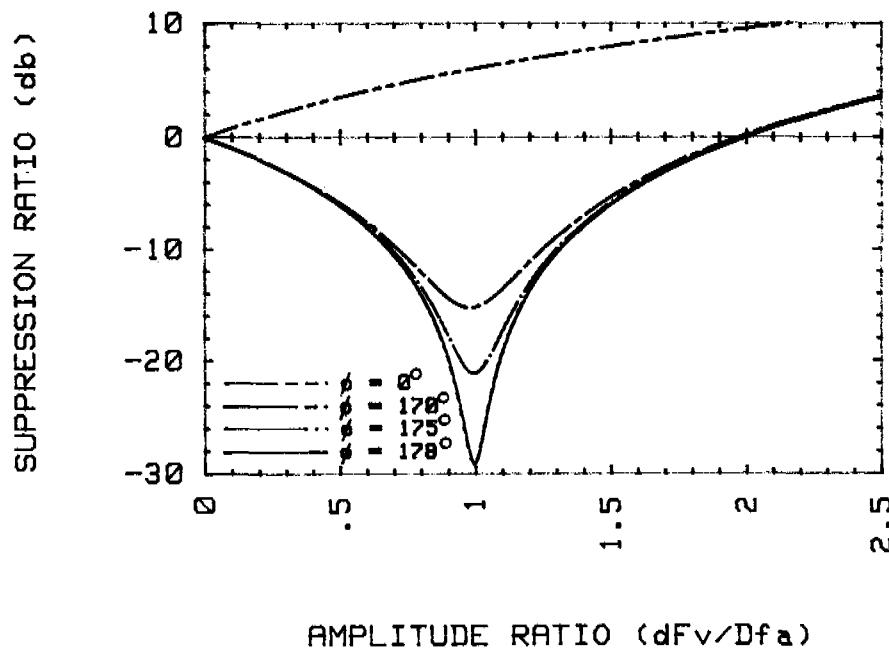


FIGURE 9. Maximum expected sideband suppression as a function of the amplitude ratio  $df_v/df_a$  of two sinusoidal modulating functions at various phase angles. Sideband suppression occurs when the phase of the acceleration effect and the voltage effect approach 180°. If the phase is close to zero, the two effects add, and no sideband suppression occurs.