Piezoelectric Resonators

Introduction

Ceramic resonators are piezoelectric ceramic devices that are designed to oscillate at certain frequencies. They are highly stable, small, inexpensive, and do not require tuning or adjusting. Other common resonant devices are quartz crystal and discrete LC/ RC resonators. Although ceramic resonators do not have as good a total oscillation frequency tolerance as quartz crystal resonators, they are much more frequency tolerant than LC or RC circuits, and smaller and cheaper than quartz.
Resonators are typically used with the clock circuitry found built-in to most microcontrollers to provide timing for the microcontrollers. The resonators by themselves cannot be clocks, because they are passive components (components that consume electrical energy). In order for a resonator to oscillate, an active component (a component that produces electrical energy) is needed. This active component is typically included in microcontrollers and is usually referred to as the clock circuit. There are prepackaged stand-alone oscillator circuits that have both the active and passive parts in one package. To explain, a discussion of oscillation principles is needed.

Principles of Oscillation

There are two main types of oscillating circuit, Colpitts and Hartley. These circuits are shown in Figure 5.

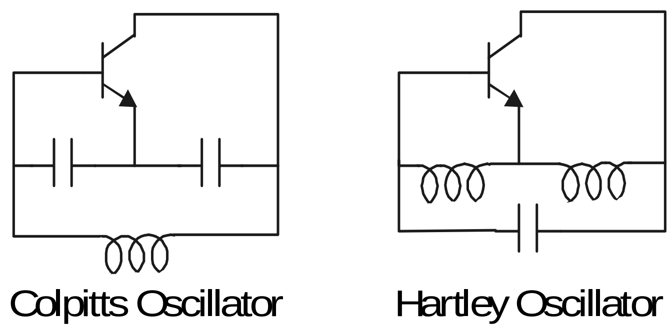

Figure 5: Colpitts and Hartley Oscillator

The Colpitts circuit is normally used (over the Hartley circuit) because it is cheaper and easier to have two capacitors and one inductor rather than two inductors and one capacitor. These circuits oscillate because the output is fed back to the input of the amplifier. Oscillation occurs when the following conditions are met (Barkhausen Criterion for oscillation): loop gain (α x β) $\geq$ 1 and phase $\phi = \phi_1 + \phi_2 = 360^o$ x n (n = 1, 2, 3, …). Figure 6 illustrates the idea of feedback oscillation.

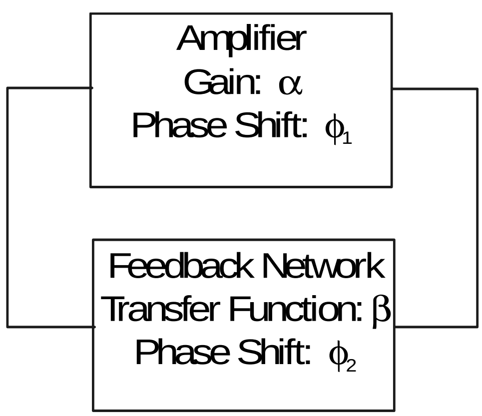

Figure 6: Block Diagram of Oscillator

Gain/Phase Conditions vs. Barkhausen Criterion

It is possible to look at the true gain and phase response of an oscillation circuit. This is different from the loop gain we refer to when talking about Barkhausen criterion. True gain / phase measurement is done by breaking open the oscillation circuit and measuring the gain and phase response of the circuit using a gain/phase analyzer or a signal generator with a vector voltmeter. Such measurement can provide a very accurate picture as to whether or not the oscillation circuit will actually oscillate.

As an example of the measured gain/phase results, the circuit gain/phase response shown in Figure 7a can oscillate because it has a gain greater than 0dB at the zero crossing point of the phase. The circuit gain/phase response in Figure 7b will not oscillate because the gain is less than 0dB when the phase crosses zero. A gain greater than 0dB is needed when the phase crosses the 0 degree axis in order for oscillation to occur.

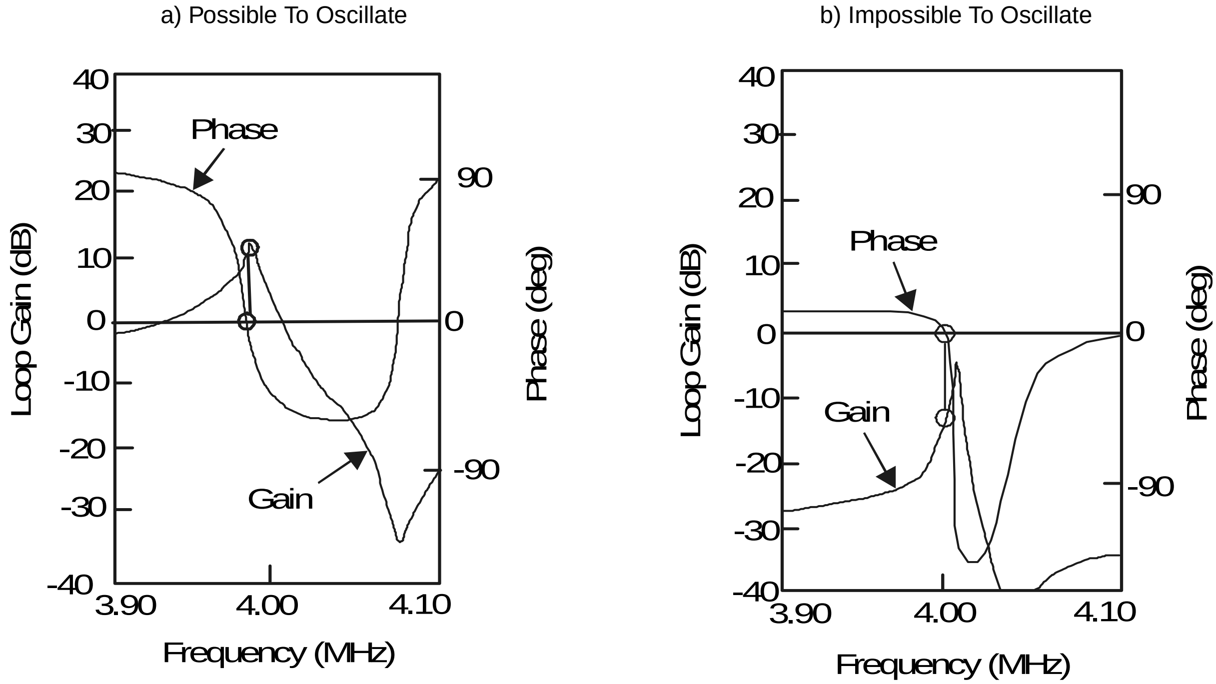

Figure 7: Gain - Phase Plots for Possible and Impossible Oscillation

The circuit in Figure 8 is the circuit used for these gain phase measurements. The oscillation circuit is broken open and a signal generator applies a range of frequencies to the inverter (amplifier). At the output of the circuit (after the resonator / feedback network), a vector voltmeter is used to measure gain and phase response at each frequency.

As mentioned in the example above, the gain must be greater than 0dB where the phase crosses the zero degree axis. Sometimes the loop gain of the Barkhausen criterion is confused for this gain condition (greater than 0dB). In the previous section, it was mentioned that for Barkhausen criterion to be met, loop gain ($\alpha \times \beta$) must be greater than or equal to one (($\alpha \times \beta$) ≥ 1). This may sound like a contradiction when we mention that the gain/phase measurement must be at least 0dB for oscillation to occur. Why is one loop gain at 1 and the other at 0?

The reason for this confusion is that Barkhausen $\alpha \times \beta$ is a unitless quantity and not a decibel measurement (like the loop gain in a gain/phase measurement). Both conditions really say the same thing, but in two different ways. The expression for calculating loop gain (in decibels) is $10\log(V_2/V_1)$, where V_2 is output voltage and V_1 is input voltage. α and β are actually gain multiplying factors and are unitless. Since the oscillation circuit is broken open, as shown in Figure 8, the voltage from the frequency generator is passed through the amplifier (multiplied by α), passed through the feedback network (multiplied by β), and passed through the vector voltmeter. From this, you can use the following expression to show what V_2 is in terms of V_1, α, and β: $V_2=V_1 \times \alpha \times \beta$. This can be re-written into this form: $V_2/V_1= \alpha \times \beta$, and substituted in to the decibel loop gain equation: Gain (dB) = $10\log(\alpha \times \beta)$.

This equation is a key point. From Barkhausen criterion, $\alpha \times \beta$ must be 1 for oscillation to occur. If 1 is substituted into the new equation: dB = 10log(1), the dB calculation will equal 0dB.

For oscillation to occur Barkhausen criterion must be meet ($\alpha \times \beta$) ≥ 1, which is the same as saying the loop gain measurement must be ≥ 0 dB (at the zero crossing of the phase).

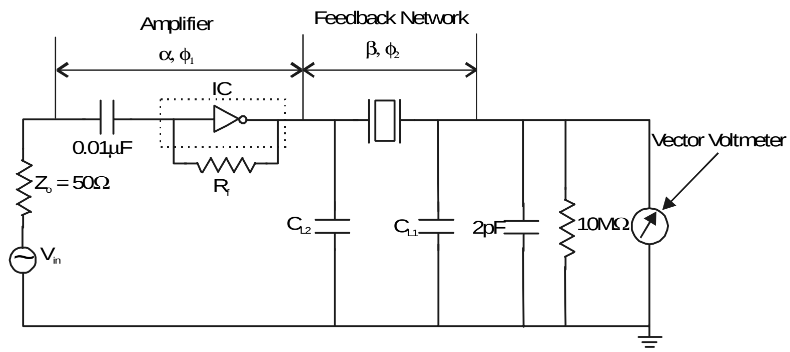

Figure 8: Gain - Phase Test Circuit

How Does It Work

Why Resonators

The most common use of a resonator, ceramic or quartz crystal, is to take advantage of the fact that the resonator becomes inductive between the resonant and anti-resonant frequencies (see Figure 9), which allows replacement of the inductor in the Colpitts circuit.

Ceramic Resonator Basics

A ceramic resonator utilizes the mechanical vibration of the piezoelectric material. Figure 9 shows the impedance and phase characteristics of a ceramic resonator. This plot of impedance and phase is made using a network analyzer, sweeping the resonator around it's oscillation frequency. The graphs show that the resonator becomes inductive between the resonant frequency, f_r, and the anti-resonant frequency, f_a. This means that the resonator can resonate (or the oscillator using the resonator can oscillate) between these two frequencies.

Figure 9 also shows that the minimum impedance for the resonator occurs at f_r (called the resonant impedance) and the maximum impedance occurs at f_a (called the anti-resonant impedance). At most other frequencies, the resonator is capacitive, but there are other frequencies at which the part is inductive (referred to as overtones). Since the resonator appears to be an inductor (with some small series resistance) at the resonant frequency, we can use this part to replace the inductor shown in the Colpitts oscillator in Figure 5. You will want to replace the inductor with a resonator that resonates at the desired frequency.

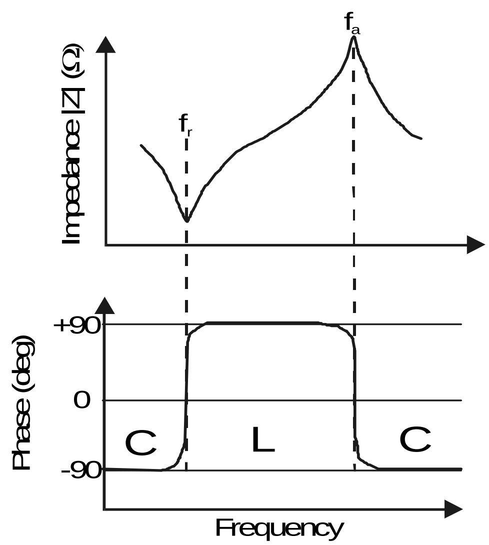

Figure 9: Resonator Impedance and Phase Plot

The Resonator Circuit Model

Looking at the resonator's characteristics we see an equivalent circuit for the resonator consisting of a capacitor (C_1), inductor (L_1), and resistor (R_1) in series and a capacitor (C_o) in parallel (Figure 10).

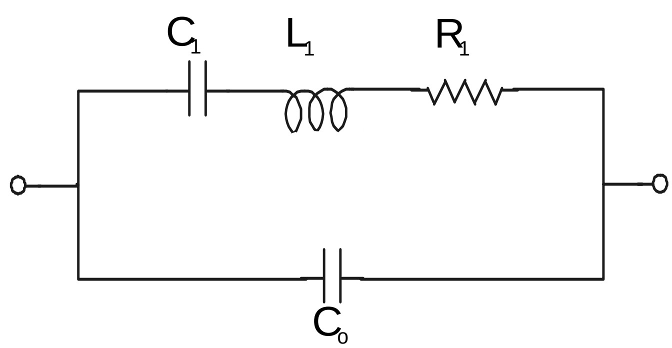

Figure 10: Equivalent Circuit Model for Two Terminal Ceramic Resonator

If the equivalent circuit values are known, then we can use this circuit to calculate the values of f_r, f_a, ΔF and Q_m using the following equations:

$$f_r = \frac{1}{2\pi\sqrt{L_1 C_1}} \qquad f_a = \frac{1}{2\pi\sqrt{\frac{L_1 C_1 C_o}{C_o + C_1}}} \qquad \Delta F = f_a - f_r \qquad Q_m = \frac{1}{2\pi f_r C_1 R_1}$$

Equation 1: Equations for Calculating Resonator Parameter based on Equivalent Circuit Model

ΔF is the difference between the resonant and anti-resonant frequencies.

$\mathbf{Q_m}$ is the mechanical Q of the resonator.

Appendix 1 gives the equivalent circuit values of some common resonators.
Between the resonant and anti-resonant frequencies (where is possible for the resonator to resonate in an oscillation circuit) the equivalent circuit simplifies to an inductor and resistor in a series connection. This is why the resonator can be used to replace the inductor in the Colpitts circuit. The resonator can be designed to work over different frequency ranges by changing the shape of the ceramic element and the vibration mode.

Overtones of the Resonator

The ceramic resonator will oscillate at a fundamental frequency (between f_r and f_a) but can also be made to oscillate at odd overtones of the fundamental frequency. This odd overtone oscillation can be done intentionally (as in the case of third overtone resonators to be discussed later) or as a result of a poorly designed oscillation circuit. These overtones occur naturally in resonators and have impedance and phase responses similar to the fundamental except that they are smaller and occur at odd multiples of the fundamental frequency (Figure 11). Even overtone oscillation is not possible with ceramic resonators.

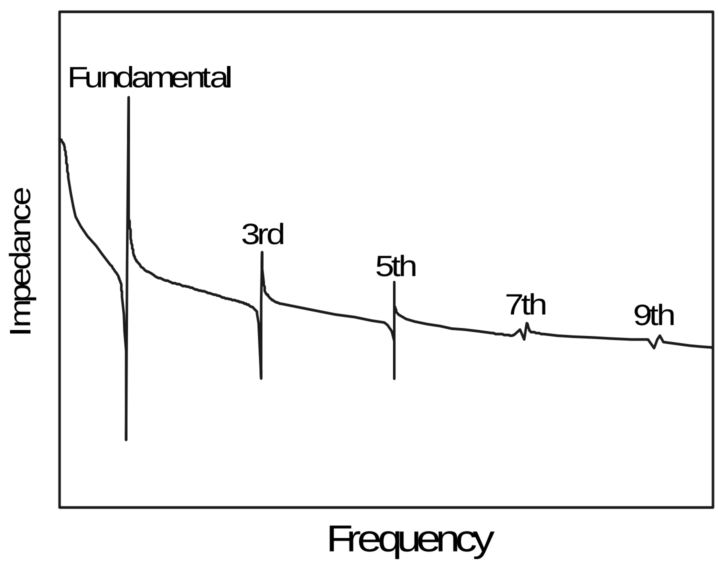

Figure 11: Ceramic Resonator Impedance Response Plot Showing Odd Overtones

In the figure, you can see the fundamental frequency and the 3rd, 5th, 7th, etc. overtones. When power is applied to the oscillation circuit, the oscillation begins as high frequency noise and drops in frequency (moves from right to left in Figure 11) until it reaches a point that meets the stable oscillation criteria (Barkhausen Criterion) discussed earlier. In a well designed circuit, this point will be at the fundamental response or an intentionally desired third overtone response. When designing lower frequency resonators (below~13MHz), we design the resonator to have the intended oscillation frequency occur at the fundamental. For higher frequency parts (above ~13MHz), we actually use the 3rd overtone response. To achieve operating frequencies above 12~13MHz, it is most efficient to use the 3rd overtone, instead of trying to design a fundamental mode resonator for these frequencies. Since we are dealing with ceramic material, a combination of various raw materials which are mixed together and then fired, we do not have to live with the weakness of quartz crystal based resonators, when used in 3rd overtone operation. Quartz crystals use a grown crystal material, which does not allow for material changes. To allow a quartz resonator to operate at the 3rd overtone, the fundamental response of the quartz resonator must be suppressed, typically by an external tank circuit. Use of an external tank circuit adds to the cost and complexity of oscillator design.
For ceramic resonators, using the aeolotropic ceramic material (different from standard ceramic material), the fundamental frequencies are naturally suppressed, <u>without the need of an external tank circuit</u>, and the 3rd harmonics can be easily used for oscillation (Figure 12). This use of aeolotropic material allows for the efficient and cost effective manufacture of higher frequency resonators.

Since the 3rd overtone is three times the fundamental frequency, using 3rd overtone can extend the frequency range covered by ceramic resonators considerably (up to 60MHz). Ceramic resonators, unlike quartz crystal resonators, do not require an external tank circuit for 3rd overtone operation, due to the aeolotropic ceramic material.

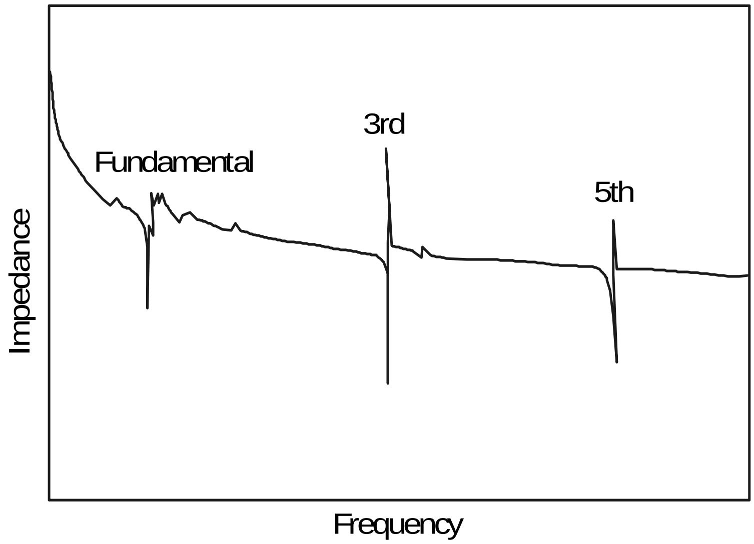

Figure 12: Impedance Response of Third Overtone Based Ceramic Resonator

As shown in Figure 12, the fundamental response of the ceramic resonator is suppressed to the point that the 3rd overtone appears to be the main ("fundamental") response of the oscillation circuit. Please note that greater care must be taken in designing the oscillation circuit, since it is easier to have suppressed fundamental or 5th overtone spurious oscillations (compared to fundamental resonator's spurious oscillations at 3rd or 5th overtone).

Vibration Modes

Ceramic resonators can employ one of several possible vibration modes, depending on the desired oscillation frequency. The vibration mode used is dictated by the target frequency of the resonator. The vibration mode selected dictates the basic shape of the resonator. In the following, each vibration mode used commonly for ceramic resonators and the range of oscillation frequencies possible are explained in more detail.

- Area Vibration (375kHz to 1250kHz)

The kHz range resonators utilize **area vibration** in their operation (Figure 13). In this mode, the center of the substrate is anchored while the corners of the material expand outward. This vibration mode suffers from spurious oscillation due to thickness vibration, but core circuit design can easily suppress such spurious oscillation. The resonant frequency is determined by the length of the square substrate. This mode operates from about 375kHz to 1250kHz.

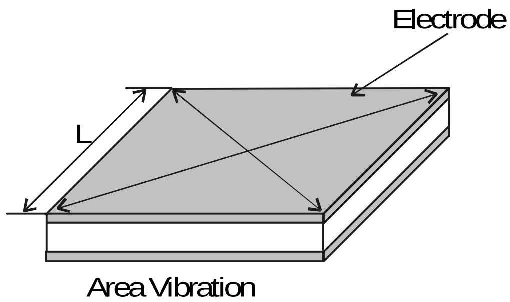

Figure 13: Ceramic Element for Area Vibration

- Thickness Shear Vibration (1.8MHz to 6.3MHz)

The MHz range resonators use two vibration modes. The first MHz range vibration mode is **thickness shear vibration** (Figure 14). In this mode, the substrate expands in thickness as well as diagonally. The resonant frequency is determined by the thickness of the substrate. This mode works from 1.8MHz to 6.3MHz.

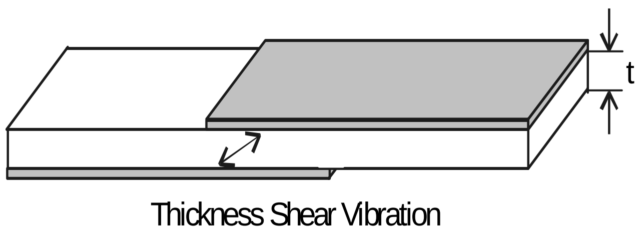

Figure 14: Ceramic Element for Thickness Shear Vibration

- Thickness Longitudinal Vibration (6.3MHz to 13.0MHz)

The second MHz range vibration mode is **thickness longitudinal vibration** (Figure 15). In this mode, the substrate thickness expands and contracts. The resonant frequency is determined by the thickness of the substrate. This mode operates from 6.3MHz to 13.0MHz. Using 3rd overtone this range can be extended to cover 12MHz to 60MHz.

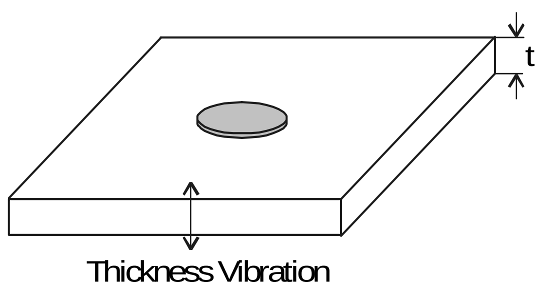

Figure 15: Ceramic Element for Thickness Longitudinal Vibration

- Thickness Longitudinal Vibration, Third Overtone (13.0MHz to 60.0MHz)

By taking the thickness longitudinal vibration mode mentioned above and changing the ceramic material to an aeolotropic ceramic material, the fundamental response of the thickness longitudinal vibration mode is suppressed allowing use of the third overtone. Figure 15 still represents this vibration mode, except that aeolotropic ceramic material is used. By using this third overtone of the thickness longitudinal vibration mode, it is possible to make ceramic resonators up to 60MHz.

Resonator Configurations

Resonators can come in two different configurations. A resonator can be supplied in a two terminal package (leaded or SMD) or in a three terminal package (leaded or SMD). For the two terminal package (Murata part numbers with the CSA prefix), the ceramic resonator element is connected between the two terminals. For the three terminal package (Murata part numbers with the CST prefix), there is an additional terminal between the two terminals of the two terminal type resonator. This third or middle terminal is a ground terminal for the built-in load capacitors. Recall from Figure 5 where the Colpitts oscillator is shown, there is a single inductor and two capacitors. The inductor would be replaced by the ceramic resonator, but the external capacitors (called load capacitors) must still be added. The three terminal resonator offers the convenience of having these two load capacitors built-in to the resonator, where this middle terminal is the ground for the load caps. The load capacitors that Murata builds into the resonator also provide some benefit in offsetting shifts in oscillation frequency due to temperature effects. Figure 16 shows the common lower frequency resonator packages for two and three terminal resonators.

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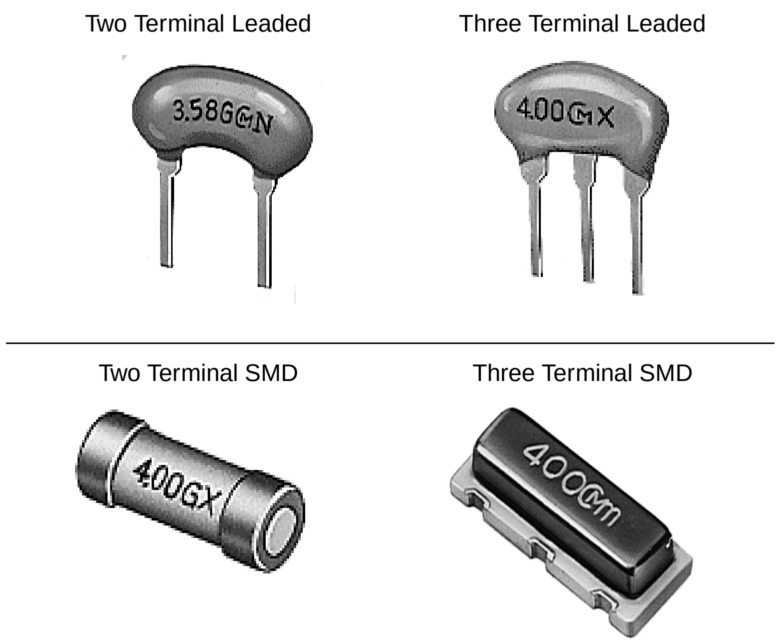


Figure 16: Two and Three Terminal Resonator

Spurious Oscillations

The odd overtones (3^{rd}, 5^{th}, etc. for fundamental mode resonators, or suppressed fundamental, 5^{th}, etc. for third overtone resonators) are always present as spurious oscillations. Also, other vibration modes can cause spurious oscillation. These other vibration modes are the same ones employed to make higher frequency resonators. These can be suppressed by properly designing the hookup circuit around the resonator. Care must be taken in determining oscillator hook-up circuit to insure desired operation. Without a correctly designed oscillation circuit, undesired spurious oscillation can occur.

Resonators are designed to use one vibration mode but suffer from spurious oscillation due to other vibration modes. These can be controlled to a certain extent by using the correct value of load capacitors or dampening resistor (R_d) to suppress gain at the overtone's frequency. One of the most common spurious oscillations for kHz range resonators is a result of an undesired vibration mode, thickness vibration. This causes a hump in the frequency response around 4 –

5 MHz (Figure 17).

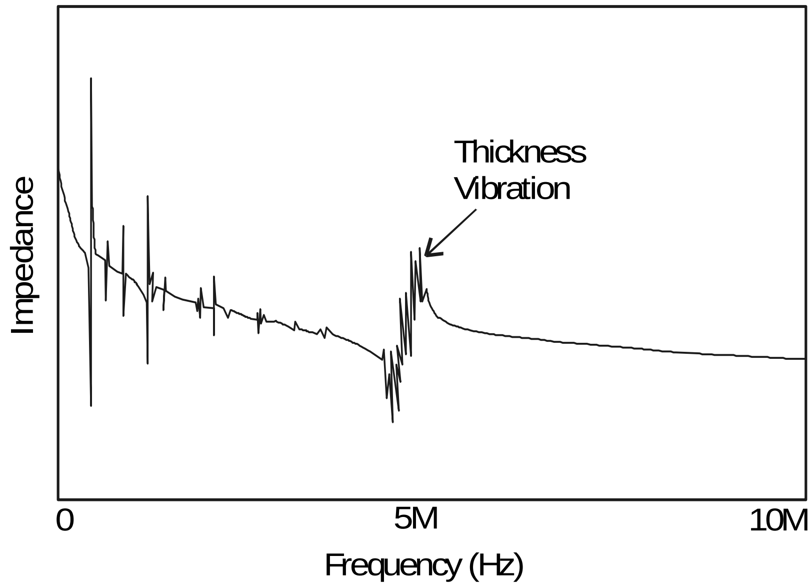


Figure 17: Impedance Response Plot of kHz Resonator Showing Thickness Vibration Spurious Response

Resonator Specifications

Nominal Oscillation Frequency

This is the oscillation frequency of the resonator measured in a specified test circuit.

Frequency Tolerance

There are three types of frequency tolerance (Initial, Temperature, and Aging) that go into the complete tolerance specification for a ceramic resonator. These tolerances are provided as a +/- percentage and are listed individually on a resonator's specification. These tolerances are all added to make the complete tolerance specification.

- *Initial tolerance*
  This is how much the frequency will vary based on slight differences in materials, production methods, and other factors, at room temperature. This tolerance results from the fact that every part cannot be exactly the same. There will always be some small difference from one part to another.
- *Temperature tolerance*
  This is a measure of how much the frequency varies with a change in temperature. Ceramic materials have a positive temperature coefficient. This means that as the temperature increases the resonator frequency increases. For the resonators that have built in load capacitors, since the capacitors are made of a ceramic material similar to the resonator ceramic, the value of the load capacitors increases with temperature. However, increasing the value of the load capacitors decreases the oscillation frequency, which helps to compensate for the increase of resonator frequency. For this reason, the resonators with built in load capacitors will have better temperature tolerance specifications than resonators without built-in load caps.
- *Aging tolerance*
  This is a measure of how much the frequency will vary over the life of the part (typically 10 years).

Built In Capacitance Values

Indicates the built-in load capacitor value inside of the resonator and the tolerance of this capacitor's values. This only applies to resonators where there part numbers start with the "CST" (like: CST..., CSTS..., CSTCV..., etc.)

Resonant Impedance

This is a specification of the impedance occurring at f_r. Lower values for resonant impedance are desired. The lower the resonant impedance is in a given resonator, then less gain is required in the oscillation circuit for oscillation to start and continue. The specification usually list a maximum value of impedance that will not be exceeded by any resonator made to this specification.

Insulation Resistance

This is the measurement of resistance between the two terminals of the resonator at some given DC voltage. At DC, the resonator should appear capacitive and have a high resistance between the terminals. Remember, the part only achieves low impedance near its oscillation frequency, not DC.

Withstanding Voltage

Indicates the maximum DC voltage that may be applied across the outside terminals (not including ground terminal of CST type resonators) for a given time.

Absolute Maximum Voltage

- Maximum D.C. Voltage

Indicates the maximum DC voltage that can be applied to the resonator continuously.

- Maximum Input Voltage

Indicates the maximum AC peak to peak voltage that may be applied to the resonator.

Operational Temperature Range

Murata offers ceramic resonators in two different temperature ranges: Standard and Automotive.

- Standard (-20C to +80C)

  Standard temperature range resonators will remain in specification over the temperature range of -20C to +80C. Exceeding this range can cause the resonator to perform outside of specification.

- Automotive (-40C to +125C)

  Automotive grade resonators are exactly the same as standard resonators, except all automotive grade parts go through additional sorting to insure performance over the wider temperature range and in an automotive environment. These sorted resonators are also capable of passing the rigorous thermal cycling requirements of automotive customers. Automotive is a bit of a misnomer since automotive grade parts are not only for automotive applications, but for any application that requires an extended temperature range.

Storage Temperature range

This temperature range indicates the temperature at which the resonator can be safely stored in a non-operating condition. This range will vary depending on whether the resonator has a standard or an automotive temperature rating.

Test Circuit

The test circuit indicates the circuit used to test the resonator for compliance with specification. The ceramic resonator is sorted for 100% spec compliance in production, using this test circuit.

Comparison of Crystal and Ceramic Resonators

In the previous sections, the basic operation of a ceramic resonator has been discussed and some comparisons made to quartz crystal resonators. At this point, we should look at the differences between these two types of resonators.
There are several advantages that ceramic resonators have over quartz crystal resonators. Figure 18 shows the characteristics of ceramic and quartz crystal resonators. As can be seen, the quartz crystal has a much tighter frequency tolerance, as indicated by a smaller difference between f_a and f_r. This tighter frequency tolerance is the major advantage of quartz crystal based resonators over ceramic based resonators.

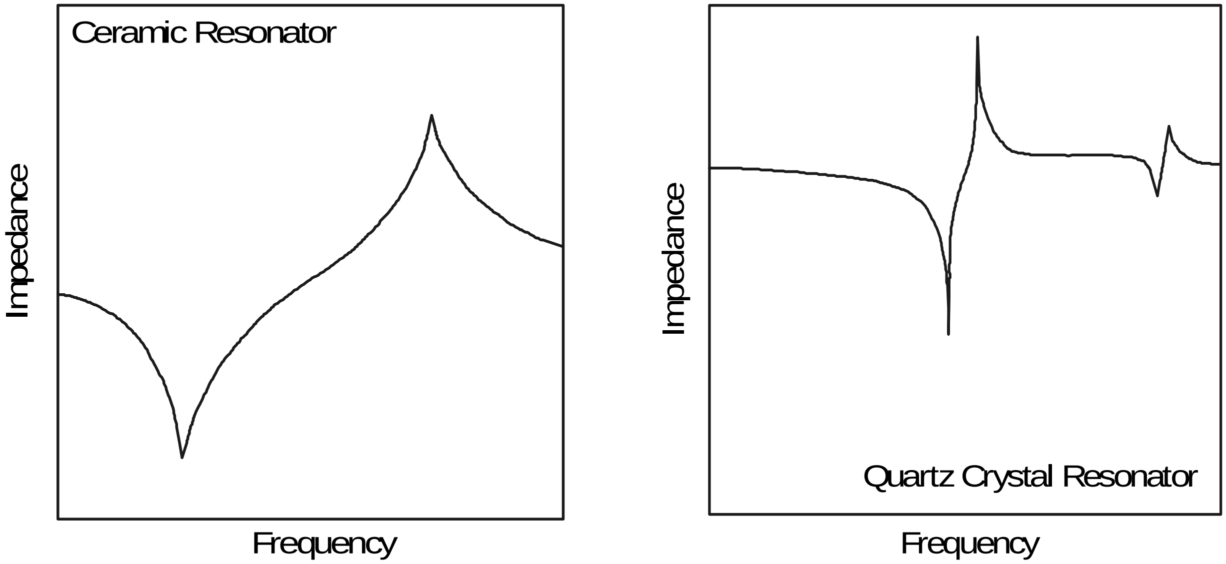


Figure 18: Impedance Response Comparison between Ceramic and Quartz Resonators

Table 1 shows a comparison of the electrical characteristics between ceramic resonators and quartz crystal resonators (**BOLD** = better, where appropriate).

	Ceramic Resonator	Quartz Crystal
Frequency Tolerance	±0.2 ~ ±0.5%	**±0.005%**
Temperature Characteristics	20 ~ 50 ppm/^{o}C	**0.5 ppm/^{o}C**
Static Capacitance	10 ~ 50pF	10pF max.
Q_m	$10^2 – 10^3$	$10^4 – 10^5$
ΔF	0.05 X F_{osc}	**0.002 X F_{osc}**
Rise Time	**$10^{-5} – 10^{-4}$ Sec**	10^{-3} - 10^{-2} Sec
Height (leaded)	**7.5mm (Typ)**	13.5mm (Typ)
Price Index	**1**	2

Table 1. Basic Resonator Parameter Comparison Between Ceramic and Quartz Resonator

As can be seen from the table, quartz crystal resonators have a much better frequency tolerance than ceramic resonators. They have a higher mechanical Q and a smaller ΔF. For tight frequency tolerance applications, quartz crystal resonators are the choice. Ceramic resonators have a much faster rise time, smaller size, and are about half the price. In addition, ceramic resonators have a better mechanical shock and vibration resistance. They will not break as easily as quartz resonators. Drive level, a big issue with quartz crystal resonators, is not an issue with ceramic resonators. Most applications can accept the looser frequency tolerance of the ceramic resonator, while enjoying the other benefits.

Quartz crystal resonators require a LC tank circuit in order to suppress the fundamental and work with 3rd overtones, where ceramic resonators do not. This saves in cost of parts for the circuit, storing the parts, space on the board, and time needed to place the parts in production.

Design Considerations

Hook Up Circuit

While Murata strongly recommends that all customers take advantage of Murata's characterization service (see Appendix 3 and some comments later in this section), the following will provide a basic explanation of the external hook-up circuit for a ceramic resonator and what effect each component in the hook up circuit has to oscillation.

Figure 19 shows a basic oscillation circuit using a CMOS inverter (you can use a HCMOS inverter for higher frequency oscillators). For oscillation circuits using inverters, it is not recommended to use buffered inverters. Unbuffered inverters are desired since they have less gain, which decreases the chance for spurious overtone oscillation.

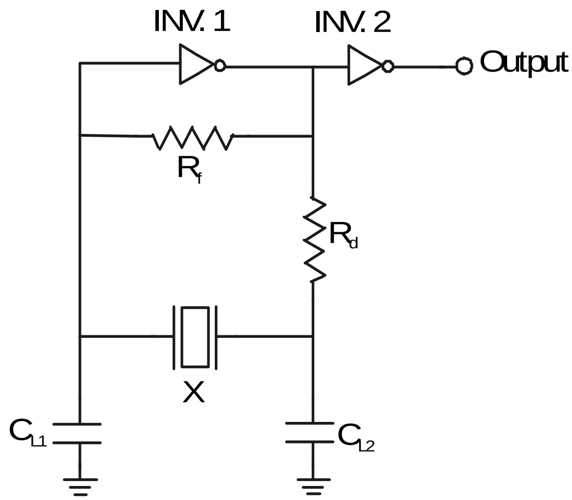


Figure 19: Typical Hook-up Circuit for Ceramic Resonator

INV. 1 is simply an inverting amplifier and is the active component of the oscillation circuit. INV. 2 is used as a waveform sharper (makes the sinusoidal output of INV. 1 into a square wave) and a buffer for the output. It squares off the output signal and provides a clear digital signal.

- R_f

R_f provides negative feedback around INV. 1 so that INV. 1 works in its linear region and allows oscillation to start once power is applied. If the feedback resistance is too large and if the insulation resistance of the inverter's input is decreased then oscillation will stop due to the loss of loop gain. If it is too small then the loop gain will be decreased and it will adversly effect the response of the fundumental and 3rd overtone response (could lead to 5^{th} overtone oscillation). A R_f of 1 MΩ is generally recommended for use with a ceramic resonator, regardless of resonator frequency.

- R_d

The damping resistor, R_d has several effects. First, without R_d, the output of the inverter sees the low impedance of the resonator. This low impedance of the resonator causes the inverter to have a high current draw. By placing R_d at the output of the inverter, the output resistance is increased and the current draw is reduced. Second, it stabilizes the phase of the feedback circuit. Finally, and most importantly, it reduces loop gain at higher frequencies. This is very helpful when dealing with a high gain inverter / clock circuits. If the gain is too high, the chance for spurious oscillations is greatly increased at the resonator's overtones or other vibration modes (i.e. high frequencies). R_d works with C_{L2} to form a low pass filter, which minimally effects gain at the fundamental frequency, while greatly effecting gain at higher frequencies. This is one tool for removing unwanted overtone or spurious oscillations.

- Load Capacitors

The load capacitors, C_{L1} and C_{L2}, provide a phase lag of 180^o as well as determine controlling frequency of oscillation. The load capacitor values depend on the application, the IC, and the resonator itself. If the values are too small, then the loop gain at all frequencies will be increased and could lead to spurious overtone oscillation. This is particularly likely around 4 – 5 MHz where the thickness vibration mode lies with kHz resonators. For MHz resonators, the spurious oscillation is likely to occur at the 3^{rd} harmonic frequencies (even with 3^{rd} overtone MHz resonators). If the resonator circuit is oscillating at a substantially higher frequency, then increasing the load capacitor may solve the problem. *Changes in load capacitance effect gain at all frequencies (unlike R_d). Increase load cap values to cut gain, decrease load cap values to boost gain, for all frequencies.

***Please Note:** As mentioned above, the resonator itself can effect which load capacitor values should used in any given oscillation circuit. This is important to note, when comparing ceramic resonators, from various ceramic resonator

manufacturers, in an oscillation circuit. Since the ceramic material used to make the resonator is a little different from manufacturer to manufacturer (thus the equivalent circuit of the resonator is slightly different), it is very common to see one manufacturer’s resonator need certain load cap value in an oscillation circuit, but another manufacturer’s resonator needs another load cap value for stable oscillation (in the same circuit). Also, the sorting IC (test circuit used in production) used to determine oscillation freqeuncy (to resonator specification) can also differ by resonator makers. Do not assume that if you get a supplier “A”’s resonator to work with a given load cap value, that supplier “B”’s resonator will need same load cap value.
Also be aware that if load cap values / IC combination works at one freqeuncy, the load caps may need to be different for the same IC at other freqeuncies. By using Murata’s free IC characterization service (later in this section or see Appendix 3), such problems and concerns can be completely avoided in your design.

- Test Circuit Types

The circuit in Figure 19 is the standard test circuit used by Murata on all of our resonators. We use an unbuffered CMOS chip (RCA/Harris CD4069UBE), an unbuffered HCMOS (Toshiba TC40H004P) or an unbuffered HCMOS (Toshiba TC74HCU04) chip as a reference for all of the published specifications. The test circuit used is indicated on the data sheet for the part. CMOS is typically used with lower frequency resonators while HCMOS is used with the higher frequency resonators. The resonator part number calls out which type of CMOS inverter is used. Please see the section on resonator part numbering for clarification of this point. Appendix 2 gives the standard test circuit values for Murata’s resonators

Irregular Oscillation

As mentioned in the section on “Spurious Oscillation”, spurious oscillations can sometimes occur if the hook-up circuit is not designed correctly for the resonator and target IC. Spurious oscillation is basically any oscillation not occurring at the resonator’s specified oscillation frequency (for example: a 4MHz resonator is used, but the circuit oscillates at 12MHz). Table 2 lists the possible causes for spurious oscillation for various frequency ranges of resonators.

General Resonator Series	Frequency Range	Vibration Mode	Possible Cause of Irregular Oscillation	
			Type 1 (Spurious Response)	Type 2 (Other)
CSB	375k - 580kHz	Area	3rd Overtone, Thickness vibration (at 4.3MHZ)	CR Oscillation LC Oscillation Ring Oscillation
	581k - 910kHz	Area	3rd Overtone, Thickness vibration (at 5.7MHZ)	
	911k - 1250kHz	Area	3rd Overtone, Thickness vibration (at 6.5MHZ)	
CSA-MK	1.26M - 1.79MHz	Shear	3rd Overtone (not common)	
CSA-MG CST-MG	1.80M - 1.99MHz	Thickness Shear	3rd Overtone (not common)	
CSA-MG CSTLS-G	2.00M - 3.39	Thickness Shear	3rd Overtone (not common)	
CSA-MG CSTS-MG	3.40M - 10.00MHz	Thickness Shear	3rd Overtone (not common)	
CSA-MTZ CST-MTW	10.01M - 13.00MHz	Thickness Longitudinal	3rd Overtone (not common)	
CSA-MXZ CST-MX	13.01M - 15.99MHz	Thickness Longitudinal Third Overtone	Fundamental and 5th Overtone	
CSALS-MX CSTLS-X	16.00 - 70.00MHz	Thickness Longitudinal Third Overtone	Fundamental and 5th Overtone	

Table 2. Possible Causes of Irregular Oscillation

Irregular oscillations can be classified into two basic type by their causes:

Type 1: Oscillation occurring at the spurious response of the resonator.

Type 2: RC, LC, or Ring oscillation.

Type 1 Irregular (Spurious) Oscillation

For ceramic resonators utilizing natural 3rd overtone operation, a greater chance is present for fundamental and 5th overtone spurious oscillations. If a LC tank circuit is used (like with quartz resonators) the chance for spurious oscillations is almost zero. However, Murata 3rd overtone resonators are designed to not need an external tank circuit.
For kHz resonators that have problems with third overtone or thickness vibration mode spurious oscillations, the solutions for 5th overtone oscillations mentioned below can correct these spurious oscillations as well.

Fundamental Oscillation

Increasing the loop gain at the 3rd (main) response, decreasing loop gain at the fundamental, and decreasing the phase shift at the fundamental are possible solutions to fundamental spurious oscillations

- Decrease the load capacitor capacitance. This will increase the gain seen at the main response (3rd). Decreasing load capacitance too much can result in 5th overtone oscillation.
- Decrease R_f to a few kΩ (10kΩ - 30kΩ). This will dump the resonator's response, especially at the fundamental.

5th Overtone Oscillation

To remove 5th overtone oscillation (or 3rd overtone oscillation for fundamental resonator), it is necessary to decrease the loop gain at this overtone.

- Increase the value of the load capacitors. This will reduce gain at the 5th overtone (or 3rd overtone for fundamental resonators). This does have the small effect of decreasing gain at the main response, so increasing load capacitance too much can send the 3rd overtone resonator in to fundamental oscillation (or the fundamental into an unexpected LC or RC oscillation).
- Add or increase the value of the existing R_d resistor. Increasing or adding R_d will decrease gain across all frequencies. If an oscillation circuit has abundant gain at the main (or fundamental) response, then the circuit could withstand increase to R_d in order to dampen the overtone oscillation. Also, R_d and C_{L2} act like a low pass filter, dampening gain at higher frequencies.
- Connect bypass capacitors to the voltage supply pin of the IC to remove high frequency noise

Type 2 Irregular (Spurious) Oscillation:

In the case of type 2 spurious oscillation, the resonator is acting like a capacitor at a capacitance value close to the resonator's shunt capacitance, C_o. For RC spurious oscillation, the resonator's shunt capacitance and the amplifier's (or inverter's) input impedance act like a RC circuit causing unwanted oscillation. For LC spurious oscillation, the resonator's shunt capacitance and stray inductance in the circuit act like a LC circuit causing unwanted oscillation.

These types of spurious oscillations are hard to identify, since this spurious oscillation usually occurs at very high or very low frequencies (not near the intended oscillation frequency). Many resonator circuits that appear not to oscillate at resonator's specified oscillation frequency (circuit appears to be dead, no oscillation) are actually oscillating at a very high frequency in a spurious oscillation mode. One way to confirm that this type of spurious oscillation is occurring is to replace the resonator with a capacitor of the same value as the resonator's shunt capacitance. If the circuit continues to have the same frequency oscillation after the resonator / capacitor swap, then the oscillation can be attributed to LC or RC oscillation.

A common cause of RC, LC, or ring oscillation is too much amplifier gain, most notably from using buffered inverters. A buffered inverter is typically three non-buffered inverters in series. Because of this, buffered inverters have a considerable amount of gain, resulting in these types of spurious oscillations. Murata recommends only using unbuffered inverters for oscillation circuits using ceramic resonators. Most clock circuits in current ICs use unbuffered type inverters. You can still feed the output of the unbuffered oscillation circuit into another unbuffered inverter to square up the output waveform from the oscillation circuit.

Ring oscillation typically occurs when there is too much phase shift through the amplifier (or inverter). Ring type oscillation really only occurs when using the unrecommended buffered inverter as the amplifier. Due to the three inverter stages in a buffered inverter, a substantial amount of phase delay is introduced to the circuit, causing the ringing. To stop ring oscillation, switch to an unbuffered inverter.

If changing to a unbuffered inverter does not stop the type 2 oscillation (or you are already using an unbuffered inverter), we must try alternate techniques to make these spurious oscillation no longer meet Barkhausen Criterion for oscillation. The following may be used to do this:

- Try changing the load capacitor values. By increasing the load capacitor values, the high frequency circuit gain is reduced without major impact to the gain at fundamental. Increasing load caps too much can result in the circuit not being able to oscillate even at the fundamental response.
- Try unbalancing the load cap values. For most applications, the two load capacitors are basically the same value. Having load capacitors at two different values can sometimes correct type 2 spurious oscillations.
- Try adding a R_d or increasing R_d (if already present in the oscillation circuit). R_d has the effect of decreasing circuit gain across all frequencies (unlike changing load capacitor values). This is a more drastic method, since the gain at the fundamental response is decreased as well as gain at the spurious oscillations.
- Try adding a bypass capacitor to the power line to the IC to remove any external noise coming into the oscillation circuit.

IC Characterization Service

The ceramic resonators produced by Murata (or any ceramic resonator maker) may or may not work with all ICs using standard external circuit values. This is mainly due to typical variations in ICs and resonators, part to part. In order to assist our customers with their designs, Murata offers a resonator / IC characterization service free of charge. The customer's IC is tested with the Murata resonator. Measurements are made to determine frequency correlation between the standard sorting ICs Murata uses in production and the customer's IC. Based on test results and Murata's long experiance with ceramic resonators / oscillation circuits, Murata provides the recommended Murata part number that should be used with their target IC and the recommended external hook up circuit for this target IC. This recommendation insures that the IC / resonator combination will have stable oscillation and good start up characteristics (taking into account any resonator that could be shipped to the resonator specification) This enables the designers to adjust their designs so that the resonator will work every time. These adjustments can be as simple as adjusting component values or as complicated as redesigning the entire circuit. If the recommendations made by Murata are followed then the resonator is guaranteed to work every time. Besides looking at oscillation stability, Murata can also test for freqeuncy correlation between customer target IC and Murata's production sorting circuit.
Murata Electronic Sales representatives are able to arrange IC characterizations. Please try to start the IC characterization process with Murata as soon as possible, since it does take time to do an IC characterization and there can be several customers at any one time waiting for this service.
Please see Appendix 3 for more information on this service and needed forms.

Characteristics of Oscillators Using A Ceramic Resonator

The next sections explain some of the characteristics of oscillation circuits using ceramic resonators.

Oscillation Rise Time

The rise time is the time it takes for oscillation to develop from a transient area to a steady state area at the time the power is applied to the circuit. It is typically defined as the time to reach 90% of the oscillation level under steady conditions. Figure 20 illustrates the rise time.

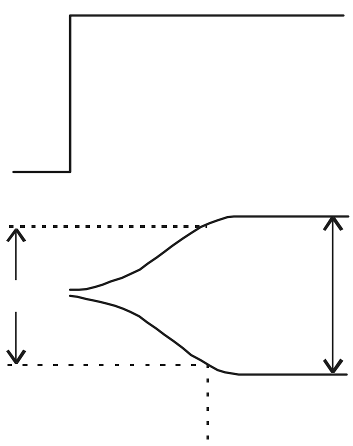


Figure 20: Diagram of Oscillation Rise Time

This area is important because without a fully developed signal, mistakes could be introduced into the digital computations in the IC. An ideal circuit would have no rise time, meaning that it would instantaneously power up and reach steady oscillation. An advantage of ceramic resonators is that the rise time is one or two decades faster than quartz crystal (Figure 21).

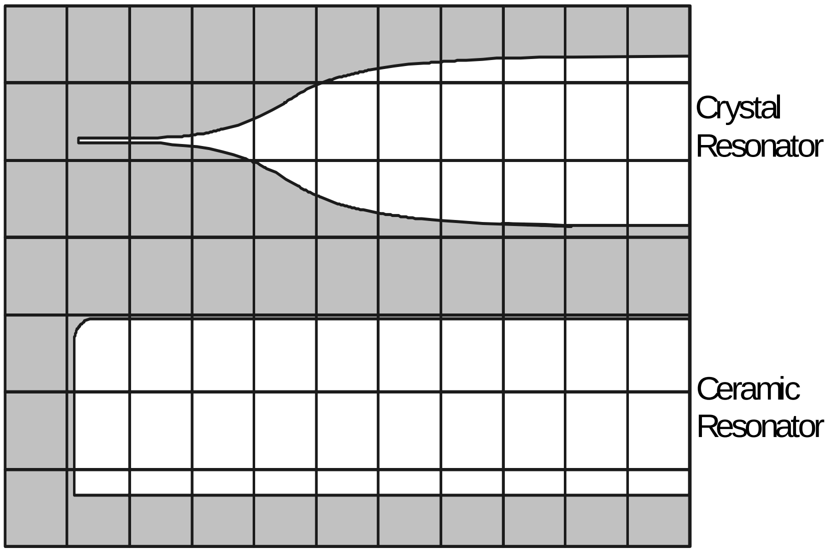


Figure 21: Comparison of Oscillation Rise Time Between Ceramic Resonator and Quartz Crystal Resonator

Starting Voltage

The starting voltage is the minimum supply voltage at which an oscillating circuit will begin to oscillate. The starting voltage is affected by all circuit elements but is determined mostly by the characteristics of the IC.

Speciality Resonator Applications

Telephone (D.T.M.F)

It is becoming more and more common to use the telephone keypad for data transmission. It is used to make selections on automated answering systems, for example. It is also becoming more important to ensure that the button pressed will be registered as the corresponding number by the receiving end. When a telephone key is pressed, a certain audible frequency is generated representing that key. It is critical that the frequency generated is accurate, so the receiving end understands what key was pressed. For this reason, a global regulation calls for a mandatory frequency tolerance. The total allowable frequency tolerance for the oscillation of a tone dialer for a telephone is ±1.5%. This tolerance is for the IC as well as the resonator, not just the resonator alone. Table 3 shows how the tolerance is divided up between the IC and the resonator.

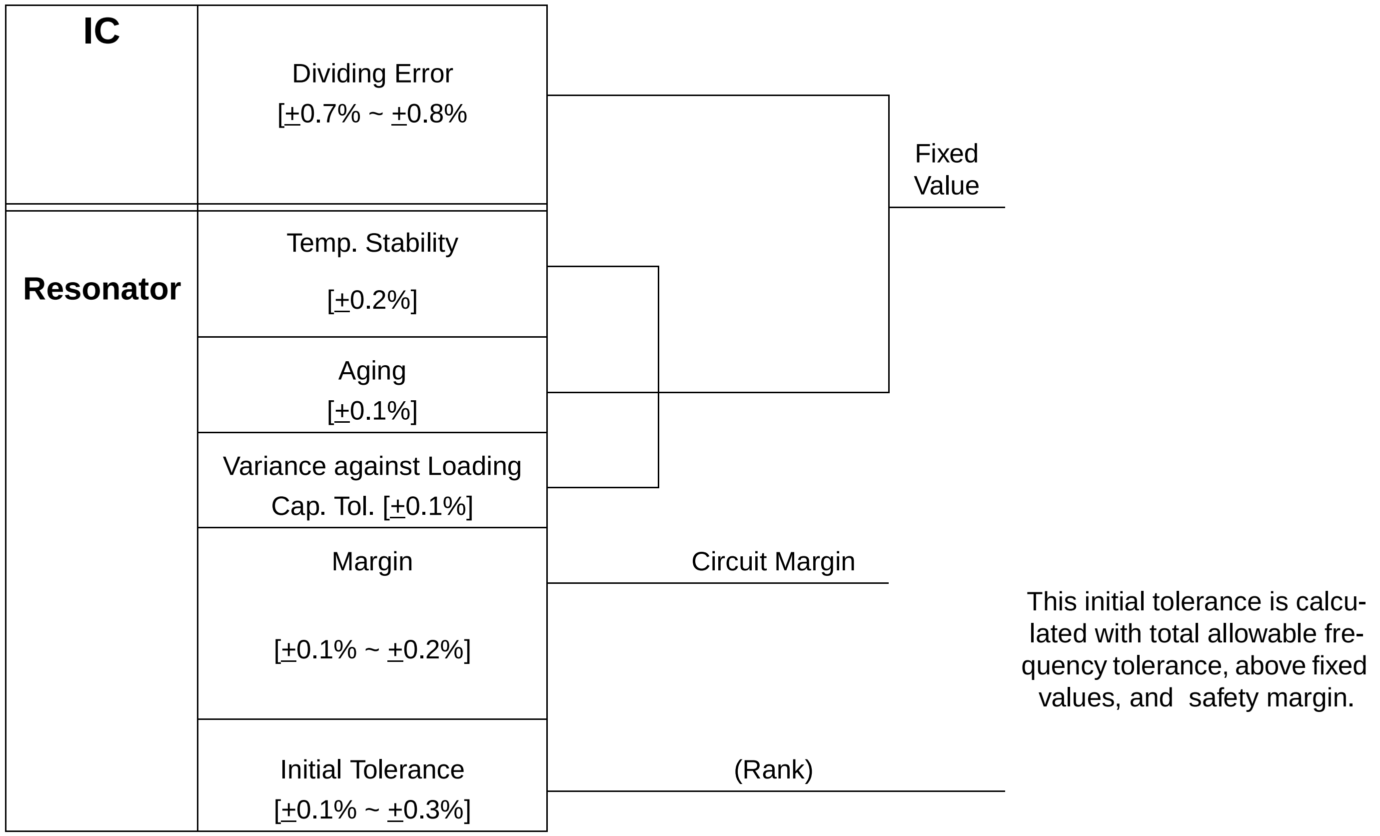


Table 3. DTMF Tolerance Chart

The typical resonator frequency used is 3.58MHz. This frequency is divided by the IC to generate the lower frequency audible tones associated with each key press. The dividing error is related to the IC that is used in the circuit and so is a fixed value. This value will usually be specified on the data sheets for the IC. Aging of the resonator is also a fixed value. The other values can be changed by changing the design of the resonator.

Murata has developed a way to account for the different tolerance specifications on our parts. We add a postscript to the part numbers based on the chart in Figure 22.

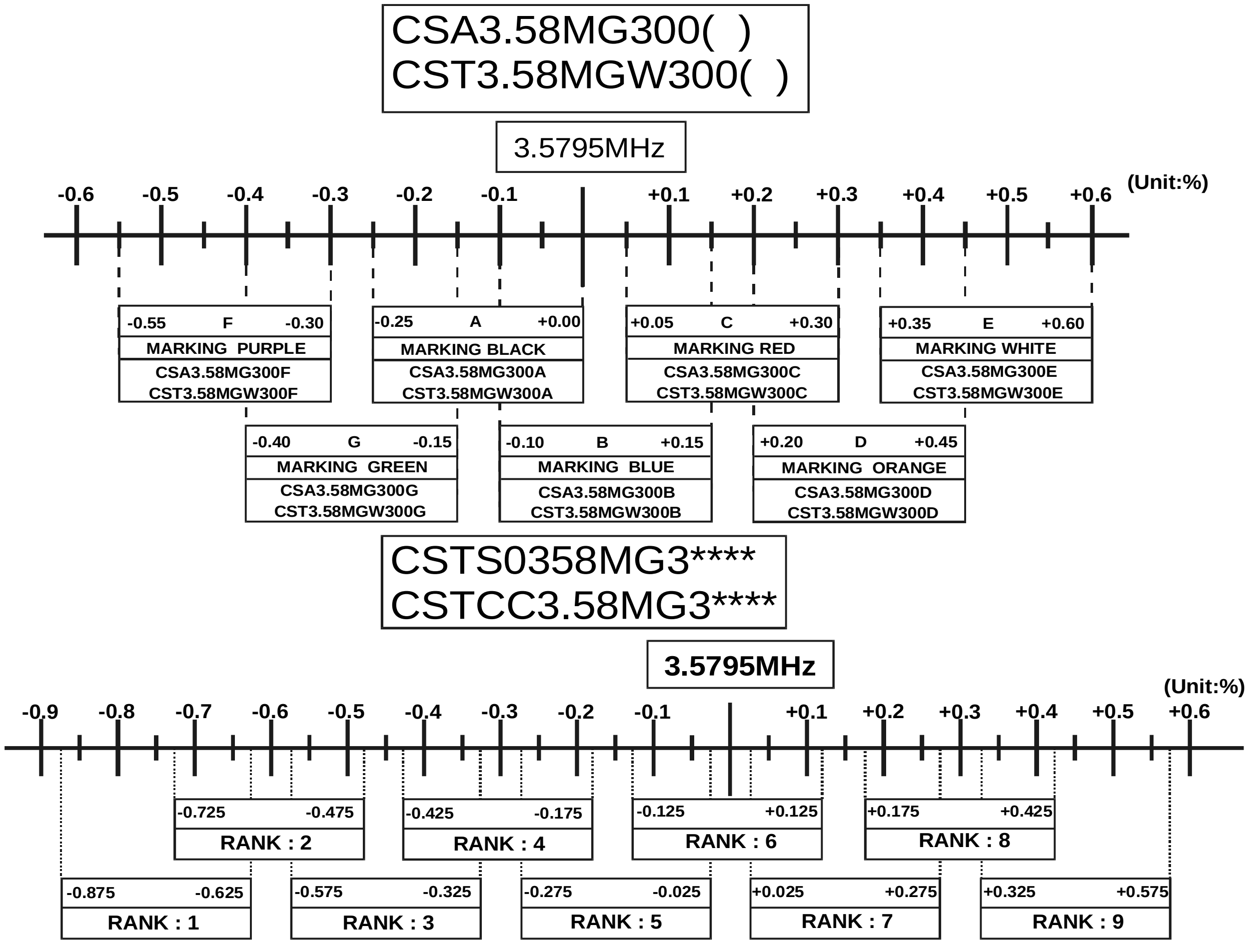


Figure 22: DTMF 3.58MHz Resonator Tolerance Chart

For example, a part with a tolerance of ±0.1% would have ABC at the end of its part number. Murata is able to produce resonators with asymmetrical tolerances (i.e. +0.1%, -0.2%) and this convention provides an easy way to label the parts.

Resonators for various commerically available DTMF ICs have already been characterized by Murata and resonator part number recommendation are available. If a particular DTMF IC has not been characterized yet by Murata, this can be handled in the same way as the common IC characterization service Murata provides.

Voltage Controlled Oscillator (VCO) Circuits

VCO circuits are used in TV and audio equipment to process signals in synchronization with reference signals transmitted from broadcasting stations. They use a DC input voltage to change the frequency of oscillation. For example, if a VCO operates at 4 MHz with a 0V DC input, then it might operate at 4.01MHz with a 1V DC input. VCOs work by varying either the resonant or anti-resonant frequencies of the resonator. To change the resonant frequency, a varactor diode is placed in series with the resonator. Changing the capacitance of the diode changes the resonant frequency of the resonator. Adding positive or negative reactance in parallel with the resonator will change the anti-resonant frequency.

Since ceramic resonators have a wide ΔF compared to quartz crystal, they are more easily used in VCO designs. The wider ΔF allows for a greater range of frequencies the resonator can be changed to. Two examples of VCO applications are TV horizontal oscillator circuits and stereo multiplexer circuits.

Like the DTMF ICs, Murata has many of the ICs requiring VCO resonators already characterized. If an IC has not been characterized with a Murata resonator, then an IC characterization will need to be performed.

Part Numbering

This section will go over Murata part number construction and how to make a ceramic resonator part number. Due to the myriad of resonator part numbers possible, this section will not cover every possible part, but should cover at least 85% to 90% of them. Figures 23 and 24 show examples of the structure for the Murata part numbering systems for the kHz and MHz resonators.

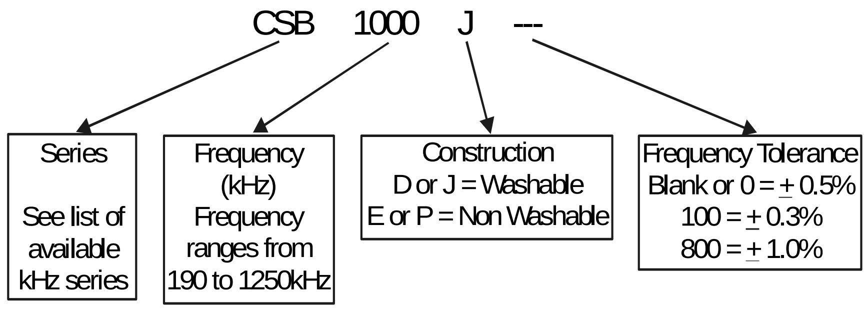


Figure 23: kHz Part Numbering System

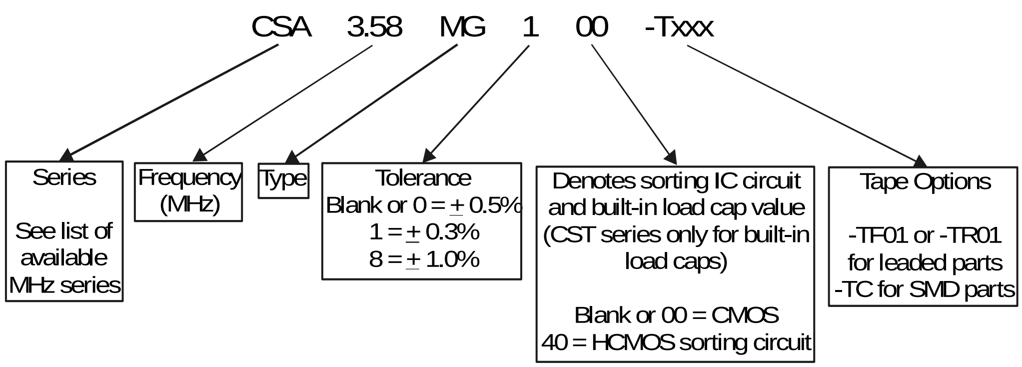


Figure 24: MHz Part Numbering System

How To Make a Resonator Part Number.

This next section will step you through making a Murata ceramic resonator part number.

- Determine Resonator Series

Table 4 lists the different resonator series offered by Murata. In the table for each listed series, we advise applicable frequency range, built-in load cap status, if the part is SMD or leaded, and if the part is washable. Please note that the second part of Table 4 list those resonators available in the automotive temperature range (adds an “A” to the suffix).

- Make the Base Part Number

From Table 4, you have picked your series. The Resonator Series column in Table 4 indicates the part prefix and suffix. Between the prefix and suffix, you need to add the frequency (where you see the “...”). You will note that SMD parts already have the taping suffix attached since SMD parts are only supplied on tape and reel (bulk SMD parts is not an option).

- Add the Frequency

Based on the series selected, the Frequency Range column will advise available frequency range
Frequency Rules:

1) kHz filters can have either 3 or 4 digits total, with no decimal places. (Example: 455 or 1000, but not 355.6 or 10.00)
2) MHz MG resonators can have three digits total, with two decimal places. (Example: 3.58 or 6.00, but not 3.586)
3) MHz MT resonators can only have three digits total, with one or two decimal places. (Example: 8.35 or 10.5, but not 8.356 or 10.55)

4) MHz MX resonators can only have 4 digits total, with two decimal places. (Example: 15.00, 55.25, but not 20.386 or 50.4567)

- Taping

For SMD parts, the series already includes the taping. Leaded kHz resonators do not have a taping option. We can supply some leaded kHz filters in tubes, but you will need to confirm availability with Murata.
For leaded MHz resonators, the parts can be supplied on tape and ammo box (-TF01, our standard and most available taping option for leaded resonators) or tape and reel (-TR01).

- Conclusion

For 80% of the part numbers, you are done making your part number by this step. The only additional options you may need to pick is initial frequency tolerance (MHz and kHz resonator, see Figures 23 and 24), IC sorting circuit (see Figures 23 and 24), and any additional suffixes (including resonators for VCO and DTMF applications).

- General Part Numbering Rules

Here is a list of general part number rules, that really do not fit into the above instructions:

1) A resonator will never have a suffix with “000” in it. This suffix calls out (first digit) initial frequency tolerance and (last two digits) IC sorting circuit / built-in load cap values. If this final suffix turns out to be “000” (with or without taping suffix), the “000’ is dropped completely (Example: CSA4.00MG and CSA4.00MG-TF01 correct, CSA4.00MG000 and CSA4.00MG000-TF01 incorrect).

Resonator Series	Frequency Range (Hz)	Load Caps Included	SMD	Washable
CSB...P	375k - 429k & 510k - 699k	N	N	N
CSB...E	430k - 509k	N	N	N
CSB...J	375k - 429k & 430k - 519k & 520k - 589k & 656k - 699k & 700k - 1250k	N	N	Y
CSB...JR	590k - 655k	N	N	Y
CSA…MK	1.26M - 1.799M	N	N	Y
CSA…MG	1.80M - 6.30M	N	N	Y
CSA…MTZ	6.31M - 13.0M	N	N	Y
CSA…MXZ	13.01M - 15.99M	N	N	Y
CSALS-X	16.00M - 70.00M	N	N	Y
CST…MG	1.80M - 1.99M	Y	N	Y
CSTLS-G	2.00M - 3.39M	Y	N	Y
CSTS...MG	3.40M - 10.00M	Y	N	Y
CST…MTW	10.01M - 13.0M	Y	N	Y
CST…MXW040	13.01M - 15.99M	Y	N	Y
CSTLS-X	16.00M - 70.00M	Y	N	Y
CSBF	430k - 1250k	N	Y	Y
CSAC…MGC-TC	1.80M - 6.00M	N	Y	Y
CSAC…MGCM-TC	1.80M - 6.00M	N	Y	Y
CSACV...MTJ-TC20	6.01M - 13.0M	N	Y	Y
CSACV...MXJ040-TC20	14.00M - 20.00M	N	Y	Y
CSACW...MX01-TC	20.01M - 70.00M	N	Y	Y
CSTCC...MG-TC	2.00M - 3.99M	Y	Y	Y
CSTCR-G-R0	4.00M - 7.99M	Y	Y	Y

Table 4. Available Resonator Frequencies by Series (Package)

CSTCC...MG-TC	8.00M - 10.00M	Y	Y	Y
CSTCV…MTJ-TC20	10.01M - 13.0M	Y	Y	Y
CSTCV…MXJ0C4-TC20	14.00M - 15.99M	Y	Y	Y
CSTCW…MX03-T	16.00M - 60.00M	Y	Y	Y
Automotive *(“A” suffix.)*				
CSB…JA	375k - 1250k	N	N	Y
CSBF…JA	430k - 1250k	Y	N	Y
CSA…MGA	1.80M - 6.30M	N	N	Y
CSA…MTZA	6.31M - 13.0M	N	N	Y
CSA…MXZA040	13.01M - 15.99M	N	N	Y
CSALS-X-A	16.00M - 70.00	N	N	Y
CST…MGA	1.80M - 1.99M	Y	N	Y
CSTLS-G-A	2.00M - 3.39M	Y	N	Y
CSTS...MGA	3.40M - 10.00M	Y	N	Y
CST…MTWA	10.01M - 13.0M	Y	N	Y
CST…MXWA040	13.01M - 15.99M	Y	N	Y
CSTLS-X-A	16.00M - 70.00M	Y	N	Y
CSAC…MGCA-TC	1.80M - 6.0M	N	Y	Y
CSAC…MGCMA-TC	1.80M - 6.0M	N	Y	Y
CSACV…MTJAQ-TC	6.01M - 13.0M	N	Y	Y
CSACV…MXAQ-TC	13.01M - 70.00M	N	Y	Y
CSTCC…MGA-TC	2.0M - 3.99M	Y	Y	Y
CSTCR-G-A-R0	4.00M - 7.99M	Y	Y	Y
CSTCC...MGA-TC	8.00M - 10.00M	Y	Y	Y
CSTCV…MTJAQ-TC	10.01M - 13.0M	Y	Y	Y
CSTCV…MXAQ-TC	13.01M - 70.00M	Y	Y	Y

Table 4. Available Resonator Frequencies by Series (Package)

The parts may have an additional suffix that refers to a special aspect of the part. Table 5 gives a list of these suffixes.

Suffix	Meaning	
A	For Automotive	
B	Bent Lead Type	
F	For V.C.O Applications	
3xx	DTMF part, usually at frequency of 3.58MHz, leaded or SMD.	
P	Custom marking on part	
Sx	Short Lead Type (std. = 5.0 ± 0.5mm)	
	S = 3.8 ± 0.5mm	
	S1 = 3.5 ± 0.5mm	
	S2 = 3.4 ± 0.5mm	
T	Lead Forming Type (Gull Wing Style)	
U	Low Supply Voltage	
Yx	Additional Color Dot (Top Left) Must check with Murata for availability.	
	Y0 = Black	Y5 = Green
	Y1 = Brown	Y6 = Blue
	Y2 = Red	Y7 = Purple
	Y3 = Orange	Y8 = Gray
	Y4 = Yellow	Y9 = White

Table 5. Resonator Part Number Suffix

The CSTS series and the CSACW/CSTCW series follow the part numbering system in Figure 25. Although the system includes numbers for several values of load capacitors, currently only 15pF and 47pF values are available for the CSTS series, and 5pF and 15pF values are available for the CSTCW series.

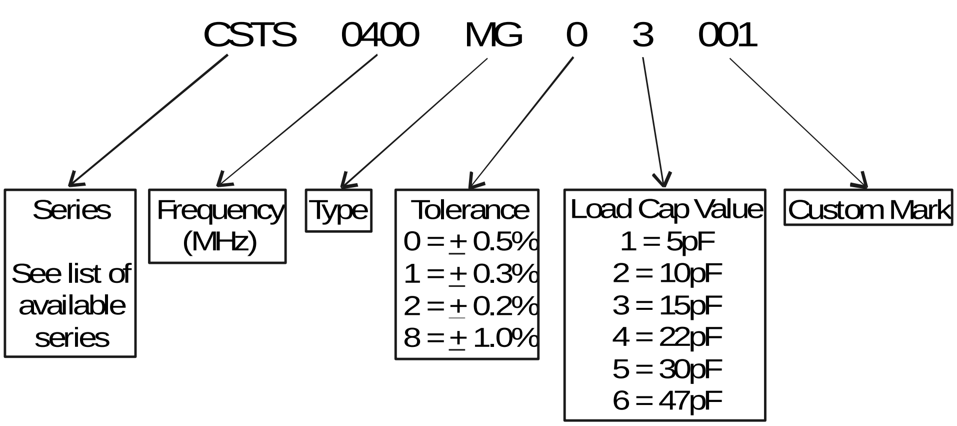
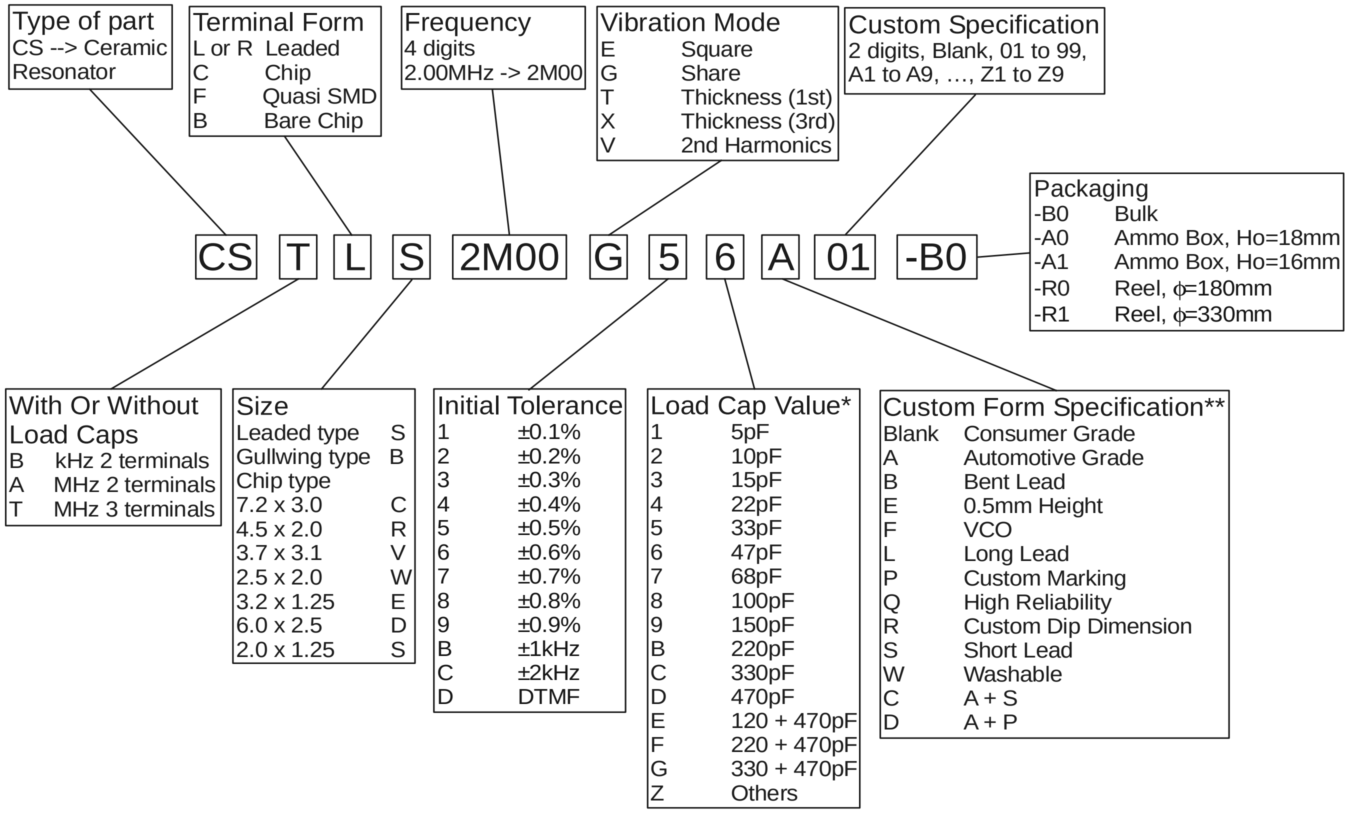


Figure 25: Resonator Part Numbering System

Beginning in the summer of 2000, a new gloabal part numbering system will be implemented by Murata. All resonators introduced in 2000 and later will follow this part numbering system, and some current resonators will be switched to this system.



* Note: Not all load cap values available with a specific part. In the case of 2 terminal resonators, cap value is for Murata standard circuit. In the case of 3 terminal resonators, cap value is for built-in capacitors.

** Note: Not all custom forms are available with a specific part.

Figure 26: New Resonator Part Numbering System

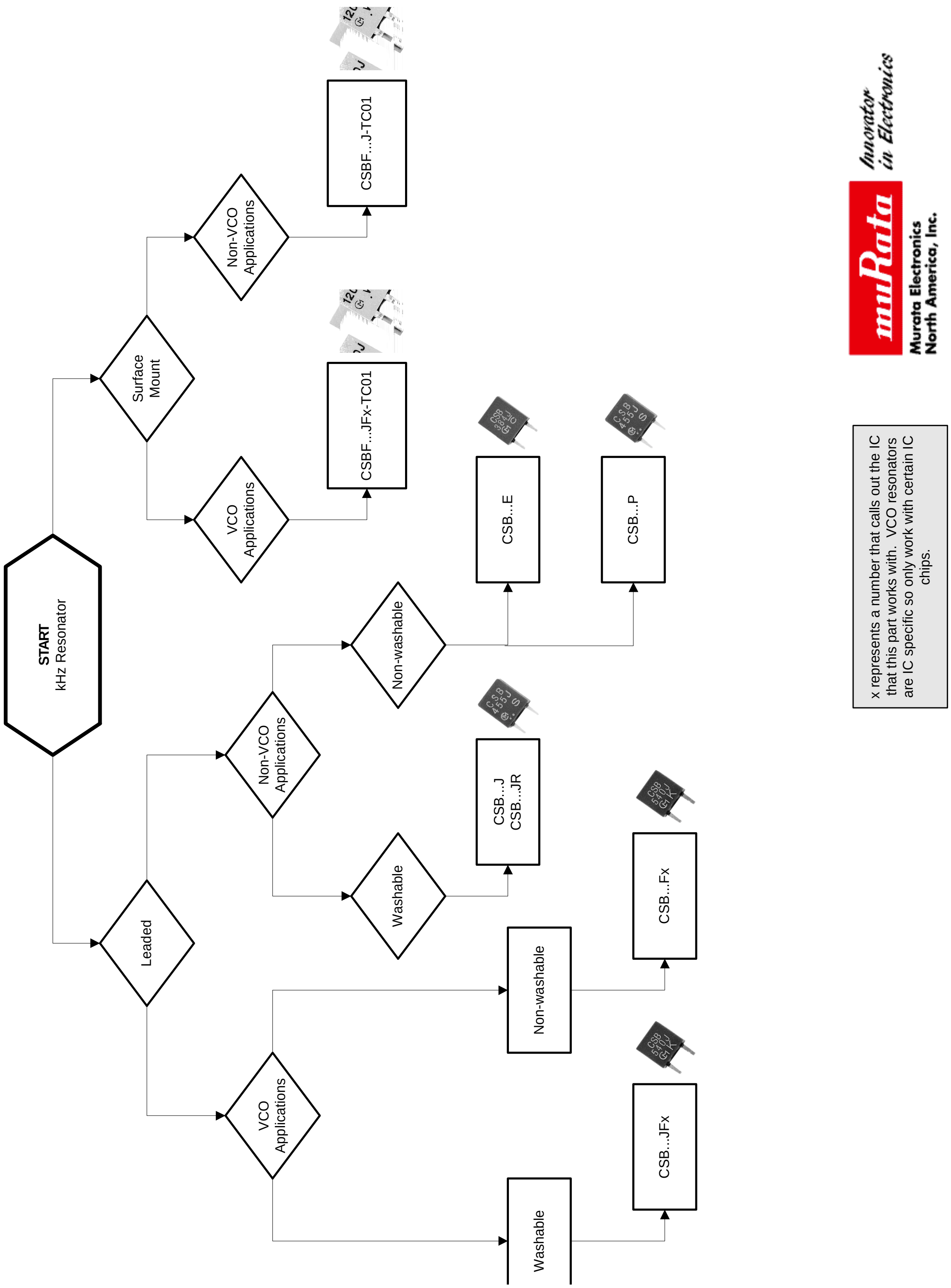


Figure 27: kHz Resonator Selection Guide

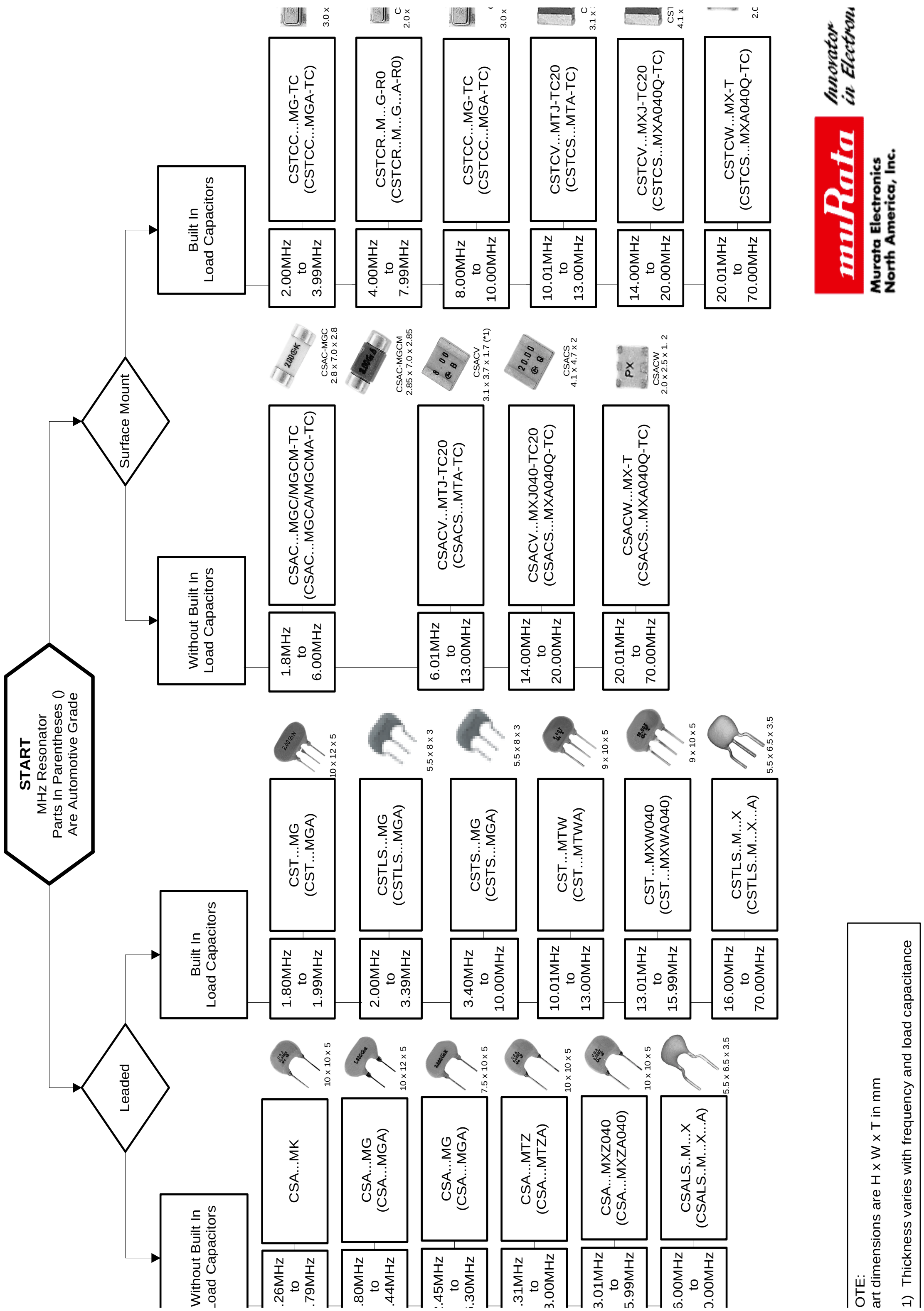


Figure 28: MHz Resonator Selection Guide