

# **FREQUENCY TOLERANCE LIMITATIONS WITH LOGIC GATE CLOCK OSCILLATORS**

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Some expensive design errors are arising on a large scale due to lack of fundamental understanding of resonant circuit theory and its place in crystal oscillator design by many designers of digital integrated circuits for clock oscillators. In some cases they are adequate for their intended purpose but the published data sheets do not point out the limitations. With better understanding of oscillator design principles, most of these devices could be far more versatile at negligible, if any, increase in cost. They should also be more completely characterized in the literature so better informed decisions can be made as to the suitability of a specific device for a given application.

First, it would be useful to have a brief qualitative review of the requirements for making a crystal unit function in an oscillator and how to best utilize its unique properties.

A crystal controlled oscillator can generally be described as an amplifier with a feedback network containing a crystal resonator. To sustain oscillation, the loop gain must exceed unity at a frequency at which the total loop phase is  $2n\pi$  ( $n=0$  or some whole integer.) The level will be determined by the self-limiting characteristics of the loop or an external AGC circuit acting upon it.

Crystal controlled oscillators can generally be divided into two groups. Those that can close the phase loop with a resistor in place of the crystal are loosely called "series resonant". The crystal is inserted in the feedback loop to correct phase instability with a minimum of frequency change. (Figure 1) The amplifier may be noninverting. It may also be an inverter followed by a transformer, LC or RC network or another active inverter.

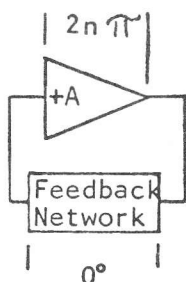


Figure 1

The other type is an inverting amplifier using the crystal as a reactance (usually positive) in a phase inverting feedback network. This is commonly (and loosely) called a "parallel" or "anti-resonant" oscillator. (Figure 2).

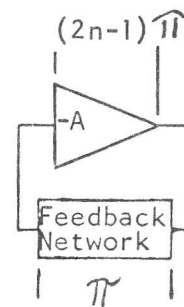


Figure 2

If some frequency adjustment is desired on the first type of oscillator, a capacitor  $C_L$  can be inserted in series with the crystal. To close the phase loop, the crystal frequency will shift until its reactance cancels  $XC_L$ . (Figure 3) If the oscillator is ideal, the crystal in this case is not operating at series resonance. This is obvious to the crystal maker but not to many spec writers and circuit "designers".

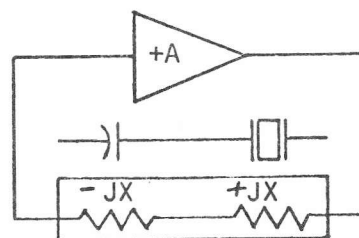


Figure 3

In the case of the positive reactance oscillator, capacitors in the phase inverting network can be varied for frequency adjustment.

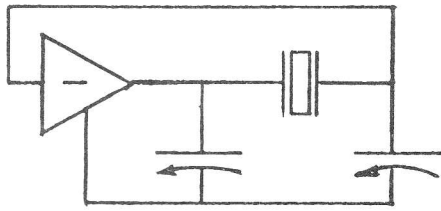
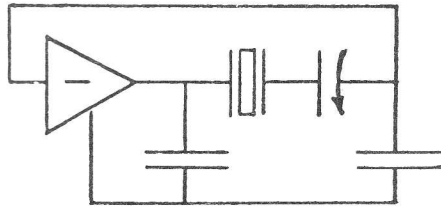


Figure 4



So far we have covered only the ideal case,  $180^\circ$  inverters or  $0^\circ$  amplifiers. With discrete circuits, the errors may be small enough to endure if not ignore in many applications. Also, the circuit designers generally had enough analog background to cope with such problems and the production feedback loop is fairly short so minor design corrections can be made as the project goes on.

With I.C.'s we have an entirely different situation. Most logic gates were not originally intended to be oscillators. They can be used for that function with varying degrees of success provided they are properly characterized. There is nothing inherently wrong with using a device for a purpose for which it was never intended, better known as improvising. There are two paths to success in such an endeavor. They are: 1: blind luck, 2: knowing what is inside the "black box" and what to do about it.

No further comment will be made on method 1, because everyone has their own system for dealing with it. Even method 2 suffers from the fact that a number of people receiving the same information, will not necessarily draw the same conclusions from it.

In the case of the non-inverting oscillator, usually made up of 2 inverters, especially in the case of I.C.'s where they are cheap and plentiful, the principal problem arises from two sources, phase error and phase instability.

- 1.) The inverter usually does not invert exactly  $180^\circ$ . For best stability the feedback loop should be capable of closing only thru the motional arm of the equivalent circuit of the crystal unit. Unfortunately in most digital I.C.'s the phase error is in the wrong direction, making the oscillator appear inductive producing the situation shown in figure 5. This allows the phase loop to be closed at some frequency by  $L_{eq}$  and  $C_0$ .

If the  $L_{eq}$  is very small so it resonates at a very high frequency with  $C_0$ , it will cause only a slight lowering of crystal frequency and not much else. As it gets larger it resonates closer to the operating frequency, causing serious frequency shifts. Generally  $L_{eq}$  increases with frequency, adding to the problem. On some devices the frequency/inductance curve is complex as in figure 6.

Figure 5

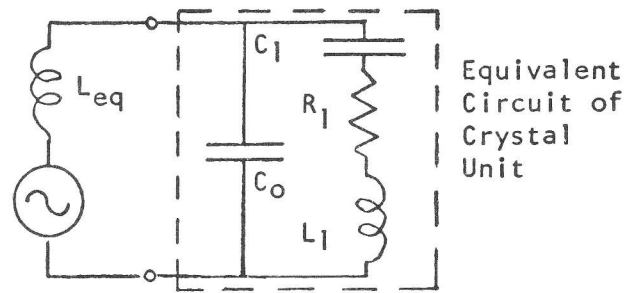
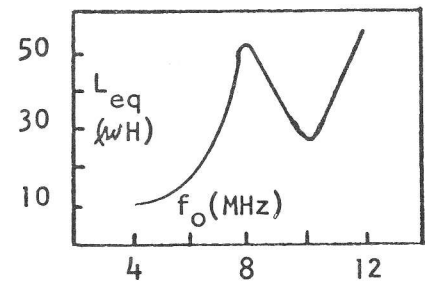


Figure 6



- 2.) Being made up of amplifier phase delay,  $L_{eq}$  is very unstable because it is a function of the instantaneous operating conditions on the amplifier elements. This is bad enough with circuits in which the capacitors and resistors are conventional components, but when they are made up of active devices the results can be many times worse. Active reactances also generally are less stable with temperature.

Both of these problems are compounded in the dual inverter circuit because the surplus of loop gain that is usually available makes it able to oscillate thru most any feedback path. If  $L_{eq}$  is fairly large it may free-run thru the pin to pin capacitance on the IC, the leads to the crystal unit or  $C_0$  on a dead crystal.

In most of these circuits, when the frequency gets high enough so the gain is falling off enough to predict some improvement, the phase delay has also increased  $L_{eq}$  so the expected improvement does not occur. Some IC makers have sought the answer to this problem by having a computer design developed for a crystal unit that will not be so susceptible to frequency pulling by the oscillator. Unfortunately the resulting designs are not very producible.

When TTL first became popular, starting was a problem because the digital approach was to have an inverter either cut off or saturated. Many designers had no background in the conditions necessary for an oscillator to start. It took some time to convey the idea that it had to be biased in the linear region to start. Unfortunately on some of the earlier devices, variations from sample to sample and temperature made reliable starting a serious question.

For the oscillator to start, the loop must contain sufficient noise at the proper frequency (and hopefully not too much at some other frequency) where the gain-phase loop could close. Fast switching is not the secret of success in this case, even if it is the "in" thing in digital circuits because most of the unwanted responses of a crystal unit are higher in frequency than the desired ones.

With flexure mode units, usually below 100 KHz, the extension mode can start faster than the desired mode, in some cases preventing the desired mode from starting, making it shift after starting or in some cases, operating on both modes simultaneously.

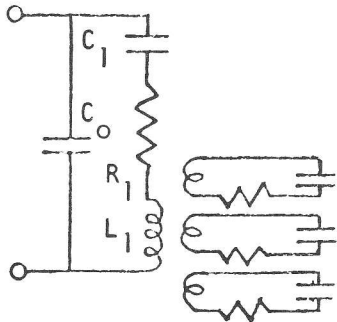


Figure 7

Another frequent problem in the range of square DT cuts is the strong extension mode at 2.28 times the main mode. Except near the upper frequency limit of most gate type oscillators, they often start easier at the higher frequencies.

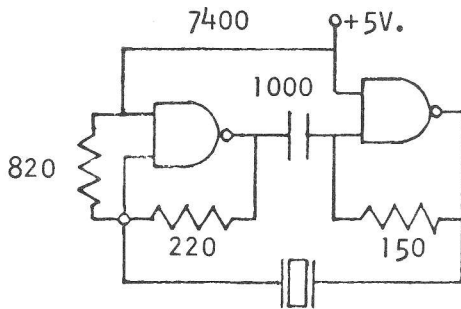


Figure 8

The fast wavefronts also represent energy at frequencies at which the reactance of  $C_o$  may be low enough to cause trouble, even with fairly low  $L_{eq}$ . One of the most popular TTL gate oscillator circuits is shown in figure 8. If the inverters were ideal it could be considered a series resonance oscillator and putting a load capacitor in series with the crystal would make the crystal operate as a positive reactance in which case it would *not* be a series resonance oscillator. In the usual gate IC the phase shift in an inverter is not  $180^\circ$  so the oscillator looks inductive at its terminals as shown in figure 9.

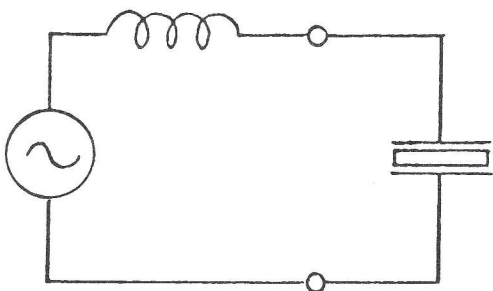


Figure 9

IN THIS CASE a capacitor must be put in series with the crystal to bring it to zero phase (series resonance) as shown in figure 10. Under these conditions, the capacitor value does not represent  $C_L$ . With an appropriate capacitor range, the crystal can be tuned either side of series resonance.

At first glance this looks like an ideal situation but it is not, for a number of reasons. The principal problem is the instability and scatter of the oscillator inductance. Also, the inductance usually increases with increasing frequency, so the capacitor required to cancel it would rapidly approach  $C_o$  and may be even smaller.

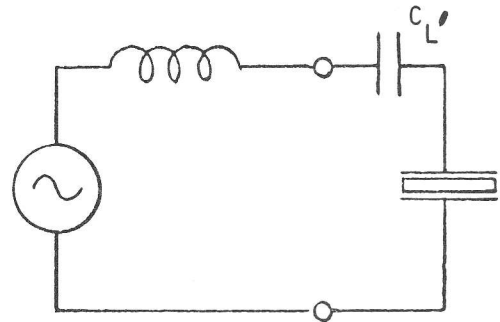


Figure 10

A good example of this problem is shown in figure 11 on the 8224 which is promoted as the standard clock oscillator for the 8080 microprocessor. The chart below shows what happens to crystal performance with this type of device and what production spread from one manufacturer looks like. Some manufacturers hold better tolerances than others but the data sheets do not specify the factors critical to oscillator stability or operation.

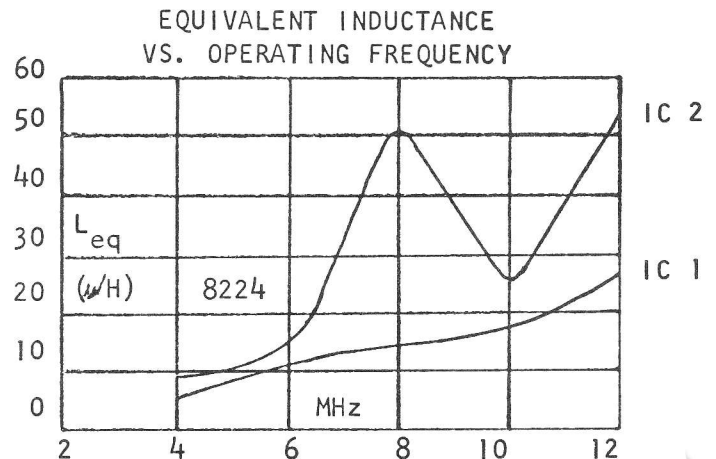


Figure 11

$f_s$ (MHz)	$\Delta f$ (Hz)	$\Delta f$ (PPM)	$L_{eq}$ ( $\mu$ /h)	$C_L$ to CANCEL $L_{eq}$ (pf)	$\Delta f$ (Hz)	$\Delta f$ (PPM)	$L_{eq}$ ( $\mu$ /h)	$C_L$ to CANCEL $L_{eq}$ (pf)
2	OPERATES ON 3RD. OVERTONE				OPERATED ON 3RD. OVERTONE			
4	-156	-39	6.8	233	-214	-53	9.4	170
8	-2958	-370	13.8	29	-7455	-932	50.8	8
10	-6776	-678	18.1	14	-8506	-851	25.2	1
12	-12200	-1017	28.2	6	-16503	-1376	54.8	3
16	-59318	-3637	-	-	-171947	-10541	-	-
18	NOT CRYSTAL CONTROLLED				NOT CRYSTAL CONTROLLED			

The data sheet on the 8224 does acknowledge a "small problem" with the following footnote. "When using crystals above 10 MHz, a *small* amount of frequency trimming may be necessary. The addition of a small capacitance (3 to 10pf) in series with the crystal will accomplish this function". In view of the data shown, this seems to be understated.

They also sanction overtone operation with the statement that overtone mode crystals generally have much lower "gain" than the fundamental type so an external LC network is necessary to provide additional gain for proper operation. Experience with this device indicates such operation is precarious at best. With 2 MHz crystals it operates only on the 3rd overtone at 6 MHz because the waveform has so much more energy at the higher frequency.

Some manufacturers of the 8224 have found that it is possible to improve these shortcomings somewhat with only minor changes, but it is still suitable only for loose tolerances.

Improvements requiring drastic changes in IC's are very expensive and take many months to put into production. In the meantime large quantities of the existing devices are in circulation, so the only solution is to provide adequate and accurate information on their limitations. This should induce the IC makers to do their design work and data sheets more thoroughly. Many of these problems could have been designed out initially at minimal cost compared to the detours to which their customers are unexpectedly subjected.

Another popular clock oscillator is the 12060L. Fortunately the manufacturer has published considerable information on its behavior as an oscillator but figure 12 presents more useful information and represents the average of several units.

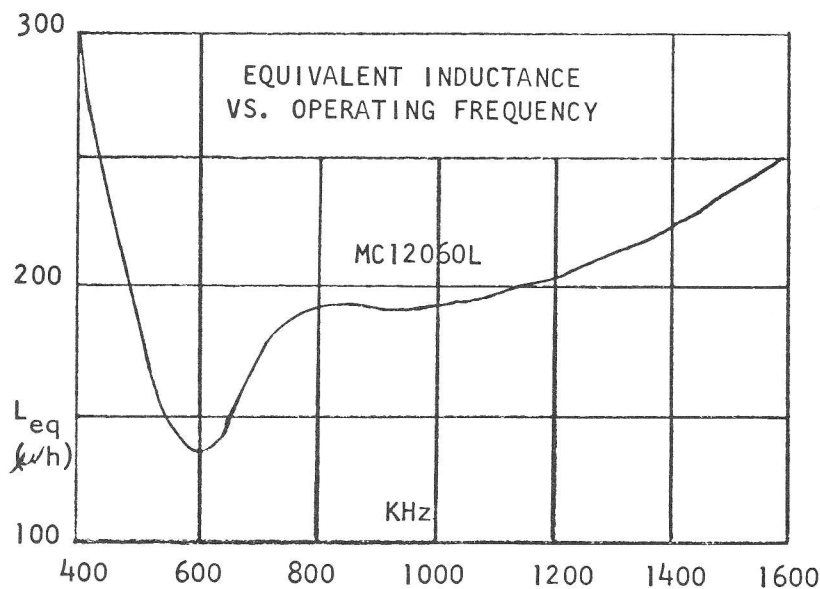


Figure 12

The production spread is not as bad as many other devices. This device gets into serious problems at a fairly low frequency. For higher frequencies the 12061L is suggested. Its behavior with frequency is shown in figure 13.

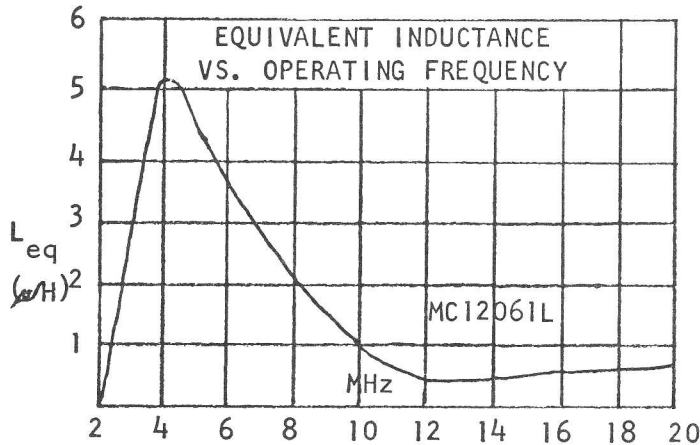


Figure 13

Note the peak at 4 MHz. It can be seen from this that measurements made only around 2 MHz or over 8 MHz can give an unrealistically optimistic picture if any part of the application is near 4 MHz.

The 14410 MOS series is an example of a good device with a deficient data sheet. For example, for 1 MHz it says: Crystal Mode - parallel. The crystal mode is fundamental, thickness shear. It operates in what is loosely called a parallel circuit but nowhere does it give the load capacitance, which is important to frequency calibration. It does give  $C_0$  as "7pf typical" which is doubtful. Few 1 MHz crystal units in the HC-6/U enclosure run much over 3pf. Electrodes large enough to provide 7pf at 1 MHz would barely fit in the can. The 7pf was taken from a 1949 vintage Mil spec for reasons unknown.

No mention is made of the fact that an improvement can be made in stability on this unit by adding capacitors from each side of the crystal to common, and the resulting effects. While this may be of little consequence in the application for which it was intended, it is often put to other uses and such basic data should be provided.

Another device that needs better published data is the 74S124 family which is basically a VCO but with a data sheet that suggests its use as a crystal controlled clock oscillator as well. Results are shown in figure 14.

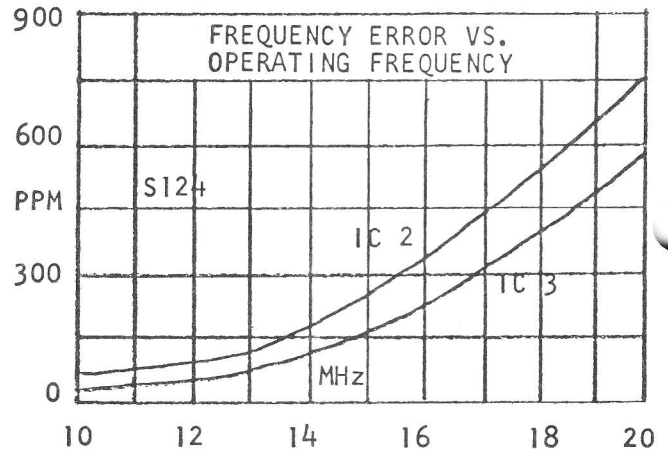
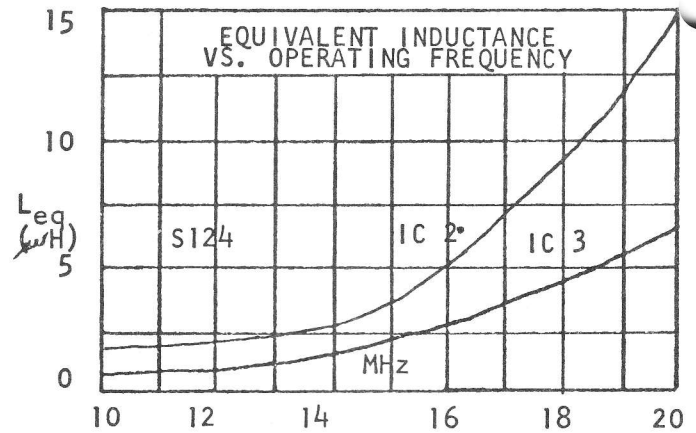


Figure 14

Another problem common to the 124 as well as the 4201 and S1856 is severe frequency shift with changes of crystal resistance. None of these effects are listed in the literature.

The data presented so far describes the primary problems with these relatively new devices. Some of the attempted solutions (with varying degrees of success or failure, depending on point of view) provide an interesting commentary on the clash of outlook between people of varying technical vintage.

Take for example, the designer who needs a calibration tolerance of  $\pm 100$ PPM for his system, so he orders crystal units to a  $\pm 50$ PPM tolerance and plugs them into a device that gives a production spread of  $\pm 500$ PPM. The obvious solution is to tighten the crystal tolerance - but the question is "How much?" There is a basic lack of understanding of how a crystal or any other tuned circuit controls frequency.

Some crystal manufacturers attempt to simplify information exchange with customers by publishing a list of crystal unit part numbers versus IC types for which they are recommended. For the devices with reasonable characteristics and systems with wide tolerances this has some virtue. It also has some drawbacks. It gives no clue as to the performance that can be expected, nor does it reveal the magnitude of the differences between types which might allow a different choice of IC if the first one turns out to be inadequate. It also implies that if you order that part number crystal unit for that IC, your troubles are over, when they have only begun.

The whole IC data situation needs drastic upgrading. One of the best is the RCA Application Note ICAN-6086. While it has some minor errors, if they were all that thorough, the savings of time and money would be well worthwhile. It was done by an engineer who did his homework, not by an advertising agent or marketing department clerk. In the words of an old Eimac satire vacuum tube data sheet, "Tests conducted in our sales department show that the performance is twice as good as you will find it to be".

Much confusion is generated by new and original names or abbreviations for well known terms. This is a quick way to identify questionable data. If the writer is not familiar with the terms he is using, the information has a high probability of being wrong, incomplete or misleading. A prime example is such terms as  $C_s$  or  $C_m$  for the motional capacitance of a crystal resonator IEEE and IEC standards list it as  $C_1$  and for good reason. Original abbreviations often turn out to have other meanings already established. For example  $C_m$  is modulus of compliance. Incorrect abbreviations are so common that seeing them in print does not give them legitimacy. The standards should be consulted.

Quite a number of crystal manufacturers make the same error. Near the back of the recent issues of the Proceedings of the Annual Frequency Control Symposium is a list of the standards with which specification and technical data sheet writers and engineers dealing with crystals should be familiar. They give terms and definitions as well as abbreviations. A similar list is on the back page of the NEL crystal catalog.

Another area that needs attention is drive level. It may or may not be a problem in a given application. The number of crystal specs for IC's or IC data sheets that have obviously taken their drive level figures from MIL-C-3098 is an indication that the people involved have not determined the level to be expected in their circuits. In many cases they represent the state of the art in an era when crystal oscillators produced watts of output from a 300+ volt supply and the transistor had not yet been developed. They are not necessarily appropriate for the latest devices of today. A missing drive level spec is better than an erroneous one.

The "engineer of yesteryear" also discovered the fact that at some frequencies capacitors are inductive, inductors are capacitive and resistors can be either or both - and active devices all 3, plus negative resistance. Thus, stray resonances could turn up unexpectedly and usually did. These problems were resolved in the process of putting the components together into a specific device for a specific purpose. If one component resulted in a problem in a given situation, it would be replaced in minutes, and a design change was complete, except for the paperwork.

With the IC this process has been moved to a stage where changing one unsuitable component in a device for one application is expensive, takes several months and may make it unsuitable for another application into which it has already been successfully designed. That is the reason it is so important for the IC designer to do his homework or ask for competent help before the design is frozen.

In the case of devices developed and used for a specific purpose, it is difficult to rationalize some of the designs now in use, especially without the limitations carefully spelled out in the application data. Some of the worst examples are casually mentioned, as if they were no real problem at all.

One example of the difficulty this can create is as follows: Microprocessors are a convenient tool for handling the complex combinations required in frequency synthesizers. The microprocessor system has its own clock oscillator so why not use it as the time base for the frequency synthesis? After the system is designed is an expensive time to discover that the clock oscillator stability of  $10^{-5}/^{\circ}\text{C}$  is not satisfactory for the carrier on a single sideband system.

There are some very good devices on the market in which the design was done or assisted by people knowledgeable in oscillator theory and requirements. These generally are also better characterized in the data.

In summmary, a quartz crystal resonator is an analog and not a digital device. To use it with a digital device, a number of factors must be taken into account that can be treated more lightly or ignored when using only digital devices.

To arrive at a given frequency, the phase shift between the oscillator terminals must be considered an integral part of the frequency determining network. In order to do this, the device must be properly characterized. Ideally this should be done by the IC manufacturer in the configuration recommended and become part of the published data. Above all, it should be correct. The IC maker should also realize that there are limits to the range of attainable crystal parameters just as there are limits to the range of semiconductor parameters. The data should also include signal levels at the crystal terminals as well as a bibliography of good references.

Certainly the technical facts presented here are well known in the crystal industry. What is not so well appreciated is the magnitude of the problems described and how rapidly they are proliferating. The digital industry has given us many marvelous new developments but the rapid expansion of digital knowledge has in some cases obscured the principles upon which it was built. If analog and digital people are to accomplish things together, each of us must learn some of the other language, or find a good translator.

This paper was presented at the 31st Annual Frequency Control Symposium, June 1977, and will appear in the Proceedings.

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- The Theory & Design of Quartz Crystal Units.* Virgil E. Bottom. McMurry Press, McMurry College, Abilene, Texas 79605.
- Handbook of Piezoelectric Crystals for Radio Equipment Designers.* Wright Air Development Center Technical Report (WADC) 56-156. John P. Buchanan.
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- Transistor Crystal Oscillator Circuitry.* Dept. of the Army, Project 3-24-02-02, Motorola Mil Electronics Division.
- Quartz Crystal Oscillator Circuits.* Design Handbook, Dept. of the Army, Project 3A99015-004, The Magnavox Company.

Most of the references listed contain extensive bibliographies.

## Standards & Guides

The following International Electro-Technical Commission publications are available from: AMERICAN NATIONAL STANDARDS INSTITUTE, 1430 Broadway, New York, N.Y. 100018.

- Publication 122.1,* Quartz Crystal Units for Oscillators; Standard Values and Test Conditions.
- Publication 122.2,* (International version of EIA Bulletin No. 6.)
- Publication 122.3,* (International version of RS-192A and RS-168-A.)
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- Publication 314 and 314A,* Temperature Control Devices for Quartz Crystal Units.
- Publication 444,* Basic Methods For The Measurement of Frequency and Equivalent Series Resistance of Quartz Crystal Units by Zero Phase Technique In a  $\pi$ -Network.

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Several of the documents listed are in the process of being updated. New publications are also being developed. Please feel free to contact NEL for the latest information.

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