

A NEW METHOD FOR GENERATING OVERTONE
FREQUENCIES IN A QUARTZ OSCILLATING CIRCUIT

Harish Bahadur & R.Parshad
National Physical Laboratory
New Delhi-110012
(INDIA)

ABSTRACT

Quartz crystals have been operated in overtones for obtaining standard frequencies. Excitation in overtones enables the inductance of the equivalent series circuit of the crystal to be made high enough (inductance value increasing as the cube of the overtone number) for obtaining a high degree of frequency stability and, also, the resistive impedance of the crystal at resonance becomes high enough in overtone excitation for proper operation in the oscillator circuit.

Along with the advantage of high stability, excitation of quartz in overtones can have another great advantage of being able to generate a high enough frequency at the output to reduce the frequency multiplier chain linking the quartz crystal frequency with the atomic frequency in atomic frequency standards.

This paper describes a simple and effective technique for generating overtone frequencies of almost any required overtone number with ease and reliability. The method consists in coupling a parallel L-C circuit to the quartz in the oscillator network. As L-C is tuned in the proximity of the overtone frequency, the quartz crystal takes control to generate the overtone frequency. Thus, overtone frequencies in the neighbourhood of 60 and 100 MHz using different crystals could be easily obtained in the first single stage of a multiplier chain.

An interesting effect noticed was the splitting of an overtone frequency in two values, the higher value being obtained when the resonance frequency of the L-C was varied from the higher to the lower values. The lower overtone frequency was obtained when the variation of the L-C resonant frequency was in the opposite direction. The frequency splitting probably arises as a result of the coupling of the two resonators, the L-C and the quartz. This explanation is supported by the fact that the splitting between the overtone doublet decreased as the coupling between the L-C and the quartz was decreased. Starting with any of the overtone doublet in each case only the lower frequency is obtained after the interruption of voltage supply and, hence, for repeatability, is the one to be used in practical application in the frequency multiplier chain.

INTRODUCTION

Quartz crystals are essential electronic components for generating standard frequencies. Earlier to the development of atomic frequency standards, the quartz crystal itself in an oscillator circuit served as the standard of frequency, the ageing of the crystal being allowed for by resetting the crystal frequency through astronomical observations. Presently, the quartz crystals serve as slave oscillators in atomic frequency standards. In both the cases it is essential that the frequency stability of the quartz crystal be the highest.

Warner (1-3) at Bell Telephone Laboratories has developed design of quartz crystals for obtaining very high Q ($\approx 5 \times 10^6$). The improvement obtained in the Q 's is an order of magnitude higher than that obtained earlier. At about the same time appreciable progress has been made to reduce the ageing rate of the crystals. Thus, the frequency stability of the quartz crystals has been pushed up from 1×10^{-8} to 1×10^{-10} . Due to this fact, the quartz crystals not only become better slave oscillators for the atomic frequency standards but also tend to compete with the atomic standards for independent working over a long period of time.

Due to the availability of high Q crystals, the question arises in what mode (fundamental or the overtone) should the crystal be excited? Due to the very high Q's, the series resistance of the quartz crystal equivalent circuit becomes so low that it becomes difficult to efficiently match the crystal to the rest of the circuit for its efficient operation. Warner has shown that for the best utilization of the high Q crystals it should be operated in higher overtones. This is because the equivalent resistance of the quartz crystal in the overtone operation will increase fast with the overtone number because the equivalent inductance of the series circuit increases as the cube of the overtone number and the $Q = \omega L/R$ itself will remain almost unchanged, both for the fundamental and the overtone frequencies. The operation in the overtone gives an additional stability of operation due to increase of inductance. It can be shown that

$$\frac{\Delta f}{f} = \frac{\Delta X_e}{2\omega L} = \frac{\Delta X_e}{S_I}$$

where X_e is the effective reactance, L is the equivalent series inductance of the quartz crystal and S_I is the stability index of the crystal.

The operation of the quartz crystal in overtones not only helps to obtain a stable frequency in the way indicated above but also can be effective in reducing the frequency multiplier chain between the slave quartz crystal oscillator and the atomic frequency. For this purpose the higher the overtone number the greater would, of course, be the multiplier chain compression, contributing to increased portability of the standard, reduction of cost and simplicity of the electronic circuitry involved.

For excitation of the quartz crystals in overtones, different workers have employed different techniques (4-14). The basic consideration in these techniques is to suppress, by use of filters or otherwise, the fundamental and provide enough gain to the oscillator circuit at one of the overtone frequencies for oscillations to take place at this frequency. It may be mentioned that much earlier to the development of high Q crystals Mason and Fair (15) had given a technique for overtone excitation in an oscillator circuit. However, the method was complex and hardly any use seems to have been made of it in subsequent frequency standard work.

This paper presents a general, practical and relatively easy method of exciting the quartz crystal in the oscillator circuit to almost any overtone number desired, limited, of course, by the frequency capability of the rest of the circuit. The technique for production of overtones simply consists of coupling an L-C network to the quartz crystal and bringing the resonant frequency of the L-C network in the neighborhood of the desired overtone frequency. At this stage the quartz crystal takes control, resulting in the generation of the overtone frequency.

EXPERIMENTAL DETAILS

Fig.1 depicts a representative example of the use of the technique for producing overtones, the oscillator circuit used being of the Colpitts fashion. In order to prevent d.c. shorting of the bias on the crystal a blocking capacitor (C_3) is used as shown in fig.1. Change of this capacitor also enables variation of the coupling between the LC and the quartz crystal.

In order to show the working of the circuit of fig. 1 for overtone generation the capacitance of the L-C circuit was varied continuously from higher C values to lower and vice-versa so that the overtone frequency of the quartz crystal lay in the range of resonant frequencies of the LC circuit. Starting from higher or lower limits of C, a region was obtained when the frequency became insensitive to further variation of capacitance, this frequency being the desired overtone frequency.

As expected, the frequency stability in this region was the maximum, showing that the quartz crystal had taken control of the frequency generated. It was found that as the capacitance was varied from either side, the onset and termination of the overtone generation in the regions I & II of stable frequencies (fig.2&3) were indicated by the production of a momentary shift of the C.R.O. waveforms appearing at the output of the oscillating circuit. This shift in the waveform can be used to monitor visually when the frequency control by the quartz crystal is taking place. As expected, no such shift was observed when the quartz crystal was replaced by its equivalent electrode capacitance. Figures 4 and 5 illustrate the voltage waveforms of the third and fifth overtones generated by a quartz crystal of fundamental resonance frequency of 1.87MHz

by use of circuit of fig. 1. The amplitude of the overtones was found to be comparable to that of the fundamental.

An interesting fact noticed from the figures 2 & 3 is, what may be called, frequency splitting of each of the third and fifth overtones in two values and the production of a hysteresis-type curve located in the region of the production of the overtone frequencies. It was found that only the lower overtone frequency was stable against interruption of voltage supply and will be, of course, the one to be used in practical applications. The splitting of the overtone frequencies was found to be a direct function of the coupling of the L-C circuit with the quartz crystal. Table (I) depicts these results. In this table the coupling capacity between the L-C circuit and the quartz crystal is progressively changed from one set of values to the others for obtaining the corresponding interval between the overtone-frequency doublet.

The method of obtaining overtone frequencies described in the paper was tried in different kinds of quartz crystal oscillating circuits apart from that described in fig. 1. In all cases, the overtone frequencies were easily obtained. In one circuit using the quartz crystal of 20MHz fundamental frequency overtone frequencies of nominal values 60 & 100 MHz were obtained. Fig. 6, 7 and 8 depict the fundamental third and fifth overtone frequencies (20, 60 & 100 MHz) of a quartz crystal.

In order to illustrate the effective control of the quartz crystal for producing the overtone frequencies the following observations were obtained for a particular circuit, using a quartz crystal of 20 MHz as fundamental frequency.

The resonant L-C frequency was changed between two limits in two different sets (I & II) of observations, the values in set I lying below the overtone frequency and those in set II lying above the overtone frequency. Table II depicts the results. It can be seen from the table that even for a big enough interval between the two frequency limits in each set the overtone frequency is obtainable, its frequency hardly changing between the two limits of set I, though there is a greater corresponding change for limits of set II. The extent of control the quartz crystal can have, seems to depend also on the type of oscillating circuit used.

The significant difference in the overtone frequencies corresponding to use of set I and II is the frequency splitting already described in fig.2 for use of the 1.87 MHz crystals.

DISCUSSION OF RESULTS

It has been shown that use of a L-C circuit directly coupled to the quartz crystal is effective in generating overtone frequencies. In principle any overtone number can be generated consistent with the frequency capability of the oscillator circuit. For example, in circuit of fig.1 the thirteenth overtone frequency of the 1.87 MHz crystal was obtained, no attempt being made to obtain still higher overtones. The usefulness of the coupled L-C network is shown by the fact that as soon as, during the production of overtone frequencies, the L-C is mechanically decoupled only the fundamental frequency gets generated.

The overtone frequency splitting is probably due to well known coupling of two tuned circuits of the same individual resonance frequencies (16-17). The doublet will tend to vanish as the coupling is decreased, as actually found.

It may be expected that by use of active solid state devices of the oscillator circuit of high enough frequency capability, generation of overtone frequencies of the order of 500 MHz should be feasible, in the first stage of a frequency multiplier chain for an atomic frequency standard. For this purpose, it would of course be desirable to have the fundamental frequency of the crystal as high as possible.

SUMMARY AND CONCLUSION

The paper presents a new method of generating overtone frequencies of quartz crystals. A parallel, tunable L-C circuit is coupled to the quartz crystal in an oscillator circuit. On tuning the L-C for its resonant frequency to lie in the neighbourhood of an overtone frequency, the quartz crystal takes control for generating the pure overtone frequency of amplitude comparable to that obtained for the fundamental oscillations.

Each overtone frequency exhibits a splitting in two, the higher frequency being obtained when the L-C resonance frequency approaches the overtone frequency from the higher values. The reverse is the case when the overtone frequency is approached from the lower values. The lower overtone split frequency is stable against the interruption of the voltage supply and, therefore, is the one to be used for practical applications.

The method for obtaining overtone frequencies makes it easily possible to excite high Q crystals in the higher overtones for which the quartz crystals would have impedance levels better matched to the oscillating circuit and also have higher stability index. In this way standard frequencies can be generated efficiently using high Q crystals. Also, exciting a crystal of preferably high fundamental frequency in an high enough overtone the frequency multiplier chain linking the quartz crystal frequency with the atomic frequency in an atomic frequency standard can be appreciably compressed, this fact leading to better portability, lower cost and simplification of electronics involved. As an example, an overtone frequency of 100 MHz was easily obtained for the first stage of a frequency multiplier.

ACKNOWLEDGEMENT

One of the authors (Harish Bahadur) thanks the Department of Atomic Energy, Govt. Of India for the award of research fellowship.

REFERENCES

1. A.W.WARNER - "Design and Performance of Ultra-Precise 2.5 Mc Quartz Crystal Units"
Bell System Tech.Jour. 39, p.1193,(1960)
2. A.W.WARNER - "Ultra Precise Quartz Crystal Frequency Standard" IRE Trans. Instrumentation, I-7, p. 185, (1958).
3. A.W.WARNER - "High Frequency Crystal Units for Primary Frequency Standards",
Proc. I.R.E. 40, p. 1030, (1952).
4. T.C.ANDERSON, F.G.MERRIL - "Crystal Controlled Primary Frequency Standards - Latest Advances for Long Term Stability" I.R.E. Trans. Instrumentation I-9, p.136, Sept.'(1960)
5. R.A.SYKES - "Modes of Motion in Quartz Crystals"
cited in QUARTZ CRYSTALS FOR ELECTRICAL CIRCUITS (ed. R.A.Heising), D.Van Nostrand, New York; also Bell Syst. Tech. Jour. 23, No.1, Jan.'(1944).
6. R.A.SYKES - "High Frequency Plated Quartz Crystal Units" Proc. I.R.E., 36, p.4 (1948).
7. J.J.VORMER - "Quartz Filter Crystals with Low Inductance" Proc.I.R.E., 36, p.802, (1948).
8. J.J.VORMER - "Crystal-Plates Without Overtones"
Proc. I.R.E., 39, p.1086 (1951).
9. W.P.MASON - "Electromechanical Transducers and Wave Filters"
D.Van Nostrand Inc., p.1941, (1948).
10. W.P.MASON - "Electrical Wave Filters Employing Quartz Crystals as Elements"
Bell.Syst. Tech.Jour. 13, p.405, July (1934).

11. W.P.MASON - "Method for Exciting a Single Harmonic of a Longitudinally Vibrating Bar" paper contributed to "PHYSICS OF SOLID STATE, Commemoration Volume to Prof. S.Bhagwantam (ed. S.Balakrishna, M.Krishnamurthi & B.R.Rao), Academic Press, London & New York p.381, (1969).
12. W.L.SMITH - "Miniature Transistorized Crystal Controlled Precision Oscillators" I.R.E. Trans. Instrumentation, I-9, P.141, (1960).
13. E.P.FELCH & J.O. ISRAEL- "A Simple Circuit for Frequency Standard Employing Overtone Crystals" Proc. I.R.E., 43, p.596, (1955).
14. O.O.LAYDEN, - "Crystal - Controlled Oscillators" W.L.SMITH, IEEE Trans. Instru. & Meas. IM-21, No. 3, A.E.ANDERSON, p. 277, Aug'(1972). M.B.BLOCK, D.E.NEWELL & P.C.SULZER
15. W.P.MASON & I.E.FAIR - "A New Direct Crystal Controlled Oscillator for Generating Ultra-Short Wave Frequencies" Proc. I.R.E. 30, p.464, Oct'(1942).
16. F.E.TERMAN - "Electronic and Radio Engineering" Mc Graw Hill Electrical and Electronic Engineering Series, Mc Graw Hill, New York, (1955).
17. SAMUEL SEELY- "Electronic Circuits" Rinehart and Winston Series in Electrical Engineering, Electronics and Systems, Rinehard and Winston, New Yor, (1968).

TABLE (I)

ILLUSTRATION OF OVERTONE FREQUENCY SPLITTING AS A FUNCTION OF THE COUPLING BETWEEN THE QUARTZ CRYSTAL (of fundamental frequency = 1.87 MHz) AND THE L-C CIRCUIT.

OVERTONE NUMBER	COUPLING CAPACITANCE	OVERTONE DOUBLET SEPARATION IN HERTZ
THIRD	0.1 μ fd	213413
	220 μ fd	79468
	110 μ fd	127
FIFTH	0.1 μ fd	413216
	220 μ fd	12624
	110 μ fd	152

TABLE (II)

ILLUSTRATION OF EFFECTIVE CONTROL OF QUARTZ AT OVERTONE FREQUENCY WITH THE CORRESPONDING L-C FREQUENCY VARIATIONS IN THE REGION OF PRODUCTION OF OVERTONES.

SET NO.	L-C FREQUENCY VARIATIONS	QUARTZ OVERTONE FREQUENCY FOR THE RANGE OF L-C FREQUENCY VARIATION
I	49.8128 MHz	60.001124 MHz
	56.7538 MHz	60.001125 MHz
II	62.3241 MHz	60.003794 MHz
	67.4629 MHz	60.009162 MHz

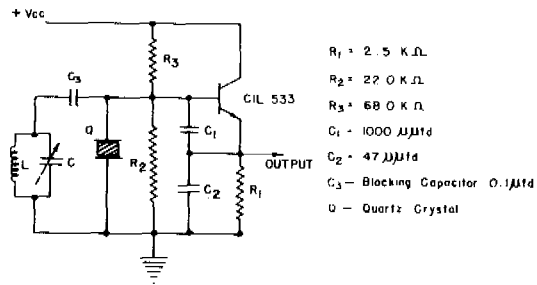


Fig 1 CIRCUIT DIAGRAM OF A CRYSTAL CONTROLLED OSCILLATOR SHOWING THE USE OF A PARRALLEL TUNED L-C CIRCUIT ACROSS THE QUARTZ CRYSTAL FOR THE GENERATION OF OVERTONE FREQUENCIES

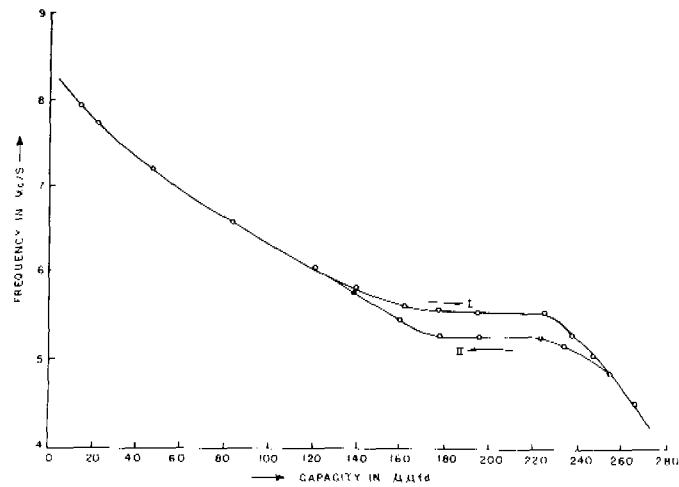


Fig 2 FREQUENCY VARIATION WITH DIRECTIONAL CHANGE OF CAPACITANCE FROM LOWER VALUES TO HIGHER AND BACK, FOR EXCITATION OF QUARTZ IN THIRD OVERTONE

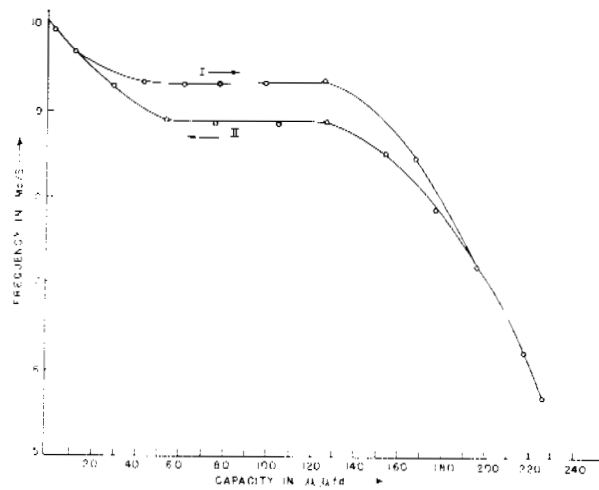


FIG. 3 FREQUENCY VARIATION WITH DIRECTIONAL CHANGE OF CAPACITANCE FROM LOWER VALUES TO HIGHER AND BACK, FOR EXCITATION OF QUARTZ IN FIFTH OVERTONE

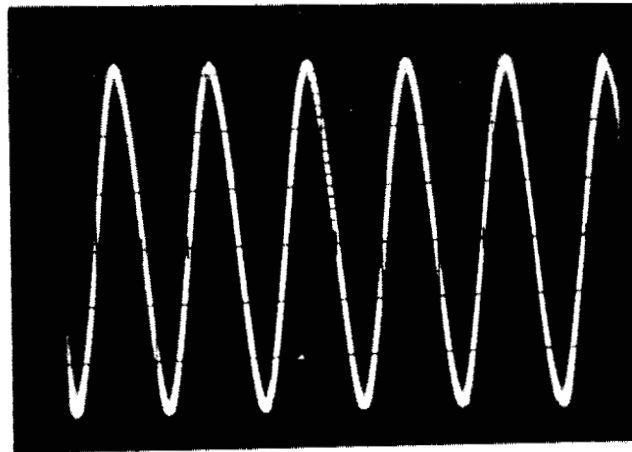


FIG. 4 GENERATION OF THIRD OVERTONE FREQUENCY (5.6 MHz) OF A QUARTZ CRYSTAL OF 1.87 MHz FUNDAMENTAL FREQUENCY.

Horizontal Scale 1 div. = 0.1 μ sec.
Vertical Scale 1 div. = 2.0 volts

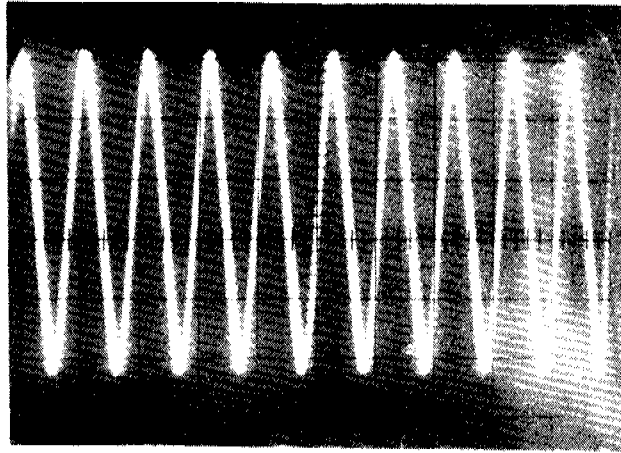


FIG. 5 GENERATION OF FIFTH OVERTONE FREQUENCY (9.3MHz)
OF A QUARTZ CRYSTAL OF 1.87 MHz FUNDAMENTAL
FREQUENCY.

Horizontal Scale 1 div. = 0.1 μ sec.
Vertical Scale 1 div. = 2.0 volts

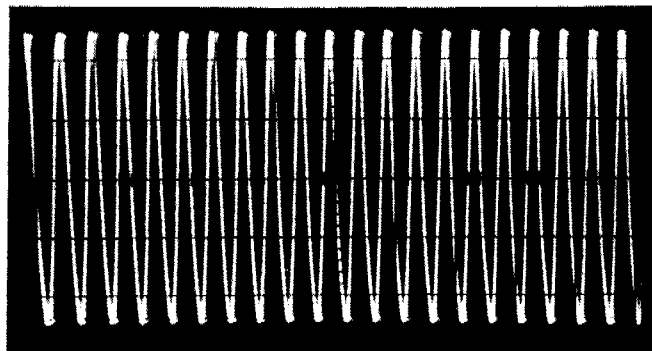


FIG. 6 GENERATION OF FUNDAMENTAL FREQUENCY OSCILLATIONS
OF A 20 MHz QUARTZ CRYSTAL.

Horizontal Scale 1 div. = 0.1 μ sec.
Vertical Scale 1 div. = 2.0 volts

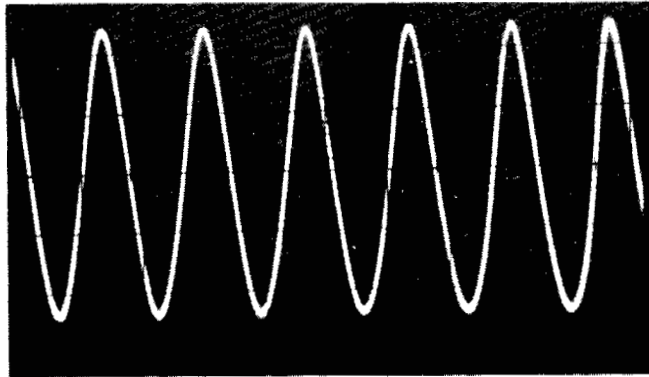


FIG.7 GENERATION OF THIRD OVERTONE FREQUENCY (60 MHz)
OF A QUARTZ CRYSTAL OF 20 MHz FUNDAMENTAL
FREQUENCY.

Horizontal Scale 1 div. = 1.0 μ sec.
Vertical Scale 1 div. = 2.0 volts

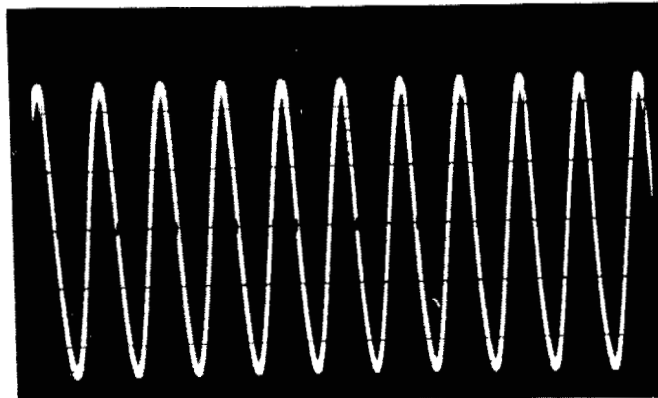


FIG.8 GENERATION OF FIFTH OVERTONE FREQUENCY (100 MHz)
OF A 20 MHz QUARTZ CRYSTAL.

Horizontal Scale 1 div. = 1.0 μ sec.
Vertical Scale 1 div. = 2.0 volts

QUESTION AND ANSWER PERIOD

NO DISCUSSION