STUDY OF AN AUDIO OSCILLATOR
STABILITY DEPENDENCE ON TEMPERATURE

by

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ABSTRACT

An investigation was carried out to see if it was possible to build inexpensive, temperature stable(0.0005% per C) precision oscillator using ordinary, as opposed to military, quality components and employing a linear compensation technique.

An oscillator whose performance was better than the design objective was built but it was found that the linear compensation technique, though it improved the performance of the oscillator significantly, was, by itself, not adequate to meet the design objective because the values of the components varied non-linearly with temperature. It was also found that the frequency of the oscillator was not repeatable because of randomness in temperature cycling characteristics of the components.

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1. INTRODUCTION

It is well known that properties of circuit components display a certain temperature dependence. In some cases, this does not matter much because the accuracy of the circuit has enough tolerance range so that the effect of temperature on the circuit can be ignored. In other cases, precaution is taken to ensure that the circuit is operated at around the temperature it was designed for by use of mechanical means such as a fan. In still other cases, where space is limited and high accuracy is required, corrective measure(s) for the temperature dependence of the circuit must be incorporated into the circuit itself.

An example of a circuit where temperature dependence plays an important part is an oscillator. For example, human ears are sensitive enough to detect a change of $\pm\frac{1}{4}$ Hz. at 500 Hz. If this kind of change occurs within a temperature span of 20 C°, say from 25°C to 45°C, the change in frequency per C° is 0.0025%. This means that the oscillator one uses to tune his musical instrument must have frequency stability coefficient of 0.0025% per C° or better. Otherwise, his guitar will not sound the same from one season to the next.

The object of this thesis was to build an inexpensive, precision oscillator whose frequency stability coefficient was 0.0005% per C° or better in the audio frequency range and between the temperatures 30°C to 60°C. Since low cost was presumed, the oscillator was not to make use of highly accurate but expensive military quality components. The design objective did not seem too unrealistic because values of components were assumed to be linearly related to the temperature and this temperature dependence could easily be neutralized by some linear compensation scheme.

Throughout this text, °C is used to indicate a temperature and C° to indicate a temperature interval.

2. DISCUSSION

2.1 VCO

The temperature dependence of a readily available oscillator was first studied. This was a voltage controlled oscillator (VCO) designed for use in course 6.717 (Audio Frequency Communication Project Lab.). Fig. 1 shows its schematic. The frequency of this oscillator is given by

$$f = (14.3 + V) / (150K \cdot C) \text{ , where}$$

V is the input voltage and C is the capacitance. The VCO had an internal mica capacitor of 300 pf but the capacitance could be varied as required by having other capacitors in parallel with the internal capacitor. Throughout the course of this work, when the VCO was not being compensated, the input voltage was grounded. With zero input, the frequency of the VCO with its internal capacitor should be

$$f = 14.3 / (150K \cdot 300 \times 10^{-12})$$

$$\approx 318K \text{ Hz.}$$

The frequency measured from 30°C to 60°C at 5 C° interval is listed in Table 1(a). At 30°C, the capacitance as calculated from

$$C = 14.3 / (150K \cdot f)$$

is 336 pf which is well within the ±20% tolerance range of the internal 300 pf capacitor. This difference in the capacitance is the reason for the difference between the calculated and the measured frequency. Table 1(b) lists the frequency measured with a 0.0047 μf paper capacitor in parallel with the internal

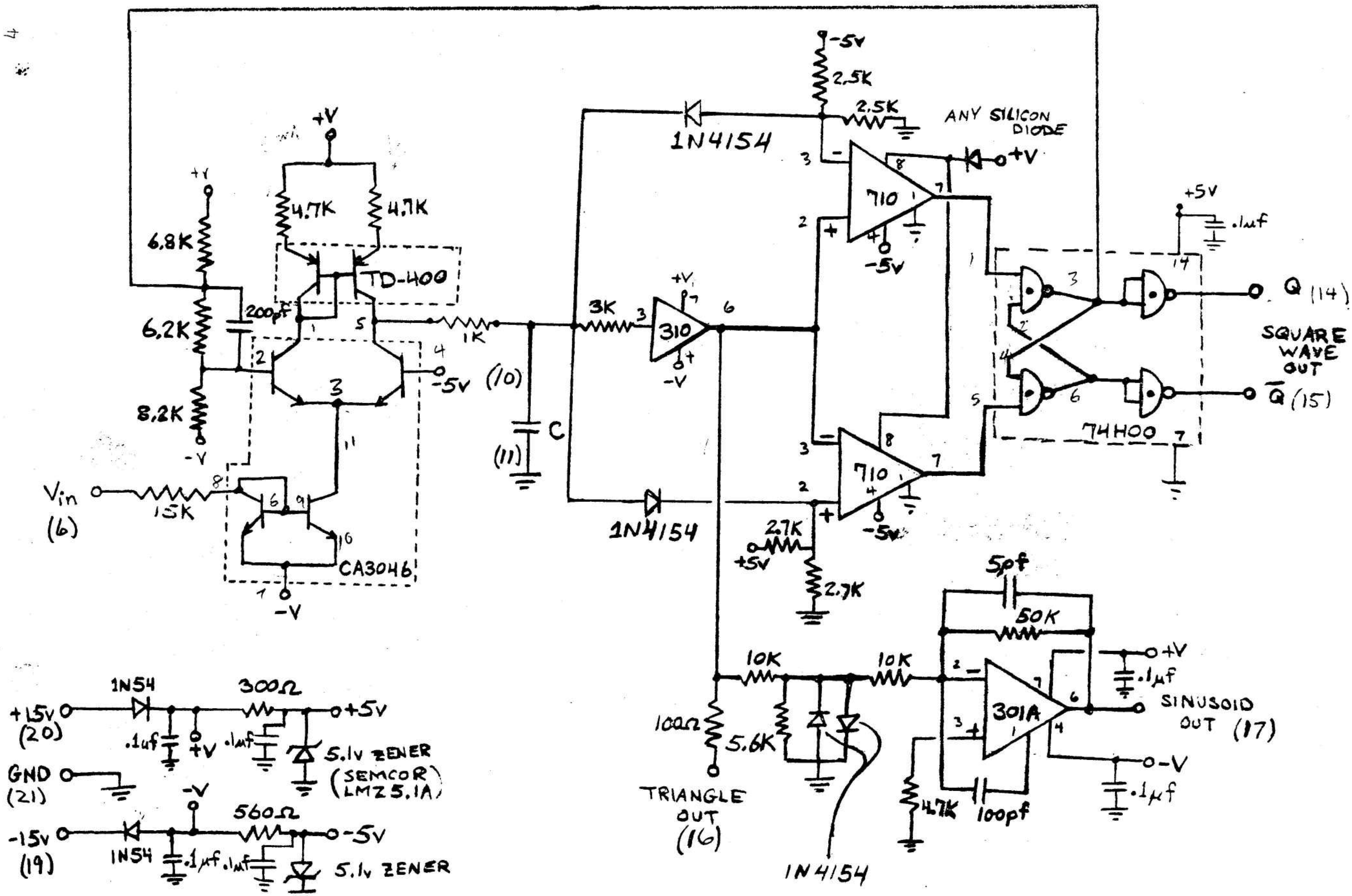


Fig. 1: Circuit Diagram of the VCO

Temperature (°C)	Frequency (KHz.)	f.s.c. (%/°C)*
30	283.57	0.0000
35	284.34	0.0544
40	284.93	0.0480
45	285.48	0.0449
50	285.98	0.0426
55	286.32	0.0388
60	286.61	0.0357

(a): With the internal capacitor of 300 pf

Temperature (°C)	Frequency (KHz)	f.s.c. (%/°C)
30	20.255	0.0000
35	20.291	0.0356
40	20.324	0.0340
45	20.347	0.0303
50	20.362	0.0264
55	20.365	0.0217
60	20.351	0.0158

(b): With 0.0047 μf paper capacitor

* frequency stability coefficient

$$= \frac{|\Delta f| \times 100}{(f \text{ at } 30\,^\circ C) \cdot \Delta T}$$

Table 1: Frequency dependence on temperature of VCO (uncompensated)

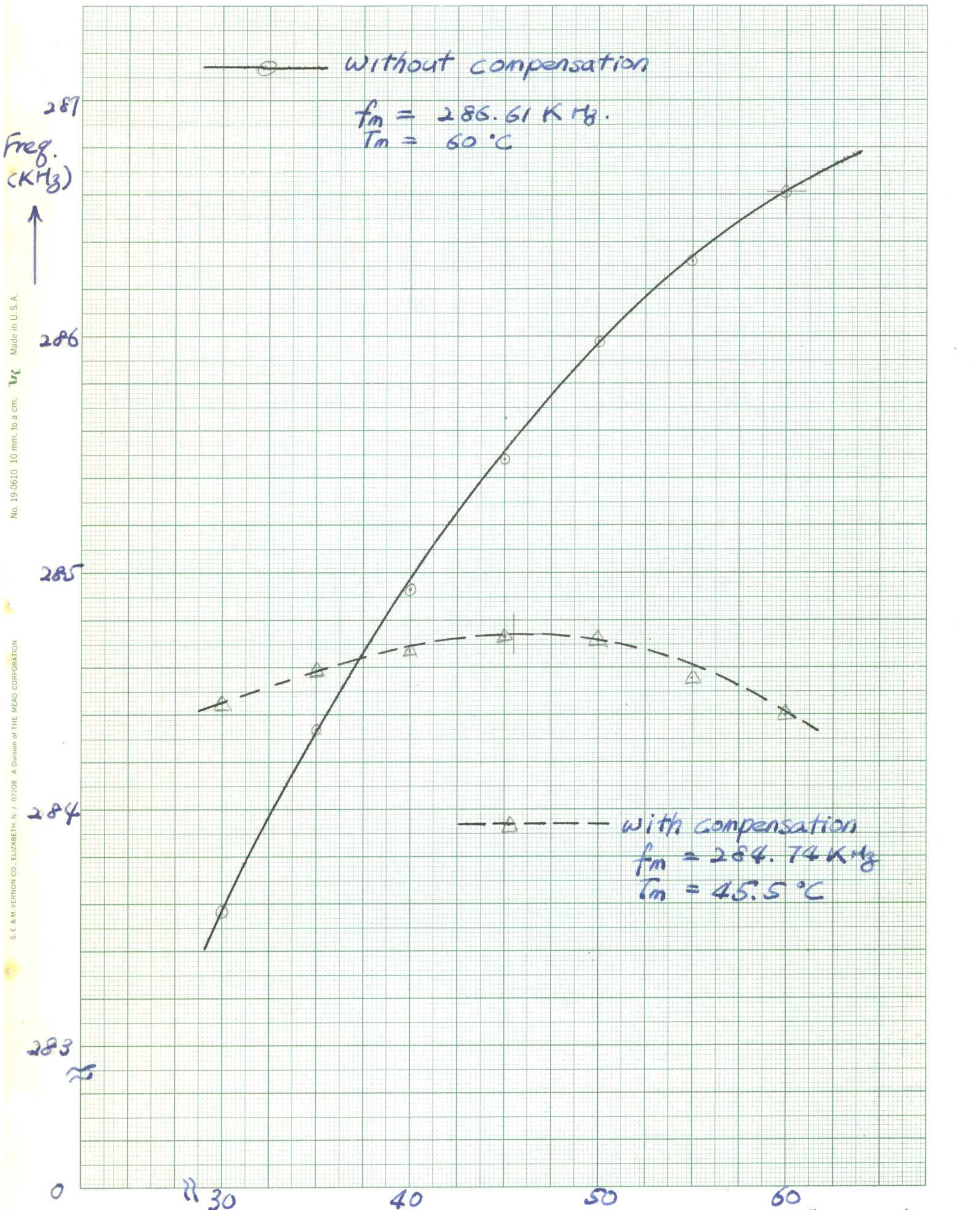


Fig. 2a): Temperature dependence of VCO

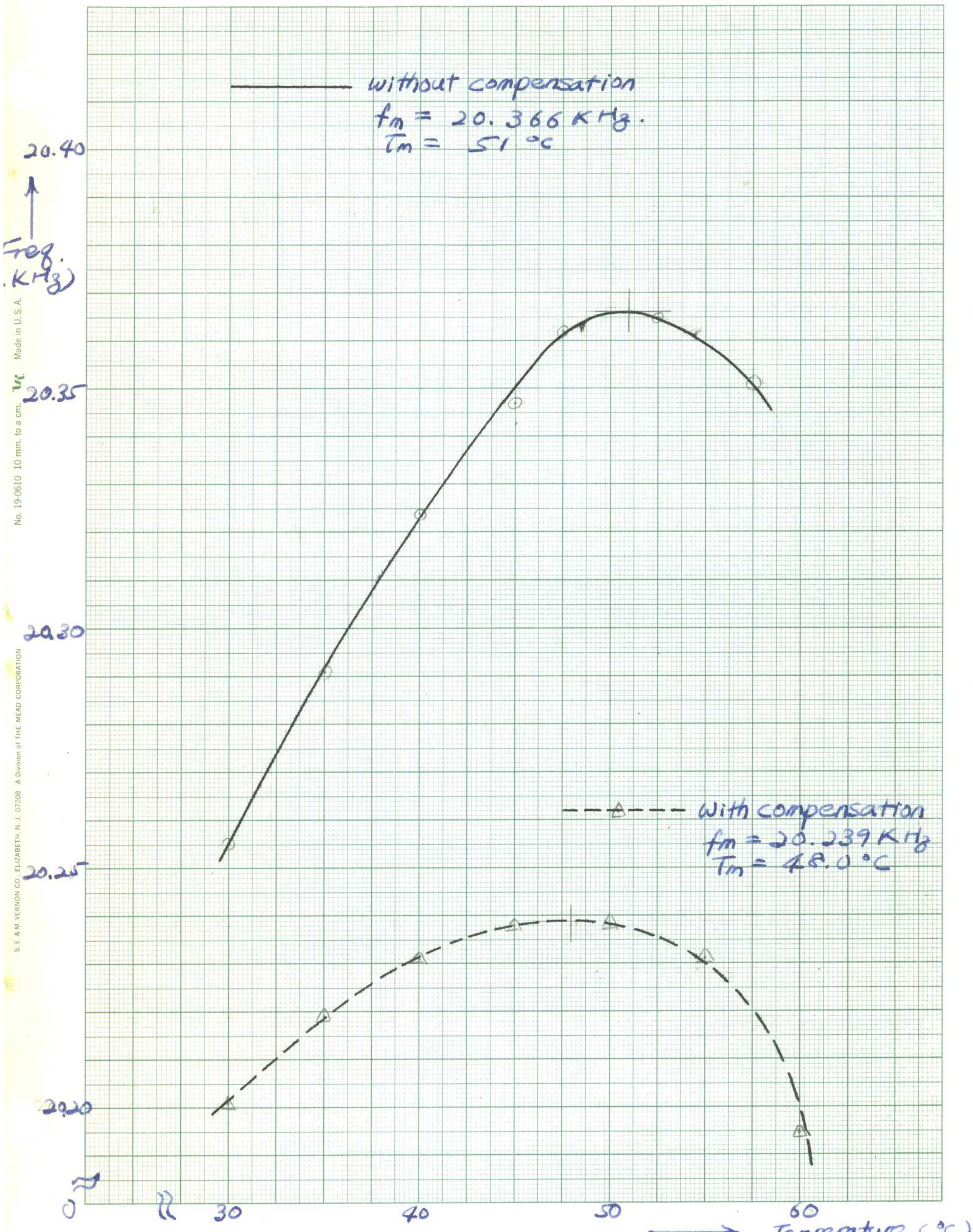


Fig. 2(b): Temp. dependence of V.C.O with 0.0047 μf capacitor.

capacitor of the VCO. Tables 1(a) and 1(b) are plotted in Figs. 2(a) and 2(b). As can be seen from the Figs. 2(a) and 2(b), the frequency dependence on the temperature is not linear but the curve is continuous and differentiable. Therefore, this dependence can be expressed in a Taylor series. The linear compensation scheme would neutralize the linear part of the Taylor series but it would have no effect on the other parts of the series. Still, this could be a significant improvement.

The maximum average frequency stability coefficient, S, is defined as

$$S = \frac{|f_m - f_o| \times 100}{f_o \cdot (T_m - T_o)} \ \% / C^\circ, \text{ where}$$

f_m is the frequency between 30 °C and 60 °C such that $|f_m - f_o|$ is maximum,
f_o is the frequency at 30 °C,
T_m is the temperature at which f_m occurs and
T_o is 30 C.

Then, S for the VCO with just the internal capacitor is 0.0358 %/C° while with a 0.0047 μf paper capacitor added in parallel, it is 0.0261 %/C°. The smaller frequency stability coefficient in the latter case is because paper capacitors usually have better temperature dependence than mica capacitors, though more non-linear.

2.2 COMPENSATION CIRCUIT

Now that the frequency dependence on temperature was known, next step was to improve it.

Since the frequency of the VCO is given by

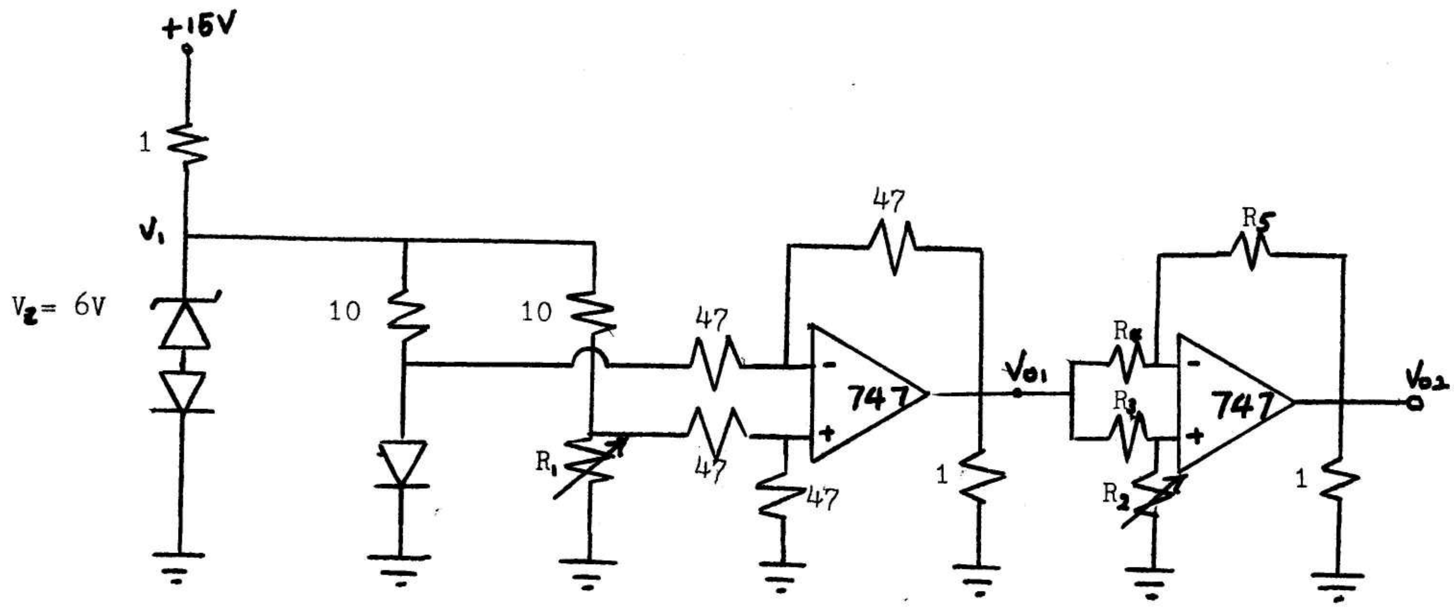
$$f = (14.3 + V) / (150K \cdot C) ,$$

the effect of the temperature on VCO can be offset by applying some temperature dependent negative voltage. A silicone diode is excellent for this purpose because the voltage across the forward biased diode drops 2 mV/C°. When used in the compensation circuit, this characteristic is tailored to the requirement by using a variable gain amplifier. The complete compensation circuit is shown in Fig. 3. The function of the circuit was to set the frequency at 60 °C to that at 30 °C. The zener diode placed back to back with a regular diode prevented the voltage V_1 from drifting about with temperature because the voltage across the back biased zener diode rises about 2 mV/C° offsetting the voltage drop across the silicone diode. The pot. #1 (R_1) was used to clamp the 30 °C frequency while pot. #2 (R_2) was used to set the frequency at 60 °C to that at 30 °C. This was accomplished by adjusting R_1 so that V_{o1} was 0 at 30 °C. V_{o2} is related to V_{o1} by

$$V_{o2} = \left[\left(\frac{R_4 + R_3}{R_2 + R_3}\right)\left(\frac{R_2}{R_4}\right) - \left(\frac{R_3}{R_4}\right)\right] V_{o1} ,$$

and, therefore, V_{o2} is 0 at 30 °C. R_2 was used to provide variable gain so that it was possible to set the frequency at 60 °C to that at 30 °C. If V_{o1} was not 0 at 30 °C, then adjusting R_2 affects V_{o1} and it would have been almost impossible to set the frequencies at 30 °C and 60 °C to be the same.

As the temperature is raised, the voltage across the diode drops and since this is fed into the negative input of the first stage whose gain is 1, the output voltage, V_{o1}, increases at the



All resistances in KΩ
R_1 = 1 KΩ
R_2 = 10 KΩ
R_3 = R_4 = R_5 = 2 KΩ

Fig. 3: Compensation circuit

rate of voltage drop across the diode. This is changed as required by adjusting R_2. Depending on the value of R_2, the gain of the compensation circuit can either be positive or negative, specifically depending on whether R_2 is greater or less than $(R_3 \cdot R_5)/R_4$, the gain is either positive or negative, respectively. This is helpful since this is the only circuit required to compensate frequencies which increase and frequencies which decrease with rising temperature, instead of requiring one compensation circuit for each case.

When the compensating circuit was used on the VCO, a marked improvement in the performance of the VCO was observed as can be seen from Tables 2(a) and 2(b) and from Figs. 2(a) and 2(b). Tables 2(a) and 2(b) have been plotted onto Figs. 2(a) and 2(b) for easier visual comparision with the non-compensated cases.

The maximum average frequency stability coefficient, S, is 0.0066 %/C° for compensated VCO with the internal capacitor and 0.0105 %/C° with 0.0047 μf paper capacitor in parallel with the internal capacitor. The improvements over the uncompensated VCO are by factors of 5.5 and 2.5, respectively. The lesser improvement in the latter case is because it contained more non-linear dependence, which could not be neutralized with linear compensation, than the former. It can be clearly seen from the Figs. 2(a) and 2(b) that linear components between 30 °C and 60 °C have been effectively neutralized while the non-linear components have been made more distinct by being separated from the linear components. One surprising feature of the compensation circuit was that, contrary to the expectation, the

Temp. (°C)	Freq. (KHz.)	f.s.c. (%/°C)
30	284.45	0.0000
35	284.59	0.0098
40	284.67	0.0077
45	284.73	0.0065
50	284.72	0.0047
55	284.56	0.0015
60	284.40	0.0006

(a): With internal capacitor

Temp. (°C)	Freq. (KHz)	f.s.c. (%/°C)
30	20.201	0.0000
35	20.219	0.0177
40	20.231	0.0149
45	20.238	0.0122
50	20.238	0.0092
55	20.231	0.0058
60	20.195	0.0010

(b): With 0.0047 μf paper capacitor

Table 2: Frequency dependence on temperature of VCO (compensated)

Temp. (°C)	V_{o2} (mV)	V_{o2} (mV)
30	-4	54
35	-37	31
40	-68	9
45	-99	-15
50	-132	-38
55	-164	-61
60	-196	-83

Table 3: Output voltages of the compensation circuit for two different settings of R_1 and R_2

output voltage, V_{o2} , of the circuit was linear. Table 3 shows V_{o2} for 2 different settings of R_1 and R_2.

2.3 TEMPERATURE CYCLING

Theoretically, the frequencies at 30 °C and 60 °C should have been the same but they were not. Not only were the frequencies different at two ends, but also the frequencies at all temperature were not consistent with the frequencies previously observed at the corresponding temperatures. At first, somebody was thought to be tempering with the circuit but soon it became obvious that this was not the case because, though the frequencies were not precisely consistent, they were consistent within ± 0.1 % of the previous frequencies observed at the corresponding temperatures. And then came the realization that these frequency drifts were there all along but I failed to give them much thought in the early part of this work. This time, this could not be ignored because ± 0.1 % frequency drift was rather large for and unbecoming of a precision oscillator. The analysis of possible causes follows.

a) Thermometer

The thermometer used in this study was a laboratory calibrated thermometer which means that the accuracy of the thermometer is ± 0.1 C° which is clearly too small to account for the kind of drift observed.

b) Frequency Counter

A GR 1153-AP type frequency counter was used. Its accuracy is given as ± 1 count ± time base stability which is specified to be less than ± 0.1 ppm/C from 20 °C to 30 °C ambient rise. Since the room temperature was about 25 °C most of the time. the time base stability is no problem. The error due to the ± 1 count accuracy is also negligible. For frequencies in 100K and 10K Hz. range, the counting time was set at 0.1 and 1 sec., respectively. With this in mind, it can be seen from Fig. 4 that the counter error is less than 0.01 % which compares very favorably with the ±0.1 % drift in frequency.

c) POWER SUPPLY

The power supply used was H.P. Harrison 6205B Dual Power Supply whose stability is given as less than 0.10% plus 5 mV drift for 8 hours of operation. Tables 4(a) and 4(b) show how the frequency of the VCO changes with power supply voltage. The positive supply drift can be ignored but the negative supply drift causes frequency changes which cannot be ignored. This strong dependence on the negative supply is due to the VCO configuration. Fig. 5 shows VCO in terms of block diagrams. The amount of current in the current source is given by

$$I = \frac{V_{IN} - V_{-} - 0.6}{15K}, \text{ where}$$

V_{IN} is the input voltage to the VCO and V_{-} is the negative supply voltage. Thus, reducing V_{-} increases I and this makes the switching circuit to switch at a faster rate. Increasing V_{-} has the opposite effects.

According to the specification, the negative supply can drift 20 mV, i.e., (15 V · 0.1%)+5 mV, which will be enough to cause the kind of frequency drift observed but the supply is not the real cause because, at the beginning of each experiment, the supply was checked with a DVM and the supply drift was consistently less than 5 mV.

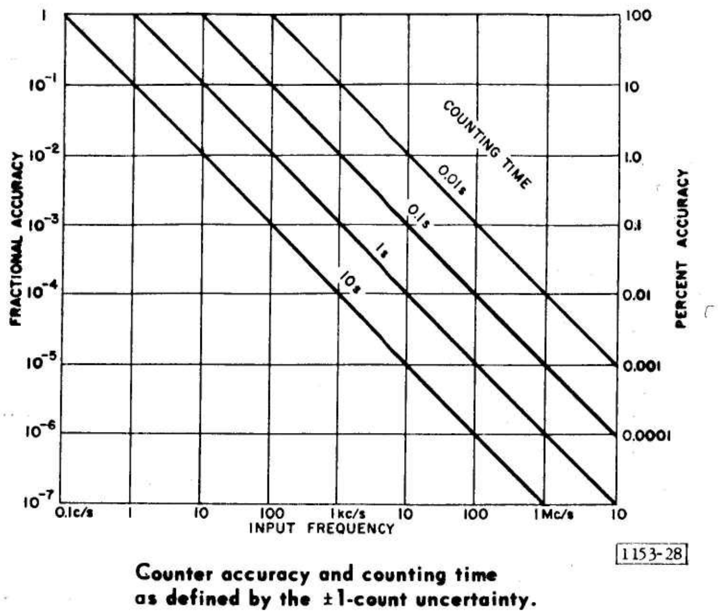


Fig. 4: Counter accuracy chart

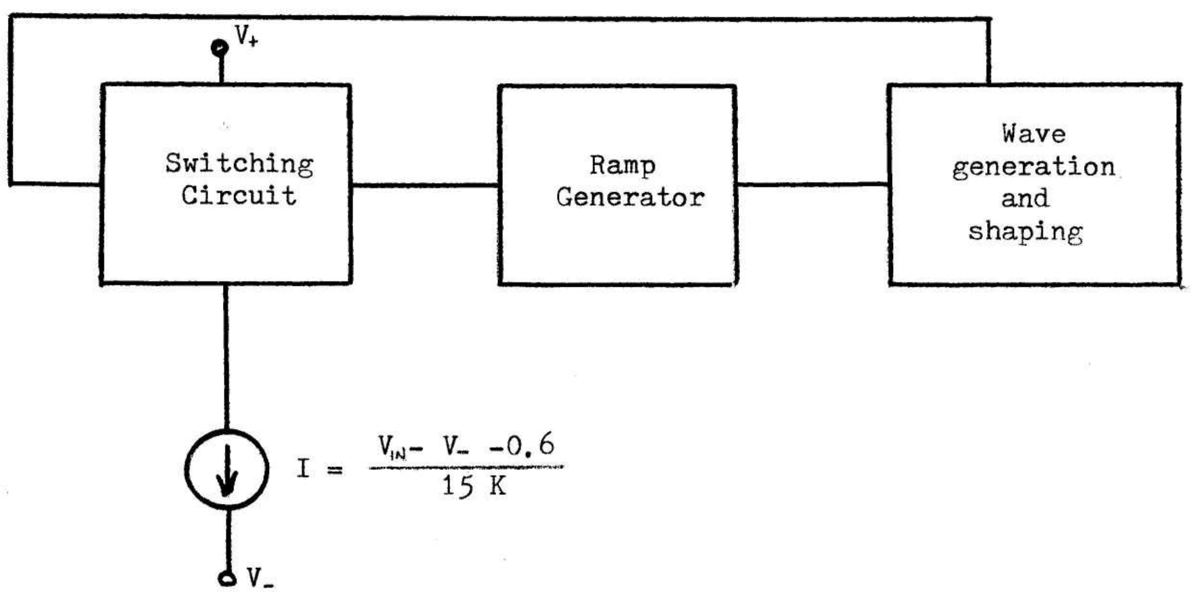


Fig. 5: Block diagram of the VCO

Voltage (V)	Frequency (KHz)
14.90	283.18
14.95	283.15
15.00	283.12
15.05	283.09
15.10	283.01

(a) +ve supply drift with -ve supply held at -15.00 V

Voltage (V)	Frequency (KHz)
14.95	282.10
14.96	282.33
14.97	282.53
14.98	282.81
14.99	282.97
15.00	283.13
15.01	283.35
15.02	283.49
15.03	283.68
15.04	283.97
15.05	284.16

(b) -ve supply drift with +ve supply held at +15.00 V

Table 4: VCO dependence on power supply drift at 30 °C

d) VCO

The analysis so far leaves the VCO as the most likely cause for the frequency drift.

Again, the frequency of the VCO is given by

$$f = 14.3 / (150K \cdot C),$$

and for $\epsilon \ll 1$,

$$1 \pm \epsilon = \frac{1}{1 \mp \epsilon} \quad .$$

Therefore,

$$f(1 \pm \epsilon) = \frac{14.3}{(150K \cdot C)(1 \mp \epsilon)}$$

Since the frequency drift observed is about $\pm$ 0.1%, ϵ is on the order of 0.001. This is a very small number and what seems likely to have happened is that when the temperature was raised, the internal capacitance of the VCO changed from 336 pf at 30 °C to 332 pf at 60 °C, a change of 1.2%, and when the VCO was allowed to cool down, the capacitance returned to within $\pm$ 0.1% of its original value. The change in humidity was thought to be the cause for this but this was ruled out when a jar of water was put into the oven without correcting the drift. It seems this phenomenon is inherent to the dielectric material used in the capacitors and, if that is the case, the only conclusion is that there is nothing that can be done for the non-repeatability of the frequency except to use better capacitors.

2.4 MULTIVIBRATOR

A free running multivibrator was chosen to meet the design objective of frequency stability coefficient of 0.0005 %/C° or better because of its simplicity. Simplicity was necessary because the small number of components made it easier to locate components which contributed excessive non-linearity or otherwise degraded the performance of the oscillator. These components could then be replaced or compensated. Also, the small number of components helps along the design objective of low cost.

Fig. 6 shows the circuit diagram of the free running multivibrator. Its output voltage is limited to ± 3V by the zener diodes. Its frequency can be controlled somewhat by varying V_{IN}.

Having seen that the capacitors have non-linear temperature dependence and also that their temperature cycling characteristic determines the repeatability of the oscillator frequency, different kinds of capacitors were studied for their temperature dependence to see which would be best suited for the design objective. As it turned out, no one kind of capacitor was best suited but it was found that a parallel combination of paper capacitors and Corning glass-K capacitors was close to what was being sought after. Fig. 7 shows the way they were put together. They were first put in series before being put in parallel so that the over all capacitance would still be .01 μf. Table 5(a) shows the frequency dependence of the multivibrator using this combination of capacitors before it was compensated and 5(b) shows the same multivibrator after compensation. This is plotted in Fig. 8.

The maximum average frequency stability coefficient, S, of the uncompensated multivibrator is 0.00216 %/C° and the compensated

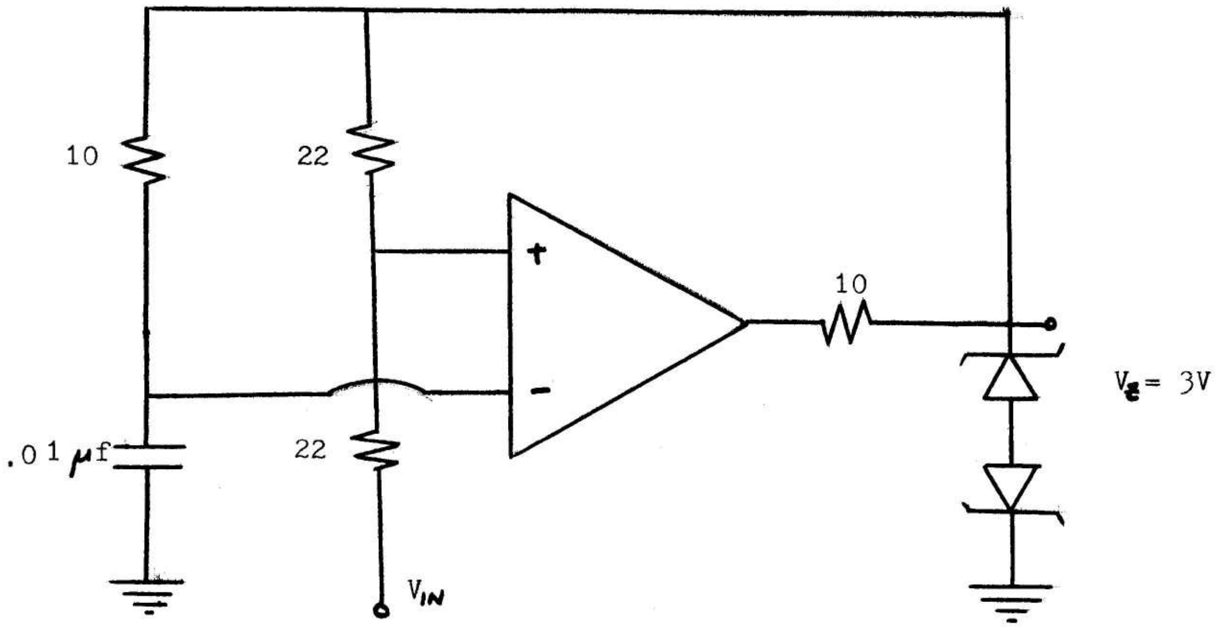


Fig. 6: Free running multivibrator

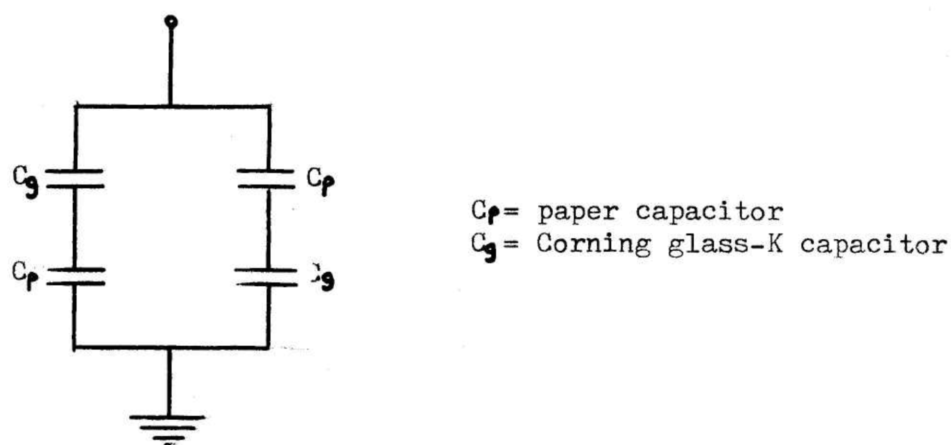


Fig. 7: Parallel combination of paper and glass-K capacitors

Temperature(C)	Frequency (KHz)	f.s.c. (%/C)
30	2778.5	0.00000
35	2778.3	0.00144
40	2777.9	0.00216
45	2777.6	0.00216
50	2777.3	0.00216
55	2777.0	0.00216
60	2776.8	0.00204

(a): Before Compensation

Temperature(C)	Frequency (KHz)	f.s.c. (%/C)
30	2779.3	0.00000
35	2779.3	0.00000
40	2779.3	0.00000
45	2779.4	0.00024
50	2779.4	0.00018
55	2779.5	0.00029
60	2779.6	0.00036

(b): After compensation

Table 5: Frequency dependence of multivibrator on temperature

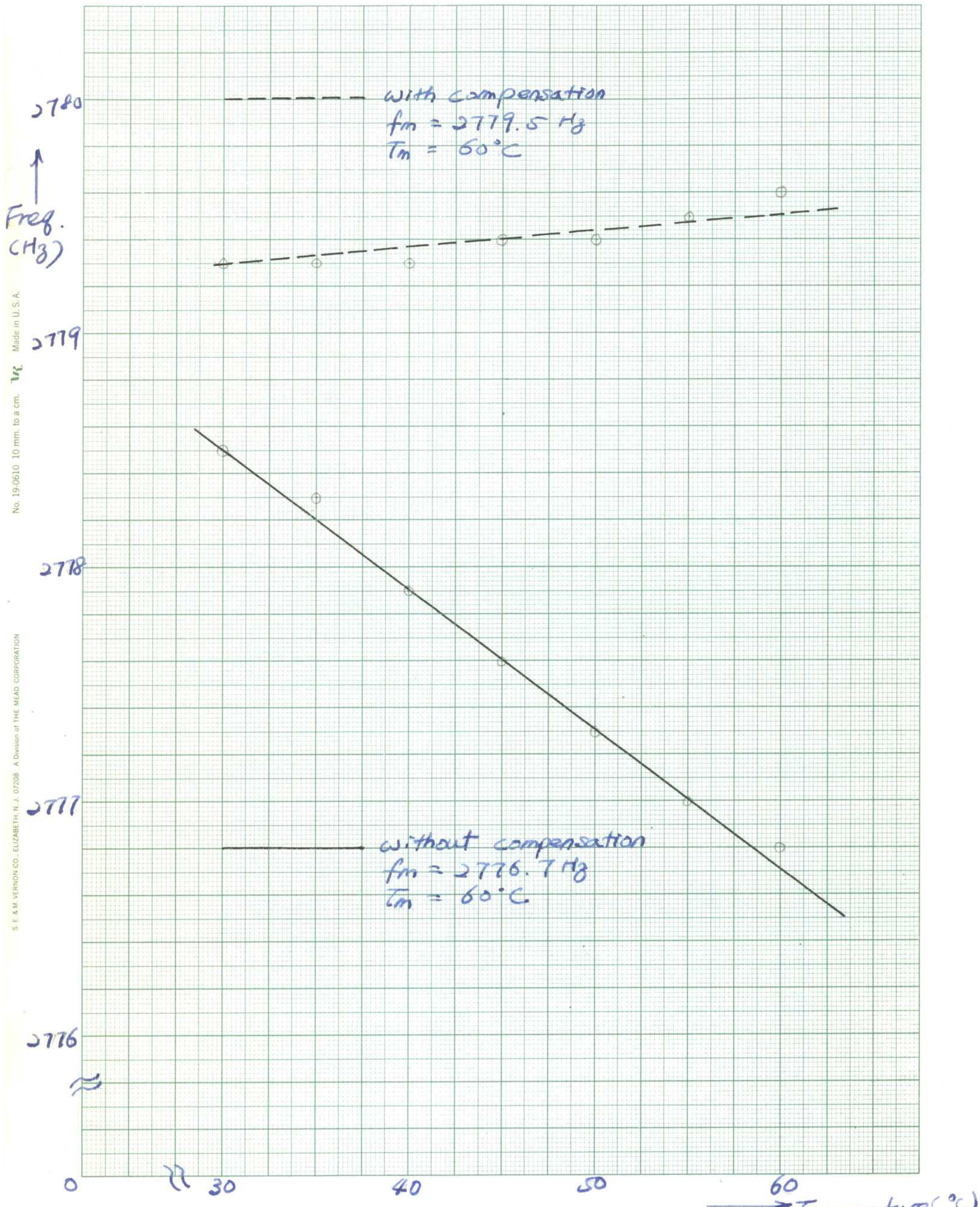


Fig. 8: Temp. dependence of the multivibrator

multivibrator has S of 0.00024 %/C°. The improvement is by a factor of 9 and the design objective of low cost has been met while that of the frequency stability coefficient has been surpassed.

If this oscillator could be mass produced, it would probably be the cheapest temperature stable oscillator on the market but mass production did not seem feasible because it was suspected that the components of identical value and make displayed different temperature dependence characteristic from each other. So next step was to study how much components really varied in their temperature dependence characteristic.

2.5 TEMPERATURE DEPENDENCE OF COMPONENTS

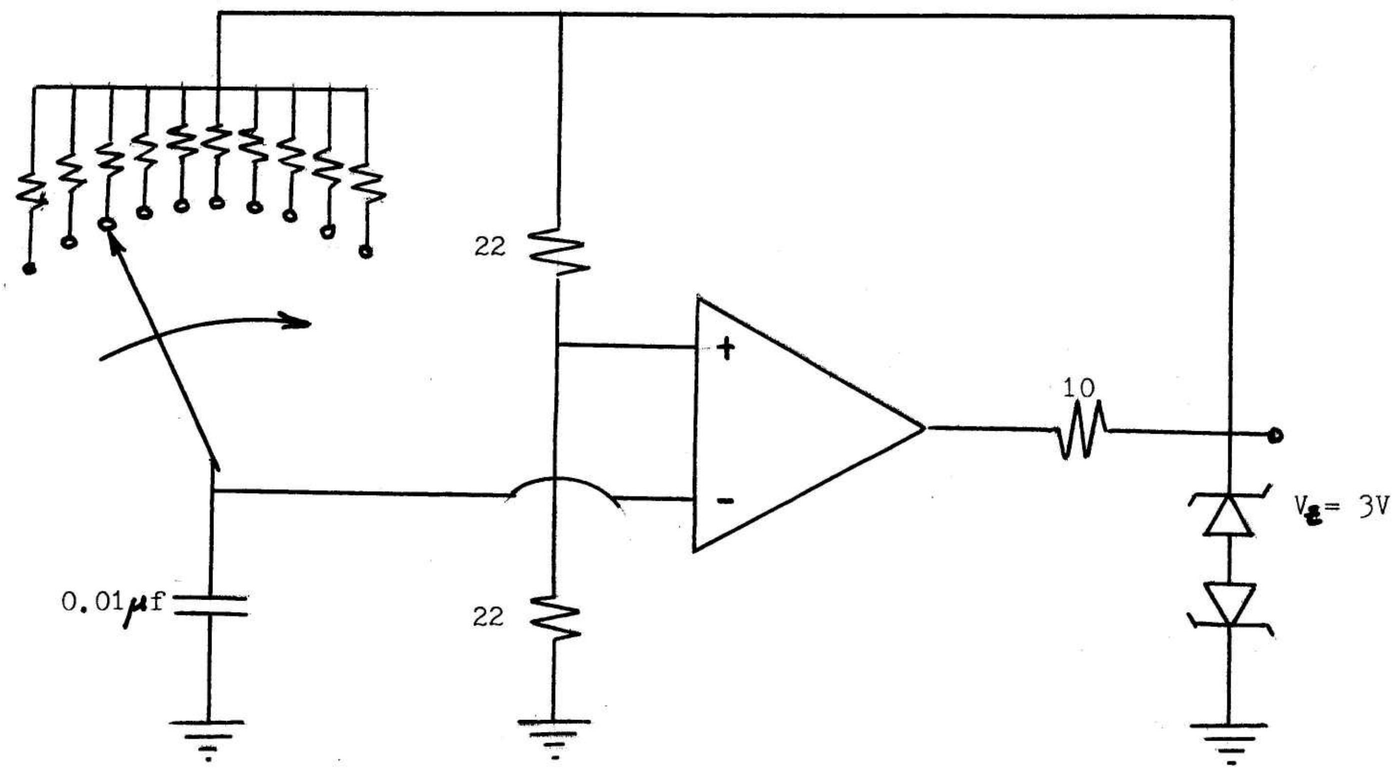
Ten from each of the following 4 different kinds of components were picked randomly.

a) 12000 pf Corning glass-K capacitors
b) 0.01 f paper capacitors
c) 12K Corning glass tin oxide film resistors
d) 10K carbon composition resistors

To make measurements under identical conditions, a rotary switch was used to enable all 10 components of one kind to be in the oven at the same time. The manner in which they were connected is depicted in Fig. 9 for the case of resistors, and the results obtained listed in Tables 6(a), 6(b), 6(c) and 6(d).

One thing that is immediately clear is that within the same kind of components, frequencies vary considerably. For example, for Corning glass-K capacitors, the frequency variation is as much as 13 %. It should be emphasized here that this difference is due to the tolerances of the two components involved, independent of the rest of the circuit, because the rest of the multivibrator was left intact. Also, there is no general pattern in the frequency stability coefficient between the components. Then, the only possible conclusion is that no two oscillators, though made from same design and components, will have same frequency dependence on temperature.

Therefore, even though the free running multivibrator with linear compensation performed better than the design objective, this does mean that this multivibrator can be mass produced with same kind of performance.



All resistances in KΩ

Fig. 9: Connection of components using a rotary switch

Temp.(C)	Freq.(Hz)	f.s.c.(%/C)	Temp.(C)	Freq.(Hz)	f.s.c.(%/C)
30	2736.6*	0.00000	30	2982.1	0.00000
40	2738.1	0.00548	40	2984.5	0.00804
50	2739.7	0.00566	50	2986.0	0.00653
60	2746.2	0.01171	60	2992.3	0.01138
30	3039.8	0.00000	30	2972.1	0.0000
40	3042.4	0.00855	40	2974.2	0.00707
50	3045.8	0.00986	50	2976.4	0.00723
60	3054.2	0.01580	60	2983.2	0.01234
30	3068.4*	0.00000	30	2918.0	0.00000
40	3071.2	0.00815	40	2921.6	0.01234
50	3073.1	0.00717	50	2925.1	0.01218
60	3080.3	0.01260	60	2933.5	0.01770
30	2904.9	0.00000	30	2913.1	0.00000
40	2909.0	0.01411	40	2916.2	0.01065
50	2912.5	0.01308	50	2919.7	0.01134
60	2920.7	0.01812	60	2927.5	0.01650
30	2962.8	0.00000	30	3066.6	0.00000
40	2965.0	0.00743	40	3070.8	0.01370
50	2966.6	0.00640	50	3075.4	0.01432
60	2973.3	0.01800	60	3084.5	0.01947

*Largest frequency variation ~13%

Table 6(a): Temperature dependence of Corning glass-K capacitors

Temp.(°C)	Freq.(Hz)	f.s.c.(%/C)	Temp.(°C)	Freq.(Hz)	f.s.c.(%/°C)
30	3321.9	0.00000	30	3546.7*	0.00000
40	3316.9	0.01505	40	3541.7	0.01408
50	3311.5	0.01567	50	3536.8	0.01395
60	3304.4	0.01758	60	3530.2	0.01550
30	3334.5	0.00000	30	3401.6	0.00000
40	3330.5	0.01200	40	3391.2	0.01295
50	3326.6	0.01185	50	3391.6	0.01470
60	3321.0	0.01351	60	3386.5	0.01480
30	3365.0	0.00000	30	3231.4*	0.00000
40	3360.0	0.01483	40	3227.0	0.01362
50	3354.7	0.01529	50	3222.8	0.01331
60	3347.5	0.01632	60	3216.1	0.01579
30	3290.0	0.00000	30	3315.5	0.00000
40	3285.7	0.01306	40	3310.5	0.01509
50	3281.0	0.01368	50	3305.6	0.01493
60	3275.0	0.01520	60	3299.3	0.01630
30	3295.9	0.00000	30	3265.6	0.00000
40	3290.6	0.01609	40	3260.8	0.01439
50	3285.7	0.01548	50	3256.1	0.01439
60	3279.2	0.01690	60	3249.0	0.01681

* Largest frequency variation ~10%

Table 6(b): Temperature dependence of 0.01 μf paper capacitors

Temp.(°C)	Freq.(Hz)	f.s.c.(%/C°)	Temp.(°C)	Freq.(Hz)	f.s.c.(%/C°)
30	2563.6	0.00000	30	2559.8	0.00000
40	2563.5	0.00039	40	2560.3	0.00196
50	2563.6	0.00000	50	2560.8	0.00196
60	2563.5	0.00013	60	2560.7	0.00117
30	2560.0	0.00000	30	2534.7*	0.00000
40	2559.4	0.00232	40	2534.7	0.00000
50	2559.2	0.00156	50	2534.7	0.00000
60	2558.7	0.00169	60	2533.5	0.00158
30	2566.7	0.00000	30	2568.7*	0.00000
40	2565.9	0.00312	40	2568.4	0.00112
50	2565.2	0.00292	50	2568.3	0.00075
60	2564.5	0.00285	60	2567.7	0.00129
30	2550.5	0.00000	30	2560.5	0.00000
40	2550.0	0.00196	40	2560.7	0.00078
50	2549.7	0.00157	50	2561.0	0.00098
60	2549.2	0.00170	60	2560.8	0.00039
30	2544.6	0.00000	30	2564.2	0.00000
40	2544.5	0.00038	40	2563.6	0.02320
50	2544.8	0.00039	50	2563.1	0.02122
60	2544.7	0.00013	60	2562.4	0.02338

* Largest frequency variation ~1.5%

Table 6(c): Temperature dependence of Corning glass tin oxide film resistors (12KΩ)

Temp. (°C)	Freq. (Hz)	f.s.c. (%/°C)	Temp. (°C)	Freq. (Hz)	f.s.c. (%/°C)
30	3013.3	0.00000	30	3007.5	0.00000
40	3012.6	0.00232	40	3007.2	0.00299
50	3009.4	0.00647	50	3003.6	0.00649
60	3001.6	0.01295	60	2995.7	0.01310
30	3004.2	0.00000	30	3008.2	0.00000
40	3003.3	0.00299	40	3007.9	0.00299
50	3000.2	0.00655	50	3004.7	0.00581
60	2992.1	0.01562	60	2996.9	0.01252
30	3014.2	0.00000	30	3035.1	0.00000
40	3013.4	0.00298	40	3034.3	0.00264
50	3010.1	0.00697	50	3030.7	0.00725
60	3002.0	0.01362	60	3022.6	0.01375
30	2968.3*	0.00000	30	3034.0	0.00000
40	2966.6	0.00538	40	3033.7	0.00297
50	2963.2	0.00842	50	3030.3	0.00610
60	2954.9	0.01495	60	3022.4	0.01278
30	3081.5*	0.00000	30	3011.8	0.00000
40	3080.4	0.00357	40	3011.0	0.00266
50	3077.0	0.0073.	50	3007.8	0.00665
60	3069.2	0.01331	60	2999.7	0.01341

* Largest frequency variation ~ 4%

Table 6(d): Temperature dependence of 10K Ω carbon composition resistors

3. CONCLUSIONS

In this work, it has been shown that frequency dependence on temperature of an oscillator can be improved significantly by using linear combination. In terms of cost-performance, this means that it will probably be better to use inexpensive, regular components and employ the compensation scheme to offset the temperature dependence than to use components which have very small temperature dependence and, consequently, expensive.

It has also been shown that precision oscillators with frequency stability coefficient of 0.0005%/C° or better cannot be mass produced. If further work is to be done in this area, it would be interesting (and could, conceivably, be commercially profitable) to see how much the frequency stability coefficient need to be sacrificed for the sake of mass production.