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N R L REPORT NO. R-3198

DEVELOPMENT OF A HIGHLY STABLE CRYSTAL CONTROLLED OSCILLATOR-EXCITER

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NAVAL RESEARCH LABORATORY

WASHINGTON, D.C.

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[redacted] UNCLASSIFIED DECLASSIFIED NRL REPORT NO. R-3

DEVELOPMENT OF A HIGHLY STABLE CRYSTAL CONTROLLED OSCILLATOR-EXCITER

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Problem No. 39R08-50 November 6, 1947

NAVAL RESEARCH LABORATORY
COMMODORE H. A. SCHADE, USN, DIRECTOR
WASHINGTON, D.C.

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ABSTRACT

To meet the need for a standardized crystal oscillator, a highly stable circuit has been developed for use from 2 to 6 megacycles. The circuit consists of a Pierce-Electron Coupled Oscillator of special design, followed by two stages of amplification. Under the combined effects of extreme temperature variation, supply and cathode heater voltage variation, stabilization, tube change and change in loading, the stability is 0.0012 percent or better. This permits a crystal unit tolerance of 0.0013 percent, if a 0.0025 percent overall tolerance limit is to be attained.

AUTHORIZATION

This project was authorized by BuShips conf. ltr. Ser. No. 1721 (930-Cb) of 27 November 1944 to NRL.

PROBLEM STATUS

This problem, Number 39R08-50 (BuShips S404R), will be considered closed one month from the date of this report. No further work is contemplated on the problem.

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DEVELOPMENT OF A HIGHLY STABLE CRYSTAL CONTROLLED OSCILLATOR-EXCITER

INTRODUCTION

The wartime experience of the Navy in operating and maintaining many different types of radio communication equipment which are dependent upon quartz crystals for frequency control has shown the acute need for an exceptionally stable standardized crystal oscillator circuit. Only by standardization of the circuit associated with the quartz crystal can the number of different types of crystals which are presently required for different equipments be reduced and the problem of maintenance of the many different existing circuits be simplified. The development of such a standardized circuit has been considered, and certain guides for the project have been established. These are as follows:

1. The oscillator shall be designed primarily for frequency control, and power output as required shall be developed in succeeding amplifier stages.

2. The oscillator shall operate over a frequency range from 2 to 6 megacycles, using Type CR-1 and Type CR-7 crystal units.

3. The oscillator circuit will not be keyed.

4. The overall frequency tolerance, including the production tolerance of the crystal units, shall be 0.0025 percent or better.

5. The entire circuit shall be miniaturized following the current Navy trend to reduce size and weight of electronic equipment.

6. Electrode potentials shall not exceed those available in a receiver.

7. The output power must be reasonably constant over the 2 to 6 megacycle range.

8. The number of circuit tuning adjustments shall be minimized, and the use of circuit components having close tolerances shall be avoided.

The actual developmental work was preceded by an extensive survey of the literature concerning crystal controlled oscillators and stabilized oscillator circuits. The characteristics of a number of types of crystal oscillator circuits used in commercial equipment were also investigated. As a result of this study, it was decided to concentrate on the development of an improved oscillator from a basic Pierce-Electron Coupled Oscillator circuit which was known to have inherently good frequency stability characteristics. An exceptionally stable circuit has been developed. Although the frequency stability data presented in this report are actually the result of the combined stability of the oscillator circuit and the crystal unit, it is believed that the values accurately represent the circuit stability since every effort was made to completely stabilize the crystal. Preliminary details of the circuit performance were presented in an interim report*. An investigation has shown that the circuit is capable of providing overall frequency stability better than

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* NRL ltr. S67/43(1210-ERL), Serial R-1210-147/46 of 24 May 1946 to BuShips.

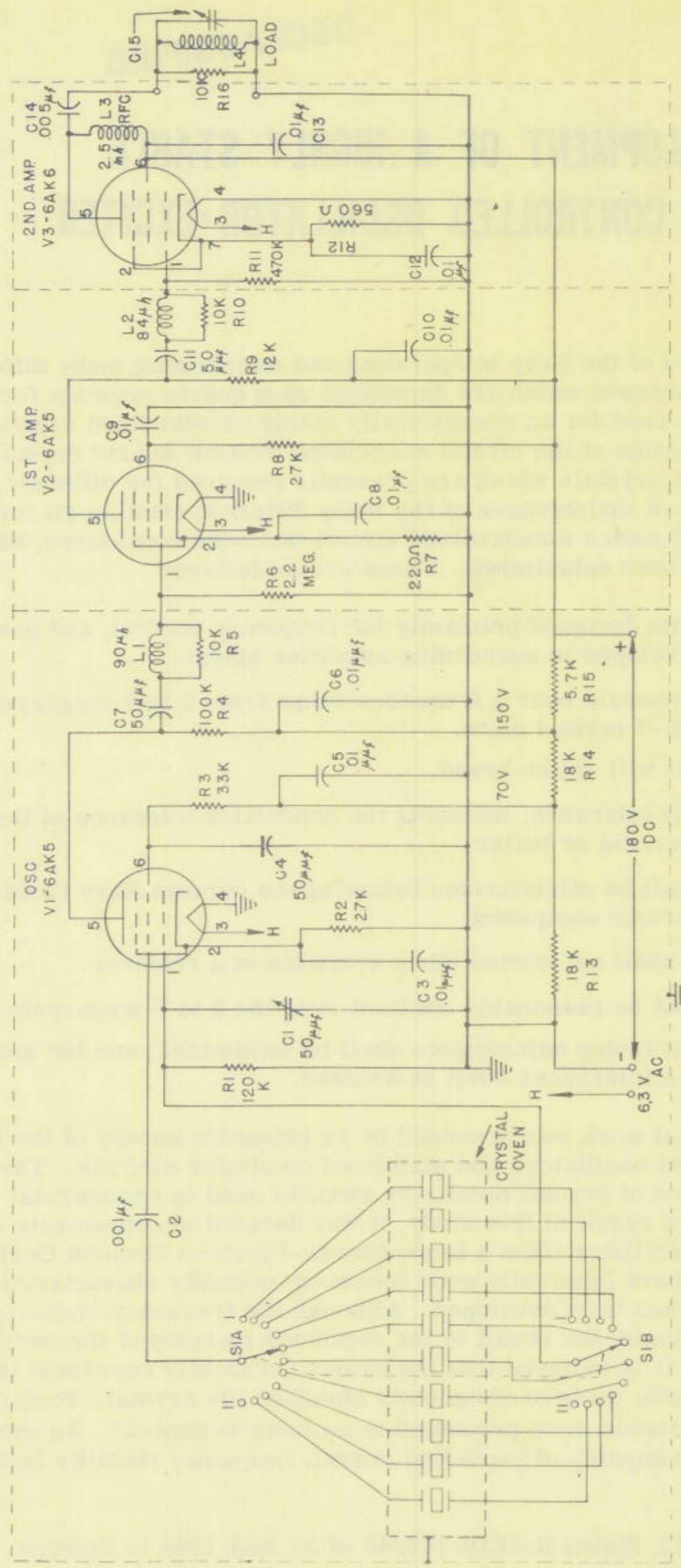

Fig. 1. Oscillator-Exciter Schematic Diagram

0.0012 percent. This does not include the possible instability introduced by vibration and shock. Since the oscillator output is very low, an oscillator-exciter unit has been provided, using amplifiers to develop sufficient power for transmitter excitation.

DESCRIPTION OF OSCILLATOR-EXCITER UNIT

The Circuit

The schematic diagram of the highly stable oscillator-exciter unit is shown in Figure 1. The unit consists of an oscillator employing a Type 6AK5 tube, followed by a voltage amplifier using a Type 6AK5 tube, and by a power amplifier using a Type 6AK6 tube. These are miniature tube types which have joint Army-Navy approval. Representative values of tube currents, with a supply voltage of 180 volts dc are indicated in Table I.

TABLE I

REPRESENTATIVE OPERATION OF THE OSCILLATOR EXCITER UNIT

Crystal Frequency (Mc)	V1 (6AK5 Osc)			V2 (6AK5 1st Amp)			V3 (6AK5 2nd Amp)			Output Power* (Watts)
	Ig_1 (μA)	I_p (ma)	I_k (ma)	Ig_1 (μA)	I_p (ma)	I_k (ma)	Ig_1 (μA)	I_p (ma)	I_k (ma)	
2000	32.0	1.15	1.50	5.0	4.35	6.1	31.0	10.5	12.5	0.92
3000	26.4	1.17	1.50	3.0	5.05	6.9	25.0	10.0	12.0	0.83
4000	12.6	1.18	1.47	2.1	4.93	6.8	6.0	15.5	17.7	0.57
5000	7.6	1.19	1.48	1.2	6.22	8.6	14.0	11.0	12.9	0.74
6000	6.8	1.19	1.49	1.2	6.05	8.35	16.0	11.0	12.9	0.70

Note: Supply voltage held at 180 volts dc.

* The output power was measured across a 10,000-ohm resonant load.

The Oscillator

The oscillator circuit potentials and component values have been chosen to provide superior frequency stability characteristics. The screen and plate potentials for the Type 6AK5 tube have been selected so that the change in frequency caused by a screen potential change cancels that resulting from a plate potential change in the same direction. For this reason, a considerable variation in supply voltage has little effect upon frequency. The circuit potentials were chosen for conservative operation, and the value of crystal load capacitance was made 32 μμfd. With most crystals, the oscillator tube operates with less than 50 microamperes of rectified grid current. With some crystals, the oscillator operates with no rectified grid current. The crystal excitation voltage varies from approximately 7 volts rms at 2 megacycles to approximately 2 volts rms at 6 megacycles. This variation may be explained by the fact that the voltage is developed across the capacative screen grid load impedance which itself varies inversely as the frequency. Light loading of the oscillatory circuit is accomplished by electron coupling from the screen grid to the plate circuit. The oscillator, which is untuned, provides an output voltage of less than 10 volts. This very low output value is a natural adjunct of the exceptional frequency stability characteristic of the circuit.

The Amplifier Stages

The unit was designed to provide sufficient power for excitation of a low power transmitting tube, such as a Type 807 beam power amplifier. The Type 807 may require up to 110 peak rf grid volts excitation, or approximately 0.4 watts driving power. Since the oscillator is not capable of supplying this power, two stages of amplification have been provided. The oscillator is followed by an untuned voltage amplifier, using a Type 6AK5 tube, and a power amplifier using a Type 6AK6 tube. An external tuned load is required to obtain maximum output from this amplifier stage. Since the oscillator output decreases at the higher operating frequencies, some compensation is necessary in order to obtain a reasonably constant output level over the 2 to 6 megacycle range. This compensating action is obtained by biasing each amplifier tube by means of a cathode resistor so that with low values of input voltage there will be no flow of rectified grid current. Under this condition, the amplifier provides high gain. When high input voltages occur, the flow of rectified grid current through the grid resistor increases the operating bias of each amplifier to reduce the overall gain. Additional compensation was found necessary and was obtained by means of interstage filters.

The Interstage Compensating Filters

These filters serve to maintain a reasonably constant output level over the 2 to 6 megacycle frequency range. Each filter is made up of a series inductance and shunt elements formed by the impedance of the plate circuit of the preceding tube and the impedance of the grid circuit of the following tube. These shunt impedances include the tube output and input capacitances, respectively, as well as the stray capacitances in the circuit. The series inductances are shunted by 10,000-ohm resistors in order to limit the sharpness of the filter response characteristic. The response characteristic of the complete amplifier system has been broadened by staggering the "peaking" frequencies of the two filters. The filter response, together with the gain limiting action of the amplifiers, provides a level of power output which is essentially constant through the frequency range of 2 to 6 megacycles, even with crystals of various activities.

The Load Circuit

When the unit is used to excite a Type 807 power amplifier, or whenever maximum transfer of power is required, the driven stage must be provided with a tuned input circuit. A representative input circuit was made up of a 10,000-ohm resistor placed across a tuned resonant circuit, and was used to load the final amplifier of the oscillator-exciter unit. This circuit, which is shown at the output side of the power amplifier stage in Figure 1, is not a part of the oscillator-exciter unit. It serves only as a load and as a means for determining the amplifier power output by measuring the radio-frequency voltage developed across the resistor in the load circuit.

PERFORMANCE OF THE CIRCUIT

Frequency Stability

The frequency stability of the oscillator-exciter has been investigated at 200-kilocycle intervals in the 2 to 6 megacycle range for each of several conditions. The resulting changes in frequency and their sum taken without regard for the sign of the change are indicated in Table II.

TABLE II

OVER-ALL STABILITY OF OSCILLATOR-EXCITER CIRCUIT

Nominal Crystal Frequency (kc)	Supply Volt. Variation 140-240 v dc (cps)	Cathode Heater Volt. Variation 5.0-7.5 v ac (cps)	One-Hour Stabilization Run (cps)	Oscillator Tube Change (10 Tubes) (cps)	Ambient Temp. Variation -40° to +70° C (cps)	Total Variation (cps)	Total Variation (%)
2000*	0.2	0.6	1.6	3.3	12.8	18.5	0.00093
2200	0.5	2.7	1.3	5.8	16.0	26.3	0.00119
2400	Erratic operation—crystal defective						
2600	0.3	2.7	1.4	5.9	16.1	26.4	0.00101
2800	0.4	5.6	2.4	6.1	13.1	27.6	0.00099
3000	Crystal too near zero beat						
3200	0.4	1.3	1.7	6.7	12.2	22.3	0.00070
3400	1.0	0.9	3.1	7.9	21.4	34.3	0.00101
3600	0.7	3.9	1.8	5.8	21.3	33.5	0.00093
3800	0.3	1.4	2.1	8.0	16.4	28.2	0.00074
4000	0.3	0.4	2.4	5.9	16.6	25.6	0.00064
4000†	0.7	0.25	0.5	2.0	4.4	7.9	0.00020
4200	Erratic operation—crystal defective						
4400	0.6	0.4	0.9	3.5	5.0	10.4	0.00024
4600	0.2	0.2	0.6	1.1	17.0	19.1	0.00042
4800	1.1	0.5	0.5	3.4	5.8	11.3	0.00024
5000	2.3	0.9	3.1	6.7	22.6	35.6	0.00071
5200	0.8	0.1	0.6	2.9	7.8	12.2	0.00024
5400	0.5	0.7	1.7	3.6	13.0	19.5	0.00036
5600	1.2	0.9	1.0	3.5	8.6	15.2	0.00027
5800	0.7	1.0	3.3	5.7	27.0	38.1	0.00066
6000	1.3	0.6	2.1	3.9	27.0	34.9	0.00058
6200	0.3	0.6	2.0	3.9	12.2	19.0	0.00031
6400	0.7	0.5	2.2	3.4	13.6	20.4	0.00032
6600	1.9	1.1	2.4	4.8	11.2	21.4	0.00033

Note: Power amplifier load variation produced no change in frequency.

* Special crystals similar to the Type CR-1 Unit used for frequencies 2000 to 4000 kc inclusive.

† Type CR-7 Crystal Units used for frequencies 4000 to 6600 kc inclusive.

This table presents data for the following specific conditions:

1. The supply voltage was varied between 140 and 240 volts dc.

2. The cathode heater voltage was varied between 5.0 and 7.5 volts ac.

3. The stabilization drift during a one-hour period was measured, maintaining the crystal oven temperature constant at 70°C and energizing the oscillator-exciter unit at the start of the run.

4. Tubes were changed. Ten tubes representing Hytron, Raytheon, Tung Sol, and Western Electric manufacture were substituted in the oscillator. The effect of amplifier tube change was negligible and is not included in the data.

5. The ambient temperature was varied from -40° to +70°C with the oven temperature held constant at 75°C. (This higher oven temperature was necessary in order to maintain control of the oven temperature when the ambient temperature was 70°C.)

6. The power amplifier load was varied from an open circuit to a short circuit condition, and no change in frequency resulted.

The total change observed with the different crystals varied from 0.00020 to 0.00119 percent. The inherent stability of the oscillator-exciter observed under these extreme conditions promises that the desired overall 0.0025-percent frequency tolerance can be achieved if an improved crystal oven is available and no excessive frequency variation is introduced by shock and vibration. In addition, the production tolerance of the crystal units must not exceed 0.001 percent.

Output Power

The oscillator-exciter unit develops 0.57 watt or more into a resonant load. This is sufficient power to drive a Type 807 tube, which is commonly used as a radio-frequency amplifier or multiplier, to its full power capabilities. The load of the oscillator-exciter final amplifier may be untuned in applications in which the tuning is objectionable, but only with considerable sacrifice in output power from the oscillator-exciter unit.

Performance of the Crystal Units

During the investigation of the frequency stability of the oscillator-exciter unit, every precaution was taken to completely stabilize the crystal in order to assure as far as possible that any variation in frequency observed was due to circuit effects alone. In order to do this, it was necessary to minimize temperature variation and the effect of shock and vibration on the crystals. The first Type CR-1 crystals obtained for use with the circuit were unstable, and therefore unsatisfactory. Light vibration of the crystal holders caused frequency changes sufficient to mask the frequency variations due to other causes. To overcome this difficulty, a special set of crystals was obtained for use in the 2 to 4 megacycle range. These crystals were approximately 11/16 inch square, and were pressure mounted in holders resembling those used for the Type CR-1 crystal units. Type CR-7 crystals were used from 4 to 6.6 megacycles. The difficulties experienced with the original Type CR-1 crystals emphasize the need for a stable shock and vibration proof crystal unit for use with the oscillator-exciter. In addition, a crystal oven capable of maintaining a crystal temperature within very close limits is essential. This detail is discussed later.

DETAILS OF THE EXPERIMENTAL UNIT

Physical Description

The experimental oscillator-exciter unit with the crystal ovens used for the 2 to 4 megacycle crystals and the Type CR-7 crystals, is shown in Figure 2.

The small oven shown is a standard Navy Type CFT-40148 crystal oven which was used to hold the Type CR-7 crystals. The large oven was constructed using a base from a Type CFT-40148 oven and holds ten of the 2 to 4 megacycle crystals. The dimensions of the oscillator-exciter unit, including the Type CFT-40148 crystal oven, are 5 3/4 x 5 1/2 x 6 1/2 inches (height x width x length). The weight of the entire unit is two pounds two ounces. With the large crystal oven, the width becomes 6 1/2 inches, and total weight is four pounds.

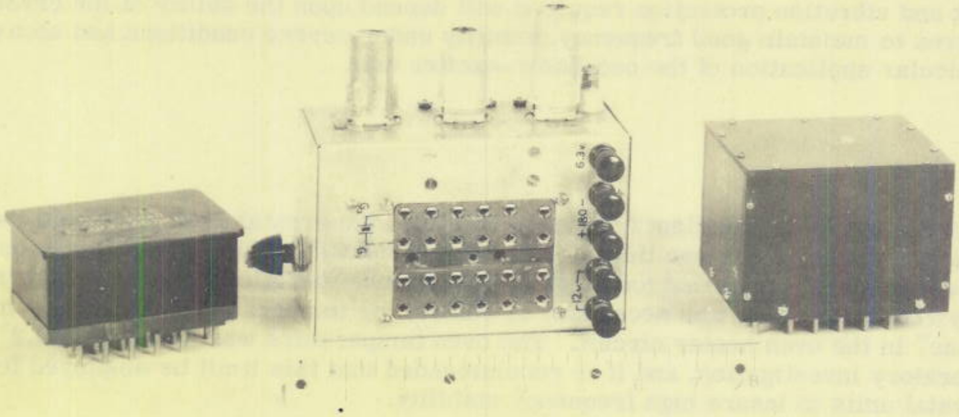

Fig. 2. Oscillator-Exciter Unit with Crystal Ovens

Power Requirements

The oscillator-exciter unit requires a high-voltage supply delivering 30 milliamperes at 180 volts dc, and a cathode heater supply of 0.5 ampere at 6.3 volts ac. The maximum crystal oven power requirement, with the Navy Type CFT-40148 oven at 75° C in an ambient temperature of -40° C, is approximately 25 watts. The use of an oven having improved insulation would reduce the power required.

SERVICE APPLICATIONS

Production Units

The oscillator-exciter circuit has been designed as a standardized circuit to be used with different types of equipment which require a crystal oscillator. It is expected that with different applications the arrangement of circuit components will vary. These changes will not appreciably affect the operation of the circuit, provided that modern construction techniques are followed. Shielding will be necessary in order to prevent self-oscillation in the relatively high-gain amplifier stages. For commercial production of the oscillator-exciter, it is desirable to use a small variable capacitor from the oscillator control grid to ground (C1 in Figure 1). This will permit the crystal load capacitance as measured at the crystal socket terminals to be adjusted in each unit to a predetermined value of 32 ±1/2 μμf, in order to provide identical crystal operating conditions for all units of a particular type. The values of other components are not critical, since they have no marked effect on the operating frequency of the unit. Navy approved components should be used.

Shock and Vibration

The unit was not subjected to any prescribed shock and vibration test because of the instability of many of the crystals under shock and vibration. Often when the crystal was jarred or vibrated by hand, changes in frequency as great as 100 cps occurred. However, with crystals which were not affected by shock and vibration the oscillator-exciter unit appeared to operate with good stability when under light shock and vibration. The degree of shock and vibration protection required will depend upon the ability of the crystals themselves to maintain good frequency stability under severe conditions, and also upon the particular application of the oscillator-exciter unit.

Crystal Oven

In order to obtain excellent frequency stability, the crystal oven must hold the crystal temperature within very close limits. The Navy Type CFT-40148 crystal oven used in the circuit development permitted too large a temperature variation for the crystal frequency stability required, and it was necessary to control the temperature manually by means of a "Variac" in the oven heater circuit. The oven temperature was held within 0.2° C during the laboratory investigation, and it is recommended that this limit be employed for production crystal units to insure high frequency stability.

METHOD OF FREQUENCY MEASUREMENT

Unusually precise frequency measuring techniques were required to evaluate the circuit stability of the oscillator-exciter. The arrangement of the equipment used for these measurements is shown in Figure 3. Briefly, a 100-kilocycle standard signal, with an average accuracy of one part in ten million, is fed to a "Decade Crystal Calibrator" or harmonic generator. The harmonic generator provides output signals at 100-kilocycle intervals. A radio receiver is used to provide an audio frequency beat note between the appropriate harmonic of the 100-kilocycle standard and the signal from the experimental oscillator-exciter unit. By means of a Lissajous figure, the General Radio Interpolation Oscillator is adjusted to the exact frequency of the audio beat notes. This provides a direct measurement of beat note frequency to an accuracy limited only by the accuracy of the interpolation oscillator and of the standard signal. By mounting the General Radio Interpolation Oscillator rigidly, and by minimizing the temperature changes within the room, frequency measurements made were accurate to within 0.2 cps.

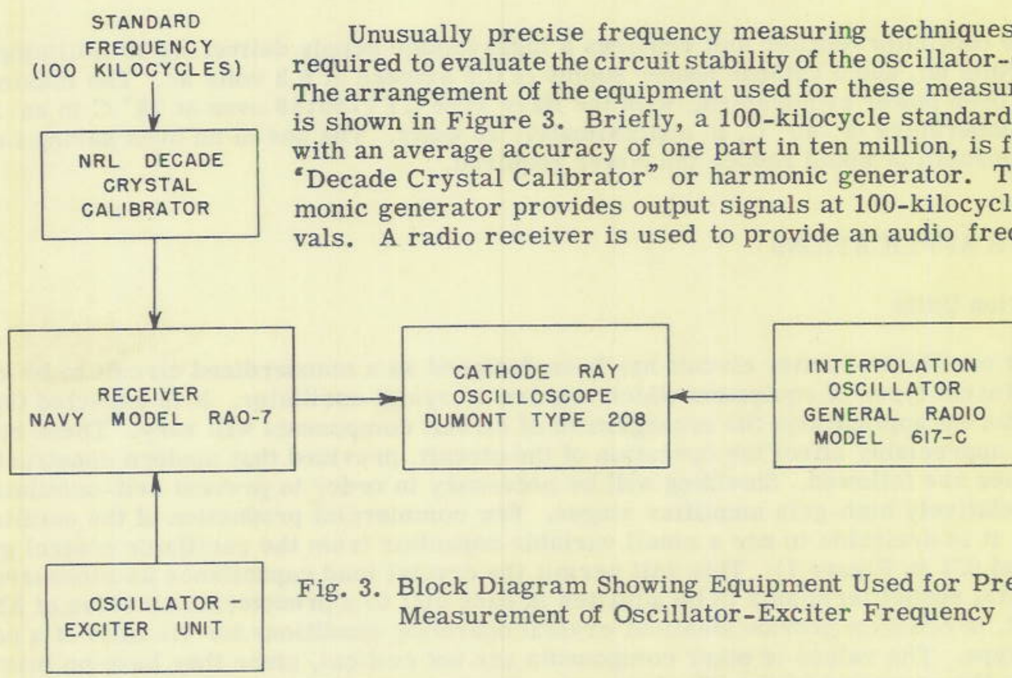

Fig. 3. Block Diagram Showing Equipment Used for Precision Measurement of Oscillator-Exciter Frequency

CONCLUSIONS

The oscillator-exciter unit possesses the high degree of frequency stability and the simplicity which are necessary for a standardized circuit. If crystals of close production tolerance are available and a satisfactory crystal oven is provided, an overall frequency tolerance of 0.0025 percent or better can be achieved. The unit provides over one-half watt output power at any frequency from 2 to 6 megacycles when the driven circuit is resonated to the crystal frequency.

PRNC-4204-1-14-48-100

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