Noise Studies on Two-Cavity CW Klystrons*

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Summary—**The noise properties of a two-cavity CW 3-cm klystron oscillator are discussed with the purpose of studying the noise contribution located close to the center frequency in the audiofrequency range. A system permitting measurements to be made of the mean square frequency deviation is described. Comparisons are made indicating the noise performance of the klystron oscillator when operated under air-cooled and water-cooled conditions.**

Introduction

THIS PAPER is concerned with the study of noise as it applies to a two-cavity CW 3-cm klystron oscillator intended for use in MTI or Doppler radar systems, where large amounts of nearly monochromatic power are required. The designers of such systems are concerned largely with noise located close to the center frequency in the audio-frequency range from 0 to 20 kc which is of interest in helicopter landing systems having a low Doppler shift.

In considering the sources of noise which are present in the measurement of microwave oscillators, we will consider only the noise produced by frequency modulation and will neglect the small order amplitude modulation effects which are cancelled out by making the measurement system (which will be described later) insensitive to amplitude modulation. Factors which contribute to the noise signal resulting in possible causes of frequency instability are:

1) Noise due to fluctuations of the power supply.

2) Noise due to the fluctuations of the admittance of the load connected to the klystron oscillator.

3) Noise due to variable thermal expansions and contractions of the dimensions of the klystron.

4) Shot noise excitation of the resonant cavities.

5) Noise mechanisms involving fluctuations in beam parameters, such as those due to changes in current density of the cathode, flicker effect, beam velocity, and beam current fluctuations.

It is believed that the fundamental mechanism contributing to frequency fluctuations in klystron oscillators depends upon the essential design parameters; namely, the applied voltages, the admittance of the load connected to the klystron and the time scale of the fluctuations being considered. Shimoda[1] presented a theory of the electronic limitation to frequency stability, which yielded a root-mean-square frequency deviation that agreed with measurement. However, Berstein[2] criticized Shimoda's result and suggested that the agreement with experiment was produced by chance since the theory given considered only electronic noise; while the experiment allowed measurement of frequency fluctuations produced by nonelectronic noises. Few attempts were made to correlate observed klystron frequency fluctuations with theory, especially comparisons of audio rate fluctuation in high powered klystron oscillators. Some attempt will be made in this report to present data which will help to bring about a better understanding of klystron oscillator noise.

The PKX-4 Klystron Oscillator

The PKX-4 klystron oscillator was used exclusively in all measurements made and described in this report. This klystron has been described previously[3] and consists essentially of a two-cavity resonator construction employing no diaphragms and tuners, with a fixed feedback coupling. These precautions are taken in the design of this tube to reduce to a minimum the effects of microphonism. The modulating cavity is dimensioned to yield the desired resonant frequency and the output cavity is adjusted mechanically to produce oscillations by applying a force to the collector, which is sufficient to strain the cavity wall beyond the elastic limit of the cavity wall material. Fig. 1 shows a cross-sectional view of the resonator system.

In addition to ruggedizing the resonator system, the design of the gun structure[4] was also improved upon to increase its rigidity, so that little if any microphonism was noted through a frequency range from 20 cycles to 20 kc. The Philips impregnated cathode operating at an emission density of approximately 2 a/cm^2 (having a perveance of 0.25×10^{-6} a/v$^{3/2}$) was used as a source of thermionic emission.

The PKX-4 klystron oscillator is liquid cooled and a maximum rate of flow required for water cooling is about $\frac{1}{2}$ gallon per minute. This tube bolts directly to standard RG-52/U waveguide fittings.

* Received by the PGMTT, February 29, 1960; revised manuscript received, April 28, 1960.
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[1] K. Shimoda, "Length of coherent microwaves generated by an electronic oscillator," *J. Phys. Soc. Japan*, vol. 8, p. 131; 1953.
[2] I. L. Berstein, "Fluctuations of klystron oscillation," *C. R. Acad. Science URSS*, vol. 106, pp. 453–456; 1956.
[3] R. A. La Plante, "Development of a low-noise X-band CW klystron power oscillator," IRE Trans. on Electron Devices, vol. ED-1, pp. 99–106; December, 1954.
[4] G. A. Espersen, "A low noise high power klystron oscillator of great reliability," *Le Vide*, pp. 270–280; September–October, 1956.

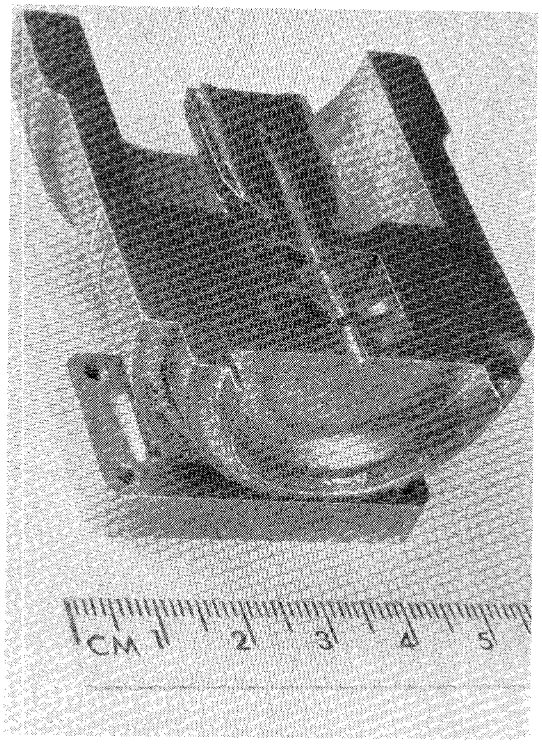

Fig. 1—Opened X-band oscillator of the PKX-4 type.

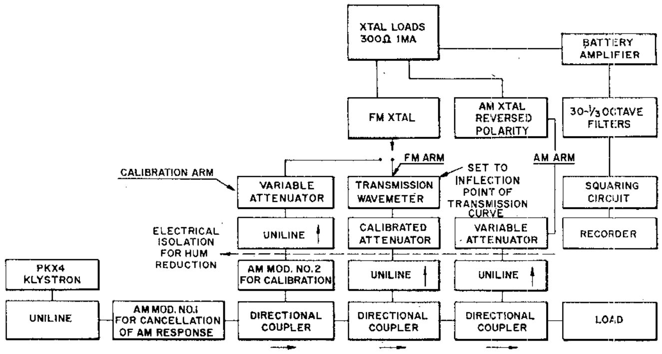

Fig. 2—Principal system for measurement of random frequency deviations.

The Noise-Measuring System

Early klystrons which were not completely corrected for microphonic defects were measured with a system[5] which proved to be inadequate for studying improved models of the klystron. Atkinson developed a system[6] of measurement which permitted measurements to be made of the mean square frequency deviation that would result from various types of electronic fluctuations being converted into frequency fluctuations. A block diagram of an improved version of this system is shown in Fig. 2. The improved system differs from the earlier measuring system in the following ways:

1) Crystal currents of 0.001 ampere (formerly 0.0005 ampere) and 300-ohm dc loads were used to increase the tube to crystal noise ratio to a value greater than could be achieved with quadratic operation of the crystal detectors and 10,000-ohm dc loads. The crystal in the FM arm is not operated in the quadratic range, hence it is necessary to use the indicated calibrated adjustable attenuator to set the discriminator to the inflection point of its transmission curve.
2) Type 1N415C and 1N415E crystals were substituted for the relatively noisy 1N23B crystals. The polarity reversibility of these crystals made possible AM cancellation without using a mixing transformer (formerly used on initial measurement system).
3) An air-driven resistive-card amplitude modulator no. 1 was placed in the main line to allow the power absorbed by the AM bucking crystal to be adjusted so as to render the system insensitive to AM, thus eliminating the need for matched crystals.
4) A calibrated air-driven resistive-card amplitude modulator no. 2 is included in the calibration arm to produce a known amount of modulation, which is used to determine the sensitivity of the crystal used in the FM arm. This modulator makes possible calibration of the crystal-load-amplifier, filter squaring circuit and indicator chain. The AM bucking crystal acts as a shunt for the FM crystal and the loading effect of the AM crystal is varied with the proper amount of excitation required for AM cancellation. During calibration of the chain, the FM crystal and its holder are moved to the calibration arm and an output reading is taken.
5) A 30-member set of third octave filters is used to form a selective amplifier in place of the previously used narrow band heterodyne arrangement. This method insured the advantages of increased bandwidth over most of the audio range.
6) The output of the selective amplifier is fed to a series of diodes to form a squaring circuit, the output of which is recorded on a chart recorder to obtain the mean square voltage from the selective amplifier.
7) The background noise of the amplifiers and crystals is found by connecting the crystal holder (normally connected to the FM branch) to the frequency insensitive calibration arm.

With these changes and using a loaded discriminator cavity having a Q of 8500, one is able to detect rms frequency deviations as small as 2 cps over a third octave band in the audio spectrum above 500 cps, with a reproducibility amounting to a rms deviation from the mean value of measured quantity of 0.7 cps. At

[5] G. A. Espersen and R. A. La Plante, "Studies and Investigations of a 100 Watt CW X-Band Klystron," AFCRC, Contract No. AF19(604)-454; March, 1954.
[6] W. R. Atkinson, "Research on Noise in High Powered Klystrons," ARDC, Contract No. AF18(603)-33 Supp. 1 (57-345); May 31, 1958.

lower ranges of the audio spectrum where the rms frequency deviations were 70 cps over a third octave, relative reproducibility was five times better.

Measurement of Random Frequency Deviations

Most measurements were made on klystrons which operated in the mode corresponding to a transit angle of 9/4 cycles and delivering a power output of approximately 20 CW watts. A number of measurements were also taken in the mode corresponding to transit angles of 11/4 and 15/4 cycles respectively. All measurements taken used the circuitry shown in Fig. 2.

A plot of rms frequency deviation against central filter frequency for a number of different klystrons, shown in Fig. 3, indicates that the frequency deviation is greatest at values of central filter frequency below 400 cps.

Fig. 4 shows how the rms frequency deviation varies when plotted against central filter frequency for various transit angles.

Fig. 5 indicates how the frequency deviation varies with respect to central filter frequency for a given klystron, comparing water cooling with air cooling.

Some measurements taken at a central filter frequency of 40 cps indicate that increasing the water flow rate from 0.08 to 0.30 gallon per minute increased the frequency deviation from 45 to 65 cps. Other measurements at a filter frequency of 40 cps show that increasing the beam voltage from 3.5 to 4.5 kv increased the frequency deviation from 38 to 75 cps.

Discussion

It is significant to point out that all measurements were taken at frequencies other than the line frequency and its harmonics. The amount of power supply ripple noise at the measured frequencies was in the order of 1 cps, while the beam modulation sensitivity of the PKX-4 klystron oscillator was approximately 7.5 kc/v.

The low frequency beam current fluctuations, as observed by connecting a 1000-ohm resistor in series with the klystron and the fluctuating voltage, indicated that the mean square current fluctuations were at least twenty times less than the full shot noise throughout the entire audio spectrum for a given klystron.

Figs. 2, 3, 4 and 5 all indicate that the rms frequency deviation increases rapidly with decreased filter frequency at values below 400 cps. This phenomenon is

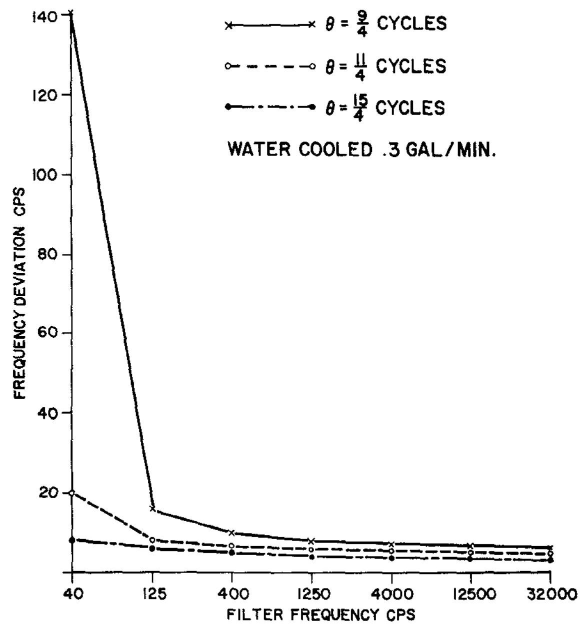

Fig. 4—RMS frequency deviation vs central filter frequency for various transit angles.

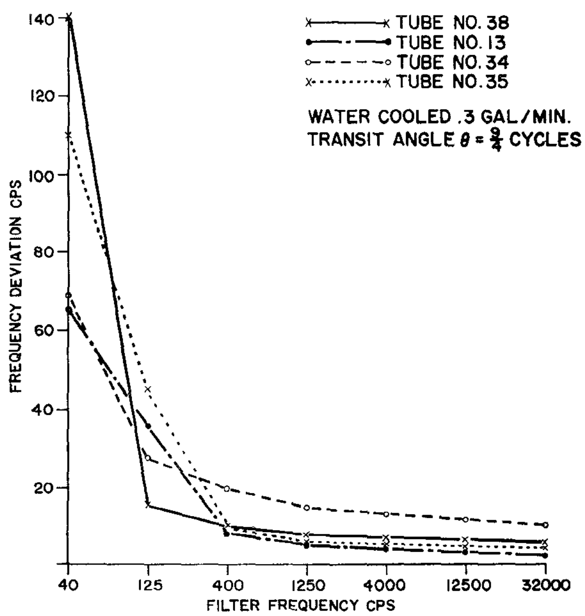

Fig. 3—RMS frequency deviation vs central filter frequency for a number of PKX-4 klystrons.

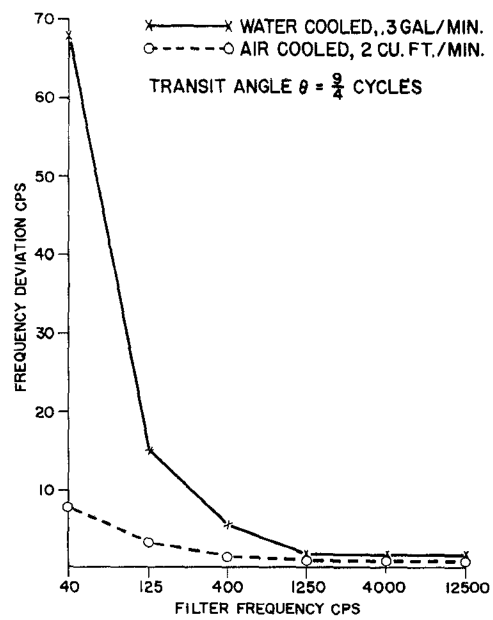

Fig. 5—RMS frequency deviation vs central filter frequency. PKX-4 klystron no. 9.

similar to that displayed by klystrons having tuning diaphragms which definitely do possess microphonism in the same frequency range. However, these klystrons are of a massive construction, and since they are supported by a shock mounted table it is felt that the main source of the microphonic excitation is probably due to the flow of the coolant both in the water-cooled and air-cooled klystrons. This is confirmed by the fact that changing the water flow rate from 0.08 to 0.30 gallon per minute increases the frequency deviation from 45 to 65 cps for a central filter frequency of 40 cps. Furthermore, Fig. 5 shows that the frequency deviation of an air-cooled klystron is only 8 cps, as compared to 68 cps in a water-cooled klystron, even though the body temperature of the air-cooled klystron is 90° greater than the water-cooled klystron, which operated at a body temperature of 30°C.

The reason for the improved performance using air cooling is not fully understood. It has been shown experimentally that when the coolant becomes hot enough to simmer audibly, the spectrum of the cathode current fluctuations indicates sharp peaks of several thousand cycles. This behavior shows that the microphonic variation of the cathode to anode spacing or the microphonic variation of the ion current flowing back to the cathode does accompany the increased simmering condition of the coolant. It is possible that the current fluctuations which accompany the simmering are responsible for the frequency fluctuations present. Since only total cathode current was measured, no data were available regarding the fluctuations of the transmitted current.

The resonant cavities of the klystrons have frequency fluctuations which contribute to the noise picture since these cavities are sensitive to gap spacings. The sensitivities range in value from 5.7×10^{12} cps/m for small gap spacings (0.020 inch) to 0.73×10^{12} cps/m for large gap spacings (0.040 inch). The frequency variation of the buncher and catcher cavities shows mode to mode alterations in which case the klystron oscillates in either the buncher or catcher mode, which can be identified by the transit angle. As the beam voltage increases, the klystron oscillates alternately in the two types of modes and in some cases it will skip a mode. The increase in the rms deviation at low frequencies that accompanies increased power input (smaller transit angle) is shown in Fig. 4.

It was believed that the addition of cooling fins to the anode collector (shown in Fig. 1) would decrease the frequency deviation. Measurements taken after cleaning the collector (no cooling fins attached) on a number of klystrons indicated that the rms deviation at 40 cps doubled in value. With cooling fins attached to the collector and with normal water flow rate and power input, no bubbling of water was observed, but without cooling fins bubbles formed on the collector. When the surface was cleaned, large bubbles would appear, but when the surface was painted, small bubbles would appear and remain attached to the collector for long periods of time. It has not been possible to determine whether the bubble phenomenon is significant with the degree of frequency fluctuation or whether some other phenomenon is responsible for both the frequency fluctuations and the bubbles. No audible simmering was noted in the observations mentioned above and the temperature of the center point of the collector was 50°C for the tests involving both the cleaned and painted collectors.

It was felt that the second catcher cone would expand to a considerable extent if the beam would momentarily strike it, thus causing frequency fluctuations of several hundred cycles per second. Attempts to measure the cone temperature fluctuations have not been successful to date. An experimental PKX-4 klystron was made in which the bore diameter of the second catcher cone was increased from 0.085 inch to 0.095 inch. Using air cooling one obtained a frequency deviation as low as 4 cps. The best result for frequency deviation of an air-cooled PKX-4 klystron having a constant bore diameter of 0.085 inch, as indicated in Fig. 5, was 8 cps at a filter frequency of 40 cps.

Conclusions

A summary of the essential results indicates that lower frequency deviation can be achieved if air cooling is used in place of water cooling, and if changes are made in the cavity configuration of the catcher cavity to reduce thermal effects from the electron beam. A frequency deviation of 4 cps at a filter frequency of 40 cps has been achieved, and with further refinement in the tube design it should be possible to attain a value of frequency deviation which is near or even less than unity. For measurements of these klystrons, it is suggested that the more elaborate system proposed by Whitwell and Williams,[7] which is capable of a resolution of a few tens of cycles, may be used to advantage.

Acknowledgment

The author would like to acknowledge the work of W. R. Atkinson, chief investigator of this project, who contributed many of the ideas expressed in this paper.

Appreciation is extended to the Air Force Cambridge Research Center and the Air Force Office of Scientific Research for providing some of the funds required for this noise study under Contracts AF19(604)-454. AF19(604)-1080, and AF18(603)-33.

[7] A. L. Whitwell and N. Williams, "A new microwave technique for determining noise spectra at frequencies close to the carrier," *Microwave J.*, vol. 2, pp. 27–32; November, 1959.