FOUR LECTURE DEMONSTRATIONS FOR COURSES ON THE THEORY OF OSCILLATIONS AND RADIO ENGINEERING

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I. NATURAL OSCILLATIONS IN A REGENERATIVE OSCILLATING CIRCUIT. THE PROCESS OF BUILDING UP OSCILLATIONS OF A QUASI-HARMONIC CHARACTER IN AN LC OSCILLATOR

IT is easy to produce a demonstration of oscillatory processes in a regenerative circuit and in an LC oscillator by using a transistor as the active element of the system, for the following reasons: 1) as a consequence of the large difference in the values of the input ($\sim 10^2$ ohms) and output ($\sim 10^6$ ohms) resistances of the transistor, the condition for self-excitation in the oscillator with transformer coupling is satisfied if the feedback coil consists of only several turns, and can be easily wound during the demonstration; 2) the supply voltages of the transistor are low and it is quite safe to experiment with such an oscillator under lecture conditions.

The experimental apparatus described makes it possible to demonstrate the following phenomena in a large auditorium.

1. Natural damped oscillations in an LC circuit and the dependence of their form on the decrement of the circuit.
2. Increase in the damping of the natural oscillations in the circuit in the presence of negative feedback.
3. Decrease in the damping of natural oscillations in a regenerative circuit for positive feedback below critical.
4. The process of building up oscillations in a generator of quasi-harmonic oscillations for different values of the positive feedback and various initial conditions.

The apparatus makes it possible to observe the shape of stationary auto oscillations in a circuit out-

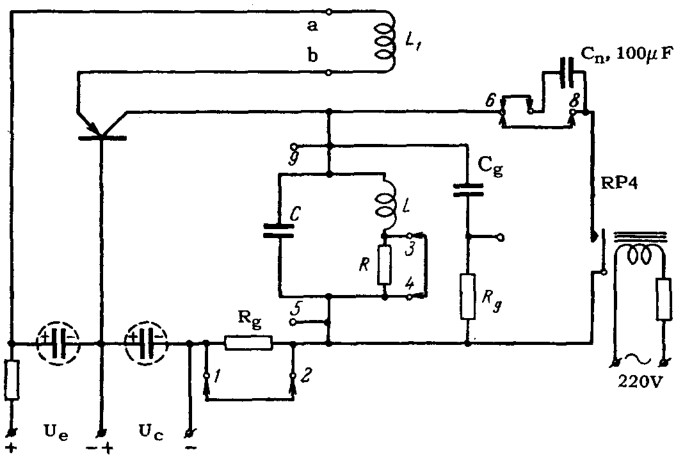

FIG. 1

side of the oscillator circuit. In all the cases enumerated, the phase picture of the corresponding process can be obtained.

The experimental apparatus shown in Fig. 1 consists of an LC oscillator with a transistor mounted on an open panel, of a relay located on the same panel, a demonstration oscilloscope and a rectifier. In the generator of quasi-harmonic oscillations, a low-frequency, low-power transistor is used, for example, type P-14. The collector—base voltage U_c does not need to be regulated. It is taken to be equal to approximately 10 V. The emitter—base voltage U_e should be regulated within the limits 0—30 V. A flexible, insulated lead of about 2 m length is connected to the points a—b in the emitter circuit. This lead, which is designated below as the conductor ab, is wound by the lecturer in the demonstration of the experiment on the coil of the circuit L; this corresponds to adding coupling coil L_1 into the circuit. The feedback coupling can be made positive or negative depending on the direction of the winding. The circuit R_gC_g is the simplest type of differentiating circuit and serves to obtain the derivative of the capacitor voltage. This is necessary to display on the oscilloscope the phase portrait of the process under demonstration. A relay of the RP-4 type periodically short circuits the oscillator circuit when demonstrating the build-up or damping of the oscillations. The purpose of the capacitor C_n will be explained below.

Order of Demonstration of the Experiments. 1. Natural damped oscillations in an LC circuit. The lead ab is not wound on the coil L. The resistance R_k and the capacitance C_n are short-circuited by jumpers. The oscilloscope is connected to the terminals 5—9. Synchronization of the oscilloscope is carried out by the supply voltage. Upon operation of the RP-4 relay there are observed on the oscilloscope screen damped oscillations, which arise in the circuit for the following reasons: After the contacts in the relay open, the capacitor C is charged rapidly to a certain voltage whose value can be regulated by varying the voltage U_e. This initial kick of the voltage on the capacitor is brought about by the fact that the time constant of the capacitor discharge circuit is chosen to be much less than the period of the natural oscillations of the LC circuit. Upon connecting a resistance R into the generator circuit (by disconnecting the contacts 3—4) the natural oscillations are damped much more rapidly. To demonstrate the phase portrait of the damped oscillations, and also all the other processes described below, one must disconnect the sweep of the oscilloscope and apply the voltage from the resistance R_g directly to the second pair of its plates.

After demonstration of the natural damped oscillations of the free circuit, negative feedback is introduced in the system, for which purpose the wire is wound on the coil L in the direction corresponding to negative feedback, to which one should especially call the attention of the audience. When the number of turns on the feedback coil becomes sufficient the process in the circuit becomes aperiodic.

Next, the polarity of the voltage on the wire ab is reversed, which corresponds to positive feedback. It is shown that the regenerative circuit possesses smaller damping the larger the positive feedback. At critical feedback, the damping of the circuit is entirely compensated, and a segment of a sinusoid is observed on the oscilloscope. It should be emphasized here that exact compensation of damping of the circuit is not achievable in practice, due to fluctuations of the parameters of the system (for example, the amplification factor as a function of the voltage of the transistor). The stability of the picture observed in the experiment is explained only by the fact that the time of observation is limited, which makes it possible to see only the initial stage of highly repetitive processes.

2. The process of establishment of oscillations in a generator of quasi-harmonic oscillations. The differential equation of a transistor generator with a parallel tuned collector circuit is similar in structure to the equation of the vacuum tube generator with a tuned plate circuit. By referring to this analogy, the lecturer can derive the equation for the vacuum tube generator. The derivation of the equation for the transistor generator of Fig. 1 is given in [1].

To demonstrate the build-up of oscillations in a generator with a fixed initial level, the capacitor C_n should be shorted by the connecting jumper, just as for demonstrations of the natural oscillations of the circuit. By regulating the value of the positive feedback, one can change the duration of the process of build-up of oscillations in the generator. The oscillograms observed in this case, for strong and weak regeneration in the system, are shown in Figs. 2 and 3, respectively. The phase portraits corresponding to these cases and observed on the screen of the oscilloscope are shown in Figs. 4 and 5.

For demonstration of the oscillation build-up for random values of the initial voltage on the capacitor

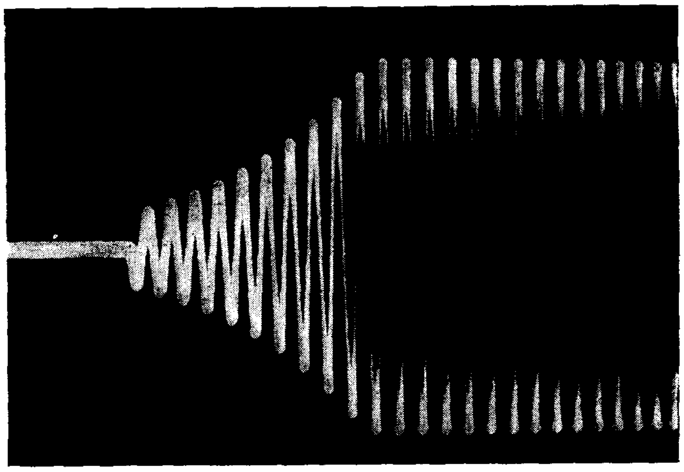

FIG. 2

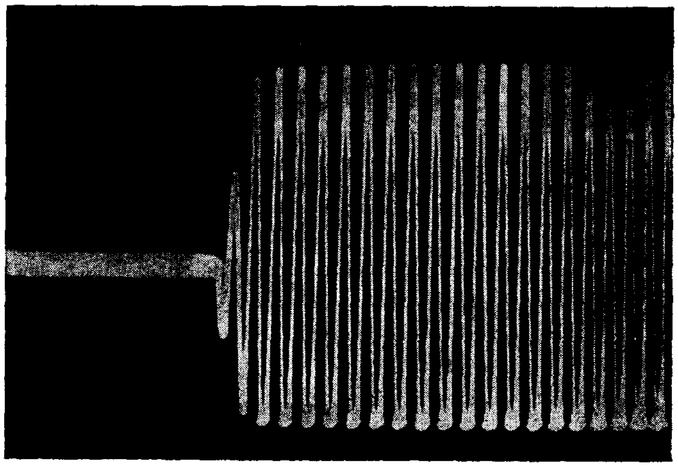

FIG. 3

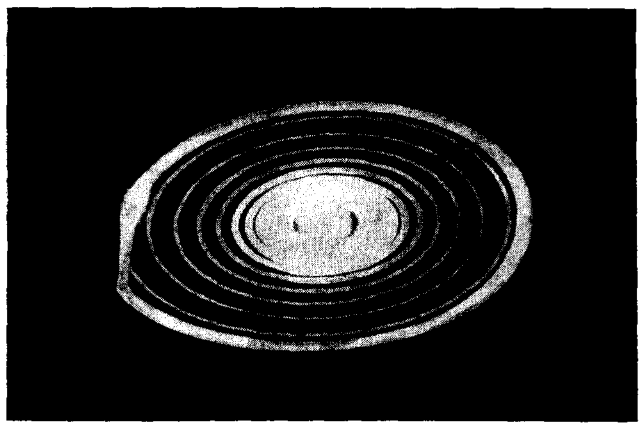

FIG. 4

C, it is necessary to add the capacitance C_n to the circuit, removing the shorting jumper 6—8 and connecting it to terminals 6—7. The charging time constant of the capacitor C_n is chosen to be so large that the voltage on C_n is always approximately equal to the voltage on the condenser C at the moment of

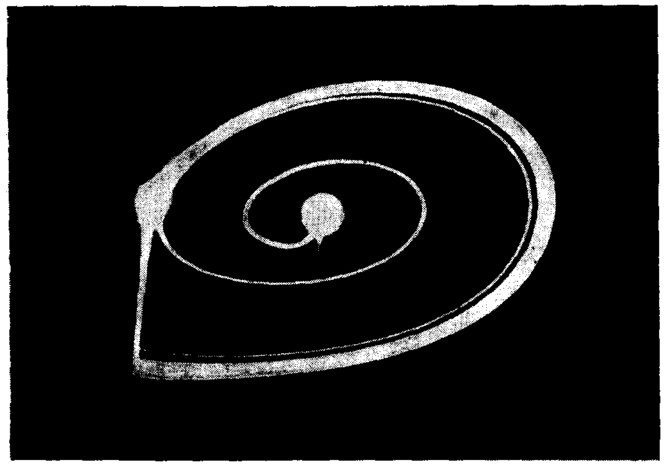

FIG. 5

connection of the contacts of the relay. In this case, the initial phase is constant but the initial amplitude fluctuates, which is easily seen on the screen of the oscilloscope.

3. Stationary self-oscillations of the generator. To demonstrate the waveform of the stationary self-oscillations of the generator, the relay must be turned off. Since the contacts of the disconnected relay may be closed, one must remove the jumpers 6—8 and 6—7. The arrangement makes it possible to observe the waveform of the voltage oscillations on the circuit capacitor C. Even for large regeneration, it remains close to sinusoidal. Then the waveform of the self-oscillations of the current of the transistor collector can be displayed by removing jumpers 1—2 and connecting the oscilloscope to the resistance R_k. The waveform of this current is close to harmonic only if the feedback slightly exceeds the critical value. For high regeneration, the waveform of the collector current is far from harmonic, while the oscillations in the tank circuit are close to harmonic. This demonstrates one of the fundamental properties of self-oscillations of systems containing high-Q resonant systems.

II. ANALYSIS OF THE SPECTRUM OF ELECTRIC OSCILLATIONS

The purpose of this experiment is to show the action of a parallel LC circuit as a simple spectrum analyzer for electric oscillations.

A block diagram of the experimental set-up is given in Fig. 6. A special attachment to a typical audio oscillator (for example, type 3G-10) makes it possible to obtain rectangular voltage oscillations. These oscillations are observed on the oscilloscope 1, the amplifier of which must have sufficient broadband so that waveform distortions of this square wave are minimal. The attachment is shown in Fig. 7. The 6N9 tube of this circuit operates without preliminary bias. Therefore the grid current of the tube changes

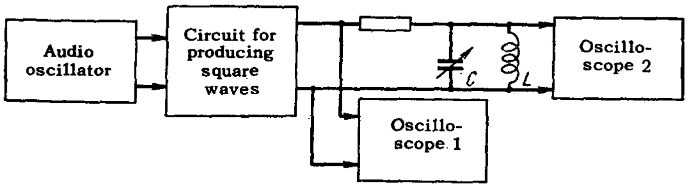

FIG. 6

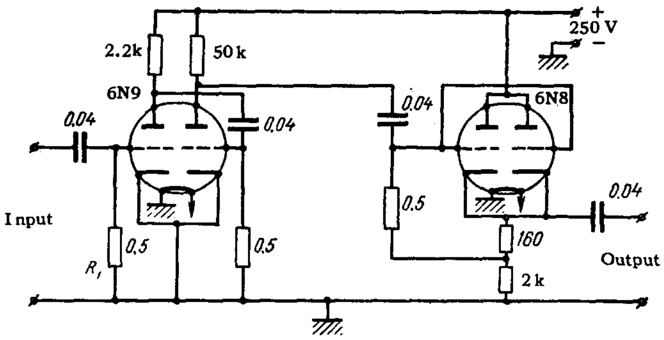

FIG. 7

with change in the amplitude of the input voltage. This produces a change in the potential drop across the resistance R_1, i.e., a shift in the operating point of the 6N9 tube. Thus, the cut-off angle of the output voltage is changed by a change in the amplitude of the input voltage; this makes it possible to regulate conveniently the off-duty factor of the output square waves in the range 0.2—0.5.

As is well known, the spectrum of the periodic series of square pulses, shown in Fig. 8, is represented in the form of the following Fourier series:

$$u(t)=U_m\gamma+\frac{2U_m}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin n\pi\gamma\cdot\cos n\Omega t, \qquad (1)$$

where the off-duty factor is

$$\gamma=\frac{t'}{T}, \qquad \Omega=\frac{2\pi}{T}.$$

It follows from Eq. (1) that the harmonic component, for which the following equality is satisfied

$$\sin n\pi\gamma=0, \quad \text{i.e. } n=\frac{1}{\gamma},$$

is not contained in the spectrum of the square wave. This circumstance is graphically demonstrated by the apparatus described above.

The order of demonstration of the experiment is as follows:

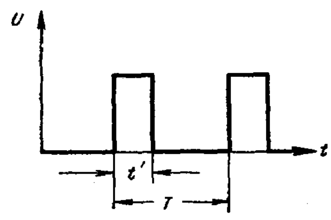

FIG. 8

The capacitance of the variable capacitor C of the analyzer circuit is increased to a value close to its maximum. The audio-frequency generator is tuned to the resonant frequency of the circuit. Then, for an arbitrary value of γ (but not equal to 0.5) the capacitor C is varied and the frequency of the second harmonic of the square-wave oscillations is found on the screen of oscilloscope 2 from the maximum amplitude of the oscillations. The scale of the capacitor C should show the corresponding resonant frequency of the circuit. Then, for the same oscillation frequency of the audio generator and the same tuning of the analyzer circuit, the off-duty cycle of the square wave is changed. At $\gamma = 0.5$, as monitored by the oscilloscope 1, the signal on the screen of oscilloscope 2 disappears almost completely. The disappearance from the spectrum of the third and fourth harmonics can be demonstrated in similar fashion. In this case, it is necessary to tune the generator so that its frequency is one half the resonant frequency of the circuit at maximum capacitance. In this case, the range of frequencies covered by the tank circuit is sufficient for observation of the third and fourth harmonic components of the square wave.

III. FORCED OSCILLATIONS IN AN ELECTRIC OSCILLATORY CIRCUIT UNDER THE ACTION ON IT OF A NOISE SIGNAL

The purpose of this experiment is to show the character of forced oscillations in an oscillatory circuit acted upon by a signal with a complicated spectrum. The circuit responds principally to those signal spectrum components whose frequencies are close to the resonant frequency of the circuit.

A block diagram of the experimental arrangement is shown in Fig. 9. The voltage from the noise generator is applied through a resistance to a parallel resonant circuit. The voltage oscillations on the circuit capacitor are amplified by a low frequency amplifier and are reproduced by a dynamic loud-speaker. By switching in different capacitors (switch positions 2, 3, 4 and 5) the resonant frequency of the circuit is changed in steps. The capacitor is removed from the circuit when the switch is in position 1.

The demonstration is begun by throwing the switch into position 1. Here the dynamic loud-speaker reproduces the hissing that is characteristic of the noise signal, in which it is impossible to distinguish any definite sort of musical tone. Simultaneously, the noise is observed on the screens of oscilloscopes 1 and 2. (The switching in of oscilloscope 1 is optional.) The capacitors C_1, C_2, C_3 and C_4 are successively switched into the circuit. Here the shape of the voltage oscillograms on oscilloscope 2 changes significantly. For each position of the switch the oscillations seen on the screen are of a definite frequency. This oscillogram differs essentially from

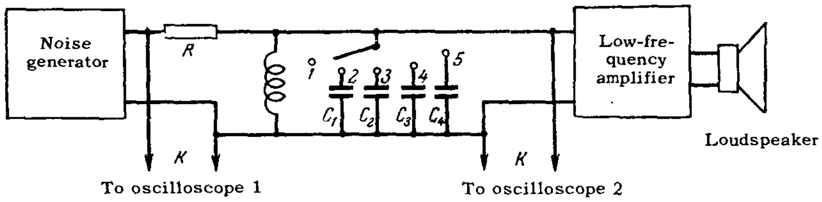

FIG. 9

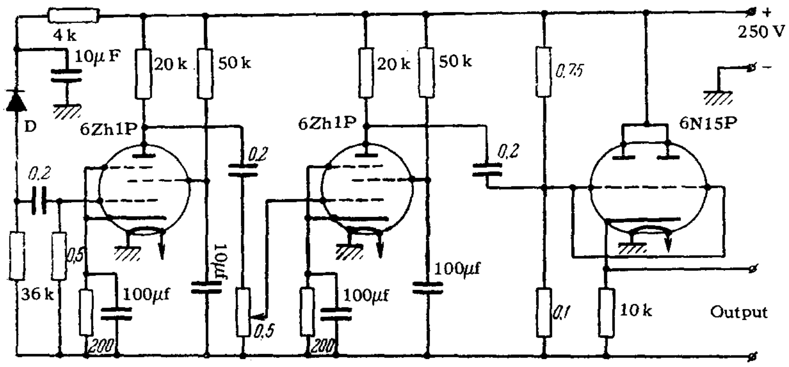

FIG. 10

the oscillogram of the noise signal observed on oscilloscope 1. Simultaneously, a definite musical tone is heard on the sound loud-speaker above the background noise. The values of C_1, C_2, C_3, and C_4 should be so chosen that the resonant frequencies of the circuit correspond to musical tones that form a chord.

A noise generator suitable for demonstration can easily be prepared, since no quantitative measurements are carried out in the experiment. The circuit of such a generator is shown in Fig. 10. The noise source in this circuit is a poor semiconductor diode D (or one of the junctions of a transistor triode) or one that is specially damaged, for example, by overheating or by breaking the hermetic seal with a comparatively large reverse current (for low power devices) of the order of 50 microamperes.

IV. THE ACTION OF THE SCREEN AND SUPPRESSOR GRIDS OF A PENTODE

This demonstration experiment makes it possible to show the change in the amplification factor with voltage and the dynamic input capacitance of an electron tube upon introduction of screen and suppressor grids. A pentode is used for the demonstration, and is successively operated as a triode, tetrode, and pentode. The circuit arrangement is shown in Fig. 11. The plate, the suppressor grid, and the screen of the pentode are connected to terminals 3, 2 and 4. When a short-circuiting plug is connected to these terminals, the tube operates as a triode. When terminals 2—3 are shorted with one plug and 4—5 by another, tetrode operation is established. To obtain pentode operation, the terminal pairs 1—2 and 4—5 are shorted.

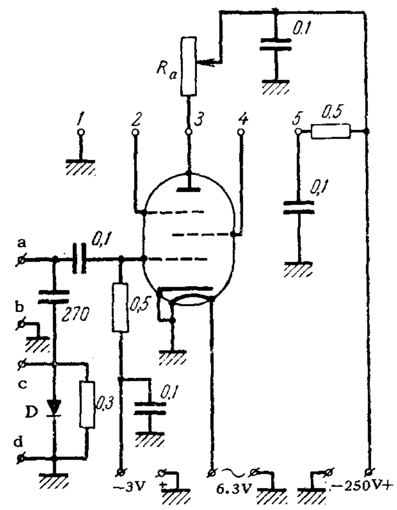

FIG. 11

1. Comparison of the voltage gain of the triode and the pentode. A voltage from a low frequency oscillator (for example, the type 3G-10) is applied to the terminals a—b of the circuit in Fig. 11. The frequency of the oscillations is chosen in the range 400—1000 cps. The output voltage on the load of the tube is observed by means of a demonstration cathode-ray oscilloscope which is connected in the plate of the tube. Before the first demonstration, the amplitude of the input voltage is chosen for no distortion in the waveform at maximum output voltage. The demonstration is carried out in the following manner. The tube is connected as a triode. The resistance of the load of the tube R_a, which is provided with a graduated scale clearly visible to the audience, is set at the position $R_a = 0$. Then the resistance R_a is increased in steps. The

attention of the listener is called to the fact that for small R_a the amplitude of the output voltage is approximately proportional to the value of R_a, as also follows from the expression for the absolute value of the gain $|K|$ of the tube with active load

$$|K|=\mu\frac{R_a}{R_i+R_a} \quad \text{for } R_a \ll R_i,$$

where R_i is the internal resistance of the tube and μ is its static amplification factor. Upon increase in R_a, the rate of increase of the output voltage decreases and for certain values $R_a > R_i$, the gain $|K|$ is a constant and is approximately equal to μ. Thus, by observing the character of the change of the output voltage with increase in R_a, one can determine the order of magnitude of the internal resistance of the tube. Attention must be given to the fact that in the triode connection of the tube R_i has a value of the order of several dozen kilohms.

The tube (with the supply voltage disconnected!) is then connected as a pentode, and the measurements made in the triode case are repeated. Here it should be emphasized that throughout the whole range of change of the resistance R_a, a direct proportionality exists between R_a and the amplitude of the output voltage. This means that, in the pentode case, the internal resistance of the tube R_i is much smaller than in the triode case, which makes it possible in almost all practical cases to compute $|K|$ by means of the relation

$$|K|=SR_a$$

where S is the static transconductance of the tube. The attention of the audience is called to the fact that for $R_a \approx 40$ kilohms the amplification factor of the tube in the pentode connection is much larger than in the triode. Optionally, this can also be tested for the tetrode operation of the tube.

2. Comparison of the input dynamic capacitance of the triode, tetrode, and pentode. Measurement of the input dynamic capacitance of the tube is carried out by the substitution method. In this case, an oscillating circuit is connected to the terminals a—b of the circuit in Fig. 12; the variable capacitor of of this circuit has a demonstration scale which is graduated in picofarads. An amplitude-modulated signal from a GSS6 generator or a similar one is applied to the circuit through a 50 kilohm resistance (Fig. 12). The operating frequency of the signal is chosen to be equal to the resonant frequency of the

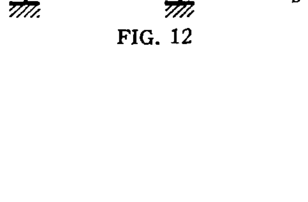

FIG. 12

circuit at a value of the capacitance C close to its maximum. The tuning of the circuit at resonance is monitored by a demonstration oscilloscope connected into the terminals c—d. A low-frequency signal on these terminals is obtained by detection of the amplitude-modulated signal which is applied to the circuit. It is advisable to use a point junction semiconductor diode as the detector. Provision should be made to permit disconnecting the tube input from the rest of the circuit. For this purpose, it is convenient to use a pentode, whose control grid lead passes through the top of the tube envelope (for example, type 6Zh7).

The demonstration is carried out in the following way. The tube is connected as a triode. R_a is set at zero and the static input capacitance of the triode is measured by the substitution method. Then the load resistance is set at $R_a = 40$ kilohms and the input dynamic capacitance of the triode is measured; it greatly exceeds static value previously mentioned. The same measurements are carried out in the tetrode and pentode connections of the tube for $R_a = 40$ kilohms. They show that the input dynamic capacitance decreases on going to the tetrode mode, and is smallest in the pentode case. For the measurements, it is convenient to place the following table on the panel:

	Value of C at resonance (pf)			Static capacitance of tube (pf)	Dynamic capacitance of tube for $R_a = 40$ k (pf)
	for tube disconnected	$R_a=0$	$R_a = 40$ k		
Triode	109	100	55	9	54
Tetrode	109	100	70	9	39
Pentode	109	100	91	9	18

The table lists values obtained with the physics demonstration apparatus of the Moscow State University. A rather large parasitic capacity between the circuits of the control grid and the plate of the tube was observed in the demonstration apparatus as a result of the measurements. The attention of the audience should be drawn to this particular circumstance. In particular, this explains the large measured value (see the table) of the dynamic input capacitance of the pentode 6Zh7.

[1]A. M. Az'yan et al., Poluprovodnikovye triody v regenerativnykh skhemakh (Transistors in Regenerative Circuits) (Moscow, Gosenergoizdat, 1959).

Translated by R. T. Beyer