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A. D. Volkov*

WIRE TENSION METER WITH ELECTROSTATIC EXCITATION OF OSCILLATION

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* E-mail: volkov@nusun.jinr.ru

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Устройство измерения натяжения проволочки с электростатическим возбуждением колебаний

Описываются схемотехническая реализация и конструктивные особенности устройства. Приведены его характеристики и возможности регистрации резонансных частот проволочек при измерении их натяжения. Относительная погрешность определения резонансных частот с помощью устройства лучше 0,3 %. Фитирование данных измерения позволяет уменьшить погрешность до 0,02 %. Высокая точность определения резонансной частоты позволяет применять устройство для идентификации старения проволочных детекторов по изменению плотности и по форме регистрируемого сигнала.

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Wire Tension Meter with Electrostatic Excitation of Oscillation

A circuitry and design features of the meter as well as its characteristics and capabilities of recording wire resonance frequencies while measuring wire tension are described. The relative error in determination of resonance frequencies by the instrument is better than 0.3%. It is possible to decrease the error to 0.02% by fitting the data. A high accuracy of determination of the resonance frequency allows the instrument to be used for identification of the aging of wire detectors by a change in the density and shape of the recorded signal.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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INTRODUCTION

A change in the tension of the wire in the process of the work of the detector serves to indicate influence of negative factors, in particular aging, on the detector. Determination of the aging of the detector at an early stage can allow its capacity to work to be restored with using the procedures [1, 2]. Thus, an increase in the accuracy of resonance frequency registration and improvement of the methods of its measurement will allow one to diagnose the wire detectors better.

Measurement of wire tension in detectors is based on dependence of the natural wire oscillation frequency f_n upon the tension T. For a wire fixed at its ends this dependence is described by the formula

$$f_n = \frac{n}{2L} \cdot \sqrt{\frac{T \cdot g}{\rho}}, \tag{1}$$

where f_n is the resonance frequency of free oscillations in Hz; L is the wire length in m; T is the tension in grams; ρ is the linear density of the wire in g/m; $g = 9.8$ m/s; n is the number of the harmonic of the excited oscillation, $n = 1, 2, 3, \ldots$ Knowing the resonance frequency of the wire oscillation one can calculate the wire tension by the formula

$$T = \left(\frac{2f_n \cdot L}{n}\right)^2 \cdot \frac{\rho}{g}. \tag{2}$$

Practically, the problem of tension measurement comprises two problems to be solved:

— to excite wire oscillation by applying external force F;

— to detect the oscillation and to determine accurately the resonance frequency.

The oscillation excitation force should not distort the determined frequency or the distortions should be taken into account when f_n is being determined. It follows from (1) that the error in determination of the tension is twice as large as the resonance frequency determination accuracy

$$\frac{\Delta T}{T} = 2\frac{\Delta f_n}{f_n}. \tag{3}$$

Among the oscillation excitation methods, the electrostatic method has been widely used recently. Its advantage is that it allows access to the wire through the data read-out connector. No access to the other end of the wire or the use of other devices immediately adjacent to the wire is required. As a result, detectors can be tested both at the stage of production and as part of the operating facilities. Excitation is generated by applying to the wire an alternating high-voltage signal with respect to the cathode or a neighbouring wire. Affected by the electrostatic force, the wire will oscillate with the excitation frequency. When the excitation frequency coincides with the resonance frequency f_n, the wire oscillation amplitude noticeably increases and the detection signal is phase shifted by $\pi/2$ relative to excitation signal. Both criteria (increase in oscillation amplitude and phase shift) are successfully used for detection purposes [3–6]. Excitation of oscillations by the electrostatic method is considered in [7]. In this paper we describe the hardware for the wire tension meter, its characteristics and capabilities. Figure 1 shows the block diagram of the wire tension meter WTM.

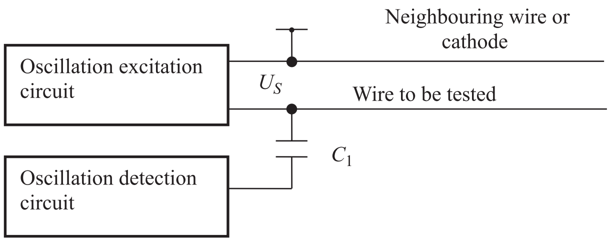

Fig. 1. Block diagram of the WTM

OSCILLATION EXCITATION CIRCUIT

The oscillation excitation circuit is designed as a stand-alone unit. It forms an alternating high-voltage signal $U_{\rm ex} = U_0\,(1 - \cos\omega t)$ applied to the excitation electrode. The choice of the signal shape is dictated by the circuitry. In our case the signal becomes a unipolar one as the voltage varies from 0 to $2U_0$. Oscillations are excited with respect to the neighbouring wire or cathode. When oscillation is excited with respect to the neighbouring wire, both wires may oscillate simultaneously, which occurs if their resonance frequencies are equal or close to each other. Therefore, it is preferable to excite oscillations with respect to the more massive cathode because only the wire to be tested oscillates. The electrostatic force acting on the wire does not depend upon the choice of the electrode to which the excitation signal is applied. The excitation force F_0 averaged over the wire length is [7]

$$F_0 = \frac{C_{\omega p} U_0^2}{\pi H \ln 4H/d}, \tag{4}$$

where $C_{\omega p}$ is the capacitance of the wire relative to the electrode to be tested; H is the distance between the electrodes; d is the diameter of the wire. The force squarely depends upon the applied voltage and decreases with increasing distance between the electrodes. The maximum voltage amplitude is limited by the breakthrough voltage of the detector. To allow safe operation of the meter in the air, the ultimate voltage U_0 was taken to be 750 V. In the test of the detector wire relative to the cathode with $d = 30$ μm and $H = 2.5$ mm the excitation force is as large as $F_0 \leqslant 37$ mg/m, which is almost three times the attraction force ($\rho = 13.6$ mg/m). The specific capacitance of the wire is $C_{\omega p} = 9.57$ pF/m.

Figure 2 shows the high-voltage oscillation excitation signal formation circuit. The low-voltage excitation signal LVLF from the generator G1 arrives at the noninverting input of the operational amplifier U2. The output voltage U2 controls

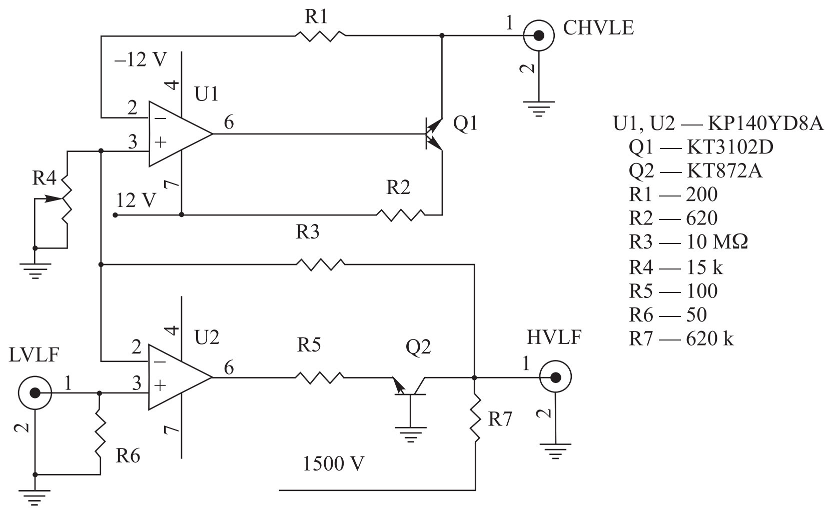

Fig. 2. Oscillation excitation circuit

the emitter current of the transistor Q2 by comparing the amplitudes of the LVLF and feedback signals. The feedback circuit R_3–R_4 sets the input signal gain K defined by the ratio of the resistors $K = 1 + R_3/R_4$. It is taken to be $K = 1000$. The variable resistor R_4 allows fine tuning of the gain. The high-voltage wire oscillation excitation signal HVLF is taken from the collector Q2. The resistor R_7 and the capacitor C_c of the excitation signal transmission cable limit the signal frequency band defined by the time constant $\tau = C_c \cdot R_7$. The nominal value for R_7 was taken to be 620 k, which allows transmission of the excitation signal without distortion over a coaxial cable up to 8 m long at the excitation signal frequency up to 380 Hz. The feedback signal is simultaneously applied to the compound follower U1–Q1 whose output serves as the control signal CHVLF. The transistor Q1 allows operation on a load of 50 Ω. The elements Q2, R_3, and

R_7 are chosen with regard for their operation in the high-voltage circuit (1500 V) at a considerable dissipated power (the resistor R_7 may dissipate up to four watts at the peak).

OSCILLATION DETECTION CIRCUIT

Detection of the resonance frequency is based on variation of the wire capacitance during oscillation. The maximum oscillation amplitude and thus variation of the wire capacitance occurs at the frequency of natural oscillation f_n. The $\pi/2$ phase shift relative to the CHVLF signal is simultaneously controlled. An oscilloscope is used for the in-line control. A high sensitivity of the detection device is achieved by placing the wire to be tested in the high-Q LC tuned circuit which is a good filter for separation of signals near the resonance frequency f_0 of the tuned circuit. If a signal with the frequency f_s close to the resonance frequency $f_0 = 1/2\pi\sqrt{LC}$ is applied for excitation of the tuned circuit while its capacitance is simultaneously varied, the amplitude of the signal in the tuned circuit will be modulated by the capacitance variation law. In this case small variation in the capacitance is followed by large variation in the signal in the tuned circuit. This approach, proposed in [3], appreciably increases sensitivity of the device. Excitement of the LC circuit with use the nearby wire [4] gives smaller sensitivity. The input signal frequency f_s is chosen such that the capacitance variation results in the maximum amplitude variation. A shift of the frequency f_s by 3 dB relative to f_0 meets this condition. Demodulation of the signal from the LC circuit and its filtration from the high-frequency component make it possible to separate the signal of wire capacitance variation arising from excitation of oscillation. Figure 3 shows the oscillation detection circuit. The

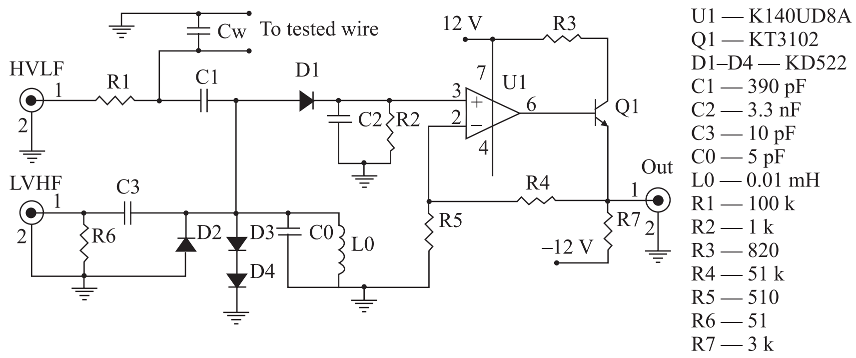

Fig. 3. Oscillation detection circuit

oscillation excitation HVLF signal is applied to the wire to be tested through the resistor R_1. The capacitor C_1 allows the LC circuit to be connected directly to the wire. The resistor R_1 screens the effect of the capacitance of the excitation signal cable on the LC circuit. Elements R_1–C_1–L_0 make up an excitation signal voltage divider. The capacitance C_1 should not be too large to decrease excitation signal shunting. A small capacitance C_1 decreases sensitivity of the tuned circuit to wire capacitance variation. The choice of the capacitance in the range 300–400 pF is a tolerable trade-off. In this case the resistance of the capacitor at oscillation excitation frequencies up to 200 Hz is larger than 2.5 MΩ and shunting of the HVLF signal to earth is insignificant. At the same time the wire capacitance relative to the cathode is no larger that 10 pF for most detectors and the interwire capacitance is almost half as large. Therefore, an effective decrease in the value of C_w obtained by connecting it in series with C_1 is no larger than 3% and it can be considered that $C_e = C_0 + C_3 + C_w || C_1 \approx C_0 + C_3 + C_w$. The diodes D_2–D_4 serve to protect the circuit against the high-voltage signal and should show fast response. The LC circuit excitation LVHF signal is sent from the external generator G2 through the capacitor C_3. The amplitude U_s of the signal in the tuned circuit is defined by the relation

$$U_s = -U_{G2} \cdot \frac{\omega^2 L_0 C_3}{1 - \omega^2 L_0 C_e}, \tag{5}$$

where U_{G2} is the amplitude at the generator output. It follows from (5) that the capacitor C_3 affects both the resonance frequency of the tuned circuit and the amplitude of the signal excited in it. Near the resonance frequency of the tuned circuit $\omega_s = \omega_0 \mp \Delta\omega$ expression (5) can be simplified because $\Delta\omega \ll \omega_0$:

$$U_s = -U_{G2} \cdot \frac{\omega_0^2 \left(1 \mp \Delta\omega/\omega_0\right)^2 L C_3}{1 - \omega_0^2 \left(1 \mp \Delta\omega/\omega_0\right)^2 L C_e} \approx -U_{G2} \frac{\omega_0^2 L C_3}{1 - \omega_0^2 \left(1 \mp 2\Delta\omega/\omega_0\right) L C_e} =$$

$$= \mp \frac{U_{G2}}{2} \cdot \frac{C_3}{C_e} \cdot \frac{\omega_0}{\Delta\omega} \approx \mp \frac{U_{G2}}{2} \cdot \frac{C_3}{C_e} \cdot Q, \tag{6}$$

where Q is the Q factor of the tuned circuit.

Expression (6) shows that at the excitation frequency below the resonance the signal in the tuned circuit has a reversed polarity relative to excitation signal. As a result of the oscillation caused change in the wire capacitance dC_w, the amplitude dU_s of the signal to be recorded is

$$dU_s = \pm \frac{U_{G2}}{2} \cdot \frac{C_3 \cdot dC_w}{C_e^2} \cdot Q. \tag{7}$$

The capacitor C_3 has the optimum capacitance $C_{30} = C_0 + C_w$ at which the amplitude dU_s is the largest possible. Note that expressions (5)–(7) show the increase in the amplitude of recorded signal with growing resonance frequency of the LC circuit. For this reason this frequency should be chosen as high as possible. The expressions are valid for the ideal LC tuned circuit without attenuation. They qualitatively describe the behavior of the real tuned circuit with attenuation but give an error in calculation of the signal amplitudes. The positive amplitude of the signal from the LC circuit passes through the diode D1 and is then filtered from the tuned circuit excitation signal by the elements R_2–C_2. The thus separated low-frequency detection signal dU_s is amplified by the operation amplifier U1 and output through the transistor Q1. The gain factor $K = 1 + R_4/R_5$ is set to $K = 100$. The transistor allows matching the amplifier operation on a load of 50 Ω.

An important feature of this detection circuit is that part of the high-voltage wire oscillation excitation signal always finds itself in the resonance circuit due to the active component of the inductor resistance. Therefore, the ohmic inductor resistance L_0 should be the smallest possible. Direct passage of the HVLF signal to the tuned circuit $U_{\rm bp}$ is

$$U_{\rm bp} \approx 2U_0 \frac{r}{r + \frac{1}{\omega C_1}} = 2U_0 \frac{r\omega\, C_1}{1 + r\omega\, C_1} \approx 2U_0 r\omega C_1, \tag{8}$$

where r is the ohmic inductor resistance. For assessment, if $r = 1\ \Omega$, $C_1 = 390$ pF, $2U_0 = 1000$ V, and $f = 100$ Hz, the amplitude $U_{\rm bp} \approx 0.25$ mV. Considering $U_{\rm bp}$, the detected signal $U_{\rm out}$ is defined by the relation

$$U_{out} = K\,(dU_s \cos\omega t + U_{\rm bp} \cos\omega t) = K\,(dU_s + U_{\rm bp}) \cos\omega t. \tag{9}$$

Near the resonance frequency of the wire oscillation there occurs a phase shift φ_r of the signal dU_s relative to the oscillation excitation signal and expression (9) takes the form

$$\begin{aligned} U_{\rm out} = K\,[dU_s \cos(\omega\, t - \varphi_r) + U_{\rm bp} \cos\omega\, t] = \\ = K\,[(dU_s \cos\varphi_r + U_{\rm bp}) \cos\omega t + dU_s \sin\varphi_r \sin\omega\, t]\,. \end{aligned} \tag{10}$$

At the resonance frequency of wire oscillation $\varphi_r = \pi/2$ and the detected signal is $U_{\rm out} = K\sqrt{(dU_s)^2 + U_{\rm bp}^2}\,\sin(\omega\, t + \varphi_0)$. An additional phase shift φ_0 caused by the effect of $U_{\rm bp}$ is

$$\varphi_0 = \arcsin \frac{U_{\rm bp}}{\sqrt{(dU_s)^2 + U_{\rm bp}^2}}. \tag{11}$$

This effect should be taken into account when the $\pi/2$ phase shift of the detected signal is used as the main criterion for determination of the resonance frequency.

In this case the CHVLF control signal should be taken from the connection point of the wire to be tested because the delay of the transmission of the excitation signal over the cable also causes a phase shift of the detected signal.

Note that the detection circuit should be well screened against the noise due to wire oscillation excitation HVLF signal and power voltage of 220 V to ensure successful operation of the meter.

CHARACTERISTICS AND CAPABILITIES OF THE METER

Figure 4 is the detected signal amplitude U_{out} as a function of the test wire excitation frequency f_{ex}. The excitation signal U_0 was 500 V and U_{G2} was 1 V.

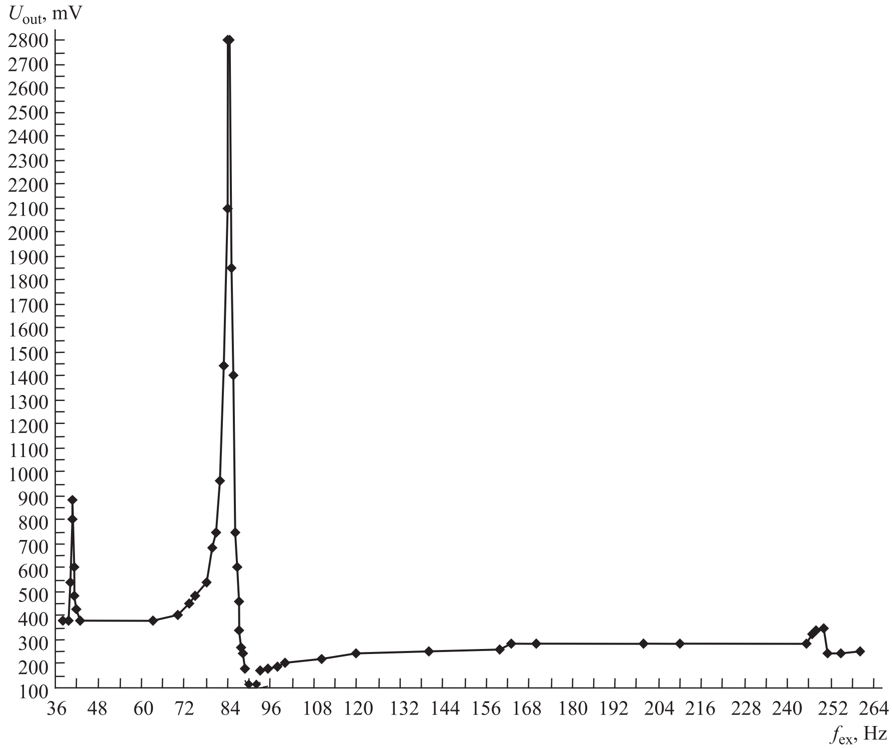

Fig. 4. Dependence of the signal amplitude U_{out} from the excitation frequency f_{ex}

The first peak corresponds to the excitation at the frequency $f_1/2$, the peak of the maximum amplitude corresponds to the first harmonic frequency f_1. The amplitude of oscillation at the third harmonic frequency is 70 mV larger than the amplitude of forced oscillation at the frequency near f_3 (third peak) and is also successfully recorded. The behavior of the amplitude characteristic agrees with the solution of the equation of forced oscillation obtained in [7].

The meter sensitivity S is characterized by the ratio between the magnitude of the change in the output signal amplitude and the magnitude of the change in frequency $S = \Delta U_{\rm out}/\Delta f$. In the region of the resonance response it was $S_{1/2} = 500$ mV/Hz for $f_1/2$, $S_1 = 490$ mV/Hz for f_1, and $S_3 = 35$ mV/Hz for f_3.

The resonance frequency of the LC circuit f_0 was increased to 14 MHz to have this high sensitivity. Beyond the resonance response region the sensitivity of the meter is equal to zero. As the wire resonance frequency increases, the sensitivity decreases because the wire oscillation amplitude decreases. Low sensitivity in recording of the third harmonic frequency is due to a decrease in the oscillation amplitude as the third power of the harmonic number n^3 [7]. The signal of the detected oscillations actually decreased by a factor of 32.5 in comparison with the first harmonic amplitude. Fitting of the dependence of the output signal amplitude upon the excitation frequency at the measurement accuracy 10 mV allows the resonance frequencies $f_1/2$ and f_1 to be found with an error of 0.02 Hz. In most generators the excitation frequency is set in a step of 0.1 Hz. Therefore, the relative error in measurement of the resonance frequency without a fit for the given wire will be 0.12%. In wire tension measurements carried out for real detectors the error did not exceed 0.3%. Typical oscillograms of wire oscillation in the course of searching for the resonance frequency are shown in Fig. 5. The upper curves are the CHVLF signal and the lower ones are the detected signal.

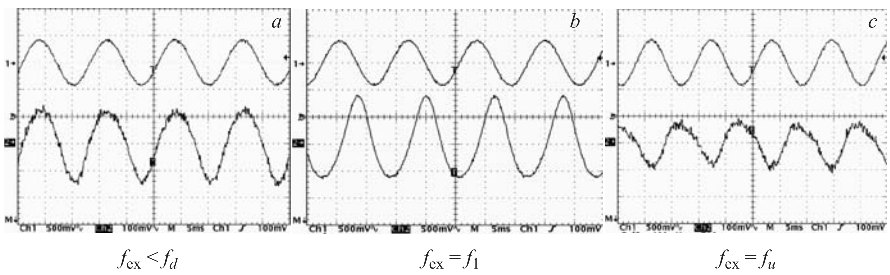

Fig. 5. Typical oscillograms in searching of resonance frequency

The signal amplitude at the resonance (Fig. 5, b) was 5.5 times larger than the forced oscillation signal at the boundary of the resonance response region (Fig. 5, a, c). For the lower boundary of this region we took the frequency f_d at which the amplitude of the output signal begins to increase by 5%. The upper boundary corresponds to the frequency f_u at which the signal amplitude decreases to its minimum. At this frequency the phase shift is as large as 180°. The behavior of the detected signal amplitude near the resonance frequency shown in Fig. 4 is characterized by asymmetry about f_n. A sharper change is observed in the region $f_n < f_{\rm ex} < f_u$. This is caused by the phase shift of the signal dU_s relative to the excitation signal, which results in addition of $U_{\rm bp}$ to the signal dU_s (10) in front of the resonance region and subtraction from it behind the resonance region. The amplitude of the signal U_u at the frequency $f_{\rm ex} = f_u$ decreases by a factor of 2.7 as compared with the signal U_d in the preresonance region at the frequency $f_{\rm ex} = f_d$. A further slight increase in the signal amplitude stops around the second harmonic resonance frequency at the level of 73% of U_d.

The meter allows a group of wires to be simultaneously tested. Figure 6 shows the results of the simultaneous test of 12 wires for the first harmonic.

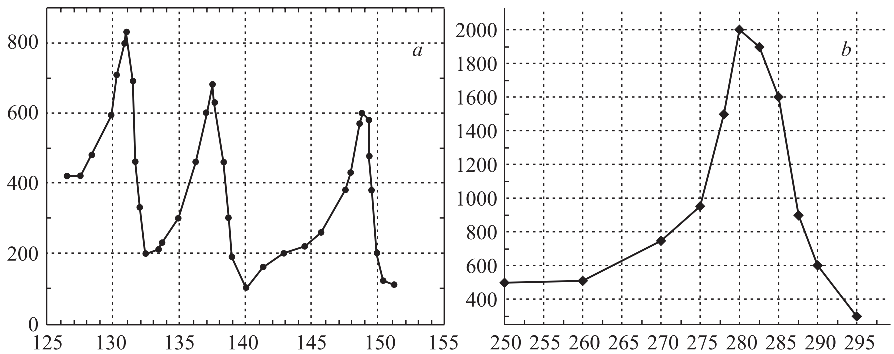

Fig. 6. Simultaneous test of 12 wires

The ordinates show the signal amplitude in mV and the abscissa show the oscillation excitation frequency in Hz. The case where the resonance frequencies differ by 5 Hz and more is shown in Fig. 6, a. The test results for wires with more uniform tension are shown in Fig. 6, b. In that case ten wires had resonance frequencies within the range 282–285 Hz, one had the resonance frequency 275 Hz and another one 288 Hz. There are no distinct peaks corresponding to the resonance frequencies of individual wires. The output signal is a sum of each wire's oscillation amplitudes with allowance for the signal phase. The maximum of the recorded signal may not correspond to the actual resonance frequency of either of the wires as in the above example.

A high accuracy of determination of the wire resonance frequency allows wire aging to be identified. Aging of wire detectors is caused by precipitation of chemical radical on the wire surface. This process depends upon the composition of the gas mixture used in the detector, its working voltage, materials used in it, and some other factors. Aging is normally more intense in the region subject to the radioactive effect of the beam and nuclear reactions studied. Precipitation of radicals on the wire results in its increasing density with accordingly decreasing resonance frequency. It follows from (1) that the resonance frequency change and the density are connected by the relation

$$-2\frac{df_n}{f_n} = \frac{d\rho}{\rho}. \tag{12}$$

Practical measurements of the resonance frequency of various wire detectors show a possibility of detecting a relative density change by 0.5%. In the case of uniform precipitation of radicals over the length of the wire the density change will be

$$\frac{d\rho}{\rho} = \frac{2\pi h R_w}{\pi R_w^2} \cdot \frac{\rho_d}{\rho} = \frac{2h\rho_d}{R_w \rho}, \tag{13}$$

where R_w is radius of the wire, ρ_d is the linear density of radicals, h is the height of the precipitate. For a wire 25 μm in diameter with a precipitate 0.5 μm high the density change is $\frac{d\rho}{\rho} = 8\% \cdot \frac{\rho_d}{\rho}$, which can be successfully detected by the meter.

However, a solid precipitate causes loss of plasticity of the wire and prevents excitation of oscillation. In this case the amplitude of the recorded signal remains constant up to the resonance frequency. Then a sharp decrease is observed which is typical of the region $f_n < f_{\text{ex}} < f_u$. This is also indication for aging of the detector. Aging most often occurs at individual sections of the wire. In this case a local change in the density is not always enough to identify aging by a change in the resonance frequency. Loss of plasticity in a small segment of the wire leads to a change in the shape of the oscillation signal, which may be used for identification.

The signal becomes asymmetrical and may have two or more characteristic peaks in its shape, as shown in Fig. 7. In this case the shape of the signal is

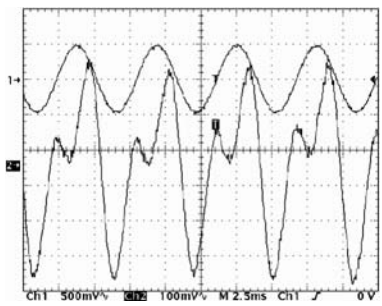

Fig. 7. The form of the signal having the local wire aging

similar to the shape of the signal from oscillation at the resonance frequency $f_1/2$. A distinctive feature of the signal is its large amplitude in comparison with the amplitude at the frequency $f_1/2$. The phase shift of the recorded signal in the resonance region is described by a more complicated dependence than in the case of testing a precipitate-free wire. This dependence is beyond the scope of this work.

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Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@pds.jinr.ru
www.jinr.ru/publish/