E13-2005-198

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STUDY OF WIRE OSCILLATION PROCESSES IN STRETCHING MEASUREMENT

Submitted to «Nuclear Instruments and Methods A»

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Волков А. Д. E13-2005-198
Исследование процессов колебания проволочки при измерении натяжения

Исследуются процессы колебания проволочки при измерении натяжения. Рассматривается электростатический метод возбуждения колебаний проволочки в процессе нахождения резонансной частоты, зависящей от натяжения и параметров проволочки. Колебания проволочки описываются волновым уравнением. Решение уравнения свободных и вынужденных колебаний проволочки позволяет оценить влияние различных факторов на резонансную частоту. Рассматриваются вопросы влияния среды и внешней силы на точность нахождения резонансной частоты. Показано, что начальные условия накладывают ограничение на возбуждение четных гармоник колебаний вне зависимости от метода регистрации. Приводится экспериментальная зависимость и осциллограммы основных частот возбуждения, подтверждающие правильность полученных аналитических выражений и сделанных выводов.

Работа выполнена в Лаборатории ядерных проблем им. В. П. Джелепова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2005

Volkov A. D. E13-2005-198
Study of Wire Oscillation Processes in Stretching Measurement

Wire oscillations in stretching measurements are analyzed. The electrostatic method of excitement of wire oscillation is considered in process of the resonance frequency finding, hanging on tension and parameters of wire. Wire oscillations are described by wave equation. The solutions of the equation of free and forced wire oscillation allow the effect of various factors on the resonance frequency to be estimated. Effects of ambient conditions and external force on the accuracy of resonance frequency determination are considered. The initial conditions are shown to impose limitations on excitation of even oscillation harmonics irrespective of the detection method. Experimental dependence and oscillograms of basic excitation frequencies confirming correctness of the analytical expressions obtained and conclusions drawn are given.

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

Preprint of the Joint Institute for Nuclear Research. Dubna, 2005

INTRODUCTION

Wire detectors are at the heart of detection systems used in high energy physics research. In modern facilities ATLAS, CMS, ALICE and others recording channels of these detectors can number in a hundred thousand. As reliable long-term operation of the detectors is important for the experiment, stringent requirements are placed upon them and it is necessary to check their characteristics at all stages of their production and operation in experimental setups. It is essential to have a possibility of testing detectors and electronics. For wire detectors it is important to check wire stretching as it largely governs the electrostatic properties of the detector. Measuring the resonance frequency of wire oscillation one can judge both stretching and density variation of the wire. The variation arises from deposition of organic radicals on its surface (aging of the detector), which adversely affects the detection efficiency. Therefore, improvement of stretching check methods and an increase in the detection sensitivity are still a crucial issue. Understanding and allowance for factors affecting the detector checking results ensures successful operation of detectors in experiments.

Measurement of wire stretching in detectors is related to excitation of its oscillation at a resonance frequency ω_n. When found, the resonance frequency allows unambiguous determination of the tension T

$$T = \left(\frac{\omega_n L}{n\pi}\right)^2 \frac{\rho}{g}. \tag{1}$$

Here ω_n is the resonance frequency of free oscillation in Hz; L is the wire length in m; T is tension in grams; ρ is the linear density in g/m; $g = 9.8$ m/s^2; n is the oscillation excitation harmonic, $n = 1, 2, 3 \ldots$ Various methods are used to excite oscillation. However, determination of the resonance frequency does not depend upon the method. It is constant in solution of the equation of free oscillation of a string and depends only upon the parameters of the wire. The value of ω_n may be affected by the oscillation excitation device circuitry leading to the presence of a constantly acting force. Resistance of the medium can also affect the resonance frequency. These issues are considered in the paper as applied to the use of the electrostatic method for excitation of oscillation. The advantage of this method is that the wire is accessible only on one side through the readout connector and no other devices have to be used near the wire. This allows detectors to be tested both at the production stage and during their operation as part of physical setups.

FREE OSCILLATION

The equation of free oscillation of the wire is

$$T\frac{d^2y}{dx^2} = \rho\frac{d^2y}{dt^2}, \tag{2}$$

where y is the transverse deflection of the wire and x is the coordinate of the wire over its length. Solution of this equation can be found in virtually all textbooks on mathematical physics equations [1, 2]. Note that the wave equation is derived for an undeformed wire and constant tension over its length. A shift of all points of the wire takes place in a plane orthogonal to its length. From this follows independence of the equation from the wire slope angle with respect to the gravity direction and constancy of the resonance frequency. An effective method for solution of equations like that is the Fourier method. Superposition of all solutions of the equation will be the expression

$$y(x,t) = \sum_{n=1}^{\infty}[a_n \cos n\omega_1 t + b_n \sin n\omega_1 t]\sin\frac{n\pi x}{L}, \tag{3}$$

where ω_1 is the resonance frequency of the first harmonic. The coefficients a_n and b_n are found from the initial conditions

$$y\,|_{t=0} = \sum_{n=1}^{\infty} a_n \sin\frac{n\pi x}{L} = \varphi(x), \quad 0 \leqslant x \leqslant L, \tag{4}$$

$$\frac{dy}{dt}\,|_{t=0} = \sum_{n=1}^{\infty} n\omega_1 b_n \sin\frac{n\pi x}{L} = \psi(x), \quad 0 \leqslant x \leqslant L. \tag{5}$$

Equalities 4 and 5 are expansions of the functions $\varphi(x)$ and $\psi(x)$ in Fourier series in the interval (0, L) in the orthogonal system of trigonometric functions $\left\{\sin\frac{n\pi x}{L}\right\}_{n=1}^{\infty}$. Then the coefficients a_n and b_n are determined by Euler–Fourier formulas

$$a_n = \varphi_n = \frac{2}{L}\int_0^L \varphi(x)\sin\frac{n\pi x}{L}dx; \quad b_n = \frac{\psi_n}{n\omega_1} = \frac{2}{n\omega_1 L}\int_0^L \psi(x)\sin\frac{n\pi x}{L}dx. \tag{6}$$

As applied to wire detectors, the function $\varphi\,(x)$ can be determined explicitly. The wire is acted upon by the tension and weight. Let us write down the Newton equation for these forces:

$$T\frac{d^2y}{dx^2} + \rho = 0. \tag{7}$$

A solution of this equation is the expression:

$$\varphi(x) = \frac{\rho}{2T}x^2 + C_1 x + C_2.$$

The boundary conditions for the wire fixed at its ends, $y(0) = y(L) = 0$, determine the constants C_1, C_2 and the function $\varphi(x)$

$$\varphi(x) = \frac{\rho}{2T}x\,(L - x)\,. \tag{8}$$

In this case the coefficients a_n are calculated as

$$a_n = \frac{2}{L}\int_0^L \frac{\rho}{2T}x\,(L-x)\sin\frac{n\pi x}{L}dx = $$
$$= \frac{2\rho L^2}{T\,(n\pi)^3}\,(1-\cos n\pi) = \frac{4g}{(2k-1)\,\pi\omega_{2k-1}^2}. \tag{9}$$

The initial position of the wire (8) affects the solution: there remain only terms with odd harmonics $n = 2k-1$. In the problem of determination of the resonance frequency of the wire ω_1 the initial oscillation rate dy/dt depends upon the method of excitation. If the rate is equal to zero, the coefficients b_n vanish and the terms $\sin n\omega_1 t$ are absent in solution (3)

$$y(x,t) = \sum_{k=1}^{\infty}\frac{4g}{(2k-1)\,\pi\omega_{2k-1}^2}\cos\omega_{2k-1}t\sin\frac{(2k-1)\,\pi x}{L}. \tag{10}$$

This mode is typical of free oscillation of the wire at the shock excitation by a high-voltage signal. In this case high voltage is applied to the wire and then is abruptly cut off. The electrostatic force causes initial deflection of the wire. Voltage cut-off and termination of the force action result in oscillation of the wire as it returns to the initial position. Forced oscillation due to electrostatic excitation by the alternating voltage signal also begins at the zero rate. The induction method of excitation is based on the action of the magnetic field upon a current-carrying conductor. A current pulse of amplitude I and duration t_s is passed through a wire placed in the magnetic field with induction B. The force F_1 acting upon the conductor of length Δl is expressed, according to the Ampere law, by the relation

$$F_1 = I\;\Delta l B\sin\beta, \tag{11}$$

where β is the angle between the directions of the magnetic induction and the current, Δl is the magnet-overlapped wire length. Under the action of the induction force the wire deflects from the stationary position and free oscillation begins after the current pulse ends.

The frequency of natural oscillation for equation (2) is defined by the relation

$$\omega_n = \frac{n\pi}{L}\sqrt{\frac{Tg}{\rho}}. \tag{12}$$

The equation of free oscillation ignores the resistance of the medium. The medium resistance force F_2 acting upon a unit length of the wire is defined in [3] as

$$F_2 = \frac{4\pi\eta}{0.5 - \nu_E - \ln R/4} \cdot \frac{dy}{dt} = \alpha\frac{dy}{dt}, \tag{13}$$

where $\nu_E = 0.577$ is the Euler constant, η is the viscosity of the medium, R is the Reynolds number.

Considering the effect of the medium, the equation of free oscillation is written as

$$T\frac{d^2y}{dx^2} = \rho\frac{d^2y}{dt^2} + \alpha\frac{dy}{dt}, \tag{14}$$

When the coefficient of friction is small, $m = \alpha/2\rho < \omega_{2k-1}$, its solution takes the form [4]

$$y(x,t) = \mathrm{e}^{-mt}\sum_{k=1}^{\infty}\frac{4g}{(2k-1)\,\pi q_{2k-1}^2}\cos q_{2k-1}t\sin\frac{(2k-1)\,\pi x}{L}. \tag{15}$$

The oscillation amplitude decays exponentially and the oscillation frequency decreases $q_{2k-1} = \sqrt{\omega_{2k-1}^2 - m^2}$. Evaluation of m made in [3] yields the value $m \approx 0.01\omega_1$, which practically does not affect the accuracy of determination of the resonance frequency. On the other hand, the constant force F_3 produces a noticeable effect on the resonance frequency. Under the action of the force $F_3 = ry(x)$ orthogonal to the x axis the wire shifts by a value y_0, where r is the proportionality coefficient. Let us write down equation of oscillation (2) for the stationary state y_0 and the variable u

$$T\frac{d^2u}{dt^2} + ry + P = 0 \quad \text{and} \quad y = y_0 + u, \tag{16}$$

$$T\frac{d^2u}{dx^2} = \rho\frac{d^2u}{dt^2} + ru. \tag{17}$$

Let us search for the solution by the method of separation of variables $u = Z(x) \cdot S(t)$. After substitution and cancellation of u the equation is rearranged in the form

$$\frac{1}{S}\frac{d^2S}{dt^2} = \frac{T}{\rho}\frac{1}{Z}\frac{d^2Z}{dx^2} + \frac{r}{\rho} \equiv \mu. \tag{18}$$

The functions $Z(x)$ and $S(t)$ can be found by solving the system of differential equations

$$S''(t) - \mu S(t) = 0, \quad Z''(x) - \left(\mu - \frac{r}{\rho}\right)\frac{\rho}{T}Z(x) = 0. \tag{19}$$

Considering the boundary conditions $Z(0) = Z(L) = 0$, the solution is

$$Z_n(x) = \sin\frac{n\pi x}{L}, \quad S_n(t) = a_n \cos q_n t + b_n \sin q_n t,$$

$$q_n = \sqrt{\left(\frac{n\pi}{L}\right)^2 \frac{Tg}{\rho} - \frac{r}{\rho}} = \sqrt{\omega_n^2 - r/\rho}. \tag{20}$$

Action of the constant force decreases the resonance frequency. This should be taken into account when wire stretching is being checked. This disadvantage is characteristic of the device reported in [5] and, to a larger extent, in [6], where voltage up to 4 kV is applied to the wire. The quantity r is the force per wire unit length referred to the bias; it is expressed as n/m^2. Figure 1 shows the measured dependence of relative variation in the first harmonic frequency ε under the action of the force. The electrostatic force acting on the wire was specified by the value of the constant negative cathode voltage U_c. The alternating excitation signal of positive polarity U_s was applied to the gold-plated tungsten wire of diameter $d = 30\,\mu$m and length $L = 1$ m. The amplitude of the signal was 250 V, the distance between the wire and the cathode was $H = 3$ mm.

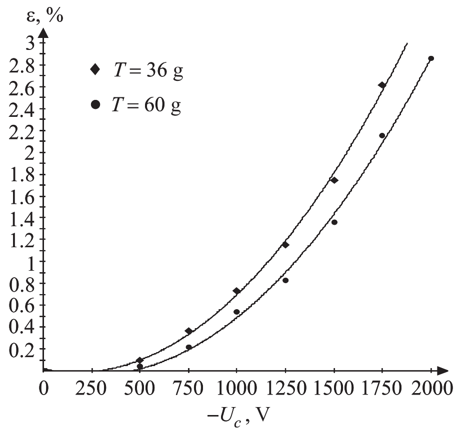


Fig. 1. Dependence of relative variation of the resonance frequency ε on constant force (U_c)

The resonance frequency varies quadratically with voltage, which agrees with (28). A relative error in determination of the resonance frequency can amount to a few per cent. An increase in the wire tension T stabilizes its position and decreases the error.

FORCED OSCILLATION

An external force is required to excite continuous oscillation of the wire. In this paper we consider excitation of oscillation under the effect of a.c. voltage U on the wire. The equation of forced oscillation involves action of a variable force F_4 upon the wire

$$T\frac{d^2y}{dx^2} = \rho\frac{d^2y}{dt^2} + F_4. \tag{21}$$

The solution of (21) is sought for in the form of an expansion in the Fourier series over the segment (0, L) in the system of orthogonal eigenfunctions $\left\{\sin\frac{n\pi x}{L}\right\}_{n=1}^{\infty}$. In the general case it is expressed as

$$y(x,t) = \sum_{n=1}^{\infty}\left[\varphi_n \cos n\omega_1 t + \frac{1}{n\omega_1}\psi_n \sin n\omega_1 t\right]\sin\frac{n\pi x}{L} + \\ + \sum_{n=1}^{\infty}\frac{1}{n\omega_1}\left[\int_0^t f_n(\tau)\sin n\omega_1(t-\tau)\,d\tau\right]\sin\frac{n\pi x}{L}, \tag{22}$$

where

$$f_n = \frac{2}{L}\int_0^L \frac{F_4(x,t)}{\rho}\sin\frac{n\pi x}{L}dx. \tag{23}$$

The fist sum is the solution of the homogeneous equation and the second sum is a partial solution resulting from the action of the force F_4, which is expanded in a Fourier series. The force F_4 can be found from the energy conservation law. The excited wire is a capacitor C relative to the electrode under test. Variation in the energy of the capacitor under the effect of the applied voltage is equal to the work done by the excitation force on the wire to change its position.

$$F_4 dH = \frac{U^2}{2}dC, \quad F_4 = \frac{dC}{dH}\frac{U^2}{2}. \tag{24}$$

Below are wire capacity formulas for the most popular configurations of electrodes: $C_{\omega p}$ — relative to the plane; $C_{\omega\omega}$ — relative to the wire; $C_{\omega t}$ — capacity of cylinder-shaped electrodes.

$$C_{\omega\, p} = \frac{2\pi\varepsilon}{\ln 4H/d}, \quad C_{\omega\,\omega} = \frac{\pi\varepsilon}{\ln 2H/d}, \quad C_{\omega\, t} = \frac{2\pi\varepsilon}{\ln D/d}. \tag{25}$$

Here H is the distance between the electrodes, d is the diameter of the wire, D is the outer diameter of the cylinder, ε is the permittivity of the medium. However, when using (24) one should bear in mind that the profile of bias dH along the wire under the effect of the excitation force is sine shaped. Therefore, a coefficient p taking into account the shape can be introduced in (24) and the value of F_4 can be averaged. The coefficient p is equal to the average value of the wire deflection amplitude at sine profile its offset over the length

$$p = \frac{1}{L}\int_0^L \sin\frac{n\pi x}{L}dx = \frac{2}{\pi}. \qquad (26)$$

For comparison, the coefficient for taking into account the shape of the parabolic profile (8) is $p = 2/3$. Let us consider excitation of wire oscillation relative to the cathode plane. It is preferable to realize the high-voltage excitation signal U in the form of a function $U = U_0\,(1 - \cos\omega\, t)$. In this case the signal becomes a single-pole one with an amplitude varying from 0 to $2U_0$. The excitation force is

$$F_3 = p\cdot\left|\frac{dC_{\omega\, p}}{dH}\right|\cdot\frac{U^2}{2} = \frac{2}{\pi}\cdot\frac{C_{\omega\, p}U_0^2}{2H\ln 4H/d}\left(1-\cos\omega\, t\right)^2 = F_0\left(1-\cos\omega\, t\right)^2. \qquad (27)$$

The averaged value of the excitation force is

$$F_0 = \frac{C_{\omega\, p}U_0^2}{\pi\, H\ln 4H/d}. \qquad (28)$$

The Fourier series expansion coefficients f_n for the force are, according to (23),

$$f_n = \frac{2F_0}{n\pi\rho}\left(1-\cos n\pi\right)\cdot\left(1-\cos\omega\, t\right)^2. \qquad (29)$$

Now let us calculate the integral J_0 which enters the sum of partial solution (22)

$$J_0 = \int_0^t f_n\left(\tau\right)\sin n\omega_1\left(t-\tau\right)\left(1-\cos\omega\, t\right)^2 d\tau =$$

$$= \frac{2F_0}{n\pi\rho}\left(1-\cos n\pi\right)\int_0^t \sin n\omega_1\left(t-\tau\right)\left(1-2\cos\omega\tau+\cos^2\omega\tau\right)\, d\tau. \qquad (30)$$

For the integral we shall use the trigonometric relation $\sin\alpha\cos\beta = \frac{1}{2}[\sin(\alpha-\beta)+\sin\left(\alpha+\beta\right)]$. The integral of interest consists of three parts:

$$J_0 = \frac{2F_0}{n\pi\rho}\left(1-\cos n\pi\right)\left(J_1+J_2+J_3\right), \qquad (31)$$

$$J_1 = \int_0^t \sin n\omega_1 (t-\tau)\ d\tau = \frac{1}{n\omega_1}(1-\cos n\omega_1 t), \tag{32}$$

$$J_2 = -2\int_0^t \sin n\omega_1 (t-\tau)\cdot\cos\omega\tau = \frac{2n\omega_1}{(n\omega_1)^2-\omega^2}(\cos\omega t - \cos n\omega_1 t), \tag{33}$$

$$J_3 = \int_0^t \sin n\omega_1 (t-\tau)\cdot\cos^2\omega\tau = \frac{0.5n\omega_1}{(n\omega_1)^2-4\omega^2}(\cos 2\omega\, t - \cos n\omega_1 t) + \\ + \frac{1}{2n\omega_1}(1-\cos n\omega_1 t). \tag{34}$$

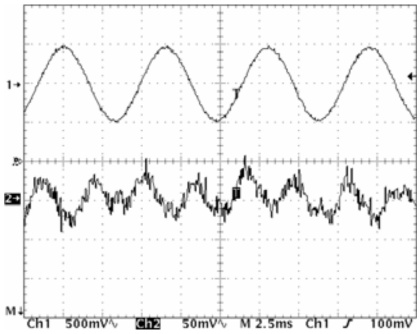
The factor $1-\cos n\pi$ shows that the forced oscillation solution will also involve only odd harmonics $n = 2k-1$. Thus the common decision of the equation of forced oscillation (21) will be

$$y(x,t) = \sum_{k=1}^{\infty} \frac{4g}{(2k-1)\pi\omega_{2k-1}^2}\cos\omega_{2k-1}t\sin\frac{(2k-1)\ \pi x}{L} + \\ + \sum_{k=1}^{\infty}\frac{4F_0}{(2k-1)\ \pi\rho}\left[\frac{3(1-\cos\omega_{2k-1}t)}{2\omega_{2k-1}^2} + \frac{2(\cos\omega\, t - \cos\omega_{2k-1}t)}{\omega_{2k-1}^2-\omega^2} + \right. \\ \left. + \frac{0.5(\cos 2\omega\, t - \cos\omega_{2k-1}t)}{\omega_{2k-1}^2 - 4\omega^2}\right]\sin\frac{(2k-1)\,\pi x}{L}. \tag{35}$$

The second sum of this solution characterizes the forced oscillation amplitude. When the excitation frequency coincides with the frequency of natural oscillation, e. g. with the basic harmonic $k = 1$, $\omega = \omega_1$, the oscillation amplitude will be defined by the second term of the sum, being

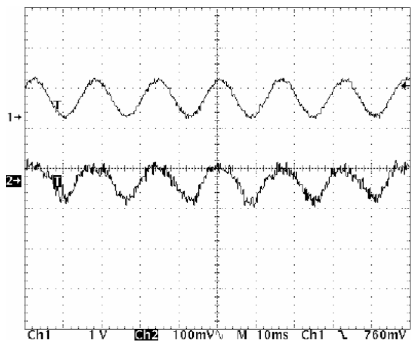
$$\lim_{\omega\to\omega_1}\frac{2(\cos\omega\, t - \cos\omega_1 t)}{\omega_1^2-\omega^2} = -\frac{4\sin\frac{\omega-\omega_1}{2}t\sin\frac{\omega+\omega_1}{2}t}{\omega_1^2-\omega^2} = \frac{t\sin\omega_1 t}{\omega_1}. \tag{36}$$

Due to the factor t the amplitude increases linearly and the oscillation is phase shifted by $\pi/2$ relative to the excitation signal that is characterized by $\sin\omega_1 t$. The increase in the oscillation amplitude is limited by plastic deformation of the wire and partially by the resistance of the medium. At the resonance frequency there occur self-sustained oscillations with the decrease in the amplitude due to damping being offset by the effect of the excitation force. Excitation of other odd resonance harmonic is also determined by the second term of the sum. Its third term explains the possibility of exciting the fundamental harmonic of oscillation at the frequency $\omega = \omega_1/2$ with the amplitude $0.5t \sin \omega_1 t/\omega_1$. Forced oscillations defined by third term are distinctly registered on frequency small exceeding ω_1, (Fig. 2). It is impossible to excite odd harmonics ω_{2k-1} with the third term at



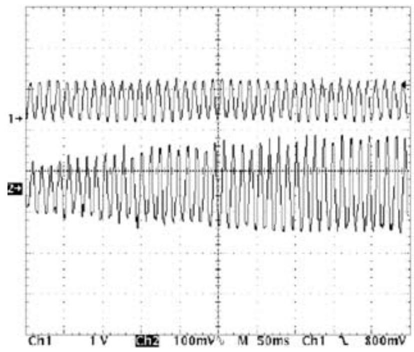
$\omega \geqslant \omega_1$

Fig. 2. Forced oscillation defined by the third term



$\omega \neq \omega_1$

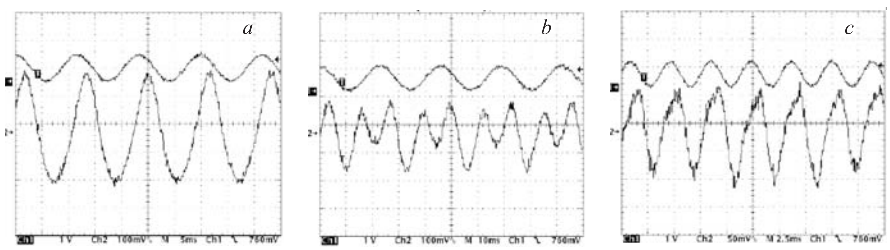
Fig. 3. Forced oscillation far from resonance frequency



$\omega = \omega_1$

Fig. 4. The reaching of maximum oscillation amplitude with time on resonance frequency

$\omega = \omega_{2k-1}/2$, probably because of symmetry breaking: one cannot try to excite an odd number of waves of frequency ω_{2k-1} at the even wave frequency 2ω. In addition, due to the second term, the excitation force is four time larger with total symmetry conservation $\omega = \omega_{2k-1}$. Te first term shows the constant amplitude of oscillation faraway from resonance frequency ω_{2k-1}. The phase shift of the oscillation signal with respect to the excitation signal by $\pi/2$ at the resonance can be successfully used to find resonance frequencies [6, 7]. Below are oscillograms of tested wire oscillation. Characteristics of the wire are given above. The excitation signal amplitude was 500 V. Figure 3 shows the oscillogram of forced oscillation far from the resonance frequency. The oscillation is in phase with the acting force and has small amplitude. Figure 4 shows the oscillogram of reaching maximum oscillation amplitude with time on resonance frequency. For standard detectors the amplitude reaches this steady-state value within 0.5–0.9 s. Figure 5 shows oscillograms of excitation of basic resonance frequencies. Ray 1 is the



$\omega = \omega_1$ $\omega = \omega_1/2$ $\omega = 3\omega_1$

Fig. 5. The oscillograms of excitation of basic resonance frequencies

excitation signal decreased by a factor of 10^3, ray 2 is the recorded oscillation signal. It is impossible to excite oscillation at frequencies higher than the third harmonic with voltage variation in the range 0–1000 V. The use of the voltage higher than 1500 V for this purpose requires the use of working gas mixture to prevent breakdown in the detector. Oscillations at the frequency $\omega_1/2$ are nonsymmetrical though the phase shift by $\pi/2$ with respect to the excitation signal remains.

CONCLUSIONS

The above oscillograms confirm correctness of the relations derived for the amplitude and resonance frequencies:

— the wire oscillates in the plane orthogonal to its length, therefore the resonance frequency does not depend upon the angle of slope with respect to the gravity.

Experimental checks at wire slope angles of 0, 45, and 90 degrees confirmed this fact with a measurement error of 0.1%;

— only odd resonance frequencies ω_{2k-1} and $\omega_1/2$ are excited, which is also confirmed by the authors of [8] in finding the resonance frequency;

— the oscillation amplitude decreases cubically with the number of the frequency, therefore it is practically impossible to excite frequencies above the third harmonic;

— the oscillation amplitude increases within less than one second.

Investigations of the authors of [3] and the experimental measuring show that:

— the effect produced by the resistance of the medium on the determination of the resonance frequency can be ignored;

— the constant force acting upon the wire decreases the resonance frequency and thus should be taken into account. The variable excitation force does not affect the resonance frequency.

Acknowledgements. The author is grateful to V. I. Komarov for his interest and support of the investigations on this topic, to A. V. Kulikov for discussions and helpful comments during the preparation of the manuscript.

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Received on December 9, 2005.

Корректор *Т. Е. Попеко*

Подписано в печать 27.02.2006.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,93. Уч.-изд. л. 1,35. Тираж 315 экз. Заказ № 55243.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
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