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MEASUREMENT OF TUBE TENSION IN STRAW DETECTORS

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Измерение натяжения трубки в строу-детекторах

Рассмотрено устройство для контроля натяжения трубок в строу-детекторах. Его работа основана на измерении резонансной частоты трубки при электростатическом возбуждении колебаний относительно опорного электрода. Чувствительность устройства позволяет регистрировать резонансную частоту с точностью 0,1 Гц. Величина натяжения вычисляется с использованием полученной автором аналитической зависимости, которая имеет ошибку менее 3 %. Достигнутая точность подтверждается экспериментальными данными. Устройство может эффективно использоваться при создании детекторов в диапазоне натяжений 250–1200 г/м, а также для измерения натяжения проволочек.

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Volkov A. D. E13-2014-68
Measurement of Tube Tension in Straw Detectors

A device and a method for controlling tension of tubes in straw detectors are presented. The method is based on measuring the resonance frequency of a tube at electrostatic excitation of its oscillations relative to the reference electrode. The sensitivity of the device allows the resonance frequency to be detected with an accuracy of 0.1 Hz. The tension is determined using analytical dependence obtained by the author. The relative error of the experimental data against the analytical dependence is below 3%. The device proved to be effective in a range of tensions from 250 to 1200 g/m used in development of the detectors, and it can be employed for measuring tension of wires.

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

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INTRODUCTION

Finding the resonance frequency of a cylindrical shell subject to the action of forces is an often encountered problem of a physical experiment technique. This problem arises, for example, in development of straw detectors [1–3] used in experimental physics. These detectors consist of cylindrical counters. Many aspects of the mechanical behavior of thin-wall counters are considered within the theory of shells [4–6]. Note that the shape of the tube changes with time due to dielectric yield and should therefore be maintained during long-term operation. The solution to the problem is to tension the tube, which helps maintain its shape and decreases its sag, thus improving the coordinate resolution of the detector. The tube can be tensioned by the overpressure of the working gas in the tube [1] or mechanically. The mechanical option was adopted for straw detectors in the experiments [2, 3]. Tension affects characteristics of the detector and is an important parameter controlled by the resonance frequency of tube oscillation.

The purpose of this work was to adapt the method for wire tension measurement [7] to a straw tube and to find out whether the tension can be controlled using its dependence on the resonance frequency.

EXCITATION MODE OF TUBE OSCILLATION

An effective way to find the resonance frequency of the tube is electrostatic excitation of its oscillation. The oscillation amplitude reaches its maximum under the action of the excitation force at the tube resonance frequency. Thus, the problem of finding the resonance frequency is reduced to finding the maximum amplitude of the forced tube oscillation while scanning the excitation frequency. Figure 1 shows a block diagram of the monitor for detection of the straw tube resonance frequency. Circuit designs of its main units, Driver and Sensor, are presented in [7]. The Driver

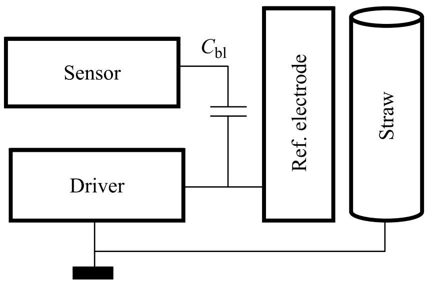

Fig. 1. Block diagram of the monitor

forms a high ac voltage signal applied to the reference electrode that is near the tube under investigation. The inner surface of the tube has a metal coating and serves as a cathode, which is connected to the zero potential during tests. The reference electrode and the cathode of the tube make up a capacitor. The excitation signal induces charges of the opposite signs on the capacitor plates. The variable force of the Coulomb interaction causes oscillation of the tube. Since the force acts on both plates, reference electrode oscillations are prevented from being blocked by increasing the mass of the electrode and fixing it in the holder. The Sensor detects oscillations of the tube. It forms a signal with an amplitude proportional to the deviation of the tube with respect to the electrode and a frequency coinciding with the frequency of the excitation signal. The excitation signal is prevented from entering the Sensor circuit by a blocking capacitor C_{bl} and a low input resistance of the Sensor circuit.

RESONANCE FREQUENCY OF A STRAW TUBE

The resonance frequency of the tube is found by solving a system of equations that describes its behavior. The system includes five equations and eight unknowns [4] and is indeterminate. There are a lot of approaches to description of tube behavior within the theory of shells [5, 6]. Under the indeterminateness conditions there are particular solutions governed by the assumptions made. The basic assumptions are: the linearity of the shell deformation and the validity of the Hooke law; the effect of the vertical deformation is ignored for being too small; the behavior of the shell is described in terms of its middle part. A review of various approaches and corresponding results is given in [8]. The dependence of the resonance frequency on the tension in the article is obtained from the condition of the shell equilibrium under the action of axially symmetric forces. The tube equilibrium equation has the form [4]:

$$D\frac{\partial^4 w}{\partial x^4} + \frac{Eh}{R}w = q_z - \frac{\mu}{R}N_x, \tag{1}$$

where D is the cylindrical stiffness of the tube, $D = Eh^3/12\left(1-\mu^2\right)$; E is the Young modulus; h is the thickness of the tube; μ is the Poisson coefficient; and q_z is the vertical component of the acting forces. Figure 2 shows the system of coordinates, the size of the tube, and the forces acting on the tube.

The vertical component includes a tension force ($T \cdot \partial^2 w/\partial x^2$), an external force F applied to the tube for exciting oscillations, and an inertial force. In compliance with the d'Alembert principle, the inertial force is taken with the minus sign ($-\rho h \cdot \partial^2 w/\partial t^2$), where ρ is the tube material density. In the theory of shells it is shown [4–6] that the force acting along the coordinates x has an orthogonally directed component with a coefficient μ/R. Therefore, the equilibrium equation

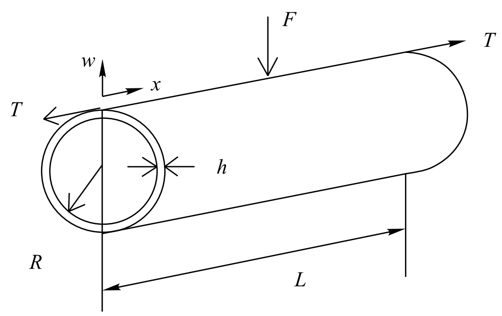

Fig. 2. Coordinate system of the tube and forces acting on it. Tube deviation w along the x-axis. Characteristics of the tube: R is the radius, L is the length, T is the tension, and F is the external oscillation excitation force

involves the vertical component of the longitudinal force N_x. Since the tube sag affects the coordinate resolution of the detector, the tube tension force T is high enough to keep it small. In this case, the tension force can be considered to be a determining force, and $N_x \cong T$. The force N_x acts at a tangent to the shell surface. For obtaining its projection onto the w-axis, it should be multiplied by the sine of the shell slope angle with respect to the x-axis, $\sin \varphi$. Considering the boundary conditions, the amplitude distribution of the shell oscillations along the x-axis is taken in the form $w(x) = w_0 \cdot \sin n\pi x/L$, where w_0 is the amplitude of the deviation at the middle point of the cylinder. Because of low deviation amplitude, a deviation along the x-axis can be approximated by a linear dependence. In this case, the tangent of the slope angle will be determined by the ratio of w_0 to $L/2$, and thus $\tan \varphi \approx \sin \varphi = 2w/L$. The vertical component of the tension force acts at a normal to the tube surface; therefore, to obtain its projection on the w-axis, it should be multiplied by $\cos \varphi$, which is taken to be unity for a small angle.

For a tube under tension T with clamped ends Eq. (1) involves forces acting inside the shell and the inertial force. All forces in the equation are taken per unit length of the normal cross section corresponding to them. As a result, the equation will have the form

$$D\frac{\partial^4 w}{\partial x^4} + \frac{Eh}{R^2}w + \frac{T}{2\pi R} \cdot \frac{\partial^2 w}{\partial x^2} + \frac{\mu T}{RL} \cdot \frac{2w}{L} = -\rho h \frac{\partial^2 w}{\partial t^2}. \tag{2}$$

The solution of (2) is sought in the form

$$w = w_0 \cdot \sin(n\pi x/L) \cdot \cos \omega t. \tag{3}$$

Substituting (3) into (2) and then cancelling out the common factor (3), we obtain a relation for finding the resonance frequency of a cylindrical tube ω_C:

$$\omega_C^2 = \frac{D}{\rho h}\left(\frac{n\pi}{L}\right)^4 + \frac{E}{\rho R^2} + \frac{T}{2\pi R \rho h}\left(\frac{n\pi}{L}\right)^2 \cdot \left[1 + \frac{4\mu}{\pi n^2}\right]. \tag{4}$$

The resonance frequency is a function of the tension and tube parameters. It has three components corresponding to the bending ω_b, transverse ω_t, and longitudinal ω_L oscillations. Squares of their resonance frequencies are successively presented in (4). Let us perform comparative estimation of frequencies for the first harmonic ($n = 1$) of the COMET straw detector tube with the parameters: $T = 9.8$ N, $L = 0.975$ m, inner radius of the shell $R = 5$ mm, $h = 36$ μm, specific weight $\rho = 1290$ kg/m^3, $E = 2 \cdot 10^9$ N/m, and $\mu = 0.3$,

$$\frac{\omega_b^2}{\omega_L^2} = \frac{2\pi RD}{T\,(1 + 4\mu/\pi n^2)} \cdot \left(\frac{\pi}{L}\right)^2 \approx 28.75 \cdot 10^{-8},$$

$$\frac{\omega_t^2}{\omega_L^2} = \frac{2\pi hE}{T \cdot (1 + 4\mu/\pi n^2)\,R} \cdot \left(\frac{L}{\pi}\right)^2 \approx 6.73 \cdot 10^6.$$

Since the resonance frequencies are very different, the tension can be controlled with a high accuracy only in terms of the longitudinal component ω_L:

$$\omega_L^2 = \frac{T}{2\pi R\rho h}\left(\frac{n\pi}{L}\right)^2 \cdot \left[1 + \frac{4\mu}{\pi n^2}\right]. \tag{5}$$

The above dependence agrees with the results obtained in [9]. In both cases, the square of the resonance frequency linearly depends on the tension. It is, however, worth noting that (5) involves parameters and tension of the tube, and thus, unlike the case in [9], there is no need to calculate its moment of inertia and bending force.

MEASUREMENT MODE OF THE TUBE RESONANCE FREQUENCY

Since the resonance frequency is determined in the mode of forced tube oscillations, let us consider characteristics and limitations of this mode. In this case, the action of the external excitation force F is added to equation of oscillations (2). The force can be determined from the energy conservation law. The cathode of the tube and the reference electrode make up a capacitor of capacitance C. The work done by the force to move the cylinder through the distance dH is equal to the change in the capacitor energy due to the change in its capacitance dC. From this equality we find the force F:

$$F = \frac{dC}{dH} \cdot \frac{U^2}{2}. \tag{6}$$

In (6), H is the effective distance between the capacitor plates, and U is the oscillation excitation voltage applied to the reference electrode. To estimate the distance between the capacitor plates H, the cylindrical shape of the tube should be taken into account, which results in that the effective distance increases by $(\pi - 2)R/\pi$. Capacitance can be estimated by the formula of a flat capacitor with allowance for the effective distance between the plates

$$C = \varepsilon_0 \cdot S/H, \tag{7}$$

where S is the tube–electrode overlap area. Substituting the capacitance value into (6), we obtain the force in the explicit form

$$F = -CU^2/2H. \tag{8}$$

The solution of the equation of forced oscillations is sought in the form similar to the free-oscillation solution of Eq. (3). To this end, the acting force is expanded in a Fourier series on the segment $(0, L)$ in the system of orthogonal functions of the tube deviation $\left\{\sin \dfrac{n\pi x}{L}\right\}_{n=1}^{\infty}$. Expansion coefficients are found using the Fourier–Euler formula [10, 11]:

$$f_n = \frac{2}{L}\int\limits_0^L \frac{F(t)}{m} \cdot \sin\frac{n\pi x}{L} \cdot dx = \frac{2F(t)}{n\pi \cdot 2\pi RhL\rho}(1 - \cos n\pi). \tag{9}$$

The coefficients f_n are zero for even harmonics, and for odd harmonics they are

$$f_{2k-1} = \frac{CU^2}{H \cdot (2k-1)\,\pi^2 RhL\rho}. \tag{10}$$

It follows from (9) that oscillations of the tube are only possible at the odd-harmonic frequency. The coefficients f_{2k-1} correspond to the acceleration of the shell during its oscillation. Note that relation (9) involves the total tube mass $m = 2\pi RhL\rho$. In some works [9, 12], they deal with even harmonics of the resonance frequency of the longitudinal tube oscillations, which contradicts the results and conclusions of [13], where it is also pointed out that there are only odd harmonics of longitudinal oscillations ω_L and their related frequencies of transverse oscillations ω_t. W. Flugge and G. Chiang made an attempt to eliminate even harmonics artificially, representing the entire frequency spectrum by two sets of odd harmonics [14]. However, this approach failed to find application. In a general case, the equation of forced oscillations involves the solution of homogeneous equation (2) and the particular solution related to the action of the external force F. The particular solution, which is of interest, is taken in the form of a convolution of the acting force with the temporal behavior function of the tube [11]:

$$w(x,t,F) = \sum_{k=1}^{\infty} \frac{1}{\omega_{2k-1}} \cdot \left[\int\limits_0^t f_{2k-1}(\tau) \cdot \sin\omega_{2k-1} \cdot (t-\tau)\, d\tau\right] \cdot \sin\frac{n\pi x}{L}. \tag{11}$$

In (11), ω_{2k-1} are the odd harmonics of the tube eigenmodes. It is reasonable to take the oscillation excitation voltage in the form $U = U_0(1 - \cos\omega t)$ with amplitude U_0 and frequency ω. This form of the voltage allows a simpler hardware-based implementation of the detection device. Since the excitation force is proportional to the square of the voltage, there arises the second harmonic, which induces oscillations with lower amplitude as compared with those induced by the first harmonic

$$(1 - \cos\omega t)^2 = 1.5 - 2\cos\omega t + 0.5\cos 2\omega t. \tag{12}$$

The procedure for calculating integral (11) is presented in [4, 15]. It involves a sum of three integrals $J = J_1 + J_2 + J_3$. Since the term J_1 is small, its effect on the oscillation amplitude can be ignored. The amplitude $w(J_1)$ is inversely proportional to the cube of the harmonic number and the square of the first-harmonic resonance frequency ω_1:

$$w(J_1) = \frac{f_{2k-1}\cdot[1 - \cos\omega_{2k-1}t]}{\omega_{2k-1}^2}. \tag{13}$$

The term $w(J_1)$ characterizes tube oscillations at resonance frequencies in phase with the excitation signal. When the excitation frequency coincides with the odd-harmonic frequency of the tube $\omega = \omega_{2k-1}$, a resonance occurs, and the oscillation amplitude is defined by the expression

$$w(J_2) = \frac{f_{2k-1}\cdot t\cdot\sin\omega_{2k-1}t}{\omega_{2k-1}}. \tag{14}$$

The second harmonic $\cos 2\omega t$ in the excitation signal spectrum also allows excitation of tube oscillations at odd harmonics of the resonance frequency. At the excitation frequency $\omega = 0.5\omega_{2k-1}$, the oscillation amplitude $w(J_3)$ is one fourth of the amplitude $w(J_2)$:

$$w(J_3) = \frac{f_{2k-1}\cdot t\cdot\sin\omega_{2k-1}t}{4\omega_{2k-1}}. \tag{15}$$

Therefore, it is preferable to search for the resonance frequency using the first harmonic of the excitation signal. At the resonance the amplitude linearly increases due to the time factor t, and the oscillation phase shifts by $\pi/2$ relative to the excitation signal because of $\sin\omega_{2k-1}t$. The amplitude is prevented from rising above the stationary value by the elastic force of the tube, and its decay is compensated by the action of the excitation force. Analysis of forced oscillations for a continuously acting variable excitation force reveals only odd harmonics and a possibility of exciting the resonance at an excitation frequency equal to half the odd-harmonic frequency of the tube. The dependence obtained for the tube resonance frequency (5) was experimentally verified and showed good agreement with the measurements.

CHARACTERISTICS OF THE DETECTION SYSTEM

The reference electrode was $400 \times 8 \times 3$ mm in size and was made of duralumin. It was inserted into the slot in the side of the $30 \times 40 \times 40$ mm fluoroplastic holder and was fast fixed by a clamp strap. During the tests it is preferable to set the electrode symmetrically about the tube to form symmetry of the excitation force along the length. Figure 3 shows oscillograms of the resonance oscillations of the tube excited by the first (*a*) and second (*b*) harmonics of the excitation signal. In the second case, the frequency of the detected signal is twice that of the excitation signal. The signal amplitude decreases by a factor of 3 as compared with the first case. In both cases, the detected frequency is equal to ω_1 within the measurement error of 0.1 Hz.

The accuracy of the resonance frequency detection depends on the Sensor sensitivity. To obtain high sensitivity, the Sensor was realized as a resonant

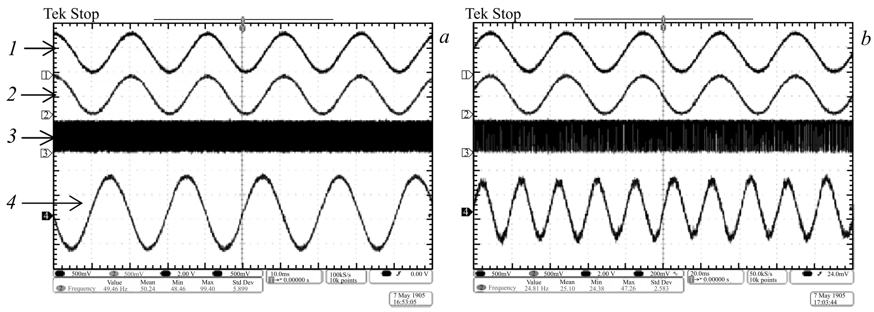

Fig. 3. The tube oscillations at first resonance frequency. Signals: *1* — Driver input; *2* — Excitation voltage control; *3* — Sensor high-frequency control signal; *4* — Sensor output signal proportional to the oscillation amplitude

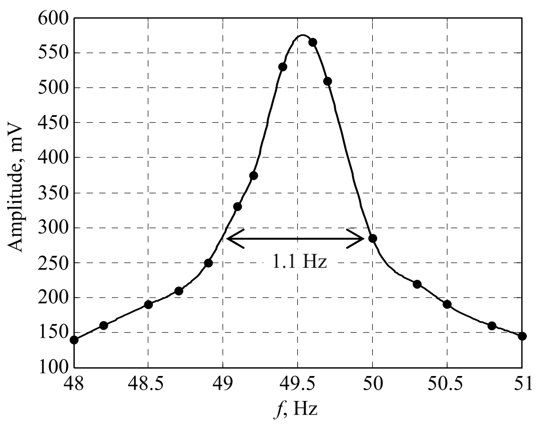

Fig. 4. Amplitude–frequency dependence of the readout signal

LC circuit with the capacitance of the reference electrode relative to the cathode of the tube used as the circuit capacitance. Figure 4 shows the behavior of the Sensor signal amplitude near the resonance frequency. The full width at half maximum (FWHM) of the dependence is 1.1 Hz, which indicates high selectivity of the circuit. The Sensor sensitivity can be estimated from the variation in the detected signal amplitude within the excitation frequency range equal to the distribution half-width. For the first harmonic, the sensitivity within the tube resonance frequency range was 530 mV/Hz. This sensitivity allows the resonance frequency to be determined with an accuracy of 0.1 Hz. For the second excitation harmonic, the sensitivity was 455 mV/Hz.

TEST RESULTS

The dependence of the resonance frequency on the tension was tested on tubes of the prototype COMET straw detector with the characteristics given above. The tubes were rigidly attached to a fixed holder using tips glued into their ends. Inside the tip there was a screw, which was rotated to set a tension. The tension was controlled using a dynamometer with a measurement accuracy of 25 g. At a given tension of the tube its resonance frequency was measured.

To obtain the maximum accuracy in determination of the resonance frequency ω_1, it was searched for at the first harmonic of the excitation signal. The excitation signal amplitude U_0 was 350 V. Figure 5 shows the measured results (•) in comparison with the analytical dependence (5) (curve). Results of measurements and check of impact factors on resonance frequency determination are given below.

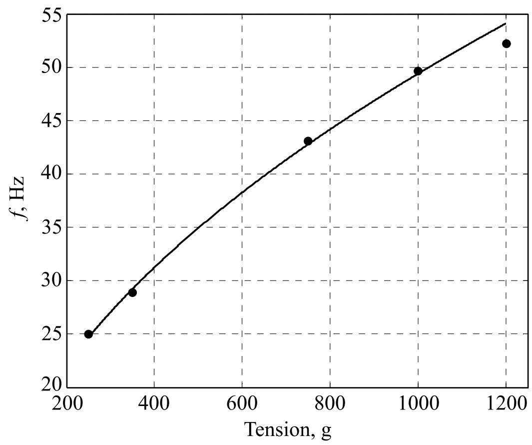

Fig. 5. Dependence of the resonance frequency on the tube tension

(i) The deviation of the experimental data from the analytical dependence in the tension range of 250 to 1000 g is below 1%. The shift of the reference electrode by 0.5 R relative to the center of the tube does not lead to a change in the detected frequency, while the signal amplitude decreases by a factor of 2–3.

(ii) At a tension of above 1000 g the measured frequency decreases in comparison with the analytical value due to the broken tube deformation linearity. At a tension of 1200 g the deviation is 3.5%.

(iii) It was examined whether other tube oscillation modes can be excited in the frequency range of 10 to 1500 Hz at the maximum excitation signal amplitude $U_0 = 650$ V. Longitudinal oscillations of the tube at other harmonics cannot be excited due to the strong damping of the oscillation amplitude proportional to the square of the harmonic number and to insufficient excitation force. Transverse oscillations of the tube in the above range cannot be excited either.

This test confirmed that there were no factors affecting the accuracy of the determination of the tube resonance frequency f_L.

CONCLUSIONS

A method of electrostatic excitation of straw tube oscillations is proposed for determining the tube resonance frequency that allows the tension to be calculated. This oscillation excitation method is well effective in the tube tension range used for detectors and is convenient in use.

The device for measuring tube tension is highly sensitive and detects the resonance frequency with an accuracy of 0.1 Hz. The device can also be used for measuring the tension of the signal wire. In this case, the excitation signal is applied to the tested wire, while the cathode is grounded.

Dependence of the tube resonance frequency on the tension is obtained for controlling the latter. It is shown during determination of the resonance frequency that there are only odd-oscillation harmonics, which is confirmed by other authors. The dependence allows a highly accurate description of the experimental data. The relative error in the tension range of 250 to 1000 g/m is 1%, which corresponds to a tension of 15 g and meets the most stringent requirements on the straw detectors. At a tube tension of above 1000 g/m the tube suffers nonlinear deformation and the tension determination error increases.

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