https://doi.org/10.33263/Materials23.367372

ISSN: 2668-5728 https://materials.international

Materials International

Article

Volume 2, Issue 3, Pages 0367-0372
2020

Received: 2.06.2020
Accepted: 1.09.2020
Published: 10.09.2020

Liquid Crystal Devise for Monitoring Vibration of Mechanisms of Machines and Aggregates

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Abstract: The work considers a modernized device for diagnosing mechanical vibrations that occur in parts, for example, bearings of pumps or compressors, or other mechanized complexes. The highlight of the device and diagnostic method is the use of a liquid crystal cell, which is a test system since the magnitude of the optical signal passing through it depends on the influence of mechanical shear displacements. A thin layer of nematic liquid crystal (MBBA) is placed between transparent substrates (layer thickness of the order of 100 μm). The third plate, which is located in the liquid crystal and between two other plates, is connected by a waveguide to a structural element of the mechanism, the oscillations of which must be controlled. Vibrations arising during the mechanism unit's operation are transmitted through the waveguide to the cell with a liquid crystal. A viscoelastic wave propagates in the volume of the liquid crystal, which affects the orientation of the liquid crystal molecules, as a result of which the magnitude of the intensity of the optical signal emerging from the cell changes. These changes are recorded by the photo-detector. Next, the signal is processed and fed to the operator's workplace in any form, convenient for observation. The measurements' physical essence lies in the occurrence of the phenomenon of photoelasticity arising from the acousto-optic effect. This effect is observed when the threshold value of vibrations is reached, which in the low-frequency range from 100 to 600 Hz demonstrates independence from the frequency. At temperatures from 18 to 42° C it is independent of temperature. The angle of inclination of the liquid crystal molecules linearly depends on the value of shear vibrations, which can significantly simplify the process of calibrating the device. Practical use of the proposed device will allow it to be used, for example, in light industry or pulp production.

Keywords: acoustooptical effect; photoelasticity phenomenon; vibration control device; shear vibration monitoring; liquid crystal.

1. Introduction

Mechanisms containing moving or rotating elements in their design require special attention during operation. The concern for their uninterrupted operation is due to the fact that if the permissible vibration readings are exceeded, an emergency stop of the equipment may occur [1-3]. Non-destructive testing methods, which are now actively being introduced into production, allow timely diagnosis and identification of problems in units and apparatuses. One of the many equipment operation indicators, but the most accessible and giving sufficient information on its technical

Cite This Article: Denisova, O. Liquid crystal devise for monitoring vibration of mechanisms of machines and aggregates. Mat Int **2020**, 1, 0367-037. https://doi.org/10.33263/Materials23.367372

condition, is vibration [4-6]. Such control methods make it possible to solve a number of technical and economic problems, such as daily monitoring of the state of units and units, which will prevent or reduce the number of accidents and failures. In cases where technical problems have been identified in a timely manner, this makes it possible to significantly reduce the money spent on repair work and technical maintenance of equipment, to avoid downtime of machine breakdowns, as a result of preventive repair, to increase production indicators, in addition, to remove equipment for a routine inspection, which gives the ability to increase the time interval between repairs.

To solve the problems identified above, in a number of sectors of the national economy, production, and science, it is necessary to increase the sensitivity and speed of diagnostic methods. This requires an expansion of the search for new solutions to scientific and technical problems. To date, a significant number of methods, techniques, and devices have been developed and constructed to determine vibration parameters, which are based on various physical effects and phenomena [7–13].

In this work, we propose a device for diagnosing vibration in nodes and mechanisms, the structural part of which includes a liquid crystal cell. The monitoring technique is based on the phenomenon of photoelasticity, which is observed in a liquid crystal when an acousto-optic effect occurs. The proposed device and method for monitoring vibrations will increase the sensitivity (up to 0.1 μm) and speed since the device includes a cell with a liquid crystal in the volume of which an orientation effect occurs under shear action (relaxation time 10^{-6} s).

2. Materials and Methods

The article proposes a highly sensitive device and method for measuring vibration parameters, which is based on the use of the acousto-optic effect in nematics. The acousto-optic effect is observed when optical and sound waves are applied to crystals. The idea of the method is to use a cell containing a liquid crystal (LC). The cell is an indicator of the occurrence of mechanical oscillations. The LC-cell is made in the form of a multilayer structure (Figure 1).

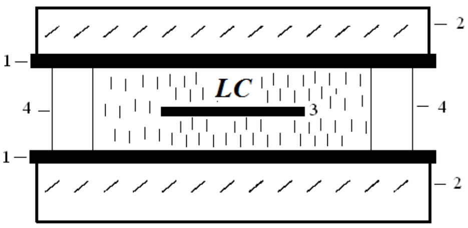

Figure 1. Acousto-optic cell (side view): 1 - chromium conducting coating, 2 – glass substrate, 3 - movable plate, 4 - spacers, which determine the thickness of the LC layer.

It consists of two massive transparent plates made of glass slides. A thin glass plate which can oscillate in the plane of the cell is placed between them. The working medium was a nematic type liquid crystal of n - methoxybenzylidene - n - butylaniline (MBBA). It is in a liquid crystalline state at temperatures from 18 to 42° C, that is, it can be used in a fairly wide temperature range. Metal chromium was sprayed onto the substrates so that the liquid crystal molecules were oriented homeotropically, i.e., liquid crystal molecules are oriented perpendicular to the plates [14-16].

In the proposed structural scheme (Figure 2), the middle movable plate of the LC-cell is connected to the mechanical unit *1* by means of a waveguide *2*.

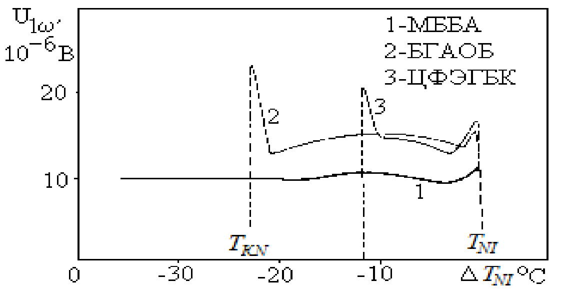

Figure 2. Structural scheme of the measuring system based on the acousto-optic effect in NLC: 1 - mechanical unit, 2 - a waveguide, 3 - light source (laser), 4 - polarizer, 5 - LC-cell, 6 - photo-detector analyzer, 7 - microcontroller, which includes an amplifier, an analog-to-digital converter, and a microprocessor, an 8 - monitor.

The cell is illuminated by a source of monochromatic polarized light (laser) *3*. The laser beam, passing through the polarizer *4* and cell *5*, falls on photo-detector analyzer *6*. The optical signal converted into an analog electrical signal is processed by a microcontroller *7*, which includes an amplifier with an analog-to-digital converter, as well as a microprocessor. After that, the microcontroller's data is output to the monitor of the operator *8* as a diagram, table, or another convenient form.

The principle of the acousto-optic system is as follows. Prior to the beginning of the action on the cell - the sensor of mechanical oscillations, the director of the liquid crystal is oriented perpendicular to the cell plates. In such a situation, when the analyzer and polarizer are crossed, the light beam does not pass. When the mechanical unit starts working, vibrations from it are transferred through the waveguide to the LC cell's middle plate. When the vibration amplitude reaches 0.8 μm, the director deviates from the normal to the cell by some angle θ_c. The director orientation of the liquid crystal begins to change sharply (this acousto-optic effect has a threshold character of occurrence) [17-19]. As a result, the light transmission of the LC-cell changes. The photo-detector fixes the signal received on it, which is reflected on the monitor. It should be noted that the scope of the described method of vibration monitoring lies in those areas where the vibrations during the operation of the mechanisms should be minimal, that is, up to 0.8 μm.

The quality of the readings of the vibration monitoring device is determined by the accuracy, i.e., the degree of correspondence between the actual value of the input quantity and its calculated value, which according to the static characteristic of the converter, corresponds to the actual value of the input quantity [20]. The lower the device's error, the higher its accuracy, i.e., to increase accuracy, it is necessary to reduce the error. The error of the device, which determines the conversion's accuracy, can be found by summing its individual components. In this case, it is necessary to take into account both the maximum values of the component errors and the nature of the change. In the proposed device to the system can be attributed to instrumental errors and random - operational.

The device's total error contains a systematic and random error and can be determined experimentally and analytically. When using the analytical method for determining the error, the error sources are analyzed, and the nature, magnitude, and influence of its components on each other is determined. It is impossible to take into account all the factors determining the error.

If the error is determined experimentally, it is necessary to carry out multiple measurements at certain points in the converter range. The conditions should be the same for all measurements. According to the measurement results, it is possible to determine random errors at selected points in the conversion range, the most probable value of the measured value, as well as determine the confidence interval with sufficient probability.

The method of standardizing errors, which means a clear indication of the error band, is selected based on the law of the distribution of errors established on the basis of the statistical data for determining the errors of the converter. The instrumental sources of error of the vibration monitoring device include the inaccuracy of adjustment and the presence of play between the stationary and moving parts, i.e., assembly of the converter without backlash and fine-tuning can reduce the instrumental component of the error. Operational errors are random in nature, so they cannot be excluded in the same way as instrumental ones. These include such factors as the aging of system elements. To prevent this component of error, timely prevention is necessary.

To determine the device's accuracy class, it is necessary to verify and determine the maximum deviation from the set value in percent. According to GOST 30296-95, there are 6 accuracy classes of vibration transducers. For verification, the existing MI 1873-88 calibration method "Vibrometers with piezoelectric and induction transducers" was taken as a basis. The calibration unit VUP-MG 4.01, designed to reproduce sinusoidal mechanical vibrations during calibration and calibration of vibration measuring equipment, as well as during vibration tests in the frequency range from 5 to 10^4 Hz, was chosen as a standard calibration vibration installation. The installation includes a model 4808 vibration generator with a power amplifier 2719, a special signal generator SFG-2004, an acceleration accelerator (hereinafter referred to as an accelerometer) model 8305 with a measuring amplifier 2525, a piezoelectric accelerometer model 4371 and a vibration measuring device VIBROTEST-MG4.E.

Verification of the vibration monitoring device was carried out. During an external examination, compliance with the following requirements should be established: compliance of the device kit with the list provided by the accompanying documentation; absence of mechanical damage to the cases of the measuring unit, device, and connecting cable; the presence of an intact control seal; marking verification. According to GOST 30296-95 and GOST 8.401-80, SI accuracy class, the main error in the operating range of amplitudes and frequencies of which is expressed as a percentage, should be selected from the values of the series: 2.5; 4; 6; 10; fifteen; 20. Based on our results, the proposed vibration monitoring device can be attributed to accuracy class 2.5.

3. Results and Discussion

The experimental cell-sensor (Figure 1) considered in the article is a system consisting of two LC-layers. A viscoelastic sound wave, due to the appearance of an acousto-optic effect on such a two-layer system, leads to the appearance of birefringence. According to the Fourier analysis, a constant intensity component P_c and an alternating signal component $P(t)$, containing the harmonic spectrum at the excitation frequency ω [17] should be recorded in the optical signal. According to Malus law for anisotropic media, the intensity of an optical signal passed through a liquid crystal:

$$P = P_o\ \{[\sin^2 A{\cdot}B + A\,[2\sin D + C]\ \sin 2A{\cdot}B + A^2\,[2D + C]^2 \cos^2 A{\cdot}B\}, \qquad (1)$$

$A=\pi hk/\lambda$, $B=\langle\sin^2\theta_c\rangle$, $C=\langle\theta^2_t\rangle$, $D=\langle\sin\theta_c{\cdot}\theta^2_t\rangle$, here, the wavelength of the light incident on the cell λ, k=0.23 is a constant, θ_c is the constant slope of the NLC director, θ_t is the component characterizing the oscillations of the NLC director.

Performing Fourier analysis, we obtain expressions for the constant component of the optical signal P_c and the variable component of the optical signal $P_{i\omega}$:

$$P_c = P_o\ \{\sin^2 A{\cdot}B + A{\cdot}C/2\ \sin 2A{\cdot}B + 2A^2{\cdot}D^2{\cdot}\cos^2 A{\cdot}B + 3/8\ A^2{\cdot}C^2 \cos^2 A{\cdot}B\}, \qquad (2)$$

$$P_{1\omega} = P_o\ \{2A{\cdot}D\ \sin 2A{\cdot}B + 3A^2{\cdot}D{\cdot}C\ \cos^2 A{\cdot}B\}{\cdot}\sin\omega t, \qquad (3)$$

$$P_{1\omega} = P_o\ \{-A{\cdot}C/2\ \sin 2A{\cdot}B - 2A^2{\cdot}D^2 \cos^2 A{\cdot}B - A^2C^2/4\ \cos^2 A{\cdot}B\}\ \cos 2\omega t. \qquad (4)$$

According to the optics of anisotropic media and the resulting expression (3), a signal that is registered at the excitation frequency ω occurs only when the director deviates by an angle θ_c towards the normal of the cell. The appearance of the acousto-optic effect can be determined by the occurrence of an alternating signal $P_{1\omega}$ at the frequency of the action. This also makes it possible to measure the threshold amplitude of the sound wave in the NLC.

We experimentally obtained graphs of the amplitude dependencies of the constant light transmission component $P_c(a)$ and its second harmonic $P_{2\omega}(a)$ (Figure 3). Then, $\langle\sin^2\theta_c\rangle$ values were calculated from these values depending on shear vibrations (Figure 4).

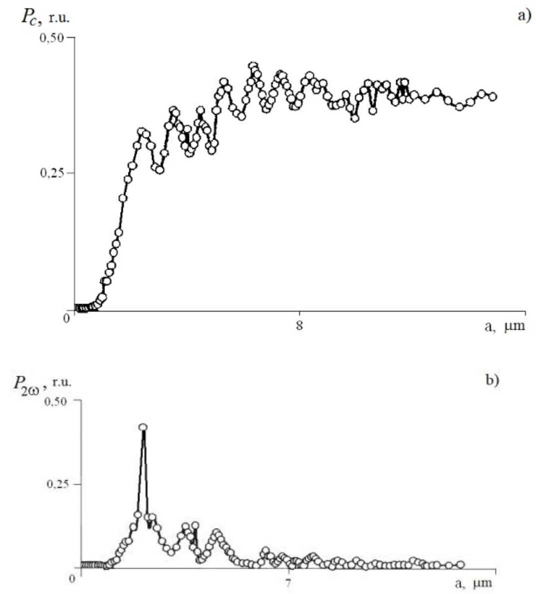

Figure 3. Graph of the constant component $P_c(a)$ (a) and the second harmonic of the light transmission $P_{2\omega}(a)$ (b).

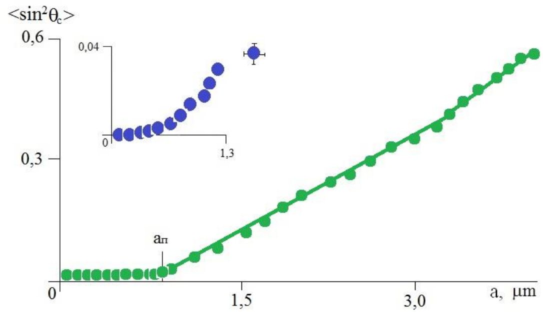

Figure 4. Graph of $\langle\sin^2\theta_c\rangle$ versus vibration amplitude.

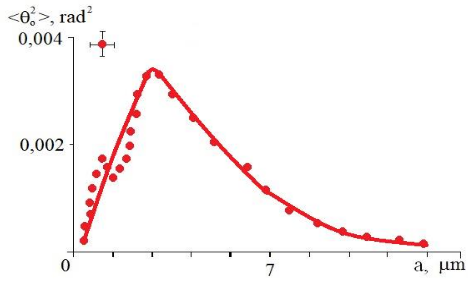

Figure 5. Amplitude dependencies of variable part $\langle\theta_o^2\rangle$ of director of the tilt angle.

This means that when the value of the amplitude of the mechanical shear is 0.8 μm, the function $\langle\sin^2\theta_c\rangle(a)$ has a threshold. The function increases linearly to unity, the angle $\langle\theta_o^2\rangle(a)$

increases to a value of 0.004 rad with an oscillation amplitude 2.8 μm, then decreases (Figure 5).

As the slope of the liquid crystal molecules increases, the dynamic susceptibility of the LC-layer decreases.

In addition, it was experimentally found that the acousto-optic effect proposed for the method of determining vibrations in the frequency range from 20 Hz to 20 kHz does not depend on the frequency of the sound wave, in the range from 18 to 45° C on the temperature, and also in the range from 20 to 125 μm on the thickness of the LC-layer [17]. The presented results give quite wide possibilities for the application of our method.

4. Conclusions

To summarize, in conclusion, the following should be noted. The article describes a method for indicating vibration, based on the phenomenon of photoelasticity that occurs during the propagation of visco-elastic waves in nematics. In this scheme, a liquid crystal cell was used as a sensor. Since liquid crystals are substances that are very sensitive to external fields (thermal, magnetic, electric), this proposal makes it possible to increase the sensitivity of the method, the measurement efficiency, and hence its speed and functionality [21, 22]. The results obtained can be useful in designing devices for monitoring mechanical vibrations of mechanisms and apparatuses and assemblies, for example, for the pulp industry.

Funding

This research received no external funding.

Acknowledgments

This research has no acknowledgment.

Conflicts of Interest

The authors declare no conflict of interest.

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