Electric fields emitted by fracture of thin glass or polyethylene fibers

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Abstruct. We study the characteristics of electric field emitted by vibration or fracture of thin glass and polyethylene fibers. The glass fibers of diameter 6.5 – 150 μm as well as polyethylene fibers of diameter 0.06 – 1 mm were tested. It turned out that the signals emitted by fracture of different kind of fibers were the same in shape and have a negative phase of length 100–400 μs and a much longer positive phase. Unexpectedly, the average values of amplitudes of signals for fibers significantly different in diameter turned out to be close to each other. This can be explained by the well-known fact that the number of fragments in fracture increases with the glass strength (a scale effect).

Introduction.

Experimental studies of time development of fracture processes in separate thin fibers and filaments (fiber bundles) under their uniaxial tension are undoubtedly of scientific interest. But, because of small transverse dimensions of the tested specimens, it is either impossible or very difficult to use numerous traditional methods. For example, the use of the acoustic emission method meets certain technical difficulties: the transducer cannot be fixed on the specimen, and the piezomaterial deposition on the specimen surface would change the characteristics of the process under study. The following question arises: Is it possible to perform stable recording of electric signals from damaged small structure elements and what are the limits of application of this method? To answer this question, we study the characteristics of electric field emitted by vibration or fracture of thin glass and polyethylene fibers. The method based on recording perturbations of electromagnetic radiation (EMR) arising in materials at fracture and has the following advantages. It is contactless, permits practically avoiding external noise, does not require complicated equipment, and allows one to prepare the specimens by a simple method according to standard techniques.

Experimental plant. The plant block diagram is shown in Fig. 1, where 1 is the fiber, 2 is the electric field transducer field (antenna), 3 is the external screen, 4 is the internal screen, 5 is the fixed gripper, 6 is the movable gripper, 7 is the source repeater, 8 is the power unit of the source repeater, 9 is the amplifier, and 10 is the oscilloscope. The external screen consists of a brass frame of dimensions 162 $\times$ 89 $\times$ 32 mm with walls of thickness of 7 mm and the upper and lower aluminum covers of thickness of 1 mm. The upper cover has a cut of dimensions 49 $\times$ 6 mm for visual observations of the process. The source repeater framed on the basis of the field transistor RP305D is located in a separate screen fixed on the external screen of the plant. The frequency band of the source repeater with a segment of cable RK50 of length 0.8 mm is bounded by a value of approximately 10 MHz.

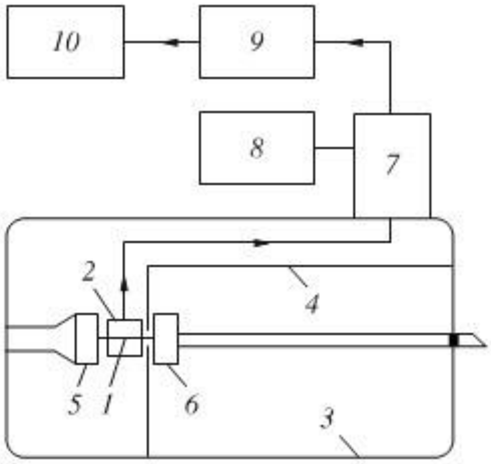

Fig. 1.

In the plant, we used the amplifier U3-29 and the double-beam digital oscilloscope LeCroy WaveSurfer 422. Their frequency bands are 20 MHz and 200 MHz, respectively. The amplifier was not used if the signal amplitude was sufficiently large. To decrease considerable high-frequency noise, the oscilloscope frequency band was bounded by 20 MHz. The electric field transducer of dimensions 7 × 6 mm, which consists of thin parallel conducting strips, has a dielectric coating and is pasted to a glass plate of dimensions 18 × 11 × 2.5 mm, which, in turn, is pasted to another glass plate of dimensions 49 × 15 × 2.5 mm fastened to the lower cover of the external screen.

The system response to a jump increase in the potential (a transient characteristic) in the oscilloscope operating regime AC1M (Alternating Current, input resistance is 1 MΩ) showed that if the characteristic time of the processes under study is less than 5 ms, then the attenuation caused by this recording device is insignificant. There were no observed distortions of rectangular video pulses of duration from 10 μs to tenth fractions of the microsecond.

Experiments for EMR recording at vibration of polyethylene and glass fibers.

Experiments with stretched fishing line diameter of 80 microns, and glass fibers of diameter 150 mm, mounted on one end were made to determine the magnitude of the signal induced by transverse vibrations. In Fig. 2 we present the signal obtained from vibration of a stretched string. Vibration were excited by the grounded conductor at the drip 6, and the antenna was located near the grip 5.

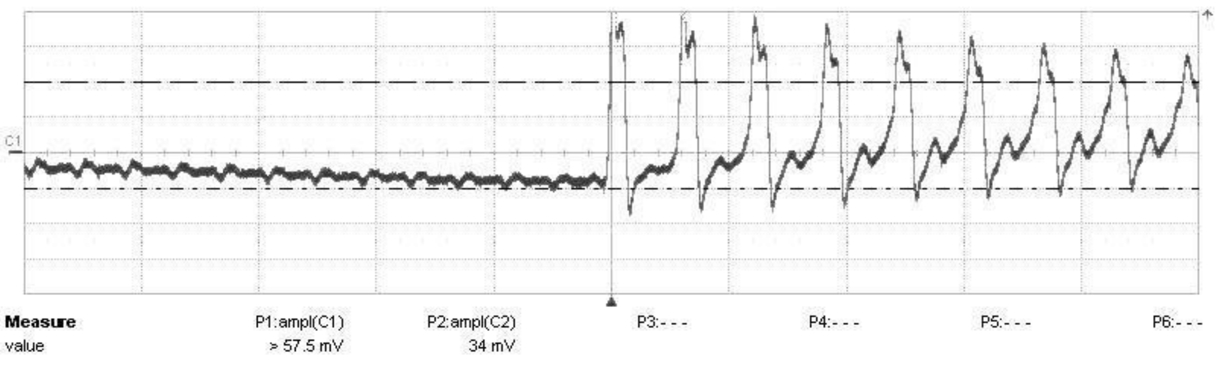

Fig. 2.

For transverse vibration of the glass fiber of length 8.5 mm and 150 μm in diameter signal has the form shown in Fig. 3. The period of oscillations on the oscillogram is 1 ms, which is almost twice the theoretical value ($E = 10^{11}\ Pa$, $\rho = 2.5 \cdot 10^{3}\ kg/m^{3}$). At the same time for a fiber length of 15.5 mm the calculated and experimental periods were almost similar: 1.8 and 2 ms. Possible reasons for differences between theoretical and experimental values may be imperfect (non-rigid) conditions at the grip due to the presence of glue.

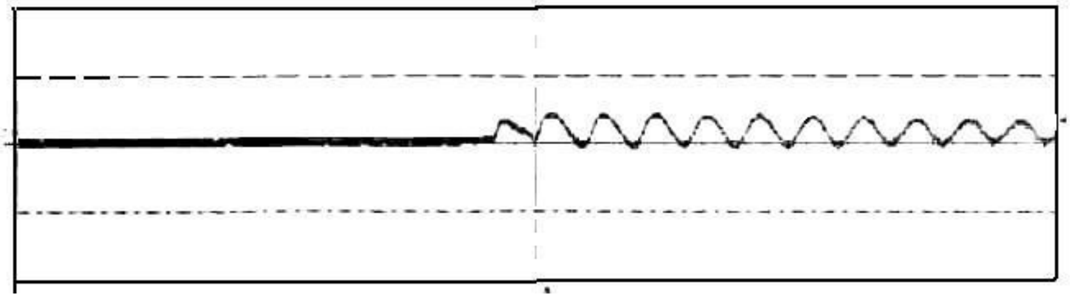

Fig. 3.

Experiments for EMR recording at fracture of glass fibers.

Such experiments were performed for glass fibers of diameter d = 150, 18, 10, 6.5 μm with the following characteristics: the density - 2.58 g/cm^{2} , the Young modulus - (95-100) GPa, and the tension strength - σ_{*} = 0.5, 1.5, 2.0, 2.5 GPa, (the variance is 20–30%), respectively. They were pasted into a paper mandrel and had the length 19–20 mm. The tested specimens together with the mandrel were fixed in the grippers. The specimen disruptive force was applied to the moving gripper. Both of the grippers were covered by shellac; its electroconductivity is by two orders of magnitude less than that of glass.

The signal from the antenna after the fracture of fibers of diameter 150 μm was seldom recorded and only if a charge was specially applied to the fiber surface and transverse vibrations of the fiber parts remaining in the grippers were excited as vibrations of elastic cantilevers. This is a result of buckling as the “rod,” which is the rest of the fiber at the moment of the unloading wave incidence and then reflection, impacts on the gripper.

In Fig. 4, we show the oscillogram of the signal induced by such vibrations, U (t), where U is the potential equal to 10 mV/div, t is the time equal to 5 ms/div, under the amplification equal to 100; the lengths of the fiber remainders are 17 and 3 mm. The experiments with direct excitation of transverse vibrations of such an elastic cantilever showed that the signal has sinusoidal shape, and the period of vibrations of fibers of length 13 mm and 8.5 mm is approximately equal to 1 and 2 ms. Comparison with the analytical results showed that, in one case, this period is twice larger than the theoretical period and, in the other case, they practically coincide: 1.8 and 2 ms. A possible cause of this noncoincidence may be the nonideal (nonrigid) fixation in the gripper because of the glue at the point of fixation.

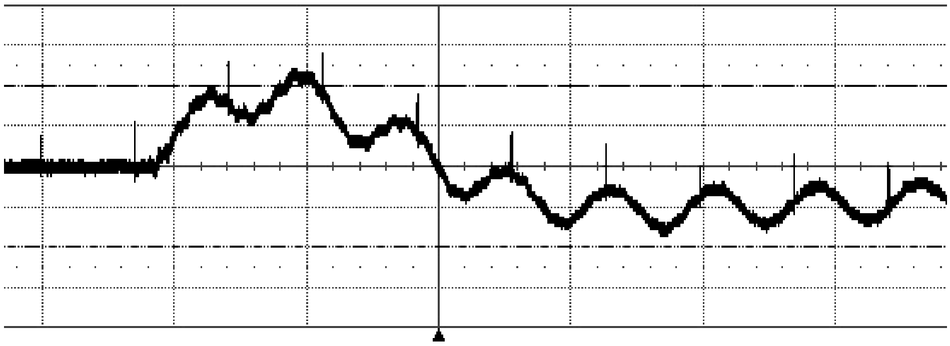

Fig.4.

In Figs. 5–7, we present typical oscillograms of the electric signals (the division value is 0.5 ms, 5 ms, and 5 ms in the axis t and 50 mV, 20 mV, and 20 mV in the axis U) induced by fracture of glass fibers of diameter 18, 10, 6.5 μm of significantly different shape as in the case of fibers whose diameters are by an order of magnitude larger. We note that no charge was applied to these fibers. For the first time, we recorded the signal induced by fracture of a fiber of diameter 6.5 μm, i.e., by an order of magnitude thinner than the human hair (Fig. 7). An analysis of oscillograms showed that the fact of fracture itself was not registered, because the brittle fracture is very fast, and the signal gets in the region of high frequencies and has a small amplitude. The cause of the EMR recording must be sought in generation of wave and vibration motion in the fiber remainders after fracture. The duration of the growth of the signal initial (negative) phase is of the order of 50–100 μm, which is much larger than the time characteristics of vibration processes caused by multiple reflections of elastic waves from the fiber ends. Thus, the vibration period for the longitudinal wave velocity c ≈ 6 km/s and $l \approx 10$ mm is equal to T = 3 μs. Therefore, these signals are associated with strong nonlinear and relatively slow bending vibrations of thin fiber remainders, which do not arise for "thick" fibers with d = 150 μm. This is also confirmed by the fact that the first two shapes of elastic vibrations of the fiber remainder operating as an elastic cantilever are imposed on the oscillogram (Fig. 6): the ratio of periods of these vibrations is very close to the theoretical value T2/T1 ≈ 0.16. This observation and the experiments with vibrations of a fiber of d = 150 μm open perspectives of object-oriented studies of the vibration spectra by using the electric effect.

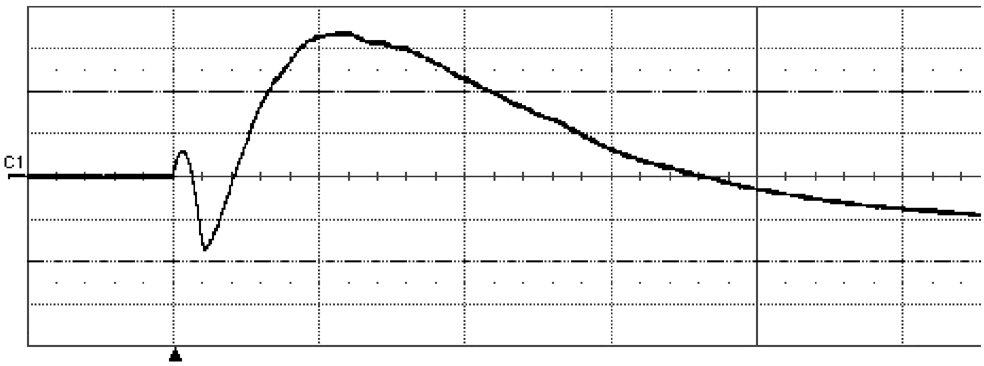

Fig. 5.

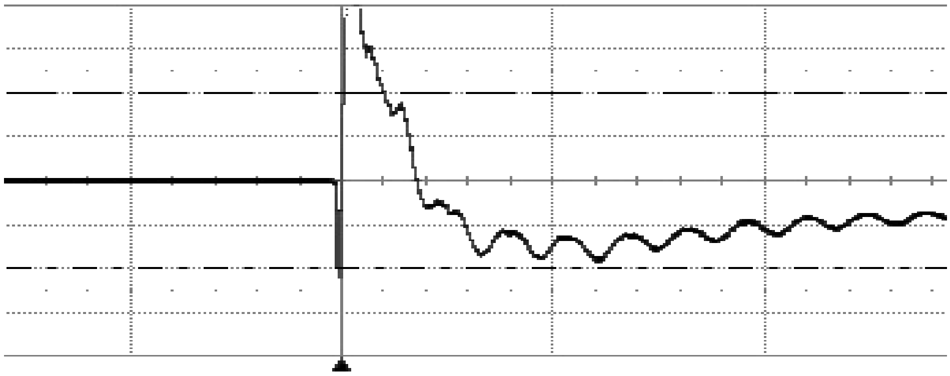

Fig. 6.

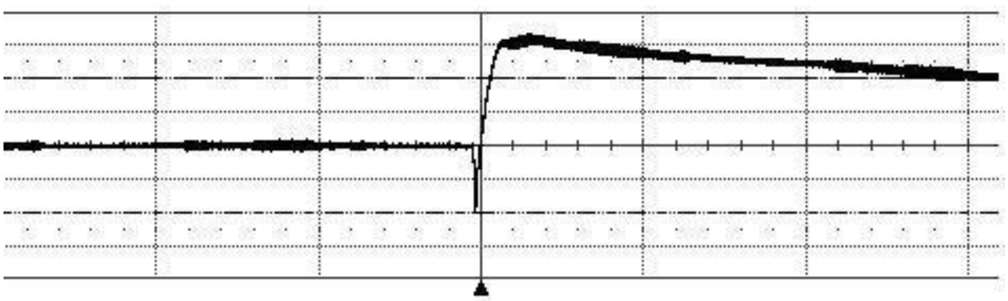

Fig. 7.

The spread of amplitude and, to a lesser extent, of duration of the first phase is specified by the well-known statistical character of the fiber fracture: the variance of the statistical procession of the strength parameters σ_* and ε_* is usually large. This is the cause of wide spread of the fracture results. So, after fracture, no cut fragments of fibers of length comparable with the nominal length (2 cm) were found, and it was difficult to estimate their number. After fracture of fibers, both parts of the fiber, one part, or none of the parts may be left in the grippers. It was also observed that one of the parts of the fractured fiber curled into a loop of diameter nearly equal to 3 mm, which also confirms that the dynamical bending of the fiber is significant. The results of the signal processing are collected below in the table 1 containing the negative phase amplitude A, the jump ΔA from the minimum to the first maximum, the time t_+ of the negative phase increase, and the time t_- of the signal increase to the maximum. The spread of amplitudes is indeed large, but, nevertheless, the variation in their average values is small as the area of the transverse cross-section varies by an order of magnitude: $\langle A \rangle \approx$ 49, 64, 40 and $\langle t_- \rangle \approx$ 84.5, 67.1, 94.7 for d = 18, 10, 6.5 μm. This can be explained by the well-known scale effect of the fiber strength increase as its diameter decreases. In this case, the accumulated specific elastic energy $e_* = \sigma_* \varepsilon_*$ increases before the fracture and, respectively, the amplitudes of transverse nonlinear waves and the dipole accelerations at molecular level also increase. The number of fracture fragments also varies (the fact that the number of glass fragments increases with the glass strength is well known). All this compensates the decrease of the volume where the radiators are concentrated. We could not fix the number of fragments directly, but the fact that the strength increases as the diameter decreases is obvious: 1.5 ≤ σ_* ≤ 2.5 GPa, 150 ≥ d ≥ 6.5 μm. Thus, as the fiber diameter is changed, the following two parameters vary simultaneously: the geometric parameter d and the fracture parameter σ_*.

Table 1.

N	A, mV	ΔA, mV	t $_-$ μs	t $_+$ μs	Comments
d = 18 μm					
1	-21.9	>39.7	70	~250	Fragment of 3 mm and 4.3 mm in grippers
2	-79.4	66.3	90	1550	one end of 11 mm
3	-20.0	>79.4	50	~520	–
4	-21.9	>79.4	160*	~800*	–
5	-39	108	45	270	no fiber remainders
6	-16	123	80	940	short remainder
7	-34	80	66	280	no fiber remainders
8	-123	89	80	360	11.5 mm in one of the grippers
9	-88	170	120	480	no fiber remainders
d = 10 μm					
N	A, mV	ΔA ,mV	t $_-$ μs	t $_+$ μs	Comments
1	-45	150	80*	400*	no fiber remainders
2	-19	75	48	452	8.4 mm in the left gripper
3	<-80.0	68.8	~100	450	9 mm in the right gripper
4	-41	52	75	3030	12 mm in the left gripper
5	-114	72	60	1250	no fiber remainders
6	-66	116	40	400	–
d = 6.5 μm					
N	A, mV	ΔA ,mV	t $_-$ μs	t $_+$ μs	Comments
1	< -40	10	120	850	fiber segment of 2 mm
2	-40	66.3	64	720	fiber segment of 2 mm
3	-10	17.5	100	1800	Remainder of 5 mm and loop d=3 mm

Experiments for EMR recording at fracture of polyethylene fibers and filaments.

The signal for the destruction of polyethylene fiber diameter of 18-20 microns is shown in Figure 8. It has the same form as that for glass fibers, and its characteristics: duration and amplitude - of the same order, although the destruction was not fractional. This can be explained by the experimental fact that polyethylene gives a greater signal than glass. Signals at fracture of polyethylene filament (consisting of about 100 fibers of diameter 7-12 μm) are shown in figure 6. But this EMR may be associated also with electrification by friction during the motion of fibers. Presence of charges on fibers before destruction also can influence on signal.

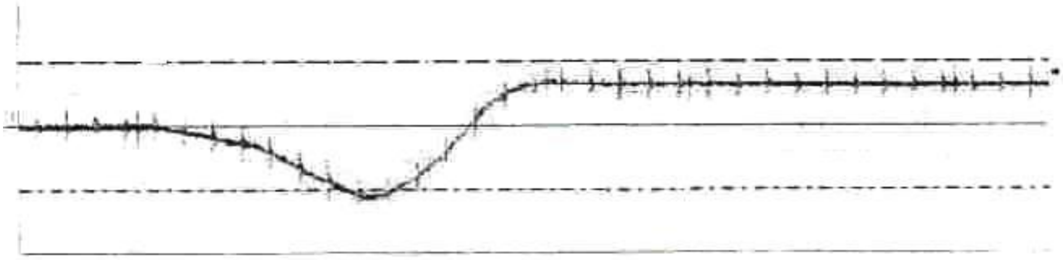

Fig. 8

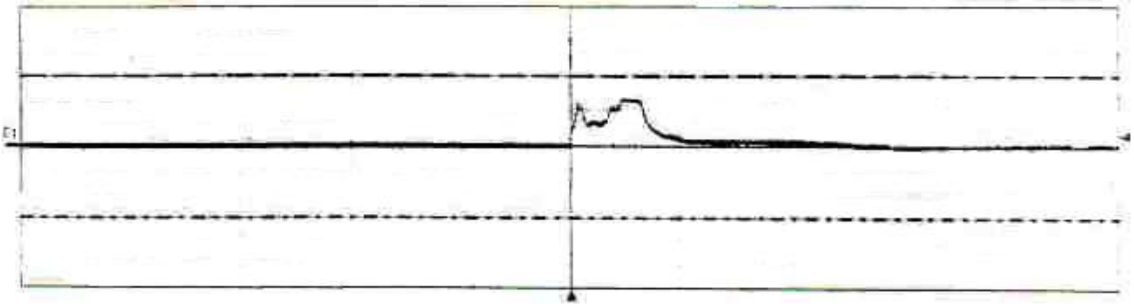

Fig. 9

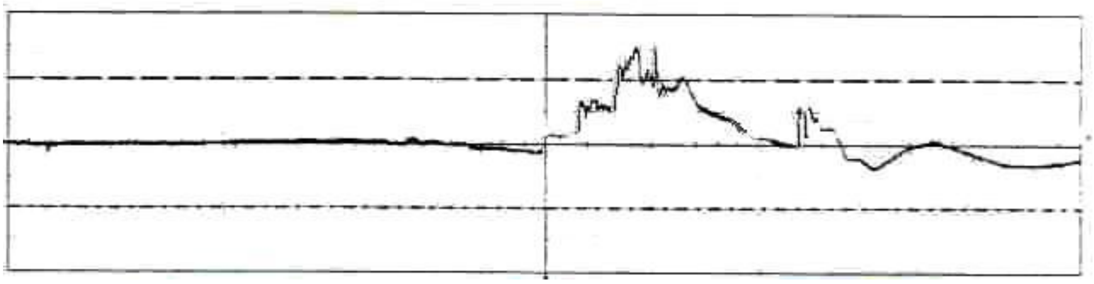

Fig. 10

The signals also appeared in the short-term loading of filament without destroying the fibers (Fig. 9). The signal at fracture of the filament is shown on a Fig. 10. This waveform is characterized by sharp bends , which can be associated with the destruction of individual fibers or groups of fibers.

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