Statistical characteristics of electromagnetic emission signals of mechanical loaded composite samples

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Abstract:
This article presents study of statistical characteristics of EME signals. The theoretical part contains a description of stochastic nature of electromagnetic emission. We describe the measuring system, the sequence of the experiment, statistical characteristics (probability density function, mean quantity and dispersion) and spectral analysis (voltage and current power spectral density of measured EME signals). In the practical part of the article we also have compared results obtained on the basis of experiment with theory.

INTRODUCTION

Our study is focused on the use of spectral characteristics of electromagnetic emission signals for damage assessment of mechanical loaded composite materials. Signals of electromagnetic and acoustic emissions appear during cracks generation when a solid is exposed to mechanical loading (tensile, compressive, shear, torsion, etc.). Generation of electromagnetic emission is related to electric charge redistribution during cracks creation and development and it is in the frequency range from 0.1 Hz to 10^{19} Hz. Acoustic emission appears due to release of elastic energy during this process and it is in the ultrasonic frequency range [1].

EME arising during crack creation carries information about the damage history and nature. Since the crack creation is a random process, we measure stochastic signals at the output of the capacitance sensor (see Figure 1), which is conveniently designed in the form of a plate capacitor, whose dielectric is the material under investigation [1].

Crack generation in solids is accompanied by the redistribution of electric charge. The crack walls are electrically charged, and their vibrations produce time variable electrical dipole moments. Therefore at the moment of occurrence, a crack generates an electromagnetic field which can be measured by suitable sensors.

STOCHASTIC NATURE OF ELECTROMAGNETIC EMISSION

Stochastic nature of EME stems from the nature of the probability of events that leads to crack formation under mechanical load.

The EME generation can be described as a stochastic process, in which separate cracks are created. They are characterized by current pulses that are related to the charge transport during crack creation.

It is possible to describe properties of these EME signals by means of a set of random variables that describe pulse amplitude, pulse shape and pulse inception time.

Let’s suppose the signal, where each pulse is characterized by the time of occurrence t_n and current amplitude I_n.

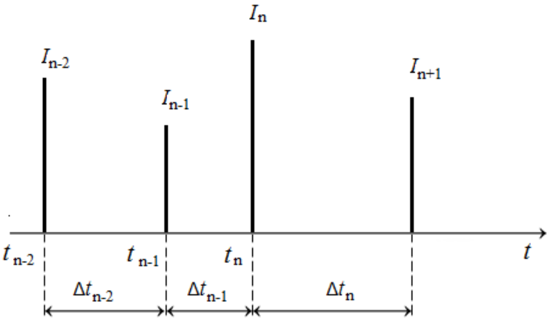

Fig. 1: Representation of EME pulses in the form of a discrete stochastic process

The time between the inception of two subsequent pulses is a random variable, which depends on the nature of the processes causing the formation of cracks. This equivalent current source represents random impulse process which can often be described approximately as the Poisson process. Therefore we can use postulates the random process of pulse generation:

1. The probability of an event (i.e. one current impulse generation) is $\lambda\Delta t + o(\Delta t)$ in the interval $(t, t + \Delta t)$.
2. The probability of more than one event in $(t, t + \Delta t)$ is $o(\Delta t)$.
3. The probability of events absence is $1 - \lambda\Delta t + o(\Delta t)$ in the interval $(t, t + \Delta t)$.

Let $P(N, t)$ denotes the probability of the event within the time interval $(0, t)$.

We can derive the Poisson, distribution from these postulates, in the form of

$$P(N,t) = \frac{(\lambda t)^N}{N!} \mathrm{e}^{-\lambda t} . \qquad (1)$$

If we denote the time between two consequent pulses inception as a random variable τ, then its probability distribution density is

$$f(\tau) = \lambda \mathrm{e}^{-\lambda\tau}, \qquad (2)$$

then the mean is

$$\tau_0 = \frac{1}{\lambda}, \qquad (3)$$

and the dispersion is

$$D = \frac{1}{\lambda^2}. \qquad (4)$$

The described process has the power spectral density of a generation-recombination type in a form of Lorentzian [5].

We used the formula for approximation of the current power spectral density in the form of

$$S_i(\omega) = \frac{S_{i0}}{1 + \omega^2 \tau_c^2}. \qquad (5)$$

where S_{i0} is a constant, ω is a radial frequency, τ_c is a time constant.

MATERIAL UNDER INVESTIGATION

The specimens to be measured are prepared from of extren 500 composite material based structural profiles. Each specimen is a block of dimensions 9.4 mm × 51.0 mm × 71.5 mm. In general, composite materials consist in a combination of fibre glass reinforcement and a resin binder.

MEASUREMENT SYSTEM

A fully automated methodology for EME and AE signals measurement (Figure 2) was developed in our laboratory. This system is based on a computer actuated hydraulic press which provides the specimen with compressive load in the range of 10 kN to 100 kN. Control signals are developed by an NI PCI-6014 interface card [1].

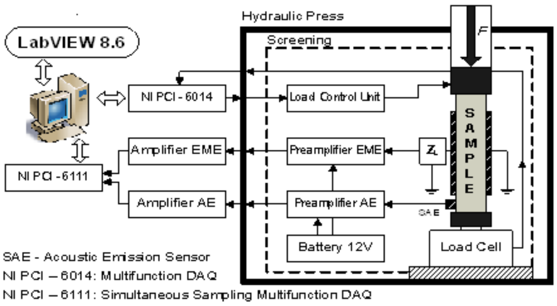

Fig. 2: Measurement system

The compressive load applied on a sample is measured by a sensitive load cell, connected in a Wheatstone bridge circuit. The bridge output voltage, is measured by the NI PCI-6014 interface card and the resulting value of applied force is obtained by means of the load cell transfer function.

A deformation meter is used for sample contraction measurements during the application of compressive stress. The output signal from this meter is loaded into the computer using by an RS-232 port.

The EME channel consists of a capacitance sensor, in which the dielectric is the stressed sample, a high pass-filter-type load impedance Z_L, a low-noise preamplifier PA31 and an amplifier AM22 with a set of filters. The total EME channel gain is 60 dB, the frequency range is from 30 kHz to 1.2 MHz and the sampling rate is 5 MHz. This sensor is composed of the specially made adjustable bracket with two electrodes, into which the rectangular samples of the material under study can be easily inserted.

The AE channel consists of a piezoelectric acoustic sensor (30 kHz ~ 1 MHz), the low-noise preamplifier PA31 and the amplifier AM22 with a set of filters. The total AE channel gain is 40 dB, the frequency range is from 30 kHz to 1.2 MHz. Piezoelectric sensors from different producers are used for AE signal measurement. These sensors meet the requirements of the AE signal frequency band (at least up to 1 MHz).

More details about the process of the signal measurement you can read in the papers [2−4].

EXPERIMENT

A linearly increasing uniaxial compression load of up to 85 kN, at a rate of 25 N/s, was applied to the experimental sample.

Figure 3 shows an example of AE and EME signals, with a duration of 0.1 seconds. The number of data points is 500000. The sampling frequency is 5 MHz. This signal is measured at the output of the measurement system.

Figure 4 shows the relationship between the deformation and the compressive load. This linear relationship indicates a region of elastic deformation. Deviation from linearity observed at the last part of the curve, suggesting plastic deformation, is occurring [2, 3].

Control points of the experiment, which will be used in this paper include:

1. Signals of EME and AE were measured before the load during the experiment.
2. Then the sample was placed in the capacitive sensor holder. Further, the sample has been exposed as shown in Figure 4. Sample was unloaded at this point.
3. The sample was placed in the measurement system and the load was applied. Measurements were made.
4. Measurements at point 4, Figure 5.
5. Measurements at point 5, Figure 5.
6. Measurements at point 6, Figure 5.

7. Measurements at point 7, Figure 5.

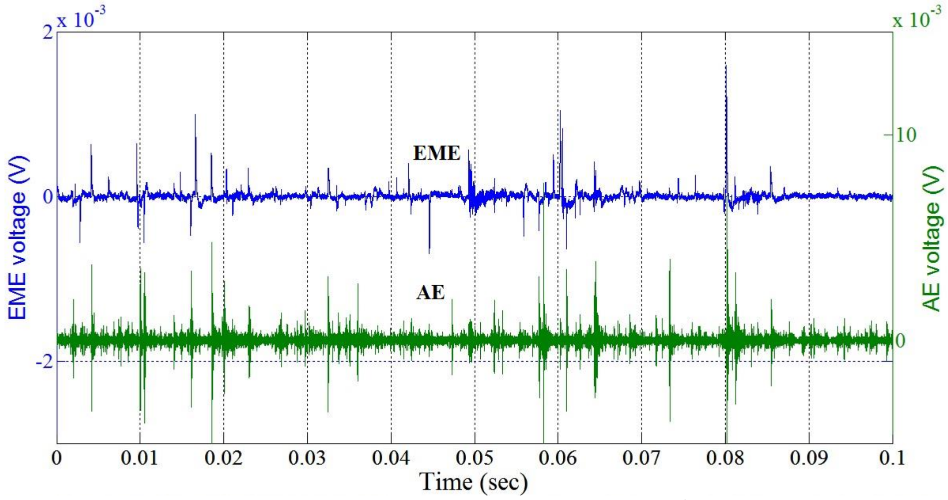

Fig. 3: Continuous EME and AE signals, sample V4, applied force 31.5 kN

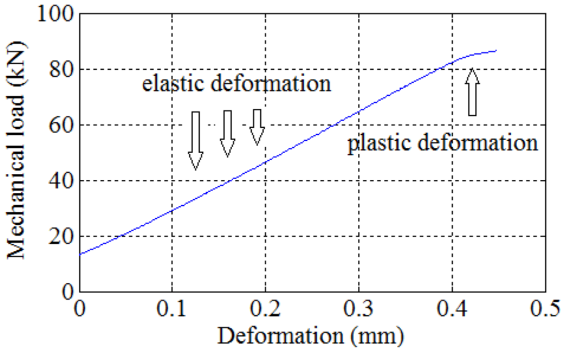

Fig. 4: Mechanical load versus sample deformation (compression) in the first phase of the experiment

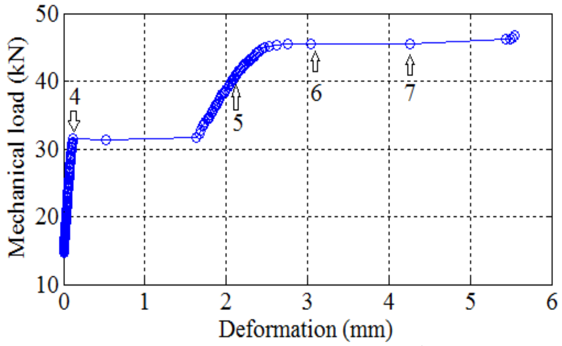

Fig. 5: Mechanical load versus sample deformation (compression) in the second phase of the experiment

STATISTICAL CHARACTERISTICS

We assume that the generation of EME pulses is a Poisson process. The time between each pair of consecutive events has an exponential distribution, which we can described by the formula (2).

Figure 6 and 7 shows probability density function of time intervals between the EME pulses under different load forces (data sets for points № 4 and № 7). These functions are based on the experimental data. We used curve fitting based on formula (2) to obtain the coefficient λ for individual applied forces. This approximation has been drawn in these figures.

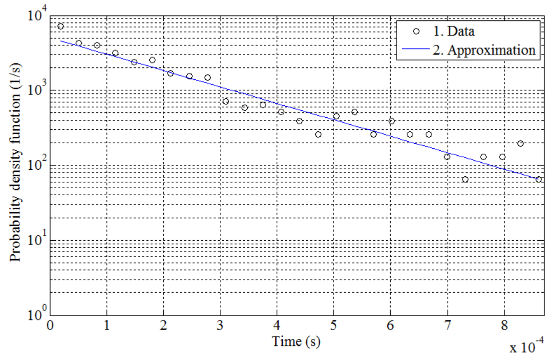

Fig. 6: Probability density function of the time between the inception of two subsequent EME pulses, sample V4, applied force 31.5 kN

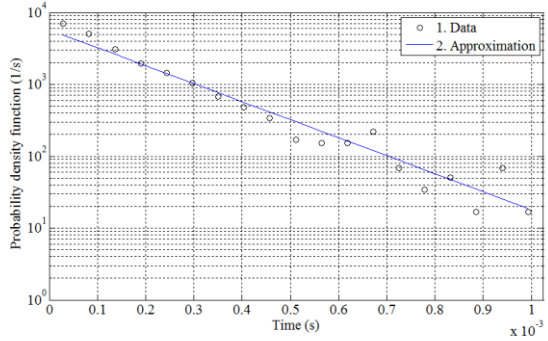

Fig. 7: Probability density function of the time between the inception of two subsequent EME pulses, sample V4, applied force 45.5 kN

Further we calculated the mean value and the dispersion of the time between two subsequent pulses for obtained coefficients λ according to the formulas (3) and (4) (see tab.1).

Tab.1: Statistical characteristics of EME signals

	Applied force 31.5 kN	Applied force 45.5 kN
λ [s^{-1}]	5048	5770
τ_0 [s]	$1{,}98 \cdot 10^{-4}$	$1{,}73 \cdot 10^{-4}$
D [s^2]	$3{,}92 \cdot 10^{-8}$	$3{,}00 \cdot 10^{-8}$
$\sqrt{D}$ [s] (standard deviation)	$1{,}98 \cdot 10^{-4}$	$1{,}73 \cdot 10^{-4}$

Generally, we can use the second way to verify that the process is a Poisson process.

We calculate the mean value and the dispersion of the random variable τ using the formulas

$$\tau_0 = \frac{\sum_1^N \tau_i}{N}, \tag{6}$$

$$D = \frac{\sum_1^N (\tau_i - \tau_0)^2}{N}. \tag{7}$$

Tab.2: Statistical characteristics of EME signals (second calculation method)

	Applied force 31.5 kN	Applied force 45.5 kN
τ_0 [s]	$1{,}86 \cdot 10^{-4}$	$1{,}52 \cdot 10^{-4}$
D [s^2]	$4{,}32 \cdot 10^{-8}$	$3{,}24 \cdot 10^{-8}$
$\sqrt{D}$ [s] (standard deviation)	$2{,}07 \cdot 10^{-4}$	$1{,}80 \cdot 10^{-4}$

From Tables 1 and 2 we see that values τ_0 and $\sqrt{D}$ are approximately equal. This means that we are entitled to assert that the generation of EME pulses can be approximately described as a Poisson process.

SPECTRAL ANALYSIS

Figure 8 shows the voltage power spectral density at various stages of loading of a composite sample. The numbering of the data points in the legend corresponds to the experiment number. Spectral densities № 1, and № 2 taken without load, corresponds to the background noise and have the smallest value. During loading, the spectral densities increase (№3, № 4, № 5, № 6, № 7). Thus it confirms the presence of EME signals. Data sets numbers № 4, and № 7 show maximum spectral densities, however 4th graph was obtained at a much lower load. This is due to the fact that the maximum is observed before the appearance of a fault.

The transition from Figure 8 to Figure 9 is described in detail in [6].

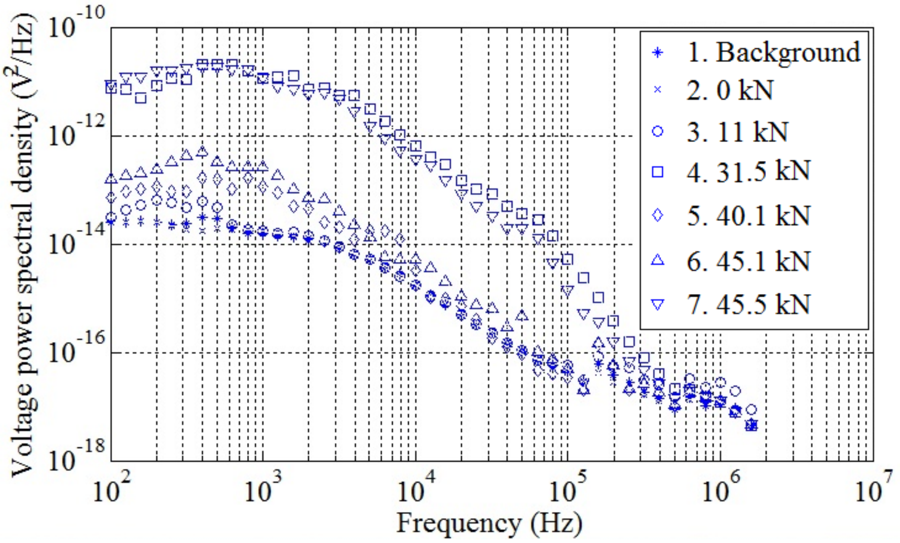

Fig. 8: Voltage power spectral density of measured EME signals at various stages of loading of the composite sample

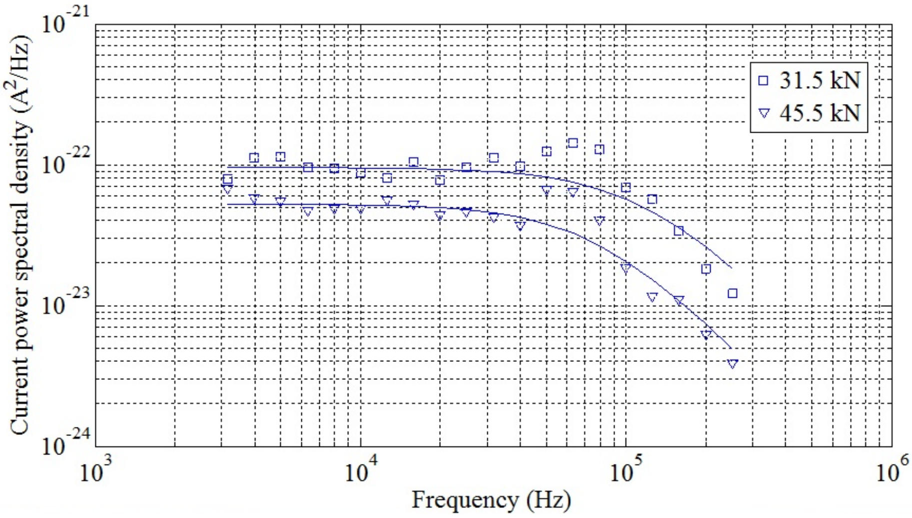

Fig. 9: Current power spectral density of the equivalent current source

Figure 9 shows the current power spectral density of the equivalent current source which represents transport of electric charges during cracks creation. We used for evaluation of these characteristics the formula [5]

$$S_i(\omega) = \frac{S_u(\omega)}{\left|K_{ui}(j\omega)\right|^2}, \qquad (8)$$

where $K_{ui}(j\omega)$ is a modulus of transfer function [6], $S_u(\omega)$ (Figure 8) is a voltage power spectral density of EME signal.

Cutoff frequencies for the curves in Figure 9 are equal to f_c = 110290 Hz for 31.5 kN and f_c = 75988 Hz for 45.5 kN.

The cut-off frequency represents the mean frequency of EME pulses.

CONCLUSION

EME signals at the output of the capacitance sensor were measured and evaluated for different phases of mechanical loading. Investigated signals were taken in a small period of time, so they can be considered for stationary.

We studied statistical characteristics of the equivalent current source which represents cracks creation process and we evaluated some important parameters of this process. We found out that the distribution of the time interval between two subsequent pulses is exponential.

The current power spectral density of the equivalent current source were evaluated by means of the measurement system transfer function. It has been found that the current power spectral density has the character of the generation-recombination spectrum.

Finally, we can conclude that cracks creation can be described approximately as the Poisson process when cracks occur in a large number of independent centers for our case.

ACKNOWLEDGMENTS

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