Global Journal of Researches in Engineering: F
Electrical and Electronics Engineering
Volume 19 Issue 3 Version 1.0 Year 2019
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

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GJRE-F Classification: FOR Code: 090609

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I. Introduction

Most of the signals that we may come across with in the real life are similar to temperature changes of the environment during some period of time, oscillations in potential difference on the resistor, changes of stock exchange rate, deviations in intensity of car traffic, etc. For instance, it is presented below the encephalogram of the cerebral cortex of the patient (fig.1).

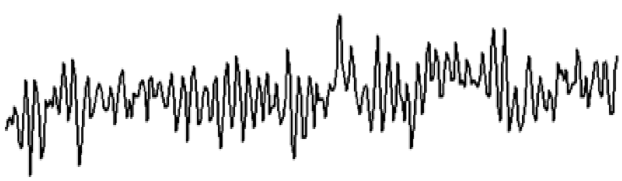

Fig. 1: Example of stochastic signal

Further processing of such signal that includes computing of its power spectral density (PSD) *S(f)* mainly leads to frequency dependence such as: $S(f)=\frac{c}{f^{\gamma}}$, where $\gamma \approx 0.8 \div 1.2$. Signals the spectrum of which corresponds to high-mentioned PSD are known as FN or *1/f*-noise.

An obstacle for creating FN model is a few of unsolved yet contradictions between the FN concept and experiment. Among them we highlight the next items: 1) contradiction between model of singular FN source and experimental results of FN studies caused by finite probability of different sources existence in the same objects; 2) contradiction between FN models of $S(f) \sim 1/f^{\gamma}$, where degree of power γ is clearly defined ($\gamma=1$ or $\gamma=2$), and results that underlines the variance of γ values ($\gamma=0.8\div1.2$); 3) models, that satisfactory describe experimental results of FN-study in electrical systems, are not able to explain of FN existence for biological, geological and other systems. and vice versa.

Therefore, the creation of an adequate FN model, which would be confirmed by the experimental results and would be able to explain the mechanisms of FN formation, seems to be quite important problem. If it could be solved, we would be able to select the electronics components with guaranteed low level of their own noise in low frequency range, and, as a result, to increase sensitivity of measuring equipment at aforementioned frequencies. That is important in medical, biological, and other branches/

II. Study of Equilibrium and Non-Equilibrium Systems Noise

Basing on own FN studies or/and on analysis of known results authors of [1-11] have suggested the mechanisms that explain the *1/f* type spectrum specific. Nevertheless, this approach his suitable more or less for the particular experimental results in contrast to most other studies unattainable using it. Reasons are rooted in limits of authors' possibilities that are the next. Finite choice of studied objects and complexity of manipulation of their parameters as well as of the measurement process usually restrict the research. This problem could be solved to some extent with simulation modeling.

Particular interest among various hypotheses on FN formation is induced to hypothesis of FN formation in non-equilibrium thermodynamic systems assured by computer simulation. Aforesaid model is developed in this paper. It allows mimicking the fluctuations in equilibrium and non-equilibrium systems by chaotic movement of balls in flat rectangle where nontransparent partitions could be placed. Size and allocation of partitions, number of balls and their speed could be changed. During chaotic movement of balls they elastically bounce from the partitions and walls of the rectangle. During defined temporal range (*N* sample) the number of balls that touched the right and left sides of the rectangle is calculated; their difference *Δ n* is computed and displayed in fig. 2. PSD of such fluctuations is also computed and presented below as diagram. Such computer model is able to mimic the change of potential difference / noise on the edges of unloaded film resistor.

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Imitation of fluctuations in the equilibrium system was performed during chaotic movement of balls in 2-dimention space of rectangle without partitions or with entire partition that divides the rectangle on parts. Probability of location of any ball at any place of considered space is the same. It explains the equilibrium of such system. Some models of equilibrium systems and corresponding PSDs of chaotic movement of balls are shown in fig.3.As you can see, PSD of simulated system is unchanged in the studied frequency range regardless of the location of the partition.

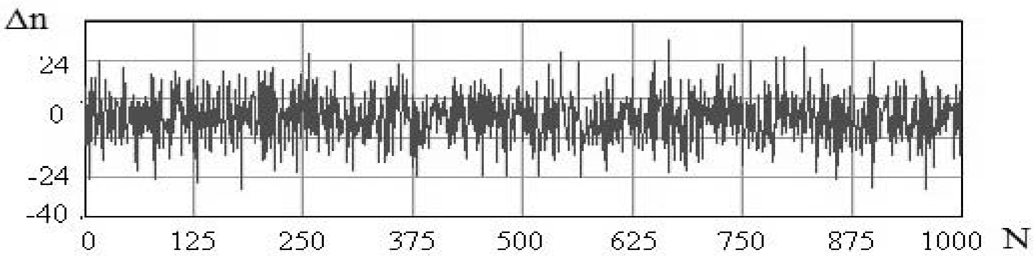

Fig. 2: Computer model of fluctuations

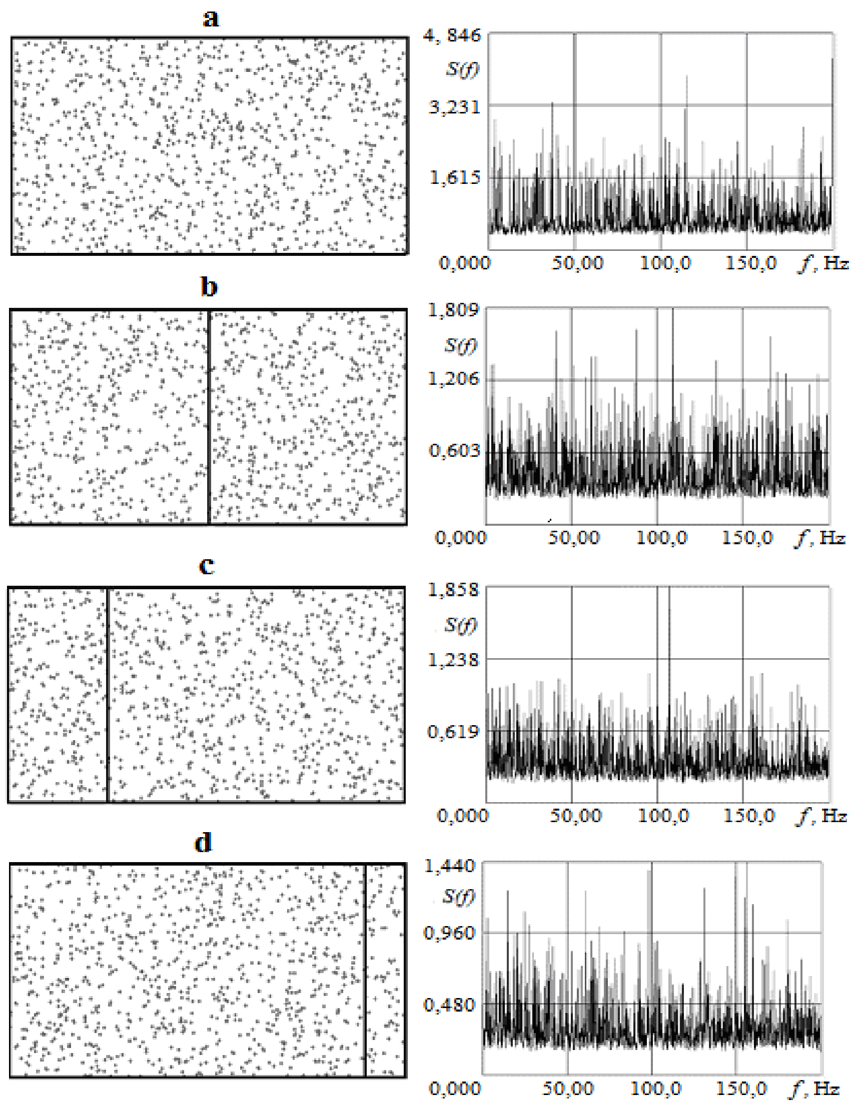

Fig. 3: Models of equilibrium systems and their corresponding PSD at chaotic movement of balls

Non-equilibrium of the system was modeled by the presence of slits in the partition (fig.4.) since the probability of location of any ball at any place of considered space is not the same. The narrower the slit or the more the non-equilibrium system is, the more similar the energy spectrum to the flicker noise. If the slit is expanding or system moves to a state of equilibrium, energy spectra smoothly transform into the spectrum of equilibrium system. Conclusion of results analysis of computer modeling leads to the possibility to state following:

- For equilibrium systems the PSDS (f) of fluctuations in the range from 0 to the frequency that tends to infinity, is the same.
- Raise of PSD *S (f)* of fluctuations when *f* moves to zero (*f*→*0*) is inherent in the systems that are in non-equilibrium state.

Since real systems are in a non-equilibrium state, non-equilibrium state can be considered as a particular case of the equilibrium state; if external influences on the system are absent or the last one is isolated, after a while appears that it is in equilibrium.

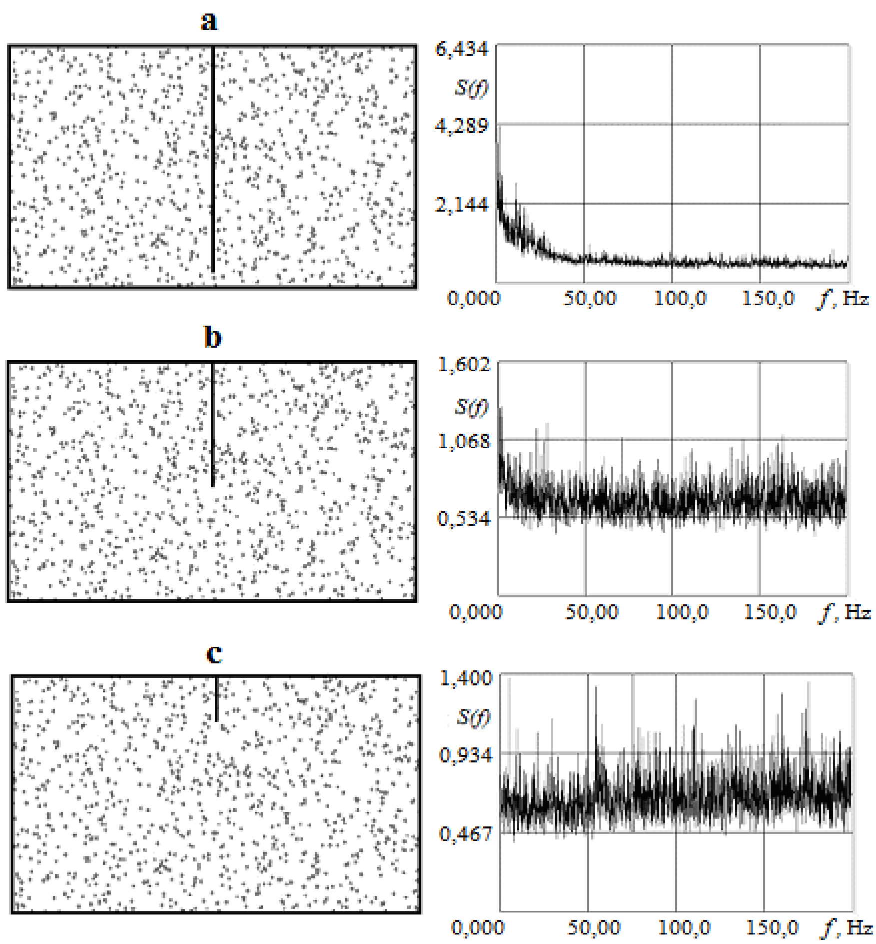

Fig. 4: Model of unbalanced system and its PSD for chaotic movement of balls

Let's designate P_B as fluctuations probability of parameters of system in an equilibrium state, and P_{NB} as similar probability of non-equilibrium system. Accordingly, PSD of fluctuations in equilibrium system is S_B *(f)*, and the same parameter in non-equilibrium system is S_{NB} *(f)*.

The link between S_B *(f)* and S_{NB} *(f)* for isolated system, that for a certain time period is smoothly changing from non-equilibrium state to equilibrium, can be expressed as:

$$P_B \cdot S_B(f) = P_{NB} \cdot S_{NB}(f)\,. \tag{1}$$

Value of P_{NB} from [12] representing the fluctuations probability of non-equilibrium system is the next:

$$P_{NB} = 1 - e^{-f\cdot\tau} \tag{2}$$

Here *f* is fluctuations frequency; τ is system relaxation time. From thermodynamics, probability of fluctuations in isolated system which is in equilibrium state, equals to 1(P_B= 1), and PSD of considered system is unchanged able S_B *(f)* = S_0 =*const* with in frequency range from 0 up to ultrahigh frequencies, where quantum effects arise [13].From (1) and (2) it can be obtained equation for PSD of fluctuations of non-equilibrium system:

$$S_{NB}(f)=\frac{e^{f\cdot\tau}}{1-e^{f\cdot\tau}}\cdot S_B(f) \qquad (3)$$

From (3) at $\tau\to\infty$ where system will be in equilibrium, $S_{NB}(f)=S_B(f)=S_0=const$. For $\tau<\infty$ and $f\to 0$ formula (3) takes the form:

$$S_{NB}(f)=\frac{e^{f\cdot\tau}}{1-e^{f\cdot\tau}}\cdot S_B(f)\approx S_B(f)+\frac{1}{f}\cdot\frac{S_B(f)}{\tau}=S_0+\frac{1}{f}\cdot\frac{S_0}{\tau} \qquad (4)$$

The last contains two components, one of which corresponds to equilibrium fluctuations $S_B(f)=S_0$, and the other one to fluctuations of $1/f$ type (flicker noise). This is consistent with known experimental results.

By experimentally determined fluctuations spectrum, from (3) at $f_0=\frac{1}{\tau}$ one can define relaxation time of system. So, $S_{NB}(f_0)\approx 1.58\cdot S_0$, where the value of S_0 corresponds to $S_{NB}(f)$ in range of middle frequencies, and relaxation time is $\tau=\frac{1}{f_0}$. Analysis of the results of computer modeling shows that the relaxation time τ depends on the characteristics of internal structure of system.

Fig.5 is given the computer modeling of the system with different inner structure and energy spectrum approximated by (3). There from, it can be seen that different structures are inherent in the different values τ. Apparently, FN can be considered not only as interference, but as informative signal that holds data about the features of internal structure of system [14].

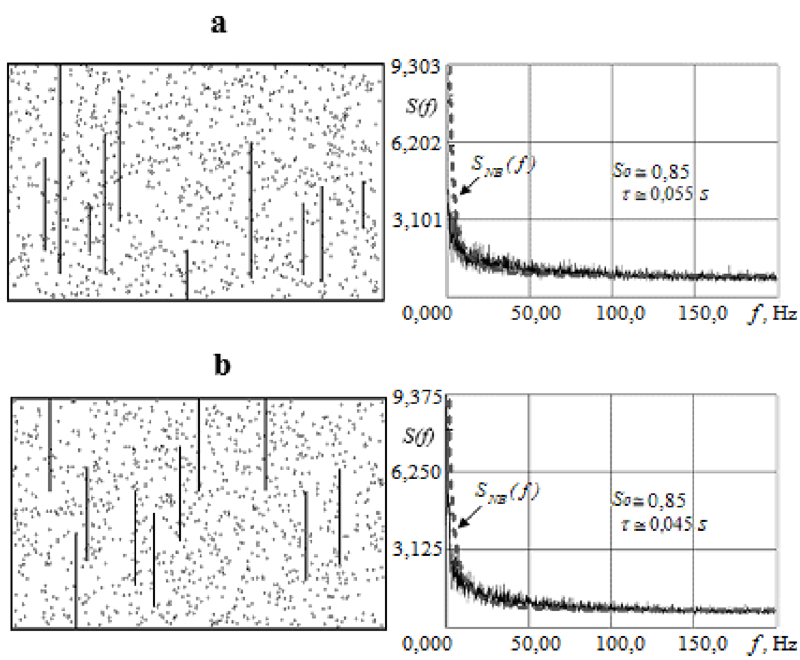

Fig. 5: Dependence of parameter τ on internal structure of system

Equation (3) is applied for approximation experimental energy spectra of: encephalograms of patients P1 and P2 (fig.6.a, [15]), noise of graphene FETs (fig.6.b, [16]), noise of FETs (fig.6. c, [17]).It can be concluded from fig.6 that the quality of approximation is sufficiently high. S_0 and τ are needed while approximation. For the electronic elements the value of $S_0$is equal to PSD the latter is computed with help of Nyquist formula designed for the equilibrium thermodynamic system; the value of τ can be found experimentally, as it was mentioned before or perhaps it is possible to calculate τ using diffusion coefficient.

III. Conclusions

Considered noise model of thermo dynamic systems that can exist in equilibrium and non-equilibrium states enables to avoid the row of contradictions between FN concept and experimental data. System in equilibrium state does not generate flicker noise.

Derived formula describes PSD fluctuations in any real non-equilibrium system, regardless of its nature. It is revealed that dependence of the PSD of FN is exponential and not $\sim 1/f^{\gamma}$. Nature of $1/f$ noise is the same as of thermal noise. The first one cannot be considered as a specific noise caused by the particularity of processes in the system (slow relaxation processes, superposition of random processes, abnormal Brownian motion, etc.).

So, it becomes possible to explain the dissimilarity between the noises of low-frequency energy spectra of two similar samples due to difference of their internal structures in τ parameter.

Growth of spectral components at $f \rightarrow 0$ indicates that the system is in a non-equilibrium state; its flicker noise is caused by chaotic motion of the particles (electrons, ions) from which the system consists and their interaction with structural elements (defects)of system.

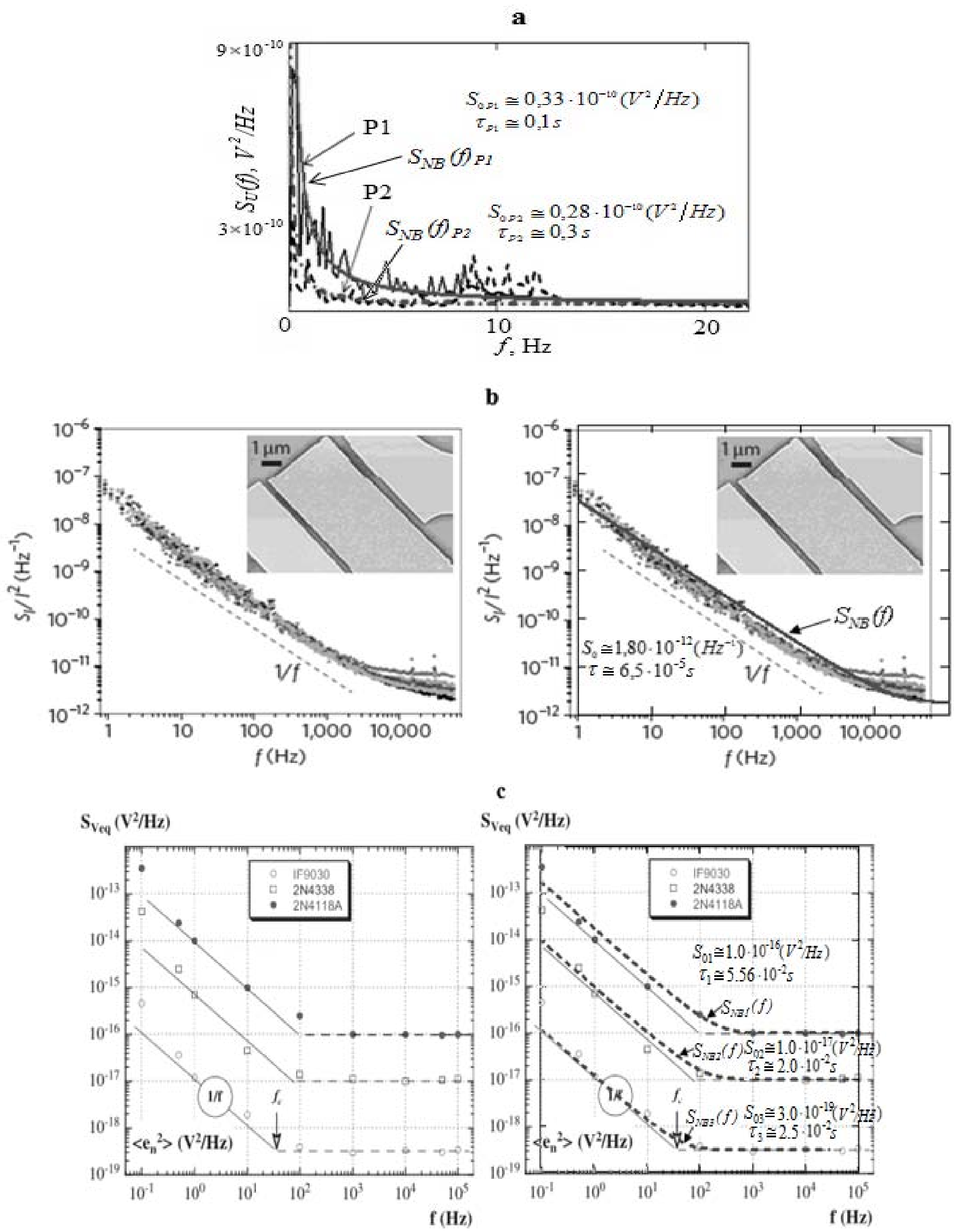

Fig. 6: Experimental PSDs and their approximation for: human encephalograms (a), noise of graphene FET (b), noise of FET (c)

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