UNIVERSITY OF SZEGED
DEPARTMENT OF EXPERIMENTAL PHYSICS

Stochastic resonance-induced signal improvement and neurocardiological fluctuations

PhD dissertation theses

Written by:
Péter Makra

Supervisor:
Dr Zoltán Gingl
senior lecturer

SZEGED
2006

Introduction

The way we think of noise changed fundamentally in the last century. While noise had been regarded as a definitely harmful factor that limits the precision of measurements and makes it more difficult to obtain information on a system, in the last decades the use of noise as an information source or the of a constructive role played by noise in some systems wherein it contributes to the optimal performance of the system came more and more to the foreground. We can take as examples of the former the monitoring of nuclear-reactor operation on the basis of neutron-flux fluctuations or the assessment of the reliability of integrated circuits through their electrical noise, while the constructive role of noise is exemplified by the phenomenon of stochastic resonance. The latter is a general term for those processes in which the noise either inherent in a system or introduced from outside optimises system performance in a certain respect—this optimisation is most often reflected in the signal-to-noise ratio at the output of the system. This dual role of noise—constructive and as information source—determines the structure of my thesis: first I report on my work related to stochastic resonance, then present the results of our cooperation with a medical research team, within the framework of which analysing the fluctuations inherent in human circulation and respiration may advance our understanding of circulatory regulation.

In respect of signal-to-noise ratio as the measure of optimisation, stochastic resonance simply means that the output signal-to-noise ratio is better in the presence of input noise than without noise. Yet the question may arise whether noise can also make the output signal-to-noise ratio greater than its input counterpart, that is, whether stochastic resonance may involve an input-output signal-to-noise ratio gain. In my thesis I show that this is possible in the double-well system—which counts as the archetypal model of stochastic resonance—if the deterministic input is not sinusoidal but pulsatile. In order to decide whether this signal-to-noise ratio gain can be attributed to the limited response time of the system that follows from its dynamics, I examine if signal-to-noise ratio improvement induced by stochastic resonance occurs in the non-dynamical Schmitt trigger. Both in the double-well system and in the Schmitt trigger I explore how the obtainable signal-to-noise ratio gain depends on the amplitude and duty cycle of the deterministic input signal. Motivated by the fact that in some systems coloured noises have been reported to optimise stochastic resonance in a way, I investigate how coloured noises at the input affect the value of the signal-to-noise ratio gain, show the differences between the narrow-band and wide-band definitions of signal-to-noise ratio also in this respect and analyse the possible reasons for the existence of a definite maximum in the narrow-band gain that occurs for certain coloured noises.

In the second part of my thesis I give an account of two medical projects in which noise (in particular, the fluctuations of human heart rate, blood pressure and respiration) serves as an information source. In the first we studied the effects of blood loss on human circulatory regulation; here my task was to analyse the frequency of the respiration. In the second experiment, for which I calculated the time-domain measures of heart-rate fluctuations and made Poincaré plots, we analysed the effects of smoking on circulatory parameters.

Methods

I used an analogue circuitry in the simulations concerning signal-to-noise ratio gain induced by stochastic resonance in a double-well system. I applied numerical simulations to study the stochastic resonance in the Schmitt trigger and the effect of coloured noises on the signal-to-noise ratio improvement by stochastic resonance. Both for processing the data of the analogue simulations and for carrying out the numerical simulations themselves I used the *LabVIEW 6i* graphical programming environment. The latter also served as the programming background of the calculations I performed for the medical projects.

New scientific results

1. Our research group was the first to demonstrate significant signal-to-noise ratio gain induced by stochastic resonance in the double-well system, contradicting all previous expectations which predicted the opposite. Using analogue simulations, I have explored how the gain depends on the amplitude and duty cycle of the pulsatile input signal. I have reinforced the view that signal improvement by stochastic resonance is strongest in the non-linear transfer range, and the gain increases with the amplitude. I have shown that the gain is greater for signals with smaller duty cycles (smaller pulse widths), which may explain why prior studies with sinusoidal excitations did not succeed in achieving gains greater than one. I have provided a simple phenomenological explanation of the mechanism behind the gain [T1].

2. Using numerical simulations, I have compared the characteristics of the signal improvement by stochastic resonance in the Schmitt trigger to those obtained in the double well. I have shown that greater gain is possible in this non-dynamical system than in the double well and this gain is less dependent on the amplitude of the input signal. The investigations have nevertheless revealed that in the Schmitt trigger the mechanism behind the signal improvement induced by stochastic resonance is highly similar to that in the double well, which suggests that the signal improvement in the latter does not arise from the dynamics of the system [T2].

3. From several different angles I have provided proof that for the purpose of characterising stochastic resonance it is more appropriate to use a wide-band interpretation of the signal-to-noise ratio that is more application-orientated than the classical narrow-band version. As the simplest demonstrations show, this interpretation of the signal-to-noise ratio—being, almost without exception, the one used in practice—reflects the noise content of a signal much more accurately than the definition adopted in the literature on stochastic resonance, while, for example, in the double well it yields signal-to-noise ratio gains greater than one for a much wider parameter range, and it does not tend to suggest a dubious optimisation effect for coloured excitations [T1, T3].

4. Through my numerical simulations I have explored, in an asymmetric level crossing detector and in the Schmitt trigger, how the signal-to-noise ratio gain induced by stochastic resonance depends on the spectral exponent κ of the $1/f^{\kappa}$-type coloured noise applied as stochastic excitation. I have pointed out that the gain based on

the wide-band definition of the signal-to-noise ratio, in contrast to the results pertaining to certain neuron models, does not show any optimisation effect in regard to the spectral exponent: with increasing κ the obtainable maximum of the gain decreases, and the standard deviation of the noise required to reach the gain maximum increases. At the same time, the gain based on the narrow-band signal-to-noise definition adopted in the literature on stochastic resonance exhibits a definite non-monotonicity: at a certain non-zero spectral exponent the gain has a distinctive maximum. I have shown that this behaviour is not so much a real optimisation as an effect inherent in the narrow-band definition, which depends on the relative frequencies of the signal and the noise [T3].

5. With a frequency-domain analysis carried out for the purpose of studying autonomic responses to volume loss during blood donation, I have shown that the central breathing frequency of the subjects does not change significantly after blood donation. The importance of this observation lies in the fact that at the same time our study reported a significant rise in power in the respiration-related high-frequency domain of the blood pressure spectrum, and since respiration affects both heart rate and blood pressure signals, we need to monitor the frequency of respiration to explore the autonomic mechanisms regulating blood pressure [T4].

6. In a study aimed at analysing the effects of smoking on cardio-vagal autonomic control, by calculating RR parameters and creating Poincaré plots, I helped to show that smoking a single cigarette can change the time-domain parameters of blood pressure and heart rate variability significantly: while the blood pressure rises, the mean and the standard deviation of RR intervals, the root mean square of the difference of successive intervals (rmsSD) and percentage of the successive intervals more than 50 ms different (pNN50) decrease significantly. Furthermore, the values of the baroreflex parameters reflecting the strength of the effect of blood pressure changes on heart rate also drop considerably. On the basis of this study, the adverse effects of smoking reported in previous studies with chronic smokers as their subjects can be generalised to include non-smokers and passive smokers as well [T5].

Papers on which the thesis is based

[T1] GINGL Z – MAKRA P – VAJTAI R. ‘High signal-to-noise ratio gain by stochastic resonance in a double well.’ *Fluctuation and Noise Letters*, **1** (2001): L181–L188. p.

[T2] MAKRA P – GINGL Z – KISH, L B. ‘Signal-to-noise ratio gain in non-dynamical and dynamical stochastic resonators.’ *Fluctuation and Noise Letters*, **2** (2002): L147–L155. p.

[T3] MAKRA P – GINGL Z – FÜLEI T. ‘Signal-to-noise ratio gain in stochastic resonators driven by coloured noises.’ *Physics Letters A*, **317** (2003): 228–232. p.

[T4] ZÖLLEI É – PAPRIKA D – MAKRA P – GINGL Z – VEZENDI K – RUDAS L. ‘Human autonomic responses to blood donation.’ *Autonomic Neuroscience: Basic and Clinical*, **110** (2004): 114–120. p.

[T5] HALMAI L – RUDAS M – MAKRA P – GINGL Z – RUDAS L. 'A dohányzás azonnali hatása a kardiovaszkuláris autonóm regulációra.' *Cardiologia Hungarica,* **33** (2003): 110–116. p.

Other papers and conference talks

[1] GINGL Z – MAKRA P – FÜLEI T – VAJTAI R – MINGESZ R. 'Colored noise driven stochastic resonance in a double well and in a FitzHugh-Nagumo neuronal model.' *16th International Conference on Noise in Physical Systems and 1/f fluctuations (ICNF).* Gainesville, USA, 22–25 October 2001. In BOSMAN, G (ED). *Proceedings of the 16th International Conference on Noise in Physical Systems and 1/f fluctuations.* World Scientific, 2001, 420–423. p.

[2] GINGL Z – VAJTAI R – MAKRA P. 'High signal-to-noise ratio gain by stochastic resonance in a double well.' *16th International Conference on Noise in Physical Systems and 1/f fluctuations (ICNF).* Gainesville, USA, 22–25 October 2001. In BOSMAN, G (ED). *Proceedings of the 16th International Conference on Noise in Physical Systems and 1/f fluctuations.* World Scientific, 2001, 545–548. p.

[3] GINGL Z – MAKRA P. 'A dynamical system exhibits high signal-to-noise ratio gain by stochastic resonance.' *Third International Conference on Unsolved Problems of Noise and Fluctuation in Physics, Biology and High Technology (UPoN).* Washington DC, USA, 2–6 September 2002. In BEZRUKOV, S M (ED). *Proceedings of the Third International Conference on Unsolved Problems of Noise and Fluctuations in Physics, Biology and High Technology (AIP Conference Proceedings 665).* Melville: American Institute of Physics, 2003, 100–108. p.

[4] GINGL Z – MINGESZ R – MAKRA P. 'On the amplitude and time-structure properties of $1/f^{\alpha}$ noises.' *Third International Conference on Unsolved Problems of Noise and Fluctuation in Physics, Biology and High Technology (UPoN).* Washington DC, USA, 2–6 September 2002. In BEZRUKOV, S M (ED). *Proceedings of the Third International Conference on Unsolved Problems of Noise and Fluctuations in Physics, Biology and High Technology (AIP Conference Proceedings 665).* Melville: American Institute of Physics, 2003, 578–583. p.

[5] RUDAS L – PAPRIKA D – ZÖLLEI É – MAKRA P – GINGL Z. 'Autonomic responses to blood donation.' *Blood Pressure and Heart Rate Variability: New Technologies – Drug Effects, Hungarian Satellite Symposium to* Hypertension (Prague). Budapest, 28 June 2002.

[6] GINGL Z – MAKRA P – GÁSPÁR M – ZÖLLEI É – PAPRIKA D – RUDAS L. 'About the frequency-domain analysis of unevenly sampled heart rate and blood pressure signals.' *Blood Pressure and Heart Rate Variability: New Technologies – Drug Effects, Hungarian Satellite Symposium to* Hypertension (Prague). Budapest, 28 June 2002.

[7] FÜLEI T – GINGL Z – MAKRA P. 'Mechanism of signal-to-noise ratio gain in a monostable threshold stochastic resonator.' *Fluctuations and Noise.* Santa Fe, USA, 1–4 June 2003. In SCHIMANSKY-GEIER, L *&al* (EDS). *Noise in Complex Systems and Stochastic Dynamics (Proceedings of SPIE Vol 5114).* Bellingham: SPIE, 2003, 327-334. p.

[8] MAKRA P – FÜLEI T – GINGL Z. 'Possibilities of signal-to-noise ratio gain in stochastic resonators driven by coloured noises.' *17th International Conference on Noise and Fluctuations.* Prague, Czech Republic, 18–22 August 2003. In SIKULA, J (ED). *Proceedings of the 17th International Conference on Noise and Fluctuations.* Brno: CNRL, 2003, 85–88. p.

[9] MINGESZ R – GINGL Z – MAKRA P. 'Level-crossing time statistics of Gaussian $1/f^{\alpha}$ noises.' *17th International Conference on Noise and Fluctuations.* Prague, Czech Republic, 18–22 August 2003. In SIKULA, J (ED). *Proceedings of the 17th International Conference on Noise and Fluctuations.* Brno: CNRL, 2003, 505–508. p.

[10] MAKRA P – GINGL Z – FÜLEI T. 'Signal-to-noise ratio gain in stochastic resonators driven by coloured noises.' *Fluctuations and Noise 2004.* Maspalomas, Gran Canaria, Spain, 26–28 May 2004. In GINGL Z *&al* (EDS). *Noise in Complex Systems and Stochastic Dynamics II (Proceedings of SPIE Vol 5471).* Bellingham: SPIE, 2004, 213–221. p.

[11] MINGESZ R – BARA P – GINGL Z – MAKRA P. 'Digital Signal Processor (DSP) based $1/f^{\alpha}$ noise generator.' *Fluctuations and Noise 2004.* Maspalomas, Gran Canaria, Spain, 26–28 May 2004. In WHITE, L B (ED). *Noise in Communication (Proceedings of SPIE Vol 5473).* Bellingham: SPIE, 2004, 213–221. p.

[12] MINGESZ R – BARA P – GINGL Z – MAKRA P. 'Digital Signal Processor (DSP) based $1/f^{\alpha}$ noise generator.' *Fluctuations and Noise Letters,* **4** (2004): L605–L616. p.

[13] MAKRA P – GINGL Z – MINGESZ R. 'Signal-to-noise ratio gain by stochastic resonance and its possible applications.' *International Workshop on Stochastic Resonance: New Horizons in Physics and Engineering.* Dresden, Germany, 4–7 October 2004.

[14] MINGESZ R – MAKRA P– GINGL Z. 'Cross-spectral analysis of signal improvement by stochastic resonance in bistable systems.' *Fluctuations and Noise 2005.* Austin, Texas, USA, 24–26 May 2005. In KISH, L B – LINDENBERG, K – GINGL Z (EDS). *Noise in Complex Systems and Stochastic Dynamics III (Proceedings of SPIE Vol 5845).* Bellingham: SPIE, 2005, 283–292. p.

[15] GINGL Z – RUDAS L – MAKRA P. 'Signal processing problems of neurocardiological fluctuations.' *4th International Conference on Unsolved Problems of Noise and Fluctuations.* Gallipoli (Lecce), Italy, 6–10 June 2005. In REGGIANI, L *&al* (EDS). *Proceedings of the Fourth International Conference on Unsolved Problems of Noise and Fluctuations in Physics, Biology and High Technology (AIP Conference Proceedings 800).* Melville: American Institute of Physics, 2005, 293–298. p.

[16] MINGESZ R – GINGL Z – MAKRA P. 'Marked signal improvement by stochastic resonance for aperiodic signals in the double-well system.' *News, Expectations and Trends in Statistical Physics, NEXT-SigmaPhi 3rd International Conference.* Kolymbari, Crete, Greece, 13–18 August 2005.

[17] MINGESZ R – GINGL Z – MAKRA P. 'Marked signal improvement by stochastic resonance for aperiodic signals in the double-well system.' *European Physical Journal B,* **50** (2006): 339–344. p.