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Research Article

Coupled blood pressure dynamics in magisterial and small arteries networks and its stabilizing effect on heart functioning within the framework of computer model

Abstract

Computer model coupled blood pressure dynamics in magisterial and small arteries networks and its stabilizing effect on heart functioning has been suggested. The Fermi-Pasta-Ulam auto recurrence in the description of the electrical activity of the heart has demonstrated the universal role of the FPU recurrence in the study of distributed dynamical systems. The heart electrical dynamics was described by the coupled Van der Pol differential equations with a time lag, linked with two additively coupled nonlinear differential equations circumscribing the blood pressure dynamics in the networks of magisterial and small arteries. The mathematical model developed by Yuen and Lake for description of the deep wave dynamics within the nonlinear Shrodinger (NSE) equation was used for description of the magisterial arterial blood pressure whereas for small arteries blood pressure dynamics was used the approach elaborated by Zabusky and Kruskal within the framework of the Korteveg de Vries (KdV) equation. The arterial blood pressure dynamics was interpreted as coupled FPU recurrences showing a rich variety of resulting FPU spectra, which were referred to different states of Cardio Vascular System. Synchronous registering of the real ECG and Pulse Wave Fourier dynamic images allowed to unify the characteristic Fourier pictures of the heart electrical activity with the hydrodynamic blood parameters developing in the networks of two types of arteries. The computer study of the suggested model and comparison of its results with the real data proved that the ECG Fourier parameters coupled with the Pulse Wave Fourier parameters form the FPU spectra that increase stability of Cardio Vascular System and can be used for diagnostics as well as for evaluation of the therapeutic arrangements results.

Introduction

In our previous paper [1], it was suggested using the Fermi-Pasta-Ulam auto recurrence phenomenon concept in the description of the electrical activity of the heart. At the same, time the character of the dynamics of blood pressure in magisterial and small arteries networks shows that it is not simply providing the blood stream propagation but plays a significant role in stabilizing the heart functioning within certain parameters as well as probably facilitates the flowing of myocardial infarct. Such assumptions came from qualitatively different pictures of blood pressure profiles in magisterial and small arteries. Assume that the blood pushed by the heart beat into aorta represents a solitary wave similar to that of Yuen and Lake one obtained in their study of deep water wave properties [2]. The role of "heart" in their experimental research played a mechanical wave producer. They developed a mathematical model for description of the deep wave dynamics within the nonlinear Shrodinger (NSE) equation and found a good agree between the mathematical solution and experimental data. Moreover, they proved forming the FPU recurrence profile during propagation of deep waves in experimental channels. In accordance with the NSE, the FPU recurrence functions were odd ones. The deep-water waves, propagation process in their experiment ended on a shallow surface. It is known, that the dynamics of shallow water waves is described by the Korteveg de Vries equation [3]. Zabusky and Kruskal showed in their mathematical model that imposing periodical boundary condition on the KdV equation forms the FPU recurrence spectrum. Considering periodical conditions as heart beatings pushing blood in the "shallow" part consisting of small arteries network and even solution of the KdV equation, one can get the FPU recurrence with even functions in its spectrum. Thus, the dynamics of blood pressure in both networks can be given as a

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mixed odd – even FPU auto recurrence spectrum reflecting the dynamic state of magisterial and small arteries together with the heart state dynamics.

Mathematical Model

The basic core for mathematical model was taken from the coupled Van der Pol model of the heart electrical activity, given in the paper [4]. Trying to simplify the solutions of the NSE and KdV there were used nonlinear second order differential equations with odd non linearity for NSE and even non linearity for KdV equation.

The coupled Van der Pol equations by agreeing coefficients were additively linked to the equations substituting NSE and KdV, forming a new model looking in the following way:

$$\frac{d^2M_1}{dt^2} - a_1(1-Y_1)\frac{dM_1}{dt} + \omega_1{}^2(1+\alpha_1 M_2)M_1 = c_1\frac{d^2M_2}{dt^2} + d_1F_1 + d_2F_2$$

$$b_1Y_1 + T_1\frac{dY_1}{dt} = M_1{}^2$$

$$\frac{d^2H_1}{dt^2} + \frac{dH_1}{dt} + (1 + e_1H_1{}^2 + e_2H_1{}^4 + e_3H_1{}^6)H_1 = k_1M_1 + k_2H_2$$

$$\frac{d^2M_2}{dt^2} - a_2(1-Y_2)\frac{dM_2}{dt} + \omega_2{}^2(1+\alpha_2 M_1)M_2 = c_2\frac{d^2M_1}{dt^2} + d_1F_1 + d_2F_2$$

$$b_2Y_2 + T_2\frac{dY_2}{dt} = M_2{}^2$$

$$\frac{d^2H_2}{dt^2} + \frac{dH_2}{dt} + j_1H_2{}^3 + j_2H_2{}^5 + j_3H_2{}^7 + H_2 = k_3M_2 + k_4H_1 \qquad (1)$$

Where M_1 - is the magnitude proportional to the dynamic electric potential of the whole myocardium, M_2 - is the magnitude proportional to the dynamic electric potential of the myocyte locality on the surface of the myocardium, H_1 - is the magnitude proportional blood pressure in the small arterial network, H_2 - is the magnitude proportional blood pressure in the magisterial arterial network, k_1, k_2, k_3, k_4 - agreeing coefficients,, $e_1, e_2, e_3, j_1, j_2, j_3$ – constant coefficients, Y_1 - is the magnitude proportional to the time lag which requires the propagation of the electric impulse in the myocardium, Y_2 - is the magnitude proportional to the time lag which requires the propagation of the electric impulse in the myocyte locality, b_1 - is the magnitude proportional to the square of the myocardium, b_2 - is the magnitude proportional to the square of the myocyte locality, T_1 - is the magnitude proportional to the time of the myocardium contraction, T_2 - is the magnitude proportional to the period of oscillations in the myocyte locality, ω_1, ω_2 - are the beating frequencies equal to 1, F_1 - is the perturbation function of the resonant external medium effect on the heart at the frequency of about 1 Hz, F_2 - is the perturbation function of the resonant external medium effect on the heart at the frequency of about 20 Hz., $c_1, c_2, d_1, d_2,\ \alpha_1, \alpha_2$ - are the constants.

The study of the model

The computer study of the developed model allowed getting the model solutions corresponding to the healthy state of the heart as well as magisterial and small arteries networks coupled functioning. Figures 1-3 show model ECGs and Pulse Wave Fourier images correspondingly.

The model Fourier images were compared with the ECG and Pulse Wave Fourier data of healthy patients. As it can be seen from the graphs (Figures 4,5), the model Fourier pictures of a healthy patient correspond to the mathematical model solutions.

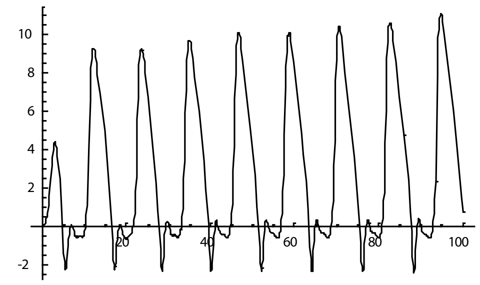

Figure 1: Model ECG of a healthy person.

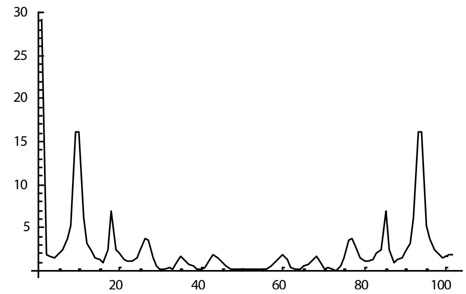

Figure 2: Fourier image of a model ECG of a healthy person.

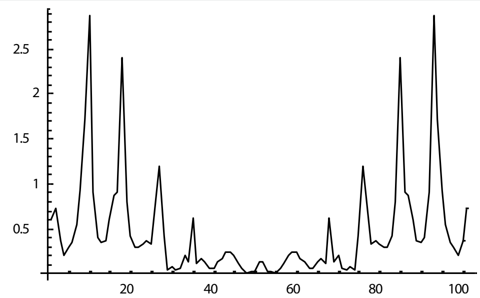

Figure 3: Fourier image of a Pulse Wave of a healthy person.

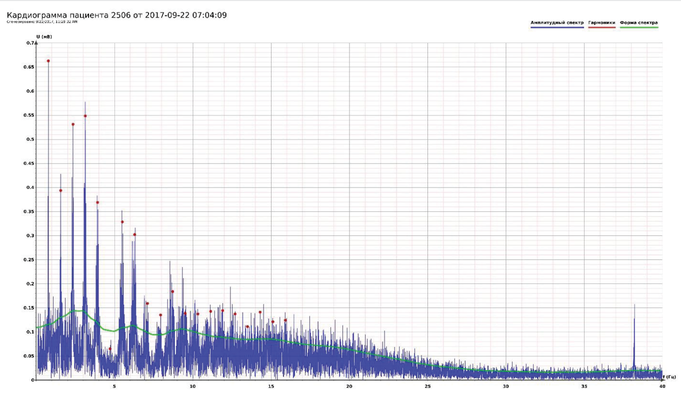

Figure 4: Real Fourier image of a healthy person ECG.

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Next step of modeling was to decrease the myocardial surface by 50% as a model of myocardial infarct. Previous model [4] showed close to fibrillation pictures whereas modeling such situation within a new model (1) demonstrated only a small deterioration of the ECG picture (Figure 6), and its Fourier image (Figure 7), as well as the images of the magisterial and small arteries networks dynamics (Figure 8).

Modeling of fibrillation within a new model proved an ability of the coupled system of the heart and magisterial and small arteries networks to withstand the cardiovascular problems happened due to different reasons. In particular, creating model fibrillation in a new model requires five times larger magnitude of the amplitude of external influence to compare with the magnitude of the amplitude in the previous modeling the state of heart fibrillation without the influence of arterial networks [4]. The arterial networks stabilize the state of heart functioning (Figures 9-11).

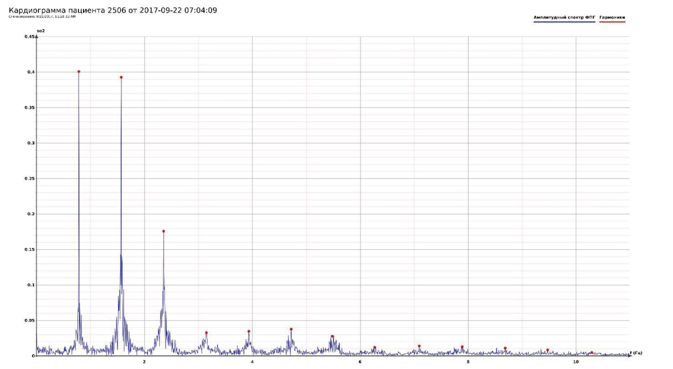

Figure 5: Real Fourier image of a healthy person Pulse Wave.

Figure 6: Model ECG with myocardial infarct.

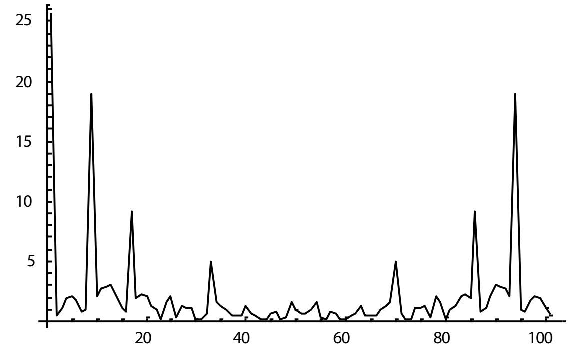

Figure 7: Fourier image of a model ECG with myocardial infarct.

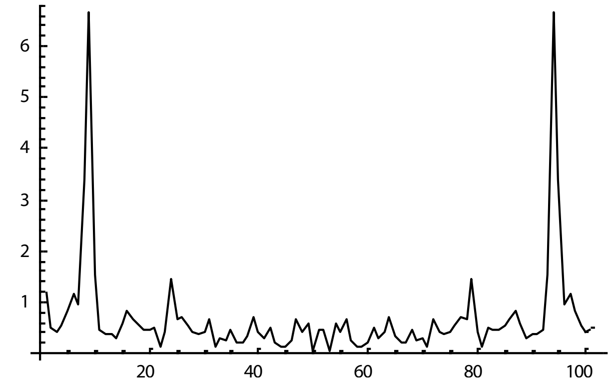

Figure 8: Fourier image of a model Pulse Wave with myocardial infarct.

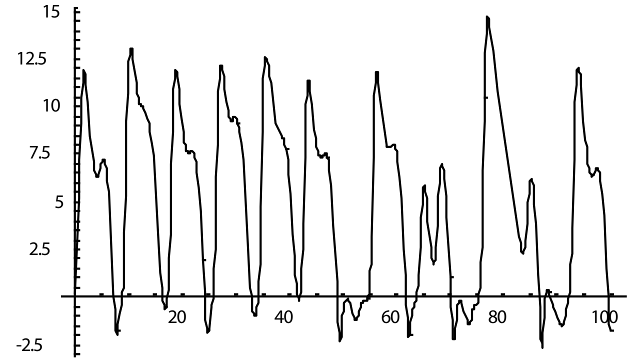

Figure 9: Model heart fibrillation partly stabilized by coupled arterial networks dynamics.

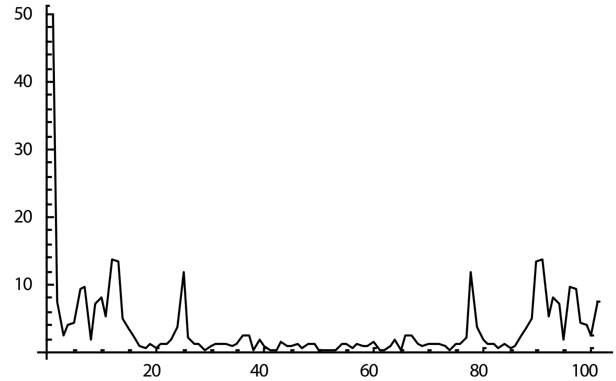

Figure 10: Model Fourier image of heart fibrillation partly stabilized by coupled arterial networks dynamics.

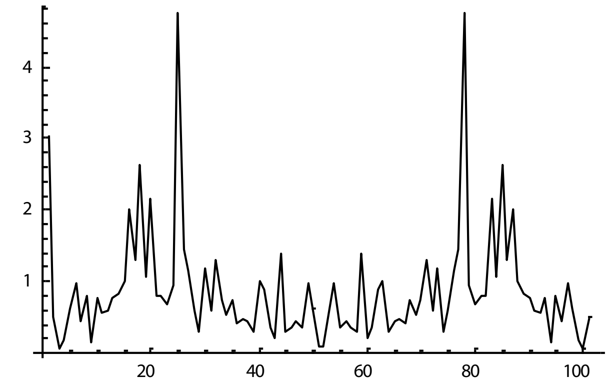

Figure 11: Model Fourier Pulse Wave image of the heart fibrillation partly stabilized by coupled arterial networks dynamics.

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Discussion

The new mathematical model of the coupled system of the heart and magisterial and small arteries networks interacting demonstrated the unified stable working of the system and its increased ability to resist the development of cardiovascular problems such as myocardial infarction. The modeling of blood pressure dynamics in small arteries shows its ability to maintain the necessary blood pressure there as well as to buffer its sharp growth in cases of emotional stress. At the same time, the self-parametric excitation in the equations modeling the dynamics of blood pressure in small arteries points at their principal possibility to blow up healthy small arteries in some anomalous cases causing a brain hemorrhage or a heart attack.

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