BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
DEPARTMENT OF RADIO ELECTRONICS
FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ
ÚSTAV RADIOELEKTRONIKY

UNCONVENTIONAL SIGNALS OSCILLATORS

OSCILÁTORY GENERUJÍCÍ NEKONVENČNÍ SIGNÁLY

SHORT VERSION OF DOCTORAL THESIS
TEZE DISERTAČNÍ PRÁCE

AUTHOR
AUTOR PRÁCE
Ing. ZDENĚK HRUBOŠ

SUPERVISOR
VEDOUCÍ PRÁCE
doc. Ing. JIŘÍ PETRŽELA, Ph.D.

BRNO 2016

KEYWORDS

Dynamical system, OTA, MO–OTA, CCII±, electronic adjusting, oscillator, chaos, vector field, state attractor, eigenvalues, eigenvectors, Poincaré section, Poincaré map, Lyapunov exponents, bifurcation diagram, circuit realizations, autonomous, nonautonomous, practical measurement, digital control, parasitic properties

KLÍČOVÁ SLOVA

Dynamické systémy, OTA, MO–OTA, CCII±, elektronické ladění, oscilátor, chaos, vektorové pole, stavový atraktor, vlastní čísla, vlastní vektory, Poincarého sekce, Poincarého mapa, Ljapunovovy exponenty, bifurkační diagram, obvodové realizace, autonomní, neautonomní, praktické měření, digitální řízení, parazitní vlastnosti

DISERTAČNÍ PRÁCE JE ULOŽENA:

Ústav radioelektroniky
Fakulta elektrotechniky a komunikačních technologií
Vysoké učení technické v Brně
Technická 3082/12
616 00 Brno

CONTENTS

1 Introduction **3**

2 State of the Art **4**
2.1 Active Elements Suitable for Analog Signal Processing 4
2.2 Modeling of the Real Physical and Biological Systems Exhibiting Chaotic Behavior 4
2.3 Aims of Dissertation 5

3 Electronically Adjustable Oscillators Employing Novel Active Elements **6**
3.1 Oscillator Based on Negative Current Conveyors 6
3.2 Study of 3R–2C Oscillator 7
3.3 Multiphase Oscillator Based on CG–BCVA 9
3.3.1 Quasi–Linear Systems vs. Chaotic Systems 10

4 Modeling of the Real Physical and the Biological Systems **11**
4.1 Autonomous Dynamical Systems 11
4.2 Inertia Neuron Model 11
4.3 Nóse–Hoover Thermostat Dynamic System 13
4.4 Chaotic Circuit Based on Memristor Properties 14
4.5 Nonautonomous Dynamical Systems 15

5 Analog–Digital Synthesis of the Nonlinear Dynamical Systems **17**

6 On the possibility of Chaos Destruction via Parasitic Properties of the Used Active Devices **19**
6.1 Influence of Parasitic Properties of Active Elements in Circuit Based on Inertia Neuron Model 19
6.2 Influence of Parasitic Properties of Active Elements in Circuit Based on Memristor Properties 20
6.3 Influence of Parasitic Properties of Active Elements in Circuit Based on Sprott system 22

7 Conclusions **24**

References **27**

1 INTRODUCTION

Chaotic motion is a very specific solution of a nonlinear dynamics systems which commonly exists in nature. Its wide area of applications ranges from simple predator–prey models to complicated signal transduction pathways in biological cells, from the motion of a pendulum to complex climate models in physics, and beyond that to further fields as diverse as chemistry (reaction kinetics), economics, engineering, sociology or demography. In particular, this broad scope of applications has provided a significant impact on the theory of dynamical systems itself, and is one of the main reasons for its popularity over the last decades [13]. It came as a surprise to most scientists when Lorenz in 1963 discovered chaos in a simple system of three autonomous ordinary differential equations with a two quadratic nonlinearities [10].

The solutions of the considered dynamical systems are a state trajectories which are usually displayed in the state area or extended in time. Each autonomous deterministic dynamical system (ADDS) and non–autonomous deterministic dynamical system (NDDS) are fully described by a set of differential equations and initial conditions. Behavior of the ADDS and NDDS should be completely predictable in every time (point of view is that system should go determine by using the phase flow in every time). Nevertheless, it is true for a linear ADDS and NDDS. In this case the solution can be only a limit point or a limit cycle enclosed in a final volume. Suggest that for some a special nonlinear systems, this long-term prediction of the position can not be done. The problem is in extreme sensitivity to initial conditions in which case is completely different pattern for the small variation in the state trajectory. For classical autonomous dynamical systems the basic law of evolution is static in the sense that the environment does not change with time. However, in many applications such a static approach is too restrictive and a temporally fluctuating environment favorable.

Two basic requirements must be meet for beginning of the chaotic oscillations. The first of them was believed to be an unstable hyperbolic fixed point which guarantee that two trajectories going in the neighbourhood are repelled from each other. Divergence of two trajectories be call in this case as a "stretching". This process guarantee sensitivity to initial conditions of the system. In this way is also necessary to eliminate expansion of the system by using curvature of the vector space by non-linear functions. It is call as a " folding". Whereas that two distinct state space trajectories cannot intersect, chaotic ADDS must have at least three state variables. We can say that chaotic attractor is not periodic nor stochastic, however is bounded and looks as a particular element of randomness. Nonlinearity can be represented as multiply of two state variables, the power of one or as a piecewise linear function, etc. This is important also in the case of various electronic circuits. Chaos has been observed in the oscillators with frequency dependent feedback, oscillators with negative resistance elements, etc. The problems covered by chaos theory are universal and can be also observed in the nonautonomous nonlinear dynamical systems with at least two degrees of freedom. There exist many examples where chaos is unwanted phenomenon and can be observed in the networks which are basically linear, for example in filters, oscillators, etc.

2 STATE OF THE ART

In this chapter we present the state of the art in the field of active elements suitable for analog signal processing and modeling of the real physical, biological systems exhibiting chaotic behavior by using analog electronic circuits and techniques for visualization and quantification of chaos.

2.1 ACTIVE ELEMENTS SUITABLE FOR ANALOG SIGNAL PROCESSING

Many active elements that are suitable for analog signal processing were introduced in [2]. Some of them have interesting features, which allow electronic control of their parameters. Therefore, these elements have also favorable features in applications. There are several common ways of electronic control of parameters in particular applications. Development in this field was started with discovery and development of current conveyors (CC) by Smith and Sedra [15], Fabre [6] and Svoboda et al. [18]. Many other active elements with possibilities of electronic adjustability were introduced, innovated and frequently utilized for circuit synthesis and design in the past, for example operational transconductance amplifier (OTA) [7], current feedback amplifiers (CFA) [14], etc. Great review of old and also recent discoveries in the field of active elements was summarized by Biolek et al. [2]. Extensive description of many modifications and novel approaches is given in [2] and in references cited therein.

2.2 MODELING OF THE REAL PHYSICAL AND BIOLOGICAL SYSTEMS EXHIBITING CHAOTIC BEHAVIOR

The research of many scientists and engineers is focused onto relations between the real physical systems and its mathematical models from the viewpoint of study of the associated nonlinear dynamical behavior. In 1963, Lorenz published a seminal paper [10] in which he showed that chaos can occur in systems of autonomous ordinary differential equations (ODEs) with as few as three variables and two quadratic nonlinearities.

Circiut synthesis of the mathematical model is the easiest way how to accurately simulate the autonomous and the non–autonomous dynamical systems. There exist several ways how to practically realize chaotic oscillators. Most of these techniques are straightforward and have been already published [9]. The design procedure can be based on the integrator block schematics or classical circuit synthesis [9, 30]. Alexandre Wagemakers discuss about analog simulations and about the possible advantages and drawbacks of using electronic circuits in his thesis [20]. Advanteges of analog simulation are evident and are many reasons why proceed to system simulation with analog circuit. The components are not perfect and their parameters are changed from component to component. That fact implement in a electronic circuit means that circuit is robust to small parameter changes and is not sensitive to these small differences. The resistance to noise is another benefits, because the influenced of external factors, such as the temperature, are part of real component. Advantages compared with the numerical integration are also in the duration of the simulation and possibilities to change the parameter directly in real time. Chaos, or deterministic chaos, is ubiquitous in nonlinear dynamical systems of the real world, including biological systems. Nerve membranes have their own nonlinear dynamics which generate and propagate action potentials, and such nonlinear dynamics can produce chaos in neurons and related bifurcations [4]. Other example from real world is Nóse–Hoover thermostat. Equations of motion have been applied to the study of fluid and solid diffusion, viscosity, and heat conduction with computer simulation and to the nonlinear generalization of linear response theory required to describe systems far from equilibrium [8].

2.3 AIMS OF DISSERTATION

We can still find areas where can be our focus concentrated in view of the fact that the possibility of the implementation and application of chaotic oscillators are not fully explored and exhausted yet. Structure of the dissertation thesis is divided into four areas and the main aims can be summarized into these categories:

- *Electronically adjustable oscillators suitable for signal generation employing active elements, study of the nonlinear properties of the active elements used, platform for evolution of the strange attractors.*

- *Modeling of the real physical and biological systems exhibiting chaotic behavior by using analog electronic circuits and modern functional blocks (OTA, MO-OTA, CCII±, DVCC±, etc.) with experimental verification of proposed structures.*

- *Research a new possibilities in the area of analog-digital synthesis of the nonlinear dynamical systems, the study of changes in the mathematical models and corresponding solutions.*

- *Detailed analysis of the impact and influences of active elements parasitics in terms of qualitative changes in the global dynamic behavior of the individual systems and possibility of chaos destruction via parasitic properties of the used active devices.*

3 ELECTRONICALLY ADJUSTABLE OSCILLATORS EMPLOYING NOVEL ACTIVE ELEMENTS

3.1 OSCILLATOR BASED ON NEGATIVE CURRENT CONVEYORS

Very simple oscillator employing two negative conveyors CCII– is presented. Oscillation frequency and condition of oscillation may be driven by varying electronically controlled current gains B. A basic variant includes four passive components (two R and two C). Also resistor–less variant with two capacitors only is given. The output signal can be taken from two internal nodes. On the other hand, the disadvantage of this circuit is that one working capacitor is floating and the oscillation frequency may be driven only in a limited range. The proposed tunable oscillator employing two negative conveyors CCII– is shown in Fig. 3.1. The basic variant (Fig. 3.1 - left) has four passive elements, two R and two C. In right Fig. 3.1, the resistor–less version is shown, using the input X resistance (R_x in Fig. 3.1) of the real conveyor. By symbolic nodal analysis the following characteristic equation is obtained

$$s^2 + \frac{C_1R_1 + C_2R_2\,(1-B_1)}{R_1R_2C_1C_2}s + \frac{1-B_1B_2}{R_1R_2C_1C_2} = 0. \tag{3.1}$$

From the characteristic equation (3.1), we can determine the oscillation condition in the following form

$$C_1R_1 + C_2R_2 = C_2R_2B_1, \tag{3.2}$$

and also the formula for the frequency of oscillations

$$\omega_0 = \sqrt{\frac{1-B_1B_2}{R_1R_2C_1C_2}} \approx \sqrt{\frac{1-V_{SET\_A}V_{SET\_B}}{R_1R_2C_1C_2}}. \tag{3.3}$$

The values of the capacitors are chosen $C_1 = C_2 = 470\,pF$, and the external resistors $R_{1ext} = R_{2ext} = 100\,\Omega$. Considering the virtual resistances $R_x = 95\,\Omega$ the total values result in $R_1 = R_2 = 195\,\Omega$. The current gain B_1 is chosen $B_1 = 2$ (then $V_{SET\_A} \approx 2V$) and B_2 will be changed taking into account the oscillation condition above. The dependence of the oscillation frequency f_0 on the control voltage V_{SET_A} is shown

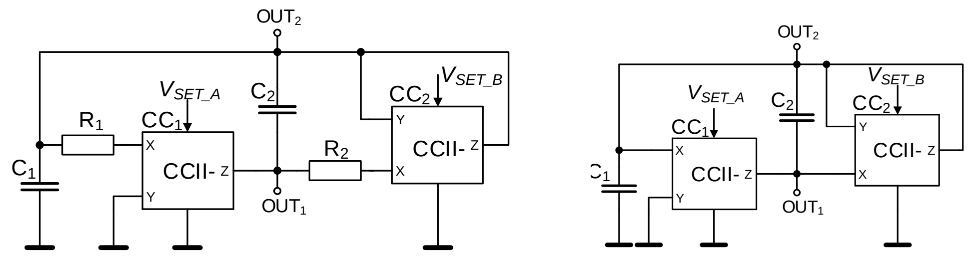

Fig. 3.1: Adjustable oscillator based on two CCII–: basic variant (left), resistor-less variant (right).

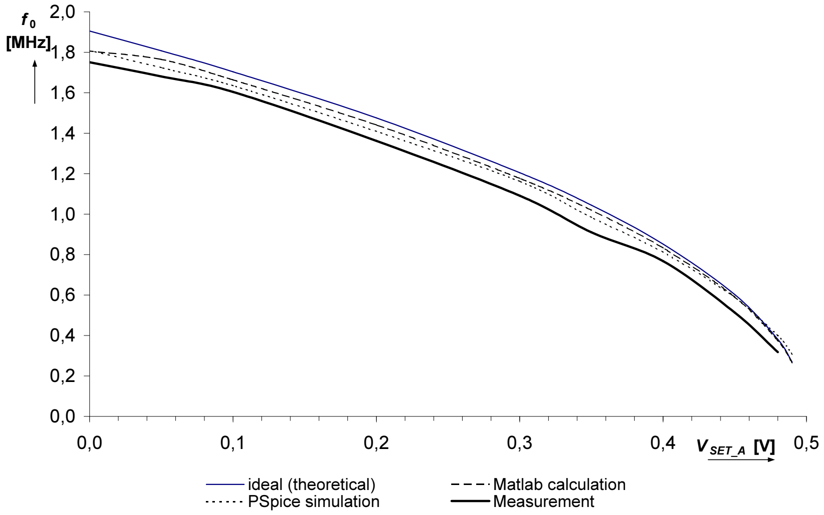

Fig. 3.2: Oscillation frequency versus control voltage.

in Fig. 3.2, namely ideal theoretical, PSpice simulation, Matlab calculation and measured too. The measurement of the output voltages (V_{OUT1} and V_{OUT2}) versus the oscillation frequency (f_0) is resulting in the Fig. 3.3.

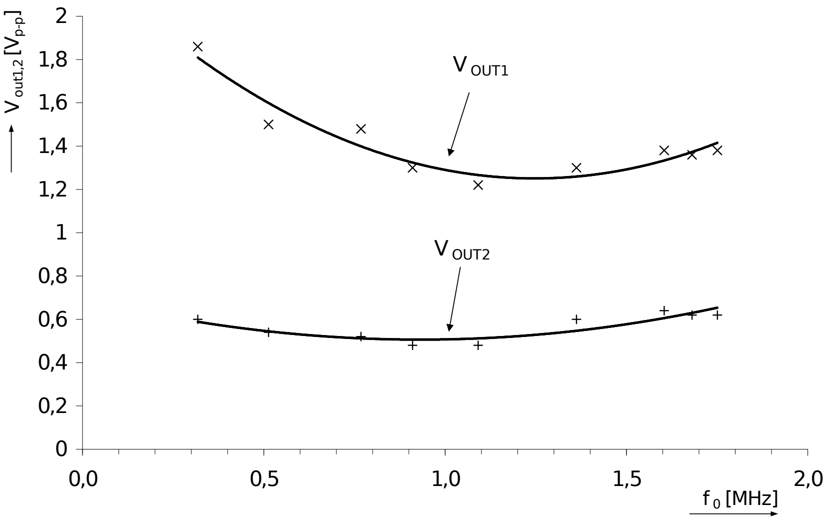

Fig. 3.3: Output voltages vs. oscillation frequency (measured).

3.2 STUDY OF 3R–2C OSCILLATOR

In this case we have used well–know and popular method for synthesis and design of oscillators. Approach is based on lossless and lossy integrators in the loop. Approach using state variable methods could also be used for this synthesis and results are identical.

$$s^2 + \frac{-G_1 - G_2 - G_3 + G_3B_2}{C_2}s + \frac{B_1G_1G_2}{C_1C_2} = 0. \tag{3.4}$$

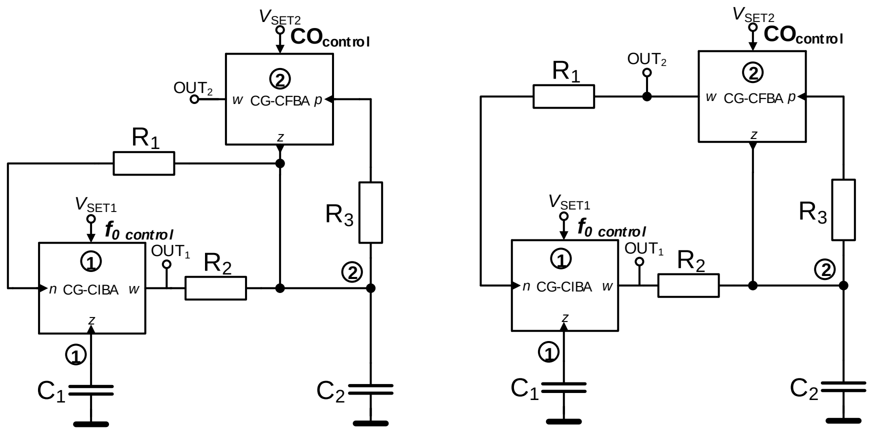

Fig. 3.4: Two versions of proposed oscillators.

Condition of oscillation and oscillation frequency are:

$$B_2 = 1 + \frac{G_1 + G_2}{G_3}, \omega_0 = \sqrt{\frac{B_1 G_1 G_2}{C_1 C_2}}. \tag{3.5}$$

where adjustable current gain B_1 stands for current gain of first active element (CG-CIBA) and B_2 represents current gain of the second active element (CG-CFBA). Second solution of the oscillator is shown in Fig. 3.4 (right). Characteristic equation has now the following form:

$$s^2 + \frac{-G_2 - G_3 + G_3 B_2}{C_2} s + \frac{B_1 G_1 G_2}{C_1 C_2} = 0. \tag{3.6}$$

Oscillation frequency has same form as in (3.5), but condition of oscillation is now:

$$B_2 = 1 + \frac{G_2}{G_3}. \tag{3.7}$$

We suppose equality of passive elements for further simplification: $R_1 = R_2 = R$ and $C_1 = C_2 = C$ and discussed simplifications and compared CO (3.5) and (3.7). Theoretical gains $B_2 = 3$ (Fig. 3.4 - left) and $B_2 = 2$ (Fig. 3.4 - right) are required to start the oscillations. Control of f_0 by only one parameter (B_1) without another matching condition is advantageous. Expected oscillation frequency is $f_0 = 1.293\,MHz$ for selected and designed parameters (if B_1 = 1). Measured value was $1.257\,MHz$. Deviation is mostly caused by inaccuracy of expected value of R_{n1}. This parameter is also dependent on bias current. Range of tunability was measured from $100\,kHz$ to $1.257\,MHz$ for B_1 changed from 0.01 to 1. Output level (V_{OUT2}) has quite constant value 2.22 ± 0.06 V_{P-P} in frequency range between $400\,kHz$ and $1.257\,MHz$ ($B_1 \in \{0.1; 1\}$), see Fig. 3.5.

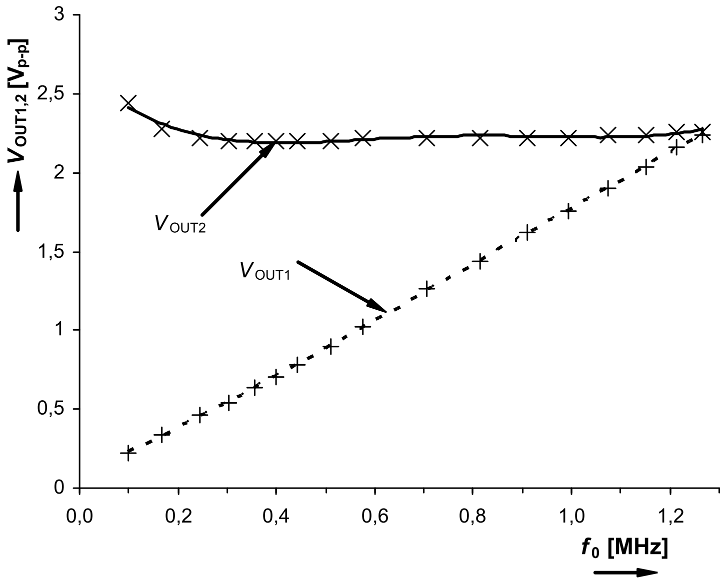

Fig. 3.5: Results of tuning process - dependence of output levels on oscillation frequency f_0.

3.3 MULTIPHASE OSCILLATOR BASED ON CG–BCVA

A new oscillator suitable for quadrature and multiphase signal generation is introduced in this contribution. Novel active element, so–called controlled gain–buffered current and voltage amplifier (CG-BCVA) with electronic possibilities of current and voltage gain adjusting is implemented together with controlled gain–current follower differential output buffered amplifier (CG-CFDOBA) for linear adjusting of oscillation frequency and precise control of oscillation condition in order to ensure stable level of generated voltages and sufficient total harmonic distortion. We used above discussed active elements for design of precise adjustable oscillator with multiphase output properties. Proposed circuit and its modification are shown in

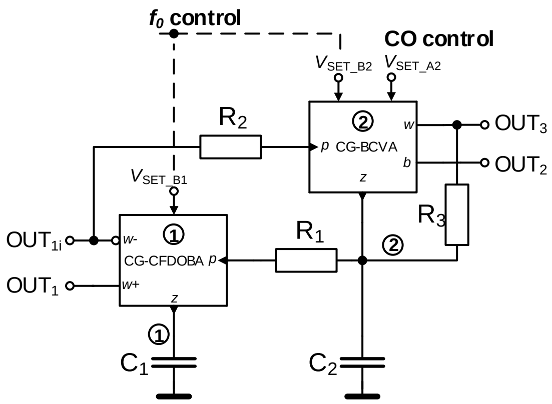

Fig. 3.6: Basic solution of tunable multiphase oscillator employing two active elements based on controlled gains.

Fig. 3.6. We created this part by adjustable voltage amplifier in frame of CG-BCVA and resistor R_3. Characteristic equation has the following form:

$$s^2 + \frac{R_1 + R_3 - R_1 A_2}{R_1 R_3 C_2} s + \frac{B_1 B_2}{R_1 R_2 C_1 C_2} = 0. \tag{3.8}$$

Condition of oscillation and frequency of oscillation are:

$$A_2 \geq 1 + \frac{R_3}{R_1}, \omega_0 = \sqrt{\frac{B_1 B_2}{R_1 R_2 C_1 C_2}}. \tag{3.9}$$

Laboratory measurements of circuit in Fig. 3.6 carried out following results. We used RIGOL DS1204B oscilloscope and HP4395A network vector/spectrum analyzer (50Ω matching of oscillator's outputs) for experimental tests. Fig. 3.7 shows the dependence of f_0 on $B_{1,2}$ ($B_{1,2}$ was adjusted between 0.1 - 2.9).

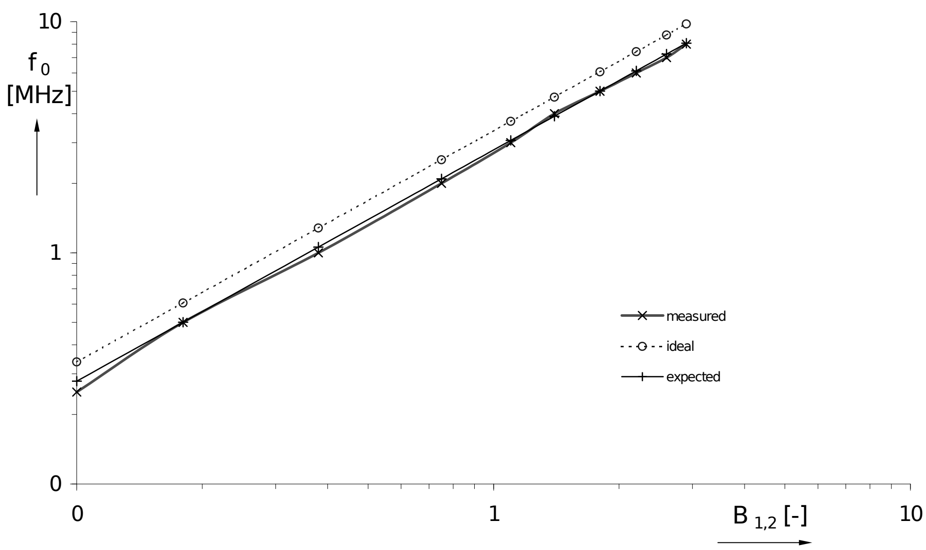

Fig. 3.7: Dependence of f_0 on adjustable current gains $B_{1,2}$.

3.3.1 Quasi–Linear Systems vs. Chaotic Systems

Basic analog building blocks for continuous–time signal processing such as oscillators, filters and amplifiers are initially designed using ideal active elements, i.e. without considering intrinsic parasitic or non–ideal properties. However these properties can seriously influence global behavior of these electronic systems. Several facts should be taken into account.

First are typical values of accumulation elements that are, in fact, include error terms into describing differential equations. Typical value of parasitic capacitor is tens pF and parasitic inductor is tens nH. Thus unwanted dynamical effects became significant in the case of high–frequency applications where parasitic inertia elements became value–comparable to working ones (above $10\,MHz$). Serious problems can be caused by fast dynamical motions and short transients; this situation corresponds to a right–hand–side of first–order differential equations multiplied by big number. Parasitic accumulation element should be placed in such a way that it creates bound between two differential equations reducing degrees of freedom. Second phenomenon is filtering effects of used active devices. In the case of chaotic oscillator design roll–off frequencies should be as high as possible. However if regular function of oscillator, filter or amplifier is required these filtering effects can prevent transitions to chaotic working regime. Last effect which needs to be considered for electronic circuit analysis is non–linear

Considering the possibility of increased circuit order and assuming the existence of transfer nonlinearities naturally quasi–linear block can eventually turn into chaotic system. If so than harmonic output signals can change into chaotic waveforms with several typical properties: few harmonics with great phase noise in time domain and broad–band noise–like frequency spectrum.

4 MODELING OF THE REAL PHYSICAL AND THE BIOLOGICAL SYSTEMS

4.1 AUTONOMOUS DYNAMICAL SYSTEMS

Simple system of three autonomous ordinary differential equations (ODEs) with any nonlinearity can exhibit chaos. Therefore, at the present time, research is focused onto relations between the real physical systems, its mathematical models and circuits realizations. From this perspective, electronic circuits can be used to modeling and observation of chaos. [17, 19]. The large number of real systems can be described as a system of the first order differential equations in matrix form of vector field

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}), \qquad \mathbf{x} \in \mathfrak{R}^n. \tag{4.1}$$

An *equilibrium solution* of (4.1) is a point $\bar{\mathbf{x}} \in \mathfrak{R}^n$ such that

$$\mathbf{f}(\bar{\mathbf{x}}) = \mathbf{0}, \tag{4.2}$$

i.e., a solution which does not change in time. The corresponding solution is $\phi(\mathbf{x}_0)$ and is called as a flow. These systems are called autonomous dynamical systems (ADS) and their phase space representations do not explicitly involve the independent variable, respectively the vector field $\mathbf{f}$ does not explicitly depend on time t.

4.2 INERTIA NEURON MODEL

Hindmarsh–Rose model is determinated by a system of three nonlinear ordinary differential equations with dynamical variables $x(t)$, $y(t)$, and $z(t)$. ODEs have the

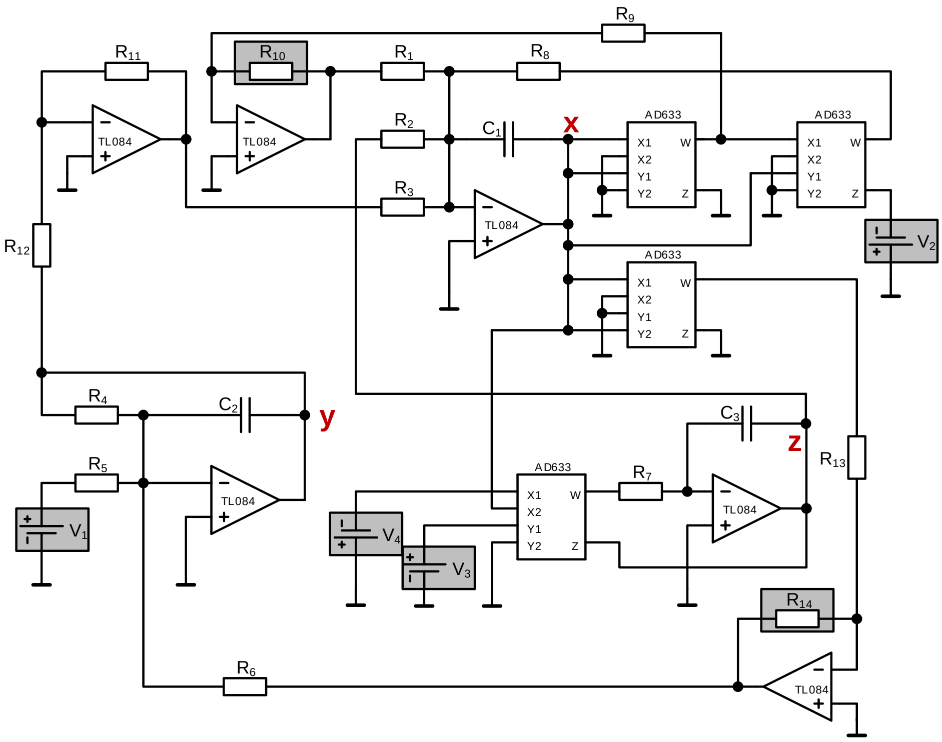

Fig. 4.1: Schematicm of the fully analog representation of single inertia neuron.

following form

$$
\begin{aligned}
\dot{x} &= ax^2 - x^3 + y - z + I \\
\dot{y} &= 1 - Dx^2 - y \qquad (4.3)\\
\dot{z} &= \mu\left(b\left(x - x_0\right) - z\right).
\end{aligned}
$$

Typical values of fixed parameters are: $a = 3$, $b = 5$, $D = 4$, $x_0 = -8/5$. The

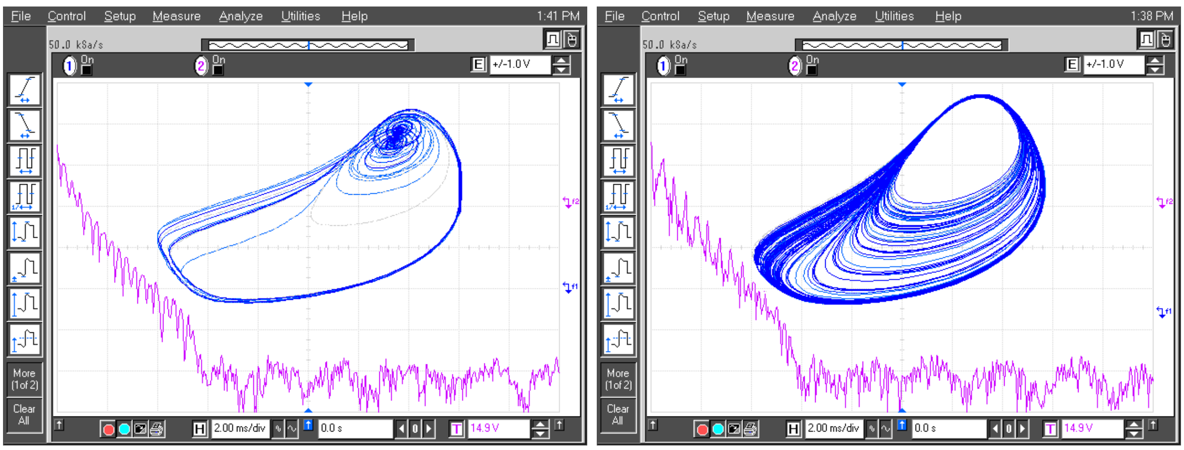

Fig. 4.2: Measured results of the inertia neuron - plane projection and frequency spectrum (Agilent Infiniium). Horizontal axis $2V/div$, vertical axis $2V/div$.

parameter μ is something of the order of 10^{-3}, and range of I is between -10 and 10 [4]. Novel circuit implementation is based on integrator synthesis and the mathematical model of the system. Circuitry realization given in Fig. 4.1 consists of three inverting integrators and amplifiers with TL084 and four analog multipliers AD633.Plane projections and frequency spectrum of the selected signals measured by means of Agilent Infinium digital oscilloscope are shown in Fig. 4.2.

4.3 NÓSE–HOOVER THERMOSTAT DYNAMIC SYSTEM

The aim of this section is in the new circuit implementation of the Nóse–Hoover thermostat dynamic system

$$\begin{aligned} \dot{x} &= y, \\ \dot{y} &= -x - yz, \\ \dot{z} &= \alpha\left(y^2 - 1\right). \end{aligned} \tag{4.4}$$

An unique property of this system is that it is conservative equilibrium–less system whereas all the other chaotic ADS are dissipative having single or more fixed points. Hoover [8] pointed out that the conservative system (4.4) found by Sprott is a special case of the Nóse-Hoover thermostat dynamic system which one had been earlier shown [12] to exhibit time reversible Hamiltonian chaos. Fig. 4.3 shows schematic of the Nóse–Hoover thermostat system oscillator. For circuitry implementation of mathematical model are used four operational amplifiers AD844 which are realized as non–inverting integrators and inverter. Values of used passive elements were chosen $C_1 = C_2 = C_3 = 100\,nF$, $R_1 = R_2 = 1\,k\Omega$, $R_3 = R_4 = R_5 = 10\,k\Omega$. Fig. 4.4 shows plane projections.

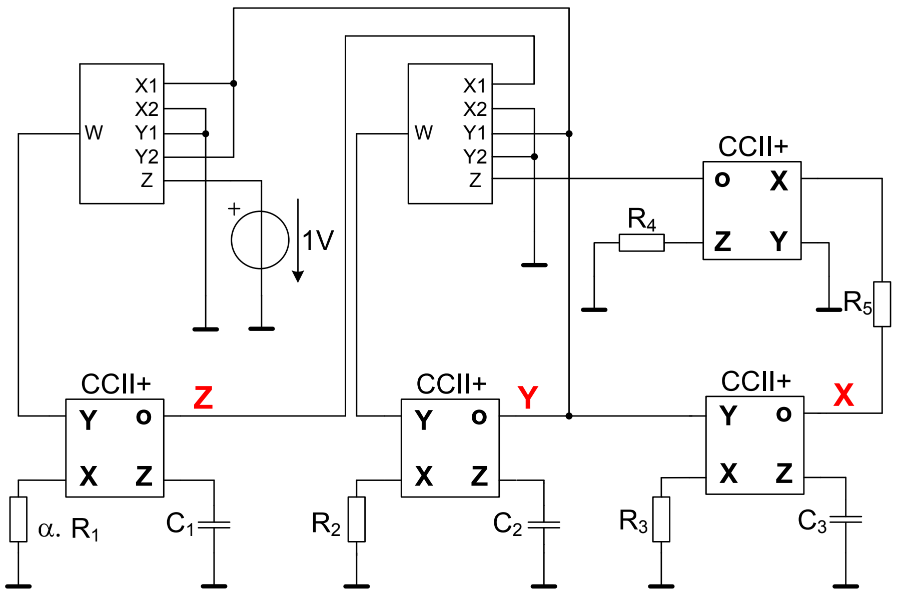

Fig. 4.3: Circuit realization of the Nóse-Hoover thermostat system with AD844 as a non–inverting integrator.

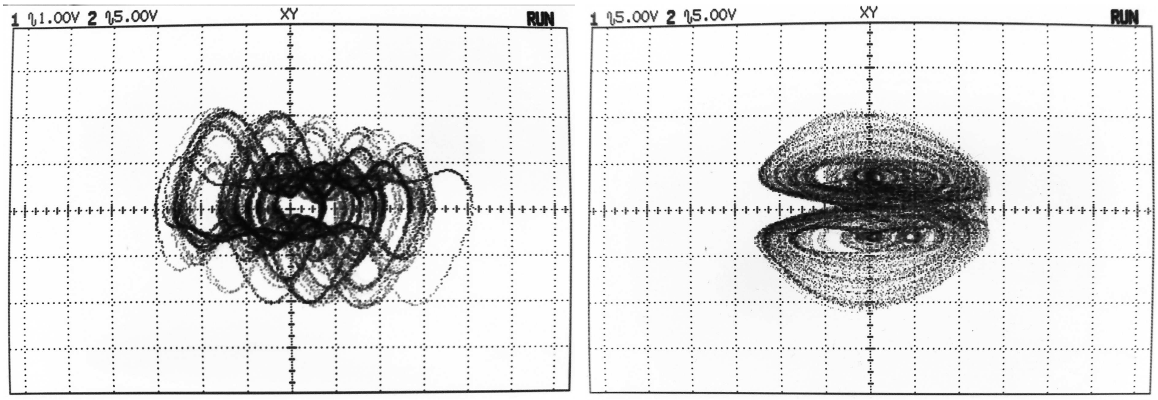

Fig. 4.4: Measurements results of the Nóse-Hoover oscillator. Horizontal axis $1\,V/div$, vertical axis $5\,V/div$(left), horizontal axis $5\,V/div$, vertical axis $5\,V/div$(bottom right)

4.4 CHAOTIC CIRCUIT BASED ON MEMRISTOR PROPERTIES

In this part is presented memristor based chaotic circuit synthesis based on mathematical model published by Muthuswamy and Chua [11]. Muthuswamy and Chua used the classical operational amplifier as the basic building block for circuit syn-

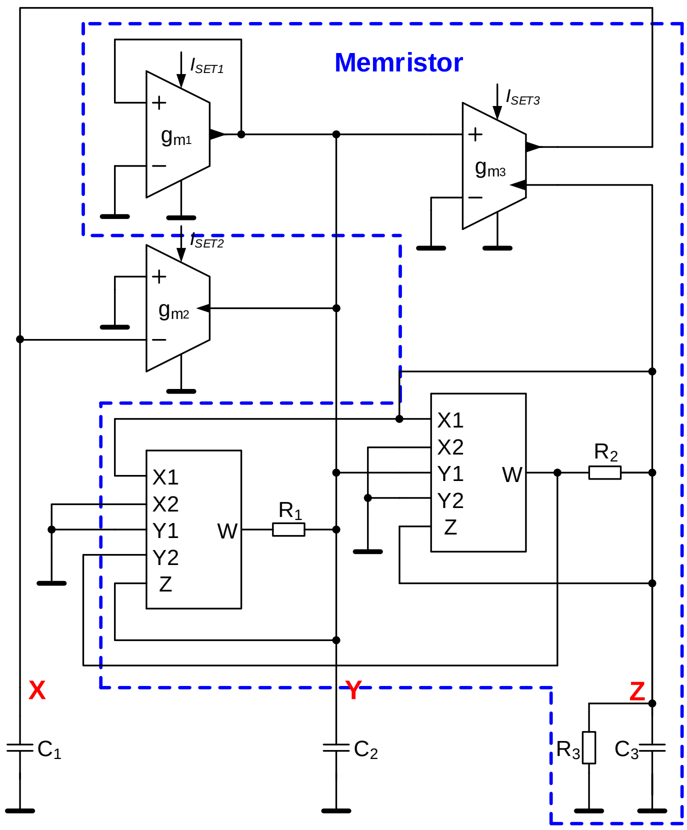

Fig. 4.5: Circuit realization of the chaotic system with OTA (OPA860), MO-OTA (MAX435) and analog multiplier (AD633) based on Eq. (4.5).

thesis. Compared to them we used an operational transconductance amplifier with a single output (OTA) and multiple output (MO-OTA). This step led to the simplify the overall circuit structure and we saved one active element. The equations for the memristor based chaotic circuit are described by set of follows an ordinary differential equations (ODE)

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= -\tfrac{1}{3}x + \tfrac{1}{2}y - \tfrac{1}{2}z^2 y \\ \dot{z} &= -y - \alpha z + zy, \end{aligned} \tag{4.5}$$

where parameter $\alpha = 0.6$ can be considered as a bifurcation parameter [11]. Operational transconductance amplifier OPA860 and multiple output transconductance amplifier MAX435 are used for circuitry implementation of the mathematical model equations (4.5). Nonlinearities are formed by a connection of four–quadrant analog multipliers AD633. The schematic of the chaotic oscillator is shown in Fig. 4.5. Values of used passive elements were choosen $C_1 = C_2 = C_3 = 470nF$, $R_1 = 15\,\Omega$, $R_2 = 100\,\Omega$ and $R_3 = 600\,\Omega$. Resistor R_3 should be adjustable from $0\,\Omega$ to $1\,k\Omega$. We used the following simplifications: $g_{m1} = \frac{1}{3}\,mS$, $R_{SET1} = 250\,\Omega$, $I_{SET1} = 11.2\,mA$, $g_{m2} = \frac{1}{2}\,mS$, $R_{SET2} = 250\,\Omega$, $I_{SET2} = 11.2\,mA$, $g_{m3} = 1\,mS$, $R_{SET3} = \infty$, $I_{SET3} = 450\,\mu A$. Fig. 4.6 shows a photo of the measurement results.

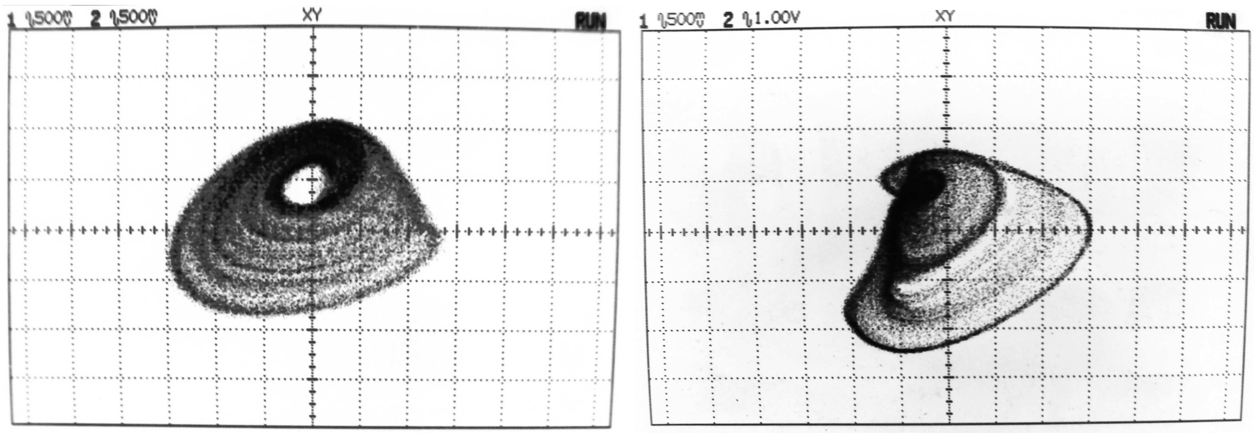

Fig. 4.6: Measured data of realized circuit (Fig. 4.5). Horizontal axis $500mV/div$, vertical axis $500\,mV/div$ (left), horizontal axis $500mV/div$, vertical axis $1\,V/div$ (right).

4.5 NONAUTONOMOUS DYNAMICAL SYSTEMS

Nonautonomous dynamical systems are systems with two degree of freedom and one independent variable [17]. For a nonautonomous system is specific, that the current time t and time of the initialization t_0 are important rather than just their

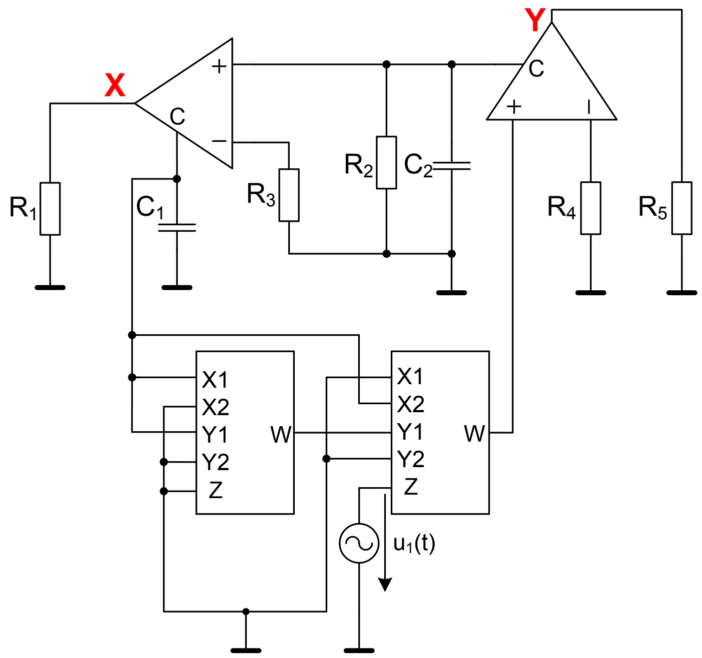

Fig. 4.7: Circuitry implementation of the Ueda oscillator.

difference. If we consider an initial value for a nonautonomous ordinary differential equation in $\mathfrak{R}^n$ we can use following mathematical formalism:

$$\dot{\mathbf{x}} = f(t,x), \qquad x(t_0) = x_0. \tag{4.6}$$

Ueda's oscillator is one example of such system and can be assumed as a biologically and physically important dynamical model exhibiting chaotic motion. System have two degrees of freedom and chaotic attractor in some parameter domains. The system described by a nonlinear second order differential equation can

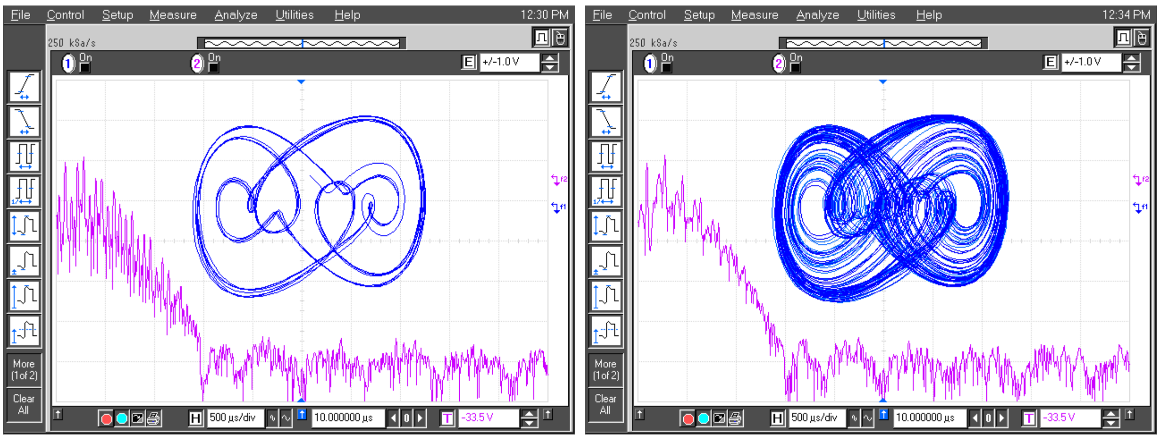

Fig. 4.8: Measured results of the chaos oscillator in hybrid mode - plane projections and frequency spectrum (Agilent Infiniium). Horizontal axis $1\,V/div$, vertical axis $2\,V/div$

be also describe in a following matrix form:

$$\begin{pmatrix} \dot{x} \\ \ddot{x} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & -b \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ -x^3 \end{pmatrix} + \begin{pmatrix} 0 \\ A\sin(\omega t) \end{pmatrix}, \tag{4.7}$$

where A, b and ω are parameters.

The schematic of the Ueda oscillator is shown in Fig. 4.7. Operational amplifiers AD844 and analog multipliers AD633 are used. Values of used passive elements were chosen $C_1 = C_2 = 15\,nF$, $R_1 = R_5 = 1\,M\Omega$, $R_2 = 20\,k\Omega$, $R_3 = R_4 = 1\,k\Omega$. The frequency was changed over the range $(1,5kHz < f < 4kHz)$. Fig. 4.8 shows the measurement results.

5 ANALOG–DIGITAL SYNTHESIS OF THE NONLINEAR DYNAMICAL SYSTEMS

We are presenting a generalized method for generating 2D *m x n* grid scroll, where a special case of solution is set of 1D grid scrolls [16]. The chosen 2D *m x n* scroll attractor can be in fact considered as particular case of Chua's attractor. Of course similar approach can be utilized for 3D grid scrolls by adding another nonlinear functional block. Our solution involves only analog to digital converters (AD) and digital to analog converters (DA) for implementation of the nonlinear function. It comes to this, that there is no need for any microcontroller [5]. The model describing chaotic 2D *m x n* scroll generation is described by three first–order differential equations.

$$\dot{\mathbf{x}} = \mathbf{A}\,\mathbf{x} + \mathbf{B}\,\varphi(\mathbf{C}\,\mathbf{x}). \tag{5.1}$$

Matrix **A** and **B** are represented as

$$\mathbf{A} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -a & -b & -c \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ a & b & c \end{pmatrix}, \tag{5.2}$$

matrix **C** is an identity matrix and function $\varphi(.)$

$$\mathbf{C} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \varphi = \begin{pmatrix} f(x) \\ f(y) \\ 0 \end{pmatrix}, \tag{5.3}$$

For synthesis of the nonlinear step function, connecting the ADC directly with the DAC generate step transfer function. Then output value with steps is defined as

$$out(x) = \begin{cases} \text{ł}\,\Delta + \frac{\Delta}{2} & \text{if } x > 0 \\ l\,\Delta - \frac{\Delta}{2} & \text{if } x < 0, \end{cases} \tag{5.4}$$

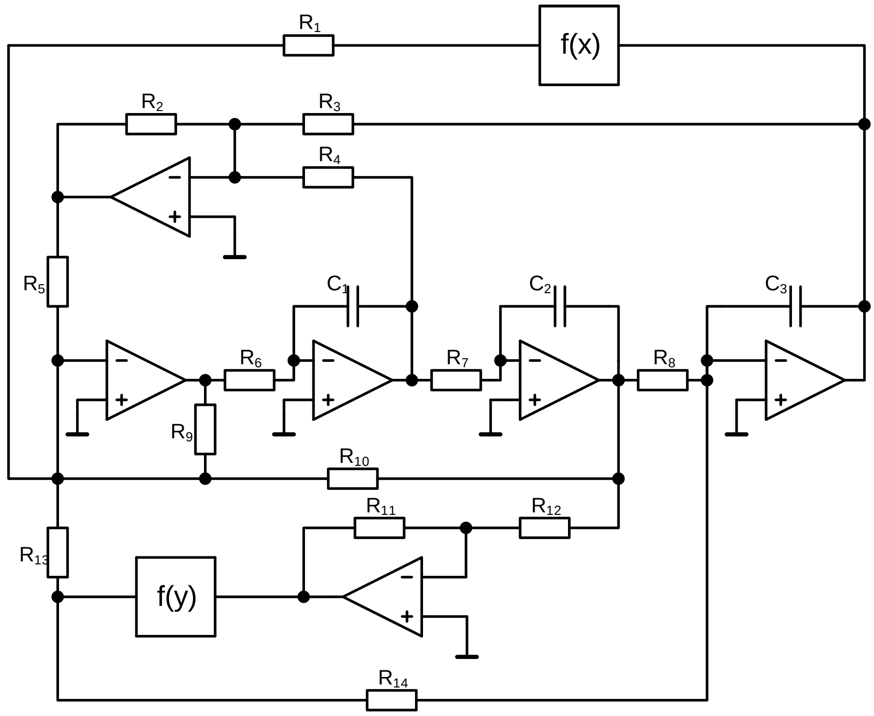

Fig. 5.1: The block schematics of realization of equations (5.1).

where

$$l = \frac{x}{\Delta} \wedge l \in \mathbb{N}. \tag{5.5}$$

Where $\mathbb{N}$ stands for set of natural numbers. Then model representing ADC connected directly to DAC, the step function with saturation can be written as

$$f(x) = \begin{cases} out(x) & \text{if } |x| < \Psi \\ -\Psi + \frac{\Delta}{2} & \text{if } x \leq -\Psi \\ \Psi - \frac{\Delta}{2} & \text{if } x \geq \Psi, \end{cases} \tag{5.6}$$

where Ψ can be expressed as $\Psi = \frac{Dynamical\ range[V]}{2}$.

Only few basic building blocks are necessary: inverting integrators, summing amplifier, AD and DA converters and voltage sources. Electronic circuit system consists of three integrator circuits (using operational amplifier AD713).Values of passive parts are estimated directly from the equations. To create step transfer functions $f(x)$ and $f(y)$, the data converters are used. The values of passive resistors are $R_1 = R_{13} = 118\,k\Omega$, $R_2 = R_5 = R_9 = R_{11} = R_{12} = 100\,k\Omega$, $R_3 = R_4 = R_{10} = 125\,k\Omega$, $R_6 = R_7 = R_8 = R_{14} = 1\,k\Omega$, $R_{Out} = 1\,\Omega$ and values of the capacitors are $C_1 = C_2 = C_3 = 100\,nF$. The measurements presented in Fig. 5.2 were done using HP 54645D oscilloscope.

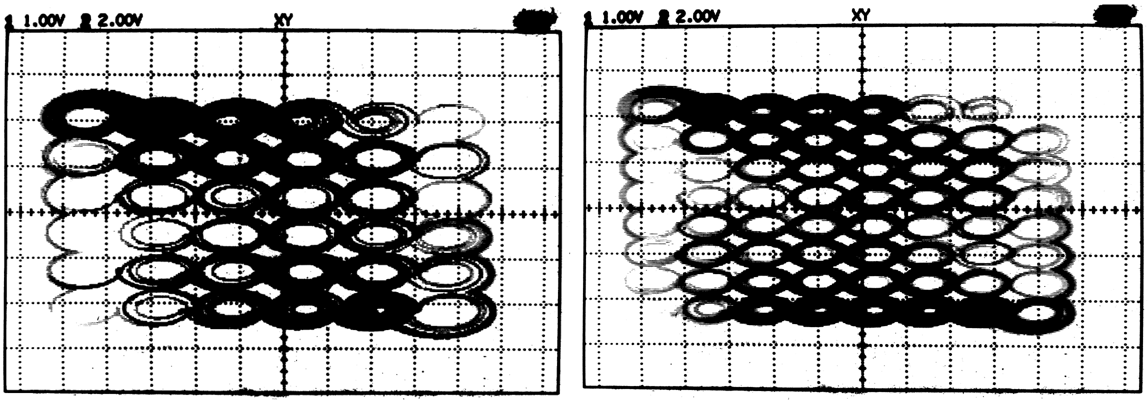

Fig. 5.2: 2–D 6x6 scroll, 8x8 scroll. Projections $V(x)$ vs. $V(-y)$, horizontal axis $1V/div$, vertical axis $2V/div$.

6 ON THE POSSIBILITY OF CHAOS DESTRUCTION VIA PARASITIC PROPERTIES OF THE USED ACTIVE DEVICES

This part deals with the study of influences of input and output parasitic properties of used real active elements. It is very interesting thing, because chaos systems are very sensitive on initial condition and values of circuit elements which should be kept very precisely. From this point of view it is very important to deal with question, whether parasitic properties are critical for system function and how global behavior changes with some sort of uncertainty. The question is whether or not these parasitic elements can cause significant problems in formation of the state space and chaos destruction in the worst case. Important parasitic admittances of the circuit are caused by the real input and output properties of used active elements.

6.1 INFLUENCE OF PARASITIC PROPERTIES OF ACTIVE ELEMENTS IN CIRCUIT BASED ON INERTIA NEURON MODEL

In system based on inertia neuron model from the previous subchapter section 4.2 we suppose three locations (input and output admittances in three nodes) where is the highest impact of parasitic properties. These parasitic admittances are described by a following set of the equations

$$\begin{aligned} -(C_1+C_{p1})\tfrac{du_1}{dt} &= u_2 + au_1{}^2 - u_1{}^2 - u_3 + I - G_{p1}u_1 \\ -(C_2+C_{p2})\tfrac{du_2}{dt} &= 1 - Du_1{}^2 - u_2 - G_{p2}u_2 \\ -(C_3+C_{p3})\tfrac{du_3}{dt} &= \mu\,(b\,(u_1-x_0)-u_3) - G_{p3}u_3. \end{aligned} \tag{6.1}$$

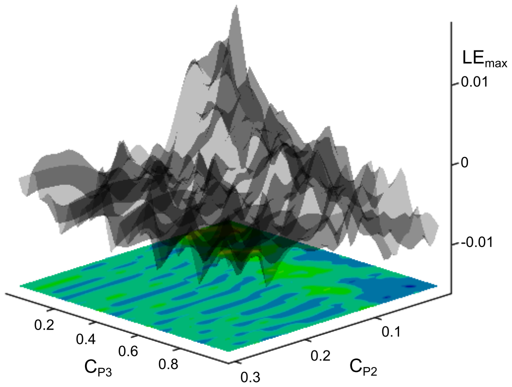

Fig. 6.1: Influence of parasitic capacitances on the size of the LE_{max} as a function of Cp_2 and Cp_3.

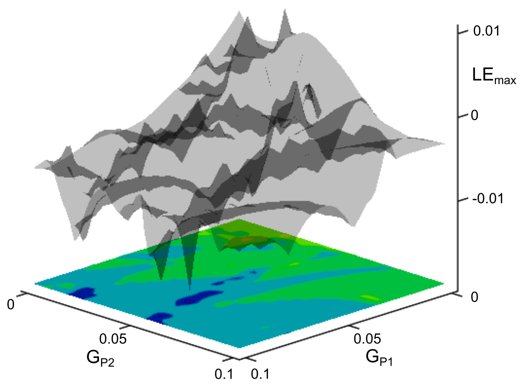

Fig. 6.2: Influence of parasitic conductances on the size of the LE_{max} as a function of Gp_1 and Gp_2.

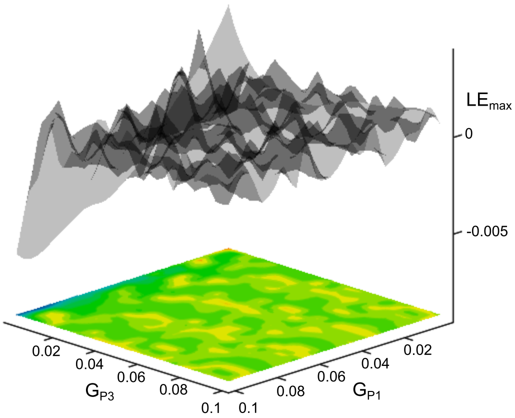

Fig. 6.3: Influence of parasitic conductances on the size of the LE_{max} as a function of Gp_1 and Gp_3.

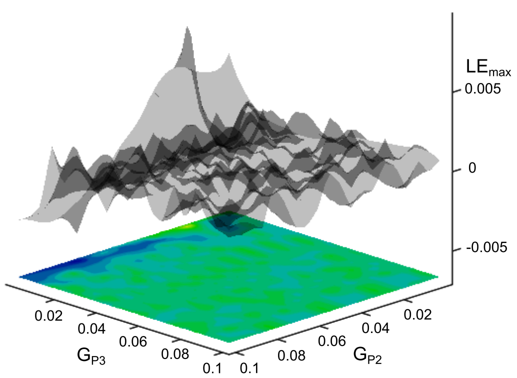

Fig. 6.4: Influence of parasitic conductances on the size of the LE_{max} as a function of Gp_2 and Gp_3.

6.2 INFLUENCE OF PARASITIC PROPERTIES OF ACTIVE ELEMENTS IN CIRCUIT BASED ON MEMRISTOR PROPERTIES

The circuit diagram from Fig. 4.5 can be supplemented as shown in Fig. 6.5 to include all parasitic influences. Elementswith crosshatch pattern are representing parasitic influences. The relations between ideal model and parasitic admittances are given by the formulas

$$\begin{aligned} -(C_1+C_{p1})\tfrac{du_1}{dt} &= G_{p1}u_1 - g_{m3}u_2 \\ -(C_2+C_{p2})\tfrac{du_2}{dt} &= \tfrac{1}{3}g_{m2}u_1 - (\tfrac{1}{2}g_{m1} - G_{p2})u_2 + \tfrac{1}{2}u_2{u_3}^2 \\ -(C_3+C_{p3})\tfrac{du_3}{dt} &= g_{m3}u_2 + (G+G_{p3})u_3 - u_2u_3 \end{aligned} \tag{6.2}$$

As is evident from plots Fig. 6.6 to Fig. 6.9 circuitry is much more sensitive to the changes of the parasitic conductances than the parasitic capacitances. The influence

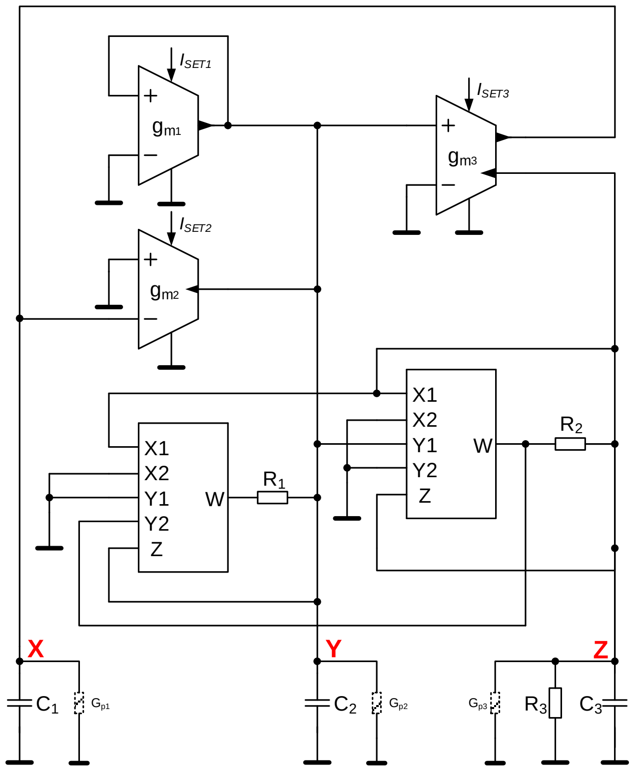

Fig. 6.5: Circuit realization of the chaotic system with influence of parasitic properties of active elements.

of the parasitic capacitance will be applied in cases when their value will be close to the value of working capacitances. The conclusion is that at high frequencies, the values of the parasitic capacitances are comparable to those of other circuit elements and thus the resulted behavior of the circuit is unpredictable.

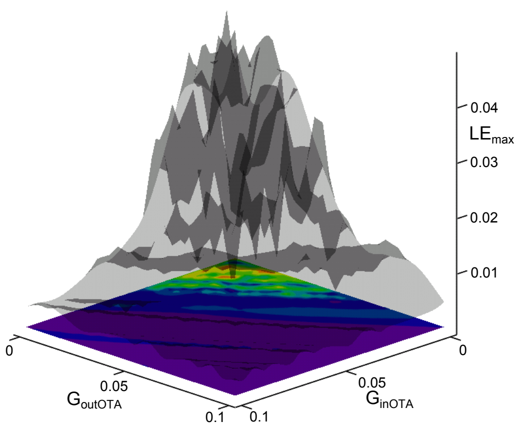

Fig. 6.6: Influence of parasitic conductances on the size of the LE_{max} as a function of OPA860 parasitic conductance.

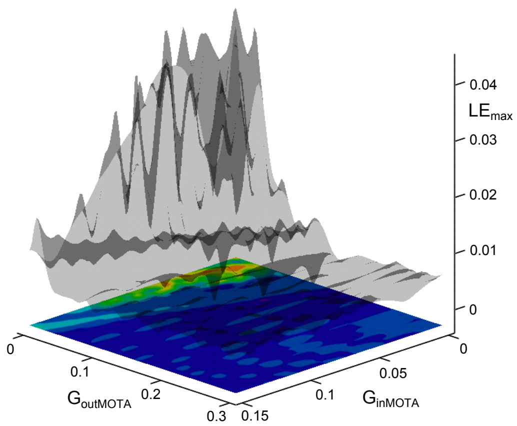

Fig. 6.7: Influence of parasitic conductances on the size of the LE_{max} as a function of MAX435 parasitic conductance.

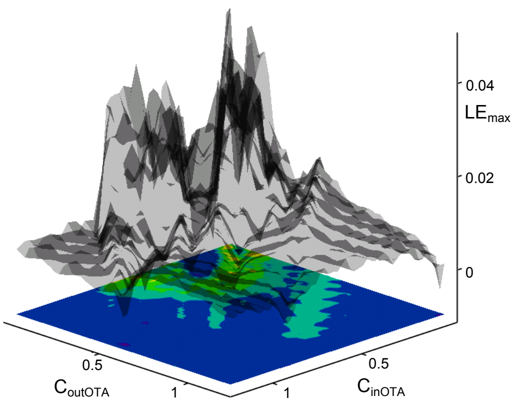

Fig. 6.8: Influence of parasitic capacitances on the size of the LE_{max} as a function of OPA860 parasitic capacitance.

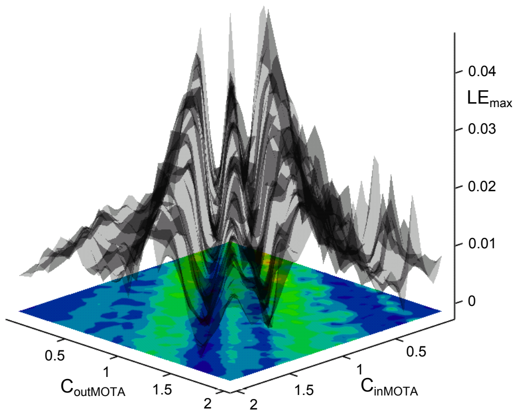

Fig. 6.9: Influence of parasitic capacitances on the size of the LE_{max} as a function of MAX435 parasitic capacitance.

6.3 INFLUENCE OF PARASITIC PROPERTIES OF ACTIVE ELEMENTS IN CIRCUIT BASED ON SPROTT SYSTEM

In circuit realization (Fig. 6.10) we suppose four locations (two nodes and two input diferences admittance) where parasitics cause the highest impact. These parasitic admittances can be expressed as

$$\begin{aligned} Y_{p1}(s) &= G_{p1} + sC_{p1} = (G_{pin1} + G_{pout1} + \\ &+ G_{pout3}) + s(C_{pin1} + C_{pout1} + C_{pout3}) = \\ &= \frac{1}{R_{in\_OTA_1}} + \frac{1}{R_{out\_OTA_1}} + \frac{1}{R_{out\_OTA_3}} + \\ &+ s\left(C_{in\_OTA_1} + C_{out\_OTA_1} + C_{out\_OTA_3}\right) \end{aligned} \tag{6.3}$$

$$\begin{aligned} Y_{p2}(s) &= G_{p2} + sC_{p2} = G_{pout2} + sC_{pout2} = \\ &= \frac{1}{R_{out\_OTA_2}} + sC_{out\_OTA_2} \end{aligned} \tag{6.4}$$

$$Y_{p3}(s) = G_{p3} + sC_{pp3} = G_{pin3} + sC_{in3} = \frac{1}{R_{in\_OTA_3}} + sC_{in\_OTA_3} \tag{6.5}$$

$$Y_{p4}(s) = G_{p4} + sC_{pp4} = G_{pin2} + sC_{in2} = \frac{1}{R_{in\_OTA_2}} + sC_{in\_OTA_2} \tag{6.6}$$

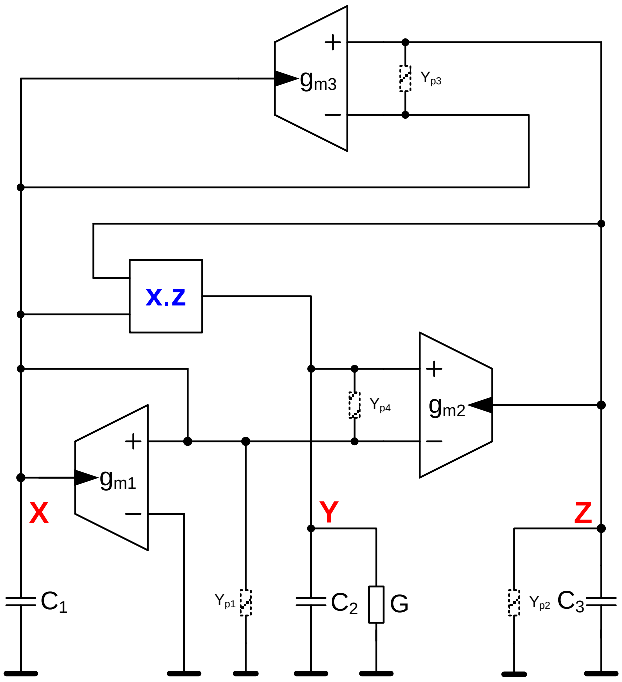

Fig. 6.10: Schematic of circuit realization with important parasitic influences.

The concrete values of the parasitic admitances of the developed circuitry shown in Fig. 6.10 are for OTA (OPA860) $R_{in\_OTA} = 455\,k\Omega$, $R_{out\_OTA} = 54\,k\Omega$, $C_{in\_OTA} = 2.2\,pF$, $C_{out\_OTA} = 2\,pF$. The positive LE_{max} dependence on values of parasitic properties are shown in Fig. 6.11 to Fig. 6.14 with scale $LE_{max} \in (0, 0.01)$. Sensitivity to change of the parasitic conductances is bigger than the sensitivity to the changes of parasitic capacitances. The most critical to chaos destruction seems to be parasitic output resistance of the MO-OTA element MAX435 with value approaching the working resistance.

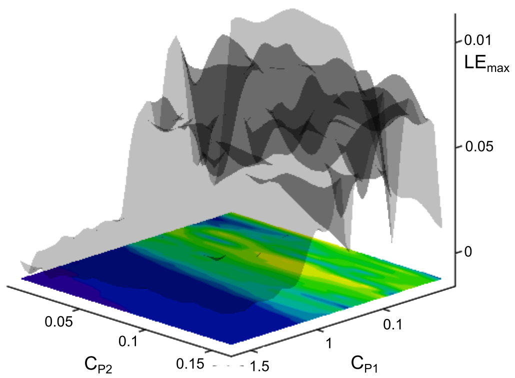

Fig. 6.11: Influence of parasitic capacitances on the size of the LE_{max} as a function of Cp_1 and Cp_2.

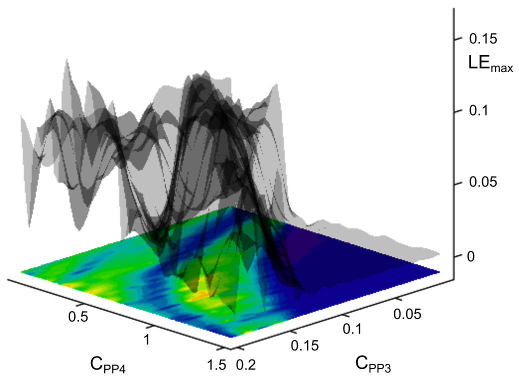

Fig. 6.12: Influence of parasitic capacitances on the size of the LE_{max} as a function of Cpp_3 and Cpp_4.

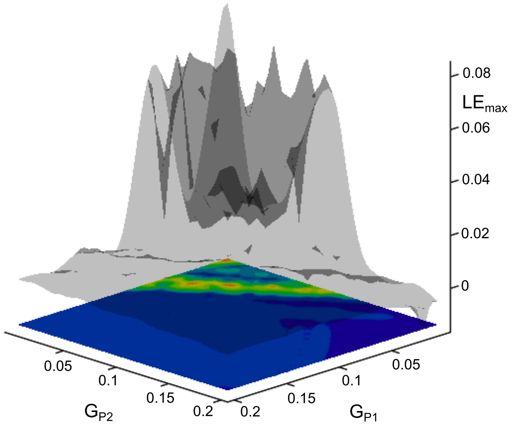

Fig. 6.13: Influence of parasitic conductances on the size of the LE_{max} as a function of Gp_1 and Gp_2.

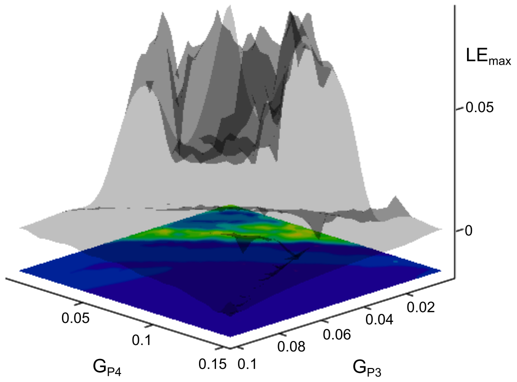

Fig. 6.14: Influence of parasitic conductances on the size of the LE_{max} as a function of Gp_3 and Gp_4.

7 CONCLUSIONS

In this doctoral thesis we have proposed several types of electronically adjustable oscillators, autonomous and nonautonomous chaotic systems, different possibilities towards analog–digital synthesis and influence of parasitic properties of used active elements on structural stability of prescribed geometrical structure of strange attractor. By referring to the best knowledge of the author, circuitry implementations and in this doctoral thesis were not so far reported.

Several novel active elements with adjustable fundamental properties (current and voltage gain) were discussed in this thesis. First of them is very simple electronically adjustable oscillator employing only two active devices (CCII–) and in the extreme only two passive elements (capacitors). It allows electronic tuning of the oscillation frequency and condition of oscillation by DC driving voltage. It was practically tested from $320\,kHz$ to $1.75\,MHz$. Under certain conditions (limited range), the harmonic distortion can be achieved below 1% and the separation of the higher harmonics more then $50\,dB$ [27]. However there are some drawbacks of this solution. The equation for oscillation frequency (3.3) is not very suitable and therefore tuning is possible only in a limited range. The network was verified without the subcircuit for amplitude stabilization (only by nonlinear limitation of used active elements). Therefore practically available range of tuning with achievable low THD is limited. For invariable level of output signal very small changes of B_1 are necessary. The first conception of the oscillator where CC1 has a fixed gain is not suitable because the control of the condition of oscillation is not possible. Operation of the proposed oscillator was verified through simulations and measurements of the real circuit in the frequency range of units MHz. Also important parasitic effects in this circuit were discussed in detail. Other types are three modified oscillator conceptions that are quite simple, directly electronically adjustable, providing independent control of oscillation condition and frequency in 3R-2C oscillator. The most important contributions of presented solutions are direct electronic and also independent control of CO and f_0, suitable AGC circuit implementation, buffered low–impedance outputs, and of course, grounded capacitors [28]. Independent tunability by only one parameter is very useful, but tuning characteristic is nonlinear. The most important drawback is dependence of amplitude V_{OUT1} on current gain B_1. It is necessary to change oscillation frequency simultaneously by two parameters (adjustable current gains) and oscillation condition by adjustable voltage gain (all in frame of two active elements). Equality (and invariability) of generated amplitudes and linearity of tuning characteristic during the tuning process are required aspects. Detailed discussion is available in [1] for example.

Last type is new oscillator suitable for quadrature and multiphase signal generation. Active element, which was defined quite recently i.e. controlled gain-current follower differential output buffered amplifier (CG-CFDOBA) [2, 3], and newly introduced element so–called controlled gain–buffered current and voltage amplifier (CG-BCVA) were used for purposes of oscillator synthesis. Electronic control of two parameters in frame of one active element is quite attractive method, which is very useful in particular applications. Presented methods of gain control allow synthesis and design of electronically controllable application (oscillator in our case) quite easily and with very favorable features. Main highlighted benefits can be found in electronic linear control of oscillation frequency (tested from $0.25\,MHz$ to $8\,MHz$) and electronic control of oscillation condition. The output levels were almost constant during the tuning process and reached about $200\,mV_{P-P}$. THD below 0.5% in range above $2\,MHz$ was achieved [29]. In comparison to some previously reported types [28] dependence of output amplitudes on tuning process was eliminated by simultaneous adjusting of both time constants of integrators [1]. Grounded capacitors are common requirement in similar types of circuits. Precise analysis of real parameters and nonidealities of active elements allows determining of more accurate description and simulations. Operation of the proposed oscillators were verified through simulations and measurements of the real circuits and published in[27, 28, 29].

In the second chapter, circuitry implementations of interesting autonomous and nonautonomous chaotic systems have been presented. Based on the optimized dynamical system of class C with PWL feedback, a fully analog chaotic oscillator works in hybrid mode has been proposed for laboratory measurements [24]. This chaotic circuit is currently used for student demontrations in Department of Radio Electronics. Main contribution is in circuitry implementation of a fully analog chaotic oscillator with a new available active elements. The advantage is immediately evident. The smaller number of active elements is in the whole circuit. Fully analog circuitry implementation of the inertia neuron based on the ordinary differential equations of Hindmarsh–Rose model has been realised and published [21]. The qualitatively different behavior of HR model in time domain were demonstrated. From experimental verification is evident that for $x_r = -0.6$ system exhibits spiking behavior. If we changed this bifurcation parameter to $x_r = -1.6$ the system began to exhibit chaotic behavior (chaotic dynamics is obtained for a small range around value $x_r = -1.6$). With other change of x_r system exhibited bursting dynamics. It is evident that all the main dynamics of a neuron (spiking, bursting and chaos) can be obtained with the proposed circuit by properly setting the control parameters and after quite long transient behavior. It eventually turns out that this system in not as sensitive as expected. Other example of real chaotic system was novel circuitry implemnation of the Nóse–Hoover thermostated dynamic system [25]. The Nóse–Hoover system has relatively many interesting limiting cycles and relatively complicated Poincare sections, but otherwise mostly reinforces the idea that small systems do not follow a statistical-mechanical average over accessible states. On the other hand, the two-dimensional calculations indicate that only slightly more complicated systems probably do fill their phase spaces in a quasiergodic way. A careful study of the two–soft–disk system, using Nóse dynamics in a phase space with the variables, led to no evidence for the failure of statistical mechanics. Based on this evidence we would expect that even very simple nonequilibrium systems, or quantum systems, with even more capability for mixing phase space, do indeed fill their phase spaces in an ergodic way [12]. New implementations of chaotic circuits using transconductance operational amplifiers and analog multipliers were proposed. We used two systems (original and modified system) publicated by Sprott [17] and chatotic system based on memristor mathematical model published by Muthuswamy and Chua [11] as an example of chaotic systems. Last circuitry implementations deals with nonautonomous chaotic system based on Ueda oscillator. First circuitry implementation works in voltage mode and second in hybrid mode [22]. Those conceptions were experimentally verified in both time domain and frequency domain. The frequency of driven sinusoidal signal was changed over the range $1.5\,kHz < f < 4\,kHz$ and study development in the motion from periodic cycle to strange attractor. The proper function of the final circuits structure has been verified by means of the PSpice simulator as well as by a practical experiments on the real oscillators and on the breadboard. Many simulations and laboratory experiments proved a good agreement between numerical integration, practical simulation and measurement. The exponential divergence of trajectories that underlies chaotic behavior, and the resulting sensitivity to initial conditions, lead to long–term unpredictability which manifests itself as deterministic randomness in the time domain.

In the third chapter, the well known 2D *m x n* scroll system was chosen and was realized utilizing novel approach using the data converters as non-linear functions. With the growing order of the system, the presence of chaotic behavior is more probable. First the models were derived to simulate the data converters connected directly (ADC-DAC). Than the connection was reduced to produce less scrolls. Other crux is in the verify chaotic behavior of proposed conception. The circuit simulator PSpice was used for theoretical verify and then the circuit prototype was build and measured. The simulation results and measurements prove a good final agreement between theory and practice and were published in[26].

In the last chapter, three types of circuitry realization in which cases the influence of parasitic properties of used active elements to shape of the desired strange attractors were described. Namely circuit based on inertia neuron model, circuit based on intrinsic memristor properties and circuit based on Sprott system were considered. We presented here also a numerical analysis of systems with influence of parasitic admitances. Experiments suggest that systems are much more sensitive to the changes of the parasitic conductances than the parasitic capacitances. The common situation is that nonzero input or output admittance increase dynamical flow dissipativity. Another conclusion is that influence of the parasitic capacitance will be applied in cases when their value will be close to the value of working capacitances. At high frequencies, the values of the parasitic capacitances are comparable to functional ones and thus the resulting behavior of the circuit is unpredictable and can lead to chaos destruction (from geometrical sense). Other crux of this section is in calculations of eigenvalues with respect to influence of parasitic properties of active elements. The possibility of chaos destruction via parasitic properties of the used active elements were published in [23].

REFERENCES

[1] BIOLEK, D., LAHIRI, A., JAIKLA, W., SIRIPRUCHYANUN, M., BAJER, J. Realisation of electronically tunable voltage–mode/current–mode quadrature sinusoidal oscillator using ZC-CG-CDBA. *Microelectronics Journal*. 2011, vol. 42, no. 10, p. 1116–1123.

[2] BIOLEK, D., SENANI, R., BIOLKOVA, V., KOLKA, Z. Active elements for analog signal processing: classification, review, and new proposal. *Radioengineering*. 2008, vol. 17, no. 4, p. 15–32.

[3] BIOLKOVA, V., BAJER, J., BIOLEK, D. Four-phase oscillators employing two active elements. *Radioengineering*. 2011, vol. 20, no. 1, p. 334–339.

[4] BIZZARRI, F., LINARO, D., STORACE, M. PWL approximation of the Hindmarsh-Rose neuron model in view of its circuit implementation. In *Proceedings of the* 18^{th} *European Conference on Circuit Theory and Design. Seville, 27-30 August, 2007*. Institute of Electrical and Electronics Engineers (IEEE), 2007, pp. 878 – 881. ISBN 978-1-4244-1341-6.

[5] ELHADJ, Z., SPROTT, J. C. Some open problems in chaos theory and dynamics. *International Journal of Open Problems in Computer Science and Mathematics*, 2011, vol. 4, pp. 1-–10.

[6] FABRE, A. Third generation current conveyor: a helpful active element. *Electronics Letters*. 1995, vol. 31, no. 5, p. 338–339.

[7] GEIGER, R. L., SANCHEZ-SINENCIO, E. Active filter design using operational transconductance amplifier: a tutorial. *IEEE Circuits and Devices Magazine*. 1985, p. 20–32.

[8] HOOVER, W. G. Remark on some simple chaotic flows. *Physical Review E*, 1995, vol. 51, no. 1, pp. 759–760.

[9] ITOH, M. Synthesis of electronic circuit for simulating nonlinear dynamics. *International Journal of Bifurcation and Chaos*. 2001, vol.11, no.3, pp. 605-653, ISSN 0218-1274.

[10] LORENZ, E. N. Deterministic nonperiodic flow. *Journal of the Atmospheric Sciences*, Jan. 1963, vol. 20, pp. 130–141.

[11] MUTHUSWAMY, B., CHUA, L. O. Simplest chaotic circuit. *International Journal of Bifurcation and Chaos*. 2010, vol. 20, no. 5, p. 1567–1580.
[12] POSCH, H. A., HOOVER, W. G., VESELY, F. J. Canonical dynamics of the Nóse Oscillator: stability, order, and chaos. *Physical Review A*, 1986, vol. 33, no. 6, pp. 4253–4265.
[13] POTZSCHE, C. Nonautonomous dynamical systems. *Lecture Notes*, WS 2010/11, TU München, Feb. 2011, 82 p.
[14] SENANI, R. Realization of a class of analog signal processing/signal generation circuits: novel configurations using current feedback opamps. *Frequenz*. 1998, vol. 52, no. 9–10, p. 196–206.
[15] SMITH, K. C., SEDRA, A. A second generation current conveyor and its applications. *IEEE Transaction on Circuit Theory CT*. 1970, vol. 17, no. 2, p. 132–134.
[16] SPANY, V., GALAJDA, P., GUZAN, M., PIVKA, L., OLEJAR, M. Chua's singularities: great moracle in circuit theory. *International Journal of Bifurcation and Chaos*, 2010, pp. 2993–3006.
[17] SPROTT, J., C. Chaos and time–series analysis. *Oxford University Press*, 2003, 507 pages, ISBN 01-985-0840-9.
[18] SVOBODA, J. A., MCGORY, L., WEBB, S. Applications of commercially available current conveyor. *International Journal of Electronics*. 1991, vol. 70, no. 1, p. 159–164.
[19] THOMPSON, J. M. T., STEWART, H. B. *Nonlinear dynamics and chaos*. 2 edition, Wiley, 2002, 460 p. ISBN 04-718-7684-4.
[20] WAGEMAKERS, A. *Electronic modelling of complex dynamics*. Disertation thesis, Madrid: Universidad Rey Juan Carlos, Departamento de Fisica, 2008, 137 p.
[21] HRUBOS, Z., GOTTHANS, T., PETRZELA, J. Circuit realization of the inertia neuron. In *Proceedings of the* 21^{st} *International Conference RADIOELEKTRONIKA 2011*. Brno, Tribun EU s.r.o. Gorkeho 41, 602 00 Brno. 2011, p. 215–218. ISBN 978-1-61284-322-3.
[22] HRUBOS, Z., GOTTHANS, T., PETRZELA, J. Two equivalent circuit realizations of the Ueda's oscillator. In *Proceedings of* 18^{th} *International Conference Mixdes 2011, Gliwice, Polsko*. 2011, p. 694–698. ISBN 978-83-932075-0-3.
[23] HRUBOS, Z., GOTTHANS, T. Analysis and synthesis of chaotic circuits using memristor properties. *Journal of Electrical Engineering*. 2014, vol. 65, no. 3, p. 129–136. ISSNĨ335-3632. (IF=0,37).
[24] HRUBOS, Z. Novel circuit implementation of universal and fully analog chaotic oscillator. *Przeglad Elektrotechniczny*. 2012, vol. 07a, p. 18–22. ISSNÕ033-2097. (IF=0,244).
[25] HRUBOS, Z., PETRZELA, J., GOTTHANS, T. Novel circuit implementation of the Nóse-Hoover thermostated dynamic system. In *Proceedings of the* 34^{th} *International Conference on Telecommunications and Signal Processing TSP 2011, 18-20.8.2011, Budapest, Hungary*. 2011, p. 307–311. ISBN 978-1-4577-1409-2.
[26] GOTTHANS, T., HRUBOS, Z. Multi grid chaotic attractors with discrete jumps. *Journal of Electrical Engineering*. 2013, vol. 64, p. 118–122. ISSNĨ335-3632. (IF=0,37).
[27] SOTNER, R., HRUBOS, Z., SLEZAK, J., DOSTAL, T. Simply adjustable sinusoidal oscillator based on negative three–port current conveyors. *Radioengineering*. 2010, vol. 19, no. 3, p. 446–453. ISSN 1210-2512. (IF=0,687).
[28] SOTNER, R., JERABEK, J., HERENCSAR, N., HRUBOS, Z., DOSTAL, T., VRBA, K. Study of adjustable gains for control of oscillation frequency and oscillation condition in 3R-2C oscillator. *Radioengineering*. 2012, vol. 21, no. 1, p. 392–4022. (IF=0,687).
[29] SOTNER, R., HRUBOS, Z., HERENCSAR, N., JERABEK, J., DOSTAL, T., VRBA, K. Precise electronically adjustable oscillator suitable for quadrature signal generation employing active elements with current and voltage gain control. *Circuits systems and signal processing*. 2014, vol. 33, no. 1, p. 1–35. ISSNÕ278-081X. (IF=1,118).
[30] PETRZELA, J., GOTTHANS, T., HRUBOS, Z. Modeling deterministic chaos using electronic circuits. In *Radioengineering*. 2011, vol. 20, no. 2, p. 438–444.(IF=0,687).

CURRICULUM VITAE

Personal	
Name	**Ing. Zdeněk Hruboš**
Born	November 06, 1984 in Uherské Hradiště
Address	Huštěnovice 107, 687 03 Huštěnovice, Czech Republic
Contact	zdenekhrubos@gmail.com
Work experience	
02/2013 – present	VVÚ Brno s.p. (Military Research Institute, State Enterprise) Profession: RF Design Engineer, PCB Designer Engineer
Education	
2009 – present	Doctor of Philosophy (PhD) Brno University of Technology (Department of Radio Electronics) Thesis: Unconventional Signals Oscillators
2007 – 2009	Master's degree (MSc) – inženýr (Ing.) Brno University of Technology (Department of Radio Electronics) Thesis: Laboratory Device with Analog Computational Unit AD538
2004 – 2007	Bachelor's degree (BSc) – bakalář (Bc.) Brno University of Technology (Department of Radio Electronics) Thesis: Universal and Fully Analog Oscillator
Courses	
6/2012	Training School on Energy–aware RF Circuits and Systems Design Villa Griffone, University of Bologna Pontecchio Marconi, Bologna (Italy)
1/2012	Training School on Technology Challenges for the Internet of Things, University of Aveiro, Aveiro (Portugal)
6/2011	Training School on RF/Microwave System Design for Sensor and Localization Applications, CTTC, Barcelona (Spain)
Additional	
Languages	Czech – proficient / native speaker English – intermediate (B1)

ABSTRACT

The doctoral thesis deals with electronically adjustable oscillators suitable for signal generation, study of the nonlinear properties associated with the active elements used and, considering these, its capability to convert harmonic signal into chaotic waveform. Individual platforms for evolution of the strange attractors are discussed in detail. In the doctoral thesis, modeling of the real physical and biological systems exhibiting chaotic behavior by using analog electronic building blocks and modern functional devices (OTA, MO-OTA, CCII$\pm$, DVCC$\pm$, etc.) with experimental verification of proposed structures is presented. One part of theses deals with possibilities in the area of analog–digital synthesis of the nonlinear dynamical systems, the study of changes in the mathematical models and corresponding solutions. At the end is presented detailed analysis of the impact and influences of active elements parasitics in terms of qualitative changes in the global dynamic behavior of the individual systems and possibility of chaos destruction via parasitic properties of the used active devices.

ABSTRAKT

Dizertační práce se zabývá elektronicky nastavitelnými oscilátory, studiem nelineárních vlastností spojených s použitými aktivními prvky a posouzením možnosti vzniku chaotického signálu v harmonických oscilátorech. Jednotlivé příklady vzniku podivných atraktorů jsou detailně diskutovány. V doktorské práci je dále prezentováno modelování reálných fyzikálních a biologických systémů vykazujících chaotické chování pomocí analogových elektronických obvodů a moderních aktivních prvků (OTA, MO-OTA, CCII $\pm$, DVCC $\pm$, atd.), včetně experimentálního ověření navržených struktur. Další část práce se zabývá možnostmi v oblasti analogově – digitální syntézy nelineárních dynamických systémů, studiem změny matematických modelů a odpovídajícím řešením. Na závěr je uvedena analýza vlivu a dopadu parazitních vlastností aktivních prvků z hlediska kvalitativních změn v globálním dynamickém chování jednotlivých systémů s možností zániku chaosu v důsledku parazitních vlastností použitých aktivních prvků.