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doi:10.15199/48.2023.10.39

Effect of the Preamplifier Stage on the Acquisition of Low-Amplitude Nonlinear Dynamics Signals

***Abstract**. This paper investigates the influence of the preamplifier stage on the acquisition of low-amplitude nonlinear dynamics signals. Five different amplifiers were compared with a gain of about 60 dB and a bandwidth range from 10 Hz to 1 MHz. The reconstruction of the attractor correlation dimension was investigated using three chaotic signal generators built according to different principles. The results of the conducted research indicate a significant influence of the amplifier's self-noise and the bandwidth of the frequency response on the estimated dimension. In addition, a different nature of the impact on the correlation dimension caused by preamplifiers based on operational amplifiers and transistor circuits was also noticed.*

***Streszczenie.** W niniejszej pracy zaprezentowano wpływy stopnia przedwzmacniacza na akwizycję słabych sygnałów dynamiki nieliniowej. Porównano pięć różnych wzmacniaczy o wzmocnieniu 60 dB oraz paśmie przenoszenia z przedziału od 10 Hz do 1 MHz. Za pomocą trzech generatorów sygnału chaotycznego zbudowanych według różnych zasad, zbadano odtwarzanie się wymiaru korelacyjnego atraktora. Przeprowadzone badania wskazują na istotny wpływ szumów własnych wzmacniacza oraz na wpływ szerokości pasma przenoszenia na estymowany wymiar. Ponadto zauważono również odmienny charakter wpływu na wymiar korelacyjny spowodowany przez przedwzmacniacze bazujące na scalonych wzmacniaczach operacyjnych oraz na układach tranzystorowych. (**Wpływ stopnia przedwzmacniacza na akwizycję sygnałów dynamiki nieliniowej o niskiej amplitudzie**)*

Keywords: chaos, correlation dimension, preamplifier, acquisition system, low signals
Słowa kluczowe: chaos, wymiar korelacyjny, przedwzmacniacz, system pomiarowy, słabe sygnały

Introduction

The correlation dimension is an important parameter characterizing chaotic signals and distinguishing between deterministic and stochastic chaos. Correct measurement allows us to know the nature of the observed chaos and to assess the change in the stability of the tested systems. This has applications, for example, in biology and medicine. The methods of nonlinear signal analysis are commonly used to test the durability of mechanical systems [1] or in the study of the heartbeat by ECG signals [2].

One of the important sources of errors in determining the correlation dimension of the signal is the characteristics of the input preamplifiers of the measurement system. The acquisition system can be divided into a preamplifier and a sampling system. The preamplifier system can be characterized by the gain bandwidth and the value of the self-noise voltage, while the acquisition system can be by the frequency and sampling resolution. Properly selecting these parameters can significantly impact the correct estimation of signal parameters. The influence of stochastic noise [3,4], low-pass filtering [5,6,7], and the effect of the selection of sampling resolution [8] have been described in the literature. Incorrect sampling frequency or too short measurement series may cause incorrect dynamics reconstruction. Moreover, Plewka [9] suggested that selecting an appropriate type of preamplifier has been crucial in correctly recognizing the chaotic nature of the Barkhausen noise.

The above conditions and the lack of experimental analysis of the preamplifier's influence on studying dynamic systems in the literature motivated authors to discuss this topic. This work also continues the research on acquiring chaotic signals [10].

Methods

The study of the influence of the preamplifier stage on the reconstruction of chaotic dynamics consisted in comparing the parameters of the amplifier's input and output signals. Two types of measurements were made: characterizing the transmission parameters of the amplifier (frequency response, gain non-linearity, output noise) and comparing the correlation dimension of the attractor of nonlinear dynamics signal before and after amplification.

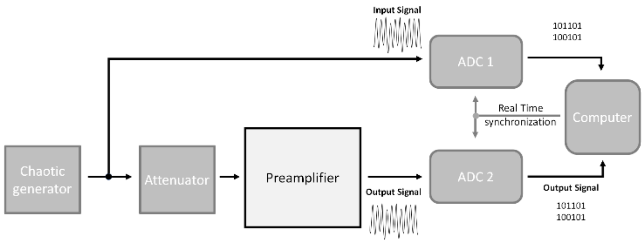

Fig.1. The measuring system simultaneously sampled the signal from the input and output of the investigated amplifier in real time, and then the parameters were determined using numerical methods. To maintain close ranges of measurement parameters in both ADC cards, a broadband voltage attenuator with attenuation of -80 dB, -60 dB, and -40 dB was placed on the input of the tested amplifier.

Hameg HM8131-2 generator with direct digital synthesis (DDS) was used as the input signal for testing the preamplifier parameters. Three self-constructed analog generators were used to analyze the correlation dimension, generating chaotic signals with a varied frequency band. The first of them, presented in Figure 2a, is the RLC series circuit (Diode Based Generator), in which a rectifying diode in the role of capacitance. The nonlinearity of the current-voltage characteristic of the diode (with adequately selected parameters) causes instability of the excitation signal amplitude [11]. The center frequency of the spectrum is about 30 kHz. The other generator (Fig. 3a), known in the literature as the Chua generator [12], is a self-excited generator based on a negative resistance diode. The signal resembles a generator starting up, and which generation is abruptly interrupted. The frequency of the generated signal oscillates around 3 kHz. The last type of generator used is a chaotic circuit using a bipolar transistor junction (Fig.4a) (Transistor-Based Generator) [13]. The signal from this generator slightly resembles the Chua generator's, but the oscillations have an additional upward trend, as shown in Figure 4d. The frequency of this signal is in the range of approx. 3 MHz.

Five simple preamplifiers were used for the investigation, with a gain of about 60 dB and the frequency response bandwidth from 10 Hz to 1 MHz. Two are transistor amplifiers: a two-stage common-emitter amplifier (*2xC549*) and a similar one with direct coupling (*2N5089+C560*). Another two are amplifiers based on operational amplifiers in an inverting circuit: a single-stage LTC6268 broadband amplifier (*1xLTC6268*) and a three-stage decade amplifier (*3xOP37*) on OP37 components. The last type of amplifier is a mixed circuit. A common emitter amplifier with a BC560 transistor implements the first stage, and the next one is a simple, low-noise operational amplifier UL1202 (*C560+UL1202*).

All measurements were made in a setup, as shown in Figure 1. The measurement system consisted of a computer and two National Instruments PCI-6251 cards that sampled the signal at the input and output of the investigated preamplifier. The cards were synchronized using the Real Time System Integration (RTSI) bus, thanks to which sampling took place simultaneously, with a frequency of 1 MSPS and a resolution of 16 bits. A series of one million samples per channel was acquired each time. The maximum integral nonlinearity error (INL) for the cards used was below -65 dB. Since the investigated preamplifiers had a high gain (approx. 60 dB), broadband (over 1 MHz) voltage attenuators were used at the input, with values of -80 dB, -60 dB, and -40 dB, respectively. As a result, it was possible to compare the output signal with the input signal of different dynamics while keeping the same sensitivity ranges of the measurement channels.

The reconstruction of chaotic dynamics consists of reconstructing a multidimensional attractor from only one measurement variable $\boldsymbol{x} = \{x_1, x_2, \cdots, x_N\}$ into m-dimensional embedding space. Each subsequent reconstructed variable x_i is obtained by delaying the original measurement series x by another multiple of the delay τ as follows:

(1) $$\boldsymbol{x}_i = \left(x_i, x_{i+\tau}, \cdots, x_{i+(m-1)\tau}\right)$$

This method is called Takens' Embedding theorem [14]. According to its assumptions, the reconstructed trajectory is diffeomorphic from the original trajectory, meaning it retains all the properties of the actual dynamics.

To estimate the correlation dimension D_2, the commonly used Grassberger-Procaccia method [15] was used, which consists in determining the correlation integral in the form:

(2) $$C_m(r) = \frac{2}{N_m(N_{m-1})}\sum_{i<j}\theta\left(r - \left\|\boldsymbol{x}_i - \boldsymbol{x}_j\right\|\right)$$

where $\theta(x)$ is the Heaviside function with $\theta(x) = 1$ for $x > 0$ and $\theta(x) = 0$ for $x \leq 0$, and $N_m = N - (m-1)\tau$. The slope of the linear area in the logarithmic plot of the $C_m(r)$ integral is called the scaling exponent. If, with the increasing dimension m of the embedding space, this exponent becomes saturated, then such a value is called the estimated dimension:

(3) $$D_2 = lim_{m\to\infty}\frac{logC(r)}{logr}$$

The plots in Figure 5 present the measurement results of the correlation dimensions determined for the 6-dimensional embedding space in relation to each investigated amplifier's output signal-to-noise ratio (SNR). In addition, four cases were considered for each amplifier: the input and output signals with one of the three voltage attenuators. As a result, the accident gain of the input signal was: -20 dB, 0 dB, and 20 dB, respectively, with the same intensity of the amplifier's noise. In addition, Figure 5 shows the influence of input signal filtering resulting from the limited bandwidth of the investigated preamplifiers. This impact was assessed based on phase shifts between the output and input signals as a function of time. In addition, it was distinguished whether the shifts come from a low-pass or high-pass filter by subjecting the input signal to numerical filtering with filters with the parameters set out in Table 1.

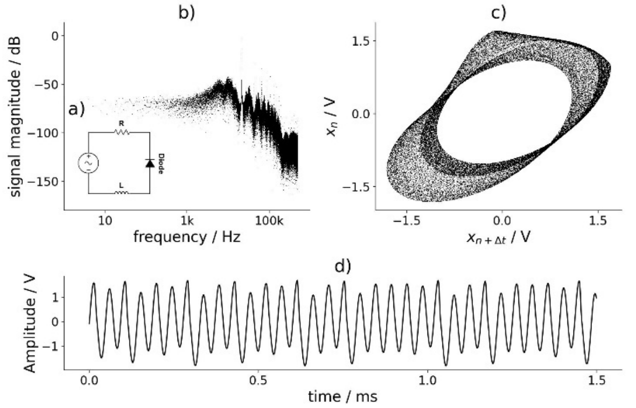

Fig.2. *Diode-Based Generator*. A chaotic circuit based on a series RLC circuit with a diode (a), whose center frequency is about 30 kHz (b). Figure d) shows the voltage signal as a function of time, and (c) the attractor reconstructed in 2-dimensional space with a delay time of $\tau = 8$ samples.

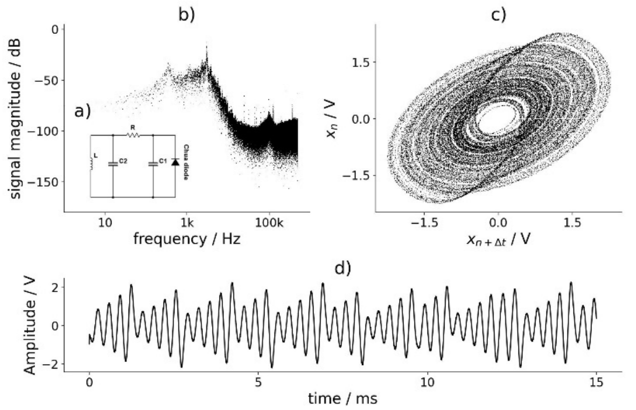

Fig.3. *Chua Generator*. Chaotic RLC system based on the Chua diode (d), whose center frequency is about 3 kHz (a). Figure c) shows the voltage signal as a function of time, and (b) the attractor reconstructed in 2-dimensional space with a delay of $\tau = 60$ samples.

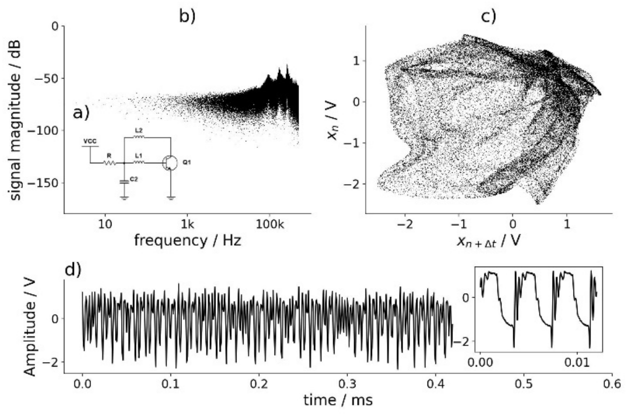

Fig.4. *Transistor-Based Generator*. RLC chaotic circuit based on the junction of a bipolar transistor (d), whose center frequency is about 3 MHz and is outside the observation bandwidth (a). Figure c) shows the voltage signal as a function of time measured in the experimental setup (f_s = 1 MHz) and in time magnification using a measurement system with a sampling frequency of f_s = 100 MHz, and (b) the attractor reconstructed in 2-dimensional space with a delay of $\tau = 1$ samples.

Table 1. The results of the parameters of the preamps

Preamps	Gain [dB]	GNE @ +1V [dB]	GNE @ -1V [dB]	Offset [mV]	Noise density @10 kHz [μV/√Hz]	Output Noise [mV]	F_L [Hz]	HP Order	F_H [kHz]	LP Order	ΔF [kHz]
2xC549	58	-41.7	-42.0	0.081	14.0	1.644	108.6	2	55.6	1	55.5
2N5089+C560	45	-51.4	-49.5	10.485	0.8	0.15	10.9	2	112.0	3	112.0
1xLTC6268	60	-37.0	-35,8	9.993	16.2	11.015	180.4	1	963.7	2	963.5
C560+UL1202	62	-30.3	-39.3	-0.052	6.6	3.169	431.4	3	90.5	1	90.1
3xOP37	60	-58.9	-71.0	-1.531	5.3	9.514	530.2	3	547.1	5	546.6

Results

Table 1 presents the results of the parameters of the investigated amplifiers. Except for *2N5089+C560*, all other amplifiers had a gain close to 60 dB. The next two columns show the Gain Nonlinearity Error (GNE), defined as the deviation of the gain from the line of best fit for the minimum (-1V) and maximum (+1V) of the amplifier's input range as follows:

$$\text{GNE} = 20\log_{10}\left|\frac{V_{in}\cdot m + b - V_{out}}{V_{out}}\right| \quad (4)$$

The *C560+UL1202* amplifier showed the highest gain nonlinearity and the *3xOP37* had the smallest. At the same time, the former was also characterized by the highest relative gain asymmetry. Each of the amplifiers had higher non-linear distortion than the National Instruments PCI-6251 card. The following columns show the results associated with the noise of the amplifiers related to the output. The first column shows the noise density for a mutual center frequency equal to 10 kHz. The next one is the total self-noise at the output of the amplifier. The lowest noise was obtained by the *2N5089+C560* amplifier and the highest by *3xOP37*, but it was the *1xLTC6268* amplifier that had the highest noise density, at around 10 kHz. The remaining columns refer to the cutoff frequencies of the amplifiers' passband and have been approximated by the characteristics of linear filters. The lower ($\boldsymbol{F_L}$) and upper ($\boldsymbol{F_H}$) cutoff frequencies were determined as a decrease in the signal amplitude by 3 dB. The order of the fitted filter is also given. The *1xLTC6268* amplifier has the widest bandpass, and the *2xC549* has the narrowest.

Figure 5a presents the results obtained for the Diode-based Generator. Apart from the signal coming from the *1xLTC6268* and *3xOP37*, all other amplifiers exhibited the effect of low-pass filtering on the input signal. The *2xC549* and *3xOP37* amplifiers had a similar signal-to-noise ratio but differed in the results of the correlation dimension. The former gave lower results, and the difference increased as the signal-to-noise ratio decreased. The *2N5089+C560* amplifier had a higher signal-to-noise ratio than the *C560+UL1202*, and despite lowers SNR, both amplifiers received similar dimension results. The *2N5089+C560* amplifier has a higher signal-to-noise ratio than the *C560+UL1202*, and yet, for lower SNR, both amplifiers gave similar dimension results. Non-bandwidth limiting amplifiers have lower SNR and give higher correlation dimensions than other amplifiers.

Figure 5b shows the results for the Chua generator. All amplifiers except *2_transitor_II* apply high-pass filtering on the input signal. The *2xC549* and *2N5089+C560* amplifiers have a similar signal-to-noise ratio, but the former gives higher correlation dimension results for -20 dB and 0 dB output signals. The *C560+UL1202* amplifier, despite the lower SNR (in the case of two output signals: -20 dB and 0 dB) and four times higher lower cutoff frequency, gives similar results of correlation dimensions as the *2xC549* amplifier. The results closest to the dimension of the input signal were obtained for the output signal at +20 dB for the *2N5089+C560* and *3xOP37* amplifiers. Both amplifiers differed significantly in frequency response (lower cutoff frequency was 50 times higher for *3xOP37*) and signal-to-noise ratio (for *3xOP37*, it was much lower).

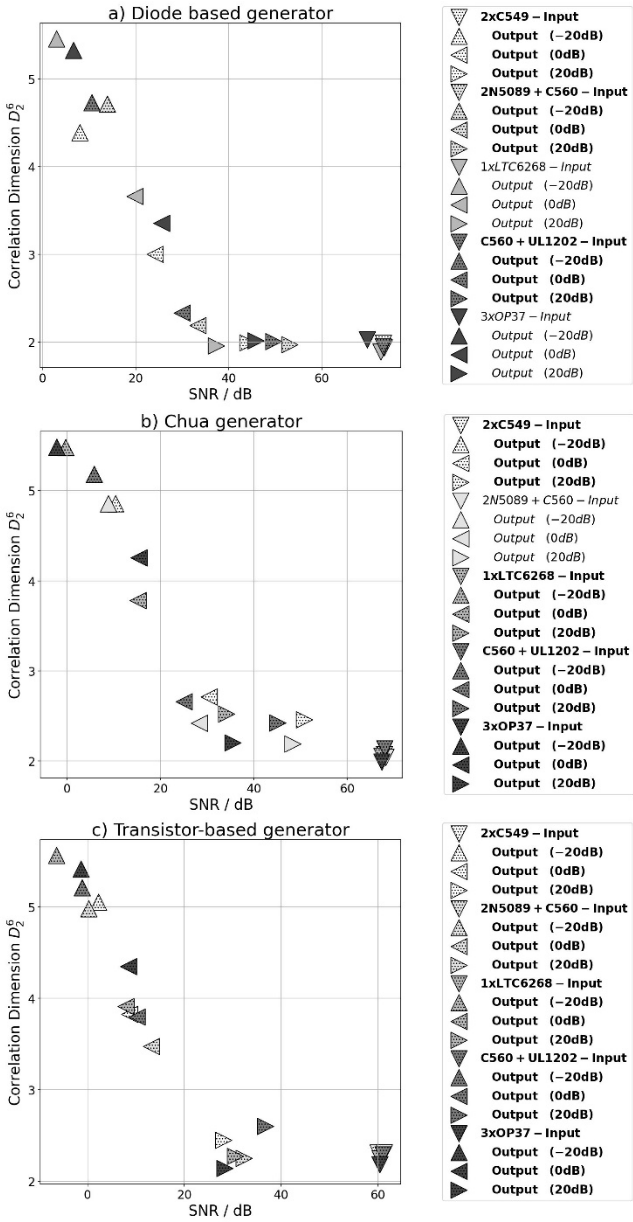

Fig.5. The results of D_2^6 correlation dimensions (determined for a 6-dimensional embedding space) in relation to the SNR signal-to-noise ratio for a) Diode-based Generator, b) Chua Generator and c) Transistor-based Generator. The following points on the graph represent the correlation dimensions for the input and output signals using appropriate voltage attenuators for the five tested preamplifiers. The values in brackets indicate the output signals level relative to the input signal (-20 dB, 0 dB, and 20 dB). The bold font on the legend and dotted marker fields on the graph emphasize the input signal filtering by the preamplifier. In the case of generators a) and c), these were low-pass filters, and in the case of a generator, c) high-pass filters.

For all three chaotic generators, the results of the correlation dimension of the input signal were similar in subsequent measurements, which proves the time coherence of these generators. Also, in all three cases, for SNR below 40 dB, as it decreased, the correlation dimension began to increase. The most significant increase occurred for amplifiers based on operational amplifiers. These also performed best for high signal-to-noise ratios. Quite an exciting result of the conducted research is the fact that the limitation of the observed bandwidth by the measuring system (as in the case of the Transistor-based Generator) does not cause the loss of information about the nature of the system from which the tested signal came from (undoubtedly it is a chaotic system). Despite that, we are unsure whether parameters such as the correlation dimension have been correctly determined.

Discussion

Amplifier noise, independently of the type of nonlinear dynamics input signal and the amplifier used, causes an increase in dimension. In the case of estimating the correlation dimension using the Grassberger-Procaccia method, this effect can already be seen in the correlation integral. Appearing noise can be associated with an additional scaling area (usually for small r), which does not saturate with the increased dimensions of the embedded space. Increasing the noise content of the signal causes this area to grow at the expense of the chaotic region. This effect has been noticed so far in works [16] and is observed in all measurements.

Signal filtering can also play a significant role in estimating the correlation dimension. Limiting the bandwidth may reduce the amount of noise in the signal, which should result in an improvement (decrease) in the value of the estimated dimension. However, the reverse situation is observed in the obtained results. For output signals with the best SNR parameters (+20 dB), filtered signals gave worst results than those in which the amplifiers did not limit the spectrum of the chaotic signal. Such an effect has also been described in the literature [6], and one of its simplest models assumes that the filter becomes part of the observed non-linear dynamics.

However, the above considerations only partially explain the observed relationships because some behaviors do not fit the models presented in the literature. It is also challenging to provide an unambiguous and universal scheme of dependence of the correlation dimension on any of the tested parameters of the amplifier, which would work for all considered generators. However, the most important conclusion that should be drawn from this work is that two types of behavior can be distinguished: those characteristic of op-amp-based amplifiers and those based on transistors. One may suppose that the simplified equivalent model of the amplifier as a band-pass filter and a source of stochastic noise is insufficient.

These results are significant in all cases involving very low signals coming from chaotic systems. The process of heavy amplifying may significantly impact the incorrect estimation of the correlation dimension and, as shown in this paper, cannot be treated as a systematic error.

Conclusion

The paper shows that the correlation dimension estimation error depends on the parameters of the amplifier used. Five preamplifiers (three transistors and two integrated) with a gain of about 60 dB, different bandwidths, and self-noise amplitudes were tested for three different dynamic systems generating chaotic signals. It was shown that the correlation dimension depends on the noise content of the signal (dimension increases with noise) and bandwidth (dimension increases or decreases with decreasing bandwidth). There is, however, no confirmation to say whether it depends on the nonlinearity of the gain or the order of the pass-band filter. In addition, the tested amplifiers could be divided into two groups with similar behavior: those based on operational amplifiers and those based on single transistors. Unfortunately, the reason for these differences could not be explained, but this will be the subject of further research. The paper does not present the influence of parameters describing non-linear time dependencies of the Slew Rate type. However, this would require additional study and a separate article. The experiments proved that the metrological aspect of acquiring process of a signal coming from a chaotic system has a significant impact on the final result. Therefore, it becomes crucial to select the appropriate amplifier and its parameters, which should be almost matched to the studied chaotic dynamics.

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