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Frequency Instability Measurement Device Based on the Pulse Coincidence Principle

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Context. The task of rapid and accurate measurement of the dynamic characteristics of modern signal sources with a frequency output, in particular, the short-time frequency instability function, calls for refining measurement techniques with account of the requirement to improve their metrological characteristics, reduce test time, and automate measurements by using information-and-measurement systems.
Objective. The goal of the work is to develop a method of measuring the short-time frequency instability function using the principle of pulse packet coincidence and experimental investigation of measurement devices based on this principle.
Method. A method was developed for measuring the short-time frequency instability function based on the principle of packet coincidence of regular independent pulse trains. The developed method has advantages over the best version of the method based on the period-time interval-code (PTC) conversion when working with the same initial value of the investigated frequency and when working with the same value of the averaging interval.
Results. Analytical relationships were obtained for basic metrological characteristics. A comparative analysis was carried out for the metrological characteristics of the developed method and the method using period-time interval-code conversion. Acceptable metrological characteristics are inherent to the short-time frequency instability function (SFIF) measurement method based on the period-time interval-code technique. The difference of investigated and reference intervals form the measurement interval, which is filled with pulses of the investigated or reference frequencies.
Conclusions. Stand-alone and virtual measurement devices were developed, and experimental studies of standard oscillators were carried out. The features of measurement devices were specified and the ways of their further improvement were described. Further development of the measurement device can involve an increase in the number of measured signal source with frequency output (SFO) parameters, in particular, changes in short-time frequency instability due to the action of destabilizing factors, and the characteristics and time of frequency setting. This calls for developing a controlled source of destabilizing factors and synchronizing its operation with the measurement device.

Key words: short-time frequency instability; stand-alone measurement device; virtual measurement device; LabVIEW; packet coincidence of pulses

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Introduction

Analysis of the current state and trends in the development of instrumentation is indicative of insufficient accuracy and short-time frequency instability function (SFIF) measurement challenges. This deficiency is being eliminated by developing new methods and tools for SFIF measurement. In this connection, along with the development and refinement of conventional measurement devices, more effort is being put into developing virtual measurement devices (VMDs) that help streamline the process of performing intricate measurements.

The object of research is a stand-alone SFIF measurement device developed on the PLD Emulator console and a virtual measurement device based on the Virtual Instruments technology by National Instruments.

The subject of research is methods for SFIF measurement and instrumentation based on these methods.

Known methods and measurement devices based on them demonstrate insufficient accuracy of measuring SFIF with specified speed and their design is challenging.

The purpose of the work is to develop a method of measuring SFIF using the principle of pulse packet coincidence and experimental investigation of measurement devices based on this principle.

1 Problem statement

Modern electronic systems comprise a wide variety of different signal sources with a frequency output (SFO) differing in their purpose and functionality that are generally signal generators, quartz oscillators or frequency synthesizers. Improvement of the systems and extension of the tasks performed with their help have translated into more stringent requirements for the specifications of such systems, namely, dynamic characteristics (short-time frequency instability, readiness time, time and rate of transfer from one frequency to another, etc.). Moreover, in many respects, the achievement of the required characteristics is possible as a result of the improvement of the SFO, which, in turn, requires the development of some qualitatively new measuring equipment for the measurement of overall and specific dynamic characteristics.

2 Review of the literature

Methods of measurement of short-time frequency instability and the measurement devices based thereupon are being improved continuously.

To determine a short-time frequency instability, often times a method of comparison to a reference frequency is used. The simplest method is an electronic counting method [1, 2] that has a relatively low measurement accuracy. In order to increase the accuracy, a two-channel frequency measurement method [3] is used. Although, these two methods have several major drawbacks: quite a high labor intensity, inability to visualize the functions of a short-time frequency instability in real time and design complexity.

A combined method using an oscillator and frequency counter measuring the period [4] and time interval [5] is a better method. A reference source is used as a comparison oscillator. Its disadvantages include low accuracy, a relatively high labor intensity of setting time averaging, and inability to visualize the functions of a short-time frequency instability.

Short-time frequency instability can also be measured using a phase or frequency demodulator [6]. When measuring an effective output signal voltage of the phase demodulator, a mean square value of the phase fluctuation is assessed. If a differentiating circuit is active at the output of the phase demodulator, then the output voltage will be directly proportional to the frequency fluctuations. To assess short-time frequency instability, a low frequency filter with a rectangular transmission characteristic needs to be included to the circuit upstream the voltmeter. But the accuracy of measurement, in this case, is relatively low.

There is a method of measuring the phase shift between periodic signals of arbitrary duration based on the principle of coincidence of pulses in packets [7]. Its drawbacks include the need to generate minimum length pulses, complexity of implementation and retrieval of information regarding SFIF, especially at short times of averaging.

A method for measuring the SFIF based on the transformation of “period-time interval-code” (PTC) has good metrological characteristics, where a measuring interval is generated as a difference between the tested and the reference frequencies [8, 9]. There are four options for implementing the PTC transformation based method. Its disadvantages include a low frequency and period resolution in some cases, and implementation complexity.

3 Materials and methods

The development of the SFIF measurement method was based on the principle of packet pulse coincidence (PPC) suggested in [10, 11]. The method assumes the performance of the following operations.

Regular independent trains of pulses of the reference signal (Fig. 1b) and investigated signal (Fig. 1a) are formed, with the period Tx(t) of the latter changing according to the law

$$T_x(t) = T_n \pm \Delta T_x(t), \tag{1}$$

where T_n is a initial value of the investigated signal pulse repetition period; $\Delta T_x(t)$ is a change in the initial value of the investigated signal pulse repetition period.

The difference of the pulse repetition periods of the investigated and reference signals ΔT should be less than the duration of the pulses of the investigated and reference signals $\tau_{\text{и}} = \tau_{\text{ио}} = \tau_{\text{их}}$. In this case, the pulses shall coincide in packets (Fig. 1c). Thereat, the number of pulses in a packet N_n is determined, as follows from analysis [10, 11] and Fig. 1, by the relationship

$$N_n = \frac{2\tau_u}{\Delta T - 1}, \tag{2}$$

where ΔT is a difference of pulse repetition periods of the investigated and reference signals.

Obviously, the averaging interval of the investigated frequency pulses $\tau_{\text{у}}$ shall coincide with the repetition period of the coincidence packets.

Function (2), with account of (1) and analysis of Fig. 1, takes the form

$$N_{nj} = \frac{2\tau_u}{\left[\Delta T_{pn} \pm \overline{\Delta T_x(t)_j}\right] - 1}, \tag{3}$$

where N_{nj} is a number of pulses in a packet on j-th averaging interval; $\tau_{\text{и}}$ is a duration of pulses of the investigated and reference signals; $\overline{\Delta T_x(t)_j}$ is a mean value of change of the period of investigated oscillations on the j-th averaging interval; ΔT_{pn} is a initial value of the difference of pulse repetition periods of the investigated and reference signals; T_o is a reference signal pulse repetition period; $\Delta T_{pn} = T_n - T_o$ should be chosen with account of the required averaging interval of the investigated frequency pulses and the maximum change of the period of investigated oscillations during the test time.

Function (3) yields

$$\Delta T_{pn} \pm \overline{T_x(t)}_j = \frac{2\tau_u}{N_{nj}+1}. \tag{4}$$

Hence, at the j-th averaging interval, the number of pulses in the respective coincidence packet will uniquely define the mean deviation of the period of investigated oscillations for ΔT_{pn}.

Let us investigate the transient response (TR) of the method. It is its response to a step change of the measured parameter. The expression of TR for the period found from condition

$$h_T = N_n\big|_{\overline{\Delta T_x(t)}_j=\Delta T_c} - N_n\big|_{\overline{\Delta T_x(t)}_j=0},$$

has the form

$$h_T = \frac{2\tau_u \cdot \Delta T_c}{(\Delta T_{pn}+\Delta T_c)+\Delta T_{pn}}, \tag{5}$$

where h_T is a period response of the method; ΔT_c is a increment of investigated period. The method resolution for period ΔT_{pc} found from condition $h_T = 1$ takes the form

$$\Delta T_{pc} = \frac{\Delta T_{pn}^2}{2\tau_u - \Delta T_{pn}}. \tag{6}$$

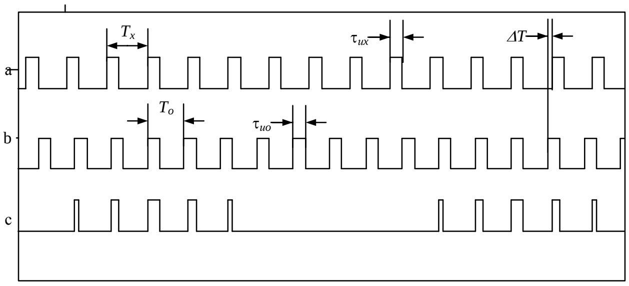


Fig. 1. Coincidence of independent regular pulse flows

It can be shown that relationships (4)-(6), depending on the parameters of the laws of variation of the frequencies of the investigated and reference signals, take the form

$$f_{pn} \pm \overline{\Delta f_x(t)}_j = \frac{2\tau_u \cdot \left(f_n \pm \overline{\Delta f_x(t)}_j\right) \cdot (f_n + f_{pn})}{N_{nj}+1}; \tag{7}$$

$$h_f = \frac{2\tau_u \cdot \Delta f_c \cdot (f_{pn}+f_n)^2}{(f_{pn}-\Delta f_c)\cdot f_{pn}}; \tag{8}$$

$$\Delta f_{pc} = \frac{f_{pn}^2}{2\tau_u \cdot (f_{pn}+f_n)^2 + f_{pn}}; \tag{9}$$

where f_{pn} is an averaging frequency; $f_{pn} = f_o - f_n$; f_o is a reference signal frequency; f_n is a initial investigated frequency; $\overline{\Delta f_x(t)}_j$ is a mean value of frequency change of investigated oscillations on the j-th averaging interval; Δf_c. is a investigated frequency increment; h_f is a frequency response of the method; Δf_{pc} is a frequency resolution of the method.

The conversion characteristic (7) has a complex functional dependence on $\overline{\Delta f_x(t)}_j$. However, since during the measurement of SFO parameters the following conditions are always satisfied: $f_n \geqslant \overline{\Delta f_x(t)}_j$, $f_n \geqslant f_{pn}$, $N_n \geqslant 1$, it can be written as

$$\left(f_{pn} \pm \overline{\Delta f_x(t)}_j\right) = \frac{2\tau_u \cdot f_n^2}{N_{nj}};$$

with an error not greater than

$$\delta = \frac{f_n \cdot (f_n/N_n - f_{pn} + \Delta f_{\max})}{(f_n - \Delta f_{\max})\cdot(f_n + f_{pn})},$$

where Δf_{max} is a maximum change of investigated SFO frequency.

Let us conduct a comparative analysis of the developed method and the method based on PTC conversion, the best version of which demonstrates a frequency resolution of

$$\Delta f_{pcPTC} = \frac{f_n}{\tau_y \cdot f_{oPTC} + 1},$$

where f_{oPTC} is a reference signal frequency of the PTC conversion method; τ_y is a averaging interval for investigated frequency pulses.

Fig. 2 shows the results of calculating the resolution of the methods.

An analysis of resolution relationships and of Fig. 2 shows the following: – the developed method has advantages over the best version of the method based on PTC conversion; – $\tau_y > (f_o - f_n)/(2\tau_u \cdot f_n^3)$ when working with the same initial value of the investigated frequency; – $f_n > \sqrt[3]{f_{oPTC}/(2\tau_u \cdot \tau_y)}$ when working with the same value of the averaging interval.

4 Experiments

The suggested principle was used to develop a standalone SFIF measurement device whose block diagram is shown in Fig. 3.

The precision one-shot multivibrator and pulse shaper generate pulses of the investigated and reference frequencies, with the duration of the pulses being respectively τ_{ux} and τ_{uo}. The AND gate output is a packet of coincidence pulses that set the first counter to zero and are input to the second counter to count their number. The flip-flop is set to “1” with the first pulse of the coincidence packet and reset to “0” if the packet has no pulses and if five reference frequency pulses were input to the first counter. This improves measurement device noise immunity. The flip-flop output signal leading edge enables a write signal to write the number of pulses in the packet from the counter to the register. The write signal is delayed and then sets the counter to “0”. Hence, this generates data on frequency instability for adjoining time intervals to improve measurement accuracy.

The code of the number of pulses in the packet and the codes of the durations of pulses and reference frequency values are input to calculation units to determine frequency instability.

The measurement device uses the standard algorithm of determining the short-time frequency instability (δ_{SFI}) with the formula $\delta_{SFI} = (f_{\max} - f_{\min})/f_{rated}$, where frated is a rated (mean) frequency during tests; fmax is a maximum frequency measured on the averaging interval; fmin is a minimal frequency measured on the averaging interval. DAC converts calculation results to voltage to visualize frequency change functions by using any commercial recorder.

5 Results

The frequency instability measurement device was developed using the PLD Emulator console [12] whose digital components design is based on programmable logic integral circuits (FPGA) by Altera and the digital-analog converter by Analog Devices.

The following features were revealed by analysis of the measurement device structure and its experimental investigation:

- the measurement device is distinguished by straightforward design due to the small bit capacity of the second counter, register, and DAC because frequency deviation is measured for a difference value, which is significantly smaller than the reference frequency;
- frequency deviation is converted to voltage, making it possible to use any commercial oscilloscopes for visualization of results;
- investigation of different signal sources presents difficulties in changing the parameters of τ_{uo}, τ_{ux} and T_o measurement settings, resulting in increased test run time.

To reduce test run time, the process of excluding information about the initial value of the investigated frequency from measurement results should be automated. This can be done, in particular, by using virtual measurement devices.

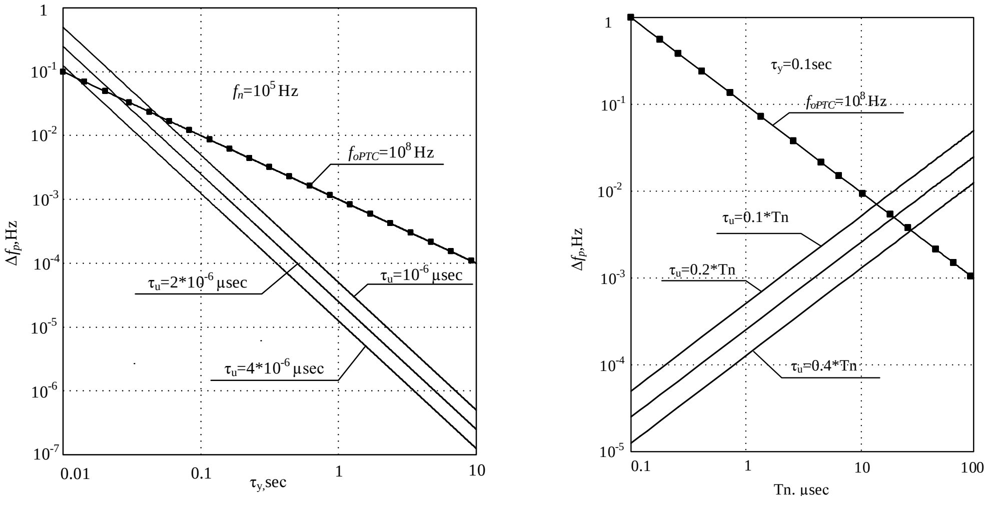
A virtual measurement device (VMD) is a measurement device based on a universal computer with additional software (an application and a driver) installed and efficient technical equipment [13]. The term “virtual” is usually applied to two VMD aspects:

- first, they are not commercial products in the sense of off-the-shelf ones, but rather a temporary item intended for solving specific measurement problems;
- second, VMD control and display members are represented as graphic images on a computer screen, and a VMD is controlled using typical input devices: keyboard, mouse, and a touch screen [14, 15]. The SFIF virtual measurement device is built around a PPC converter whose structure in Fig. 3 is shown with a dash-dotted line and a computer. Usually, three programming techniques are used for developing VMD computer programs [13,15]:
- textual or textual graphic (Pascal, Delphi, LabWindows/CVI, Measurement Studio, Visual Basic, Visual C/C++ packages) that use elements of visual textual programming focused, primarily, to experienced programmers;
- object-oriented graphic (In Touch and Trace Mode packages) using graphic images of the objects of an automated industrial process control system as programming elements;
- function-oriented graphic (LabVIEW, LabVIEW/DSC, Agilent VEE, DASYLab, DIAdem, ZETLAB, and Hypersignal packages) using the functional logic principle of designing (drawing) and graphic presentation of program algorithms.

Using textual programming for each specific project, though perhaps being the most optimal one from the view-point of solving a definite problem, loses its advantages because the problem has to be solved each time almost from scratch, involving big time and material costs. Due to this, preference is given to dedicated software, in particular, graphic programming.

National Instruments is the developer of the virtual instruments technology — a breakthrough concept that changed the approaches to and technique of developing data acquisition systems and measurement control. Its LabVIEW CAD package became de facto an international standard. It offered and patented a new graphic based programming language G. Working with familiar concepts (functional block, connection, chart), a development problem can be solved fast and, what is important, with a visual representation without getting lost in the maze of programming. According to most conservative estimates, development with programming language G can reduce a project lead time by at least 4-10 times [13, 15].

The computer program developed in LabVIEW consists of two interrelated parts: a front panel and a block diagram (Fig. 4) [16, 17].



(a) (b)

Method based on period-time interval-code conversion Method based on the pulse coincidence principle

Fig 2. Dependence of resolution of methods for measuring short-time frequency instability on: (a) — averaging interval and (b) — initial value of investigated frequency

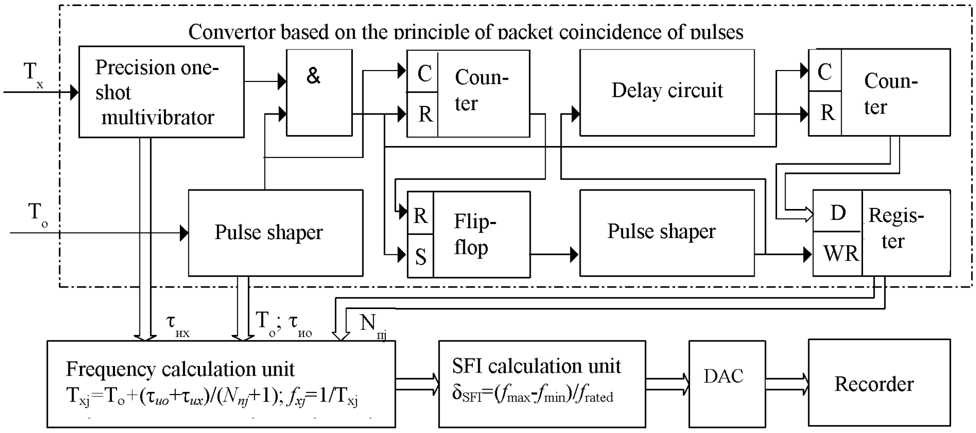


Fig 3. Block diagram of a stand-alone device for measuring frequency instability

The front panel accommodates control members, buttons, graphic indicators, and other control elements. They are the tools the user works with to input data. The indication elements display the program output data. The elements are input with a mouse and keyboard, with action results being displayed on the monitor screen.

The SFIF virtual measurement device has five indication elements on the front panel. The most interesting indication element is oscilloscope Chart, which ensures automatic Y-axle scaling. This enables visual representation of the frequency measurement without having to have to perform different adjustment of the settings during testing.

The front panel elements represented on the block diagram are shown as terminals, via which data flow from the user to the program and back. The block diagram describes the VMD operation logic: data acquisition from communication interfaces, mathematical treatment, computation of related quantities, data transfer to indicators, and saving the results.

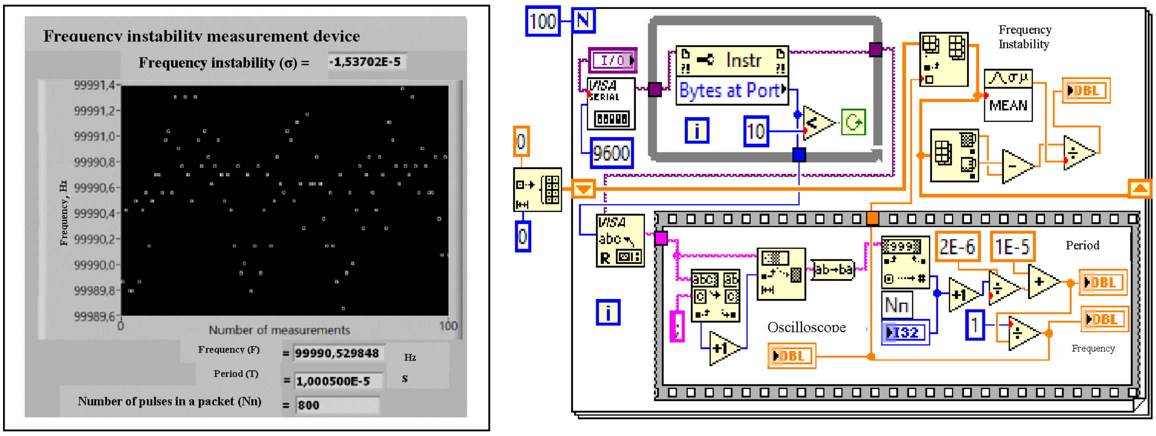
Basic functional components of the VMD block diagram:

– VICA Read and VICA Write ensure data exchange through RS-232. Use of RS-232 is dictated by the fact that the VM is based on PLD Emulator [12];

– Array Max & Min and Mean determine the maximum, minimal and mean period of investigated oscillations in an array with a user specified dimension.

Fig. 5 shows the VMD architecture.

VMD is based on a standard PC running under the Windows OS. OS UNIX, Linux, Mac OS, Microsoft Pocket PC, Microsoft Windows CE, and Palm OS can be used, and the measurement device can be set up on a laptop. The configuration files are developed with the Quartus CAD package and used for determining the schematic design of the primary convertor based on an Altera FPGA.



Frequency instability measurement device

Frequency instability (σ) = -1,53702E-5

Frequency (F) = 99990,529848 Hz

Period (T) = 1,000500E-5 s

Number of pulses in a packet (Nn) = 800

(a) (b)

Fig 4. Application software: a — front panel and b — block diagram

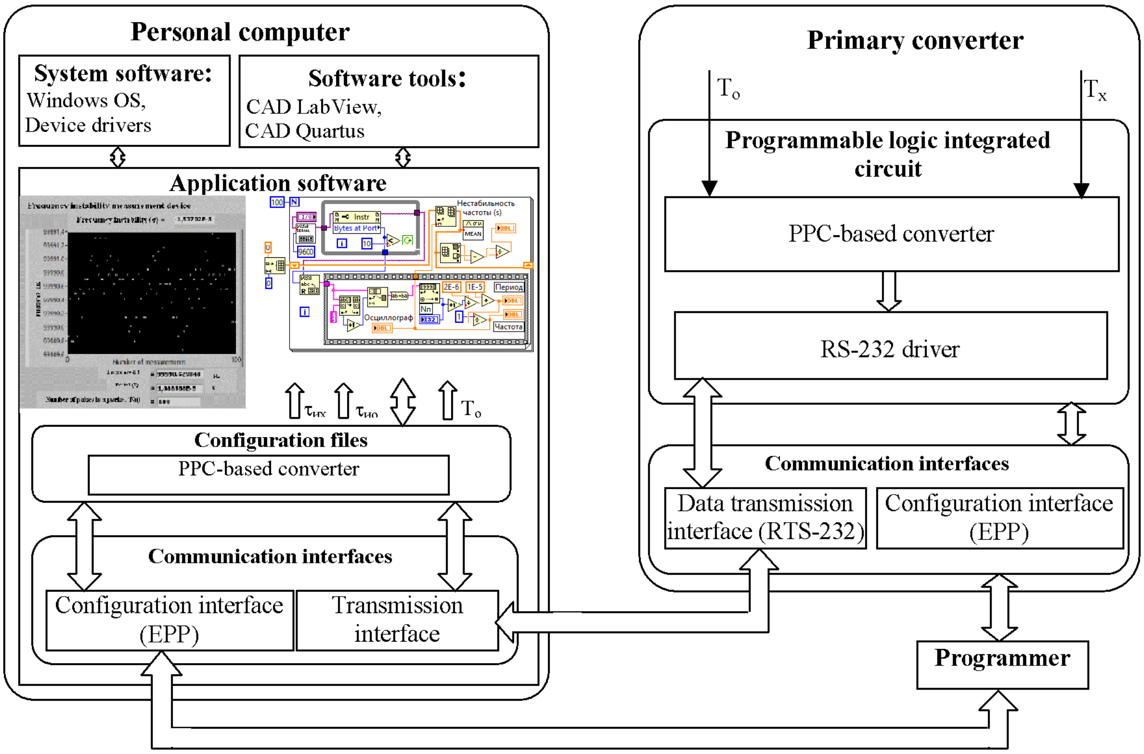


Fig 5. Architecture of virtual SFIF measurement device

The PC and the primary converter are connected via two channels: information is sent to the PC via a serial interface, and the parallel interface operating in the EPP mode serves for configuring the FPGA with the ByteBlasterMV programmer.

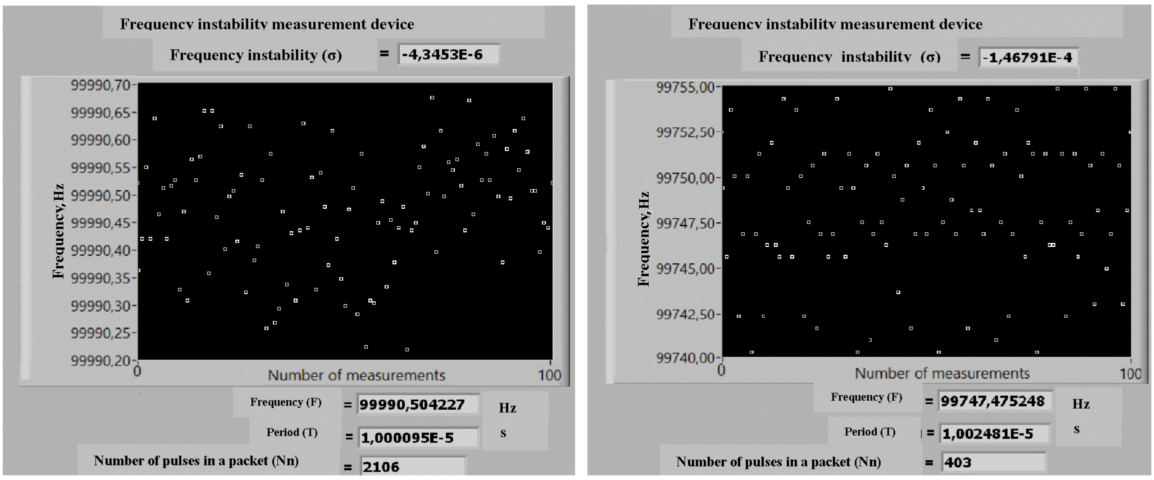
Test results for pulse generator G3-63 at $To = 10^{-5}$ sec and $\tau_u = \tau_{uo} = \tau_{ux} = 10^{-6}$ sec are shown in Fig. 6 including temporal function of frequency alteration. This function enables the increase in volume of the data regarding the parameters and characteristics of the generator tested, the sensitivity to the exposure to different destabilizing factor (input voltage, load, etc.), overall and specific dynamic attributes (transitional characteristic, temperature and frequency characteristic, time of frequency setting, etc.).

The analysis of Fig. 6 suggests that the second generator has low reliability due to the significant instability of its frequency.

6 Discussion

The developed method enabled improving the metrological characteristics of the SFIF measurement device by a minor schematic and design modification of measurement devices based on its principle.

Using the functional blocks included in CAD LabVIEW, which were tested on many occasions by different development engineers, reduced the VMD lead time and improved its operational reliability.


Frequency instability measurement device
Frequency instability (σ) = -4,3453E-6
Frequency (F) = 99990,504227 Hz
Period (T) = 1,000095E-5 s
Number of pulses in a packet (Nn) = 2106

Frequency instability measurement device
Frequency instability (σ) = -1,46791E-4
Frequency (F) = 99747,475248 Hz
Period (T) = 1,002481E-5 s
Number of pulses in a packet (Nn) = 403

(a) (b)

Fig 6. SFIF measurement results for low-frequency signal generators G3-63: a — serial No. 31116 and b — serial No. 32344

Conclusions

The scientific novelty of obtained results is that the method for measuring SFIF based on the principle of packet coincidence of regular independent trains of pulses was developed. Its metrological characteristics are described. The practical significance of obtained results is that the standalone and virtual SFIF measurement devices were developed. Using CAD LabVIEW and a reconfigurable FPGA for VMD design and operation has ensured marked advantages of the proposed measurement device over known ones: control of measurement device parameters was simplified; automatic scaling was provided for visualizing SFIF; the user can change the front panel configuration, the block diagrams of the virtual measurement device and the reconfigurable files during operation.

The downsides of the developed VMD are as follows: the need to input the reference signal frequency value and the investigated and reference frequency pulse durations on the block diagram, requiring that the VMD users have adequate skills. However, these deficiencies can be eliminated by placing control elements on the VMD front panel to input required values.

Further development of the measurement device can involve an increase in the number of measured SFO parameters, in particular, changes in short-time frequency instability due to the action of destabilizing factors, and the characteristics and time of frequency setting. This calls for developing a controlled source of destabilizing factors and synchronizing its operation with the measurement device. The resolution capacity can be increased by multiplying frequency deviation using standard instruments (a frequency comparator and synthesizer) according to a typical schematic diagram.

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Вимірювач нестабільності частоти на принципі збігів імпульсів

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Актуальність. Завдання швидкого й точного вимірювання динамічних характеристик сучасних джерел сигналів з частотним виходом, зокрема функції короткочасної нестабільності частоти (ФКНЧ), потребує вдосконалення методів вимірювання з урахуванням необхідності поліпшення їх метрологічних характеристик, зниження часу проведення випробувань, можливості автоматизації вимірювань за рахунок застосування інформаційно-вимірювальних систем. Мета роботи полягає в розробці методу вимірювання ФКНЧ на принципі збігів імпульсів пакетами та експериментальних дослідженнях вимірювачів на його основі.

Метод. Розроблено метод вимірювання функції короткочасної нестабільності частоти на принципі збігів регулярних незалежних послідовностей імпульсів пакетами. Розроблений метод має переваги в порівнянні з кращим варіантом методу на базі перетворення період-часовий інтервал-код при роботі з однаковим початковим значенням досліджуваної частоти і при роботі з однаковим значенням інтервалу усереднення.

Результати. Отримані аналітичні співвідношення для основних метрологічних характеристик. Проведено порівняльний аналіз метрологічних характеристик розробленого методу й методу на базі перетворення період-часовий інтервал-код. Добрими метрологічними характеристиками володіє метод вимірювання ФКНЧ на базі перетворення період-часовий інтервал-код, в якому формується вимірювальний інтервал як різниця досліджуваного і опорного інтервалів і заповнюється імпульсами досліджуваної або опорної частот.

Висновки. Реалізовано автономний й віртуальний вимірювачі, а також проведено експериментальні дослідження стандартних генераторів. Вказано особливості вимірювачів і шляхи їх подальшого удосконалення. Подальший розвиток вимірювача можливий в напрямку збільшення кількості вимірюваних параметрів джерел сигналів з частотним виходом, зокрема, зміни короткочасної нестабільності частоти від впливу дестабілізуючих факторів, характеристики і часу встановлення частоти. Для цього необхідно розробити керований джерело дестабілізуючих факторів і синхронізувати його роботу з вимірником.

Ключові слова: короткочасна нестабільність частоти; перетворювач на принципі збігів імпульсів пакетами; автономний вимірювач; віртуальний вимірювач; LabVIEW

Измеритель нестабильности частоты на принципе совпадения импульсов

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Задача быстрого и точного измерения динамических характеристик современных источников сигналов с частотным выходом (ИЧВ), в частности функции кратковременной нестабильности частоты (ФКНЧ), требует усовершенствования методов измерения с учетом необходимости улучшения их метрологических характеристик, снижения времени проведения испытаний, возможности автоматизации измерений за счет применения информационно-измерительных систем. Цель работы состоит в разработке метода измерения ФКНЧ на принципе совпадения импульсов пакетами и экспериментальных исследованиях измерителей на его основе. Разработан метод измерения функции кратковременной нестабильности частоты на принципе совпадений регулярных независимых последовательностей импульсов пакетами. Разработанный метод имеет преимущества в сравнении с лучшим вариантом метода на базе преобразования ПВК при работе с одинаковым начальным значением исследуемой частоты и при работе с одинаковым значением интервала усреднения. Получены аналитические соотношения для основных метрологических характеристик. Проведен сравнительный анализ метрологических характеристик разработанного метода и метода на базе преобразования период-временной интервал-код. Хорошими метрологическими характеристиками обладает метод измерения ФКНЧ на базе преобразования период-временной интервал-код (ПВК), в котором формируется измерительный интервал как разность исследуемого и опорного интервалов и заполняется импульсами исследуемой или опорной частот. Реализованы автономный и виртуальный измерители, а также проведены экспериментальные исследования стандартных генераторов. Указаны особенности измерителей и пути их дальнейшего совершенствования. Дальнейшее развитие измерителя возможно в направлении увеличения количества измеряемых параметров ИЧВ, в частности, изменения кратковременной нестабильности частоты от воздействия дестабилизирующих факторов, характеристики и времени установления частоты. Для этого необходимо разработать управляемый источник дестабилизирующих факторов и синхронизировать его работу с измерителем.

Ключевые слова: кратковременная нестабильность частоты; преобразователь на принципе совпадений импульсов пакетами; автономный измеритель; виртуальный измеритель; LabVIEW