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MODELING NONLINEAR ELEMENTS OF CRITICAL COMPUTER NETWORK

Abstract. The subject of research discussed in the paper is indicators of a critical network performance. **The research target** is a model of nonlinear elements of a critical network. **The research objective** is creation of a model for nonlinear elements of computer network (CN) telecommunications facilities of a critical system providing the desired parameters of QoS. The paper fulfills the following tasks: analysis of the main factors causing impaired service quality in CN; creation of a model for a small nonlinearity impact on forming free oscillations by generating a relevant motion equation; analysis of oscillator free motion presented in the form of the Duffing equation; working out a general integral of the Duffing equation as applied to a stiff system. The research methods used are: the foundations of the theory of computer systems and networks and the nonlinear differential equations theory. The results obtained are as follows: the main factors presumably causing impaired network services of forensic systems are analyzed; it was found that one of the main causes is the telecommunications component of CN, which possesses a number of critical parameters, including lack of stability and robustness of data signal frequency; numerical simulation of the findings was performed. Conclusions: a formula was devised to define the relationship between the free oscillation frequency and the oscillation system energy with reference to nonlinearity which takes into account the parameters of the oscillation system initial state at startup; nonlinearity of the oscillation system of a self-oscillator has a significant impact on accuracy and stability of its output oscillation frequencies; it was determined that for equivalent nonlinearity parameter values $k>0.1$ there is a considerable mismatch between the reference signal and the actual signal transmitted in the network, which can cause a large deterioration of QoS; further research should be aimed at development of hardware-software tools making it possible to reduce the impact of small nonlinearities of telecommunications equipment elements of critical networks on quality of performance.

Keywords: critical networks; nonlinearity of oscillation system; equivalent nonlinearity parameter; telecommunications component of computer network; signal frequency stability and robustness.

Introduction

Computer systems and computer networks (CN) in the modern world are becoming crucial for the performance of management and decision-making systems in various spheres of human life. To a large extent, this also applies to critical systems for which there are stricter requirements for quality, reliability, integrity and rate of data transmission. These systems include a forensic system titled "Automated system for the accumulation of empirical data on the practice of computer-technical expert examinations" that was developed by the specialists from Department of Computer Engineering, Telecommunications, Video- and Audio-recording Research of Hon. Prof. M.S. Bokarius Kharkiv Research Institute of Forensic Examinations [1].

Review of literature. A significant number of works have been devoted to the problem of providing the required parameters of service quality (QoS) [2-19]. They identified the main factors causing a decrease in the quality of service in CN. The factors can be divided into several groups:

– factors determined by CN structure and architecture;

– factors determined by the strategy of control and redistribution of the CN computational power;

– factors determined by properties and parameters of telecommunications facilities of CN.

Each of these factors has been explored in numerous research works, but the present paper focuses on the last-named factor. The properties of telecommunications facilities play an important role in ensuring compliance between the required QoS indicators and those actually realized in modern computer systems. One of the main parameters affecting the quality of service is the stability and robustness of the frequency of a signal over which data is transmitted. In [1, 21], methods and techniques for improvement of the accuracy of carrier frequency measurement in computer networks, reducing the jitter effect and increasing synchronization in communication channels, are analyzed. However, the studies were conducted without taking into account the nonlinear properties of either the signal source or the propagation medium. In reality, everything is much more complicated, because there is a need to consider the small nonlinearity of the elements of telecommunications facilities of CN.

The paper objective is creation of a model for nonlinear elements of computer network (CN) telecommunications facilities of a critical system providing the desired parameters of QoS. To solve this problem, a number of specific problems are to be solved:

1. To create a model of small nonlinearity impact on the formation of free oscillations by composing an appropriate motion equation

2. To analyze the free oscillator motion having the form of the Duffing equation

3. Construct a general integral of the Duffing equation as applied to a stiff system

Basic relationships and formulations

1. To solve the outlined problem, let us evaluate the impact of small nonlinearity on the process of forming free oscillations of a resonant oscillation system of an individual quartz generator. The free motion equation for a conservative nonlinear oscillator has the form:

$$z + f(x) = 0\,, \tag{1}$$

where $f(x)$ is the restoring force in dimensionless form.

The cross travel of the bar supporting a weightless flexible coating is described using the function:

$$f(x) = x + x^3, \ \lambda > 0. \qquad (2)$$

Free oscillations in a non-damped electric circuit of nonlinear capacitance are described (4.2) using magnetic ferrielectric. Parameter λ is called K-rating factor. Equation (1) with the restoring force (2), where $\lambda>0$ or $\lambda<0$, is commonly referred to as the Duffing equation. In case of a simple pendulum making planar motion, function $f(x)$ equals:

$$f(x) = \sin(x) = x - \frac{x^3}{6} + \frac{x^5}{120} - ... \qquad (3)$$

A mass oscillating in a direction orthogonal to the direction of the stretched spring axis gives the restoring force of the following form:

$$f(x) = x\left(1 + \beta - \beta/\sqrt{1+x^2}\right), \quad \beta > 0. \qquad (4)$$

In (2) and (4), the restoring force corresponds to a stiff (hard) system; while in (3) – to a non-stiff system.

2. Consider the free motion of an oscillator in the form of the Duffing equation:

$$\ddot{x} + x + \lambda x^3 = 0. \qquad (5)$$

Equation (5) permits reduction of order. Suppose:

$$\dot{x} = v, v = v(x),$$

then

$$\ddot{x} = \dot{v} = \frac{dv}{dx} \cdot \frac{dx}{dt} = V\frac{dv}{dx}. \qquad (6)$$

Consequently, equation (5) becomes:

$$v\frac{dv}{dx} + x + \lambda x^3 = 0. \qquad (7)$$

Separating the variables, we get:

$$vdv + (x + \lambda x^3)dx = 0,$$

By integrating the last equation, we find:

$$v^2/2 + \Pi(x) = C_0, \quad C_0 = Const, \qquad (8)$$

where $\Pi(x)$ is potential energy,

$$\Pi(x) = x^2/2 + \lambda x^4/4. \qquad (9)$$

Constant C_0 is derived from the initial conditions:

$$v(x \ ) = v_0, x(0) = x_0. \qquad (10)$$

The value of C_0 equals:

$$C_0 = v_0^2/2 + \Pi(x_0). \qquad (11)$$

We deduce v from equation (8):

$$v(x \ ) = \pm\sqrt{2C_0 - \Pi(x_0)}. \qquad (12)$$

In the plane (x,v), the phase trajectory consists of two branches. Let us consider the case of $\lambda=0$. The phase trajectory of a linear oscillator is a circle.

Let us assume that $\lambda > 0$ (a stiff system).

Constant $C_0 > 0$ for any values of v_0, x_0 in the initial conditions (10). The graphic plotting shows that the phase trajectory is closed i.e. solution (5) satisfies the initial conditions (8) and is periodic. Constant C_0 is determined by expression: $C_0 = v^2(0)/2$, where $v(0)$ is the value of velocity corresponding to the value of $x=0$.

From (11) it is seen that (for the same values of v_0, x_0) an increment of the nonlinearity parameter λ leads to an increase in velocity $v(0)$. The point of intersection of the phase trajectory and the x axis is found from equation $\Pi(\pm x_1) = C_0$, where

$$x_1 = 2\sqrt{C_0/\left(1+\sqrt{1+4\lambda C}\right)}, \quad \lim_{\lambda\to 0} x_1 = x_0. \qquad (13)$$

The limit values of x_1 correspond to a very stiff nonlinear system. In a very stiff nonlinear system ($x_0 = const$), there is a phase trajectory stretching along the v-axis. The condition $x_0 \neq 0$ is essential. Consider the case of $\lambda < 0$ (non-stiff system). Constant C_0, given by formula (11), has two upper maximums, corresponding to values of $x_0 = \pm x_2$, where x_2 equals:

$$x_2 = \sqrt{-\ell_0/\lambda}, \quad \lambda < 0. \qquad (14)$$

The value of the maximum $C_0(x_0)$ is equal to:

$$\max C_0(x_0) = v_0^2/2 - 1/(4\lambda), \quad \lambda > 0. \qquad (15)$$

Potential energy $\Pi(x)$, according to (4.9), has two upper maximums corresponding to values of $x_0 = \pm x_2$, where x_2 is found from (14)

$$\max \Pi(x) = -1/(4\lambda) = 1/(4|\lambda|) = C^* > 0. \qquad (16)$$

As can be seen from (15) and (16), there are values of C_0 which satisfy inequality $C_0 > C^*$. Let us define more precisely the range of initial values v_0, x_0 which meet the indicated inequality. We will fix the values of x_0 and define the range of values v_0^2 as an inequality:

$$v_0^2 > \left(1/|\lambda| + |\lambda| x_0^4\right)/2 - x_0^2. \qquad (17)$$

In (17) inequality $C_0 > C^*$ is satisfied.

Theorem. When meeting the initial conditions, satisfying inequality (18), the motion, described by the Cauchy problem for the Duffing equation which corresponds to a non-stiff system, is unlimited.

Proof. Consider the right side of (12). It is determined for any x and is an increasing function for $x \to \pm\infty$. *The theorem is proved.*

We will specify the description of the trajectory in the phase plane for satisfied (18). Let us denote the right side of the inequality (18).

$$v_1^2(x_0,\lambda) > \left(|\lambda| x_0^4 - 2x_0^2 + 1/|\lambda|\right)/2. \qquad (18)$$

It is not hard to prove that

$$v_1^2(x_0,\lambda) > 0, \quad x_0^2 \neq 1/|\lambda|,$$

$$v_1^2(\pm x_2,\lambda) > 0, \quad x_2 = \sqrt{1/|\lambda|}.$$

Hence, phase trajectories, satisfying inequality (17), do not cross axis X. Consider the phase trajectories of a non-stiff system, which cross X-axis. Let constant C_0 satisfy inequality $C_0 < C^*$. As a result we get:

$$v_0^2 < v_1^2(x_0,\lambda),$$

where $v_1^2(x_0,\lambda)$ is determined in (18).

Therefore, we have an inequality that is opposite to the inequality in (17). The initial conditions in (10) are set at any arbitrary time, thus it is more convenient to set the conditions at the time of crossing the phase trajectory of X-axis.

$$v(x_0)=0,\ x(0)=x_0 \qquad (19)$$

We apply (19) to (12), taking into account $C_0 < C^*$:

$$C_0 = \Pi(x), \quad x^2/2 - |\lambda| x_0^4/4 < 1/(4|\lambda|),$$

that is $v_1^2(x_0,\lambda) > 0$.

From this we derive two initial conditions:

$$v(x_0)=0,\ x(0)=x_0 \quad 0<|x_0|<1/\sqrt{|\lambda|} \qquad (20)$$

$$v(x_0)=0,\ x(0)=x_0 \quad |x_0|>1/\sqrt{|\lambda|} \qquad (21)$$

When the initial conditions (20) are met, the motion is periodic, and phase trajectories are closed lines which surround the origin of coordinates. When the initial conditions (21) are met, the solution of the Duffing equation is unbounded. We will consider the trajectories of periodic motion in more detail. According to (20), we set

$$|x_0| > 1/\sqrt{|\lambda|}, \quad 0<\varepsilon<1. \qquad (22)$$

From (20) and (11), we find C_0. From (12) we define $\sqrt{v(x)}$. As a result, we have a phase trajectory formula:

$$|v(x)| = \sqrt{(\varepsilon/|\lambda|)\cdot(1-\varepsilon/2) - x^2 + x^4|\lambda|/2}, \quad |x| \le |x_0|, \quad 0<\varepsilon<1. \qquad (23)$$

We will use (23) to calculate the ratio

$$|v(0)/x_0| = \sqrt{1-\varepsilon/2}, \quad 0<\varepsilon<1. \qquad (24)$$

It follows from (24) that the phase trajectories of the periodic motion of a non-stiff system are stretched along the *X*-axis. Therein lies the qualitative difference between the phase trajectories of periodic motions of non-stiff and stiff nonlinear systems. Formulas (23) allow estimating velocity at any point of the phase trajectory explicitly under a certain initial deviation of the system, described in (20) and (22). The equation of phase trajectory (12) in implicit form is written as $F(x,v)=0$, where *F* equals:

$$F(x,v) = v^2 - 2C_0 + x^2 + \lambda x^4/2.$$

The special points have coordinates (0,0), $(-x^2, 0)$, $(x^2, 0)$, where $x_2 = \sqrt{-1/\lambda}$. The slope of the tangent line $k = v'$, is found from the equation $A + 2Bk + Ck^2 = 0$, where *A, B, C* are values of derivatives

$$\frac{d^2F}{dx^2}, \quad \frac{d^2F}{dxdv}, \quad \frac{d^2F}{dv^2}$$

at points. Let us find the derivative of order two:

$$\frac{d^2F}{dx^2} = 2 + 6\lambda x^2, \quad \frac{d^2F}{dxdv} = 0, \quad \frac{d^2F}{dv^2} = 2.$$

A quadratic discriminant with respect to *K* has the form:

$$B^2 - AC = -2\left(2 + 6\lambda x^2\right) < 0.$$

Therefore, the special points are such that they have no tangent. These points are called isolated. In the small neighborhood of isolated points, the restoring force displays different behavior. We will analyze the restoring force by power series summation. Keeping the first term of the power series, we deduce:

$$(0,0), \quad f(x) \approx x; \quad (-x^2,0), \quad f(x) \approx -2(x+x_2);$$

$$(x^2,0), \quad f(x) \approx -2(x-x_2).$$

It is seen from the formula that in point (0,0) the restoring force is directed towards equilibrium. In the rest of the points, the restoring force turns into the repulsive one.

3. Let us create a complete integral of the Duffing equation as applied to a stiff system:

$$\ddot{x} + x + \lambda x^3 = 0, \quad \lambda > 0 \qquad (25)$$

Solution (25) is found in the form of an elliptic cosine

$$x = a\,cn(u,k), \quad u = \sigma t, \qquad (26)$$

where *a, σ, k* are unknown invariables.

We will use the known ratios from the theory of elliptic functions

$$(cnu)' = -snudu; \quad (snu)' = snu\cdot dnu; \quad (dnu)' = -k^2 snu\cdot cnu. \qquad (27)$$

Let us find the derivatives of (26)

$$\dot{x} = -a\sigma snudu; \quad \ddot{x} = (cnu\cdot dn^2u - k^2 sn^2 ucnu)\times \left(-a\sigma^2\right) = -x\sigma^2(dn^2u - k^2 sn^2u). \qquad (28)$$

(28) is transformed, using other ratios from the theory of elliptic functions:

$$sn^2u = 1 - cn^2u; \quad dn^2u = 1 - k^2sn^2u = 1 - k^2 + cn^2u. \qquad (29)$$

We get

$$\ddot{x} = -x\sigma^2\left[\left(1-k^2\right) + k^2cn^2u - k^2\left(1-cn^2y\right)\right] = = x\sigma^2\left[\left(1-k^2\right) + x^2\cdot 2k^2/a^2\right],$$

that is $$\ddot{x} + \sigma^2\left(1-k^2\right)x + \left(2k^2\sigma^2/a^2\right)\cdot x^3. \qquad (30)$$

From (26) and (30), two equations are derived

$$\sigma^2\left(1-k^2\right) = 1, \quad 2k^2\sigma^2/a^2 = \lambda. \qquad (31)$$

Equation (31) includes three unknowns; therefore we will consider the initial conditions:

$$x(0) = x_0, \quad \dot{x}(0) = 0. \qquad (32)$$

Satisfy the initial conditions, taking into account that cn(0, k) =1, sn(0, k)=0. We find that $a = x_0$, i.e. it equals the shift at the initial instant. By condition λ> 0; that is why in (31) the values of k satisfy inequality

$$0 \le k \le 1/\sqrt{2}. \qquad (33)$$

Consequently, we have a complete integral of the Duffing equation (a stiff system) in the form:

$$x = x_0 cn(\sigma t, k), \qquad (34)$$

where $$\sigma = \sqrt{\frac{1}{(1-2k^2)}}, \quad \lambda = \frac{2k^2}{x_0^2(1-2k^2)}. \qquad (35)$$

The values of *k* (equivalent parameter of nonlinearity) in (33) correspond to the interval of nonlinearity parameter *λ*, ranging from zero to infinity.

Research results

Fig. 1 presents the calculated data for the impact of nonlinearity of network equipment elements on the stability of the frequency of information transmission in the network. This graph demonstrates to what extent the stability of master generator signal varies as the parameter *k* changes.

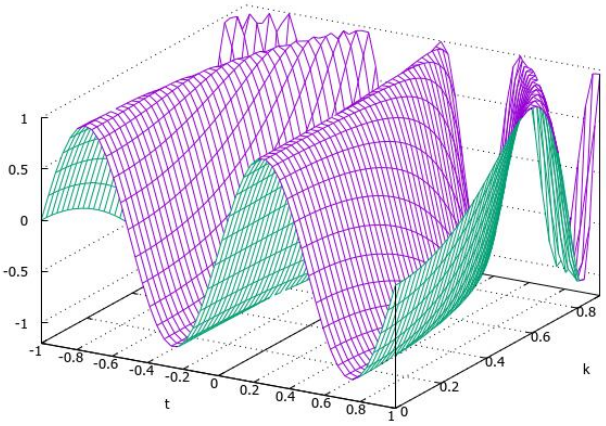

Fig. 1. Dependence of the signal variation coordinate on the equivalent parameter of nonlinearity *k*

For better illustration, Fig. 2-4 present the differences between the propagating signal and the standard harmonic signal for different ranges of the equivalent parameter of nonlinearity. Fig. 2-4 are presented in such a way that they cover the entire range of variation of the equivalent parameter of nonlinearity *k*.

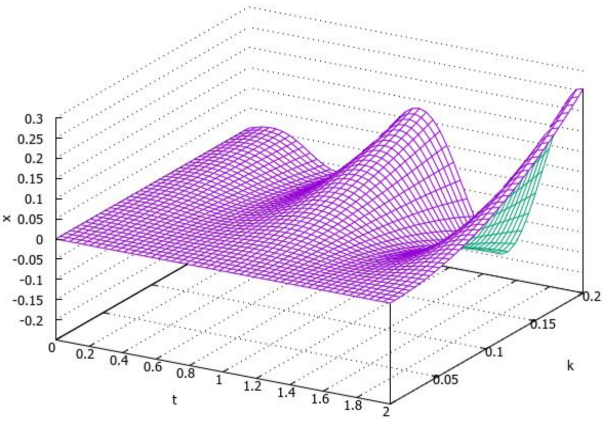

Fig. 2. The difference between the propagating signal and the standard harmonic signal for *0<k<0.2*

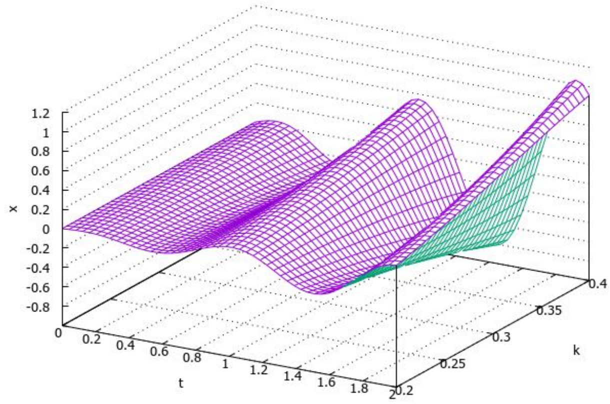

Fig. 3. The difference between the propagating signal and the standard harmonic signal for *0.2<k<0.4*

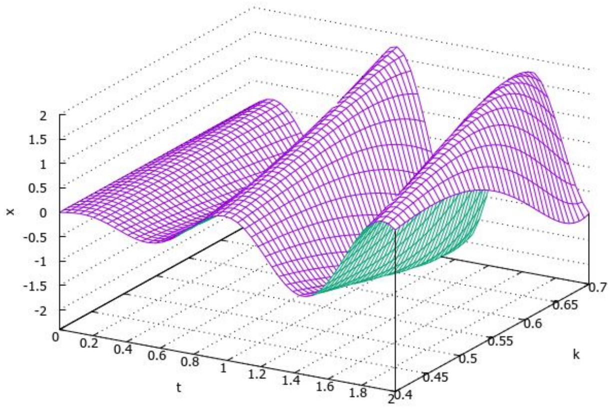

Fig. 4. The difference between the propagating signal and the standard harmonic signal for *0.4<k<0.7*

For small values of parameter *k* within the range *0<k<0.01* (Fig. 2), oscillations of the system are harmonic or very close to them. The stability of oscillation frequency is $\delta\omega \sim 2 \cdot 10^{-8}\omega$. However, for the value *k=0.25*, the frequency stability deteriorates considerably to $\delta\omega \sim 5 \cdot 10^{-6}\omega$. Such frequency fluctuations are large enough to impair the quality of CN functioning. Yet, with further increase in the value of parameter k, considerable mismatch of harmonic process is observed. Thus, as a result of numerical simulation of an oscillation process in the data transmission channels of CN, it has been established that even a slight nonlinearity can lead to significant changes in the frequency of a signal transmitted in the network, which in turn causes a severe loss of information or longer time required for a reliable transmission.

Conclusions

The paper conducts analysis of the main factors which can be regarded as the cause of the degrading quality of service of computer forensic networks. It has been established that one of the main causes is the telecommunications component of CN, which has a number of critical parameters, including lack of stability and robustness of data transmission signal frequency.

The paper studies the impact of small nonlinearity of telecommunications equipment elements (generators, multiplexing units and transmission medium) on the functioning of the relevant datalinks.

According to the results of the study, the following conclusions can be made:

1. A formula for a relationship between free oscillations frequency and oscillation system energy with regard to nonlinearity is developed, which makes it possible to take into account the parameters of the initial conditions of an oscillation system at start.

2. The nonlinearity of the oscillatory system of a self-excited generator impacts considerably the accuracy and stability of its output oscillations frequency.

3. As a result of numerical simulation, it has been established that for small values of parameter *k* within the range *0<k<0.01*system oscillations (Fig.2) are harmonic or nearly harmonic. Oscillations frequency stability $\delta\omega \sim 2\cdot 10^{-8}\omega$. But when reaching the value of *k=0.25,* frequency stability deteriorates considerably to $\delta\omega \sim 5\cdot 10^{-6}\omega$. Such frequency fluctuations are large enough to impair the quality of CN functioning. Yet, with further increase in the value of parameter k, considerable mismatch of harmonic process is observed.

4. It has been established that even a slight nonlinearity is able to cause significant changes in transmitted signal frequency, which in turn leads to substantial losses of information or increase in time required for a reliable transmission.

Further research should be directed towards the development of software and hardware tools that allow reducing the impact of small nonlinearities of telecommunications equipment elements of critical computer networks on their performance.

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Моделювання нелінійних елементів комп'ютерної мережі критичного застосування

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Анотація. Предметом дослідження в статті є показники якості функціонування комп'ютерної мережі критичного застосування. Об'єкт досліджень - модель нелінійних елементів комп'ютерної мережі критичного застосування. **Мета роботи** - створення моделі нелінійних елементів телекомунікаційного обладнання комп'ютерної мережі (КС) системи критичного застосування для забезпечення необхідних параметрів QoS. У статті вирішуються такі **завдання**: аналіз основних факторів, що викликають зниження якості обслуговування в КС; створення моделі впливу малої нелінійності на формування вільних коливань, за допомогою складання відповідного рівняння руху; аналіз вільного руху осцилятора, що має вигляд рівняння Дюффінга; побудова загального інтеграла рівняння Дюффінга в разі жорсткої системи. Використовуються такі методи дослідження: основи теорії комп'ютерних систем і мереж та основи теорії нелінійних диференціальних рівнянь. Отримані наступні результати: проведено аналіз основних факторів, які можна вважати причиною зниження якості обслуговування комп'ютерних мереж системи судової експертизи; визначено, що однією з основних причин є телекомунікаційна складова КС, яка має ряд критичних параметрів, в тому числі і недостатня стабільність і стійкість частоти сигналу передачі інформації; проведено чисельне моделювання отриманих результатів. **Висновки:** Отримана формула залежності частоти вільних коливань від енергії коливальної системи з урахуванням нелінійності, яка дозволяє врахувати параметри вихідного стану коливальної системи при її запуску; нелінійність коливальні системи автогенератора істотно впливає на точність і стабільність частот його вихідних коливань; визначено, що при значеннях еквівалентного параметра нелінійності k> 0,1 відбувається істотне неузгодженість між еталонним і реальним сигналом, які передаються в мережі, що може привести до значного зниження показників QoS, подальші дослідження необхідно направити на розробку програмно-апаратних засобів, що дозволяють знизити вплив малих нелінійностей елементів телекомунікаційного обладнання комп'ютерних мереж критичного застосування на показники якості функціонування.

Ключові слова: комп'ютерні мережі критичного застосування; нелінійність коливальні системи; еквівалентний параметр нелінійності; телекомунікаційна складова комп'ютерної мережі; стабільність і стійкість частоти сигналу.

Моделирование нелинейных элементов компьютерной сети критического применения

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Аннотация. Предметом исследования в статье являются показатели качества функционирования компьютерной сети критического применения. **Объект исследований** – модель нелинейных элементов компьютерной сети критического применения. **Цель работы** – создание модели нелинейных элементов телекоммуникационного оборудования компьютерной сети (КС) системы критического применения для обеспечения требуемых параметров QoS. В статье решаются следующие **задачи**: анализ основных факторов, вызывающих снижение качества обслуживания в КС; создание модели влияния малой нелинейности на формирование свободных колебаний, посредством составления соответствующего уравнения движения; анализ свободного движения осциллятора, имеющего вид уравнения Дюффинга; построение общего интеграла уравнения Дюффинга в случае жёсткой системы. Используются следующие методы исследования: основы теории компьютерных систем и сетей и основы теории нелинейных дифференциальных уравнений. Получены следующие результаты: проведен анализ основных факторов, которые можно считать причиной снижение качества обслуживания компьютерных сетей системы судебной экспертизы; определено, что одной из основных причин является телекоммуникационная составляющая КС, которая имеет ряд критических параметров, в том числе недостаточная стабильность и устойчивость частоты сигнала передачи информации; проведено численное моделирование полученных результатов. **Выводы:** Получена формула зависимости частоты свободных колебаний от энергии колебательной системы с учётом нелинейности, которая позволяет учесть параметры исходного состояния колебательной системы при её запуске; нелинейность колебательной системы автогенератора существенным образом влияет на точность и стабильность частот его выходных колебаний; определено, что при значениях эквивалентного параметра нелинейности $k>0,1$ происходит существенное рассогласование между эталонным и реальным сигналом, которые передаются в сети, что может привести к значительному снижению показателей QoS, дальнейшие исследования необходимо направить на разработку программно-аппаратных средств, позволяющих снизить влияние малых нелинейностей элементов телекоммуникационного оборудования компьютерных сетей критического применения на показатели качества функционирования.

Ключевые слова: компьютерные сети критического применения; нелинейность колебательной системы; эквивалентный параметр нелинейности; телекоммуникационная составляющая компьютерной сети; стабильность и устойчивость частоты сигнала.