Advances in Intelligent Systems and Computing 582

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Tomasz Walkowiak
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Advances in Dependability Engineering of Complex Systems

Proceedings of the Twelfth International Conference on Dependability and Complex Systems DepCoS-RELCOMEX, July 2–6, 2017, Brunów, Poland

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Janusz Kacprzyk, Polish Academy of Sciences, Warsaw, Poland
e-mail: kacprzyk@ibspan.waw.pl

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Editors
Wojciech Zamojski
Department of Computer Engineering
Wrocław University of Science and Technology
Wroclaw
Poland

Tomasz Walkowiak
Department of Computer Engineering
Wrocław University of Science and Technology
Wroclaw
Poland

Jacek Mazurkiewicz
Department of Computer Engineering
Wrocław University of Science and Technology
Wroclaw
Poland

Janusz Kacprzyk
Systems Research Institute
Polish Academy of Sciences
Warsaw
Poland

Jarosław Sugier
Department of Computer Engineering
Wrocław University of Science and Technology
Wroclaw
Poland

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Preface

This volume presents proceedings of the Twelfth International Conference on Dependability and Complex Systems DepCoS-RELCOMEX which took place in the Brunów Palace in Poland from 2nd to 6th July 2017.

The volume appears in the series "Advances in Intelligent Systems and Computing" (AISC) published by Springer Nature, one of the largest and most prestigious scientific publishers, in the series which is one of the fastest growing book series in their programme. The AISC is meant to include various high-quality and timely publications, primarily conference proceedings of relevant conference, congresses and symposia but also monographs, on the theory, applications and implementations of broadly perceived modern intelligent systems and intelligent computing, in their modern understanding, i.e. including tools and techniques of artificial intelligence (AI), computational intelligence (CI)–which includes neural networks, fuzzy systems, evolutionary computing, as well as hybrid approaches that synergistically combine these areas–but also topics such as multiagent systems, social intelligence, ambient intelligence, Web intelligence, computational neuroscience, artificial life, virtual worlds and societies, cognitive science and systems, perception and vision, DNA and immune-based systems, self-organizing and adaptive systems, e-learning and teaching, human-centred and human-centric computing, autonomous robotics, knowledge-based paradigms, learning paradigms, machine ethics, intelligent data analysis, various issues related to "big data", security and trust management, to just mention a few. These areas are at the forefront of science and technology, and have been found useful and powerful in a wide variety of disciplines such as engineering, natural sciences, computer, computation and information sciences, ICT, economics, business, e-commerce, environment, health care, life science and social sciences. The AISC book series is submitted for indexing in ISI Conference Proceedings Citation Index (now run by Clarivate), EI Compendex, DBLP, SCOPUS, Google Scholar and SpringerLink, and many other indexing services around the world.

DepCoS-RELCOMEX is an annual conference series organized since 2006 at the Faculty of Electronics, Wrocław University of Science and Technology, formerly by Institute of Computer Engineering, Control and Robotics (CECR) and now by Department of Computer Engineering. Its idea came from the heritage of the other two cycles of events: RELCOMEX (1977–89) and Microcomputer School (1985–95) which were organized by the Institute of Engineering Cybernetics (the previous name of CECR) under the leadership of Prof. Wojciech Zamojski, still the DepCoS chairman, so this year we can celebrate the 40th anniversary of its origins. In this volume of “Advances in Intelligent Systems and Computing”, we would like to present results of studies on selected problems of complex systems and their dependability. Effects of the previous DepCoS events were published (in chronological order) by IEEE Computer Society (2006–09), by Wrocław University of Technology Publishing House (2010–12) and presently by Springer in “Advances in Intelligent Systems and Computing” volumes no. 97 (2011), 170 (2012), 224 (2013), 286 (2014), 365 (2015) and 479 (2016).

Dependability is the contemporary answer to new challenges in reliability evaluation of complex systems. Dependability approach in theory and engineering of complex systems (not only computer systems and networks) is based on multidisciplinary attitude to system theory, technology and maintenance of the systems working in real (and very often unfriendly) environments. Dependability concentrates on efficient realization of tasks, services and jobs by a system considered as a unity of technical, information and human assets, in contrast to “classical” reliability which is more restrained to analysis of technical resources (components and structures built from them). Such a transformation has shaped natural evolution in topical range of subsequent DepCoS conferences which can be seen over the recent years. This edition additionally hosted the 7th CrISS-DESSERT Workshop devoted particularly to the challenges and solutions in analysis and assurance of critical infrastructure and computer (software and programmable logic-based) system safety and cybersecurity.

The Programme Committee of the 12th International DepCoS-RELCOMEX Conference, its organizers and the editors of these proceedings would like to gratefully acknowledge participation of all reviewers who helped to refine contents of this volume and evaluated conference submissions. Our thanks go to, in alphabetic order, Andrzej Białas, Ilona Bluemke, Eugene Brezhniev, Dariusz Caban, Frank Coolen, Manuel Gil Perez, Zbigniew Huzar, Igor Kabashkin, Vyacheslav Kharchenko, Leszek Kotulski, Alexey Lastovetsky, Jan Magott, István Majzik, Jacek Mazurkiewicz, Marek Młyńczak, Yiannis Papadopoulos, Oksana Pomorova, Krzysztof Sacha, Rafał Scherer, Mirosław Siergiejczyk, Janusz Sosnowski, Jarosław Sugier, Victor Toporkov, Tomasz Walkowiak, Irina Yatskiv, Wojciech Zamojski and Włodzimierz Zuberek.

Thanking all the authors who have chosen DepCoS as the publication platform for their research, we would like to express our hope that their papers will help in further developments in design and analysis of engineering aspects of complex systems, being a valuable source material for scientists, researchers, practitioners and students who work in these areas.

The Editors

Twelfth International Conference on Dependability and Complex Systems DepCoS-RELCOMEX

organized by
Department of Computer Engineering,
Wrocław University of Science and Technology
Brunów Palace, Poland, 2–6 July 2017

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Seventh CrISS-DESSERT Workshop

Critical Infrastructure Security and Safety (CrISS) -
Dependable Systems, Services & Technologies (DESSERT)

The CrISS-DESSERT Workshop evolved from the conference *Dependable Systems, Services & Technologies* DESSERT 2006–2016 (www.dessertcon.com). The 6th CrISS-DESSERT took place in Chernivtsi, Ukraine, 21–22 May 2016. In 2017, the 7th CrISS-DESSERT Workshop was held in the frameworks of the 12th Conference on Dependability and Complex Systems DepCoS-RELCOMEX.

The mission of the Workshop was to discuss challenges and solutions related to analysis and assurance of critical infrastructure and computer (software and programmable logic-based) system safety and cybersecurity. In particular, its focus was chosen in order to address:

- interplay and interdependencies of system of systems (telecommunication, smart grid, intelligent transportation system, etc.) and the current problems in providing its safety, security, reliability, quality of services, etc.;
- roles played by IT (SW, HW, FPGA)-based systems as the mandatory part of each infrastructure, thus turning distinct infrastructures into a complex cyber-physical system (system of systems) with emergent and cooperative behaviour, uncertainties, etc.;
- resource-effective IT-based approaches to safe and sustainable development.

The CrISS Workshop examined modelling, development, integration, verification, diagnostics and maintenance of computer and communications systems and infrastructures for safety-, mission- and business-critical applications.

Main Topics

The main topics on the workshop agenda included the following:

- Formal methods for critical IT infrastructures and systems development and verification
- Vulnerability analysis and intrusion-tolerant systems
- Evolving infrastructures and self-systems

- Dependability and resilience of Web-, cloud- and IoT-based IT infrastructures
- Safety of human–machine interfaces and systems including cooperative HMI&S
- Functional/system safety perspective of intelligent transport systems (ITS)
- Information & data modelling in ITS context
- IT infrastructures for pre- and post-accident monitoring of critical objects
- Safety- and assurance-case methodologies, techniques and tools
- Smart grid safety, reliability and security
- Power saving in IT infrastructures, data centres and computing clusters

Workshop Panel Discussion

Infrastructure and industrial systems safety and security: challenges, monitoring and assurance case-based solutions.

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Nikos Bardis	Hellenic Military Academy, Greece

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Contents

The Methodology of Studying of Active Traffic Management Module Self-oscillation Regime

Dmitry S. Kulyabov[1,2(✉)], Anna V. Korolkova[1], Tatyana R. Velieva[1], Ekaterina G. Eferina[1], and Leonid A. Sevastianov[1,3]

[1] Department of Applied Probability and Informatics, Peoples' Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya Street, Moscow 117198, Russian Federation
{kulyabov_ds,korolkova_av,sevastianov_la}@rudn.university, trvelieva@gmail.com, eg.eferina@gmail.com

[2] Laboratory of Information Technologies, Joint Institute for Nuclear Research, 6 Joliot-Curie Street, Dubna, Moscow Region 141980, Russian Federation

[3] Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 6 Joliot-Curie Street, Dubna, Moscow Region 141980, Russian Federation

Abstract. Self-oscillating modes in computer networks control systems quite negatively affect the characteristics of these networks. The problem of finding the areas of self-oscillations is actual and important as the study of parameters of self-oscillations. Due to the significant nonlinearity of control characteristics, the study of the oscillatory modes presents certain difficulties. This paper describes the technique of research of self-oscillating modes on the basis of the control theory. This material is rather methodical than exploratory one.

Keywords: Traffic active management · Control theory · Self-oscillating mode

1 Introduction

While modeling technical systems with control it is often required to study characteristics of these systems. Also it is necessary to study the influence of system parameters on characteristics. In systems with control there is a parasitic phenomenon as self-oscillating mode. We carried out studies to determine the region of the self-oscillations emergence. However, the parameters of these oscillations were not investigated. In this paper, we propose to use the harmonic linearization method for this task. This method is used in control theory, but this branch of mathematics rarely used in classical mathematical modeling. The authors offer a methodological article in order to introduce this method to non-specialists.

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2 The RED Congestion Adaptive Control Mechanism

To improve the performance of the channel it is necessary to optimize the queue management at the routers. One of possible approaches is the application of the Random Early Detection (RED) algorithm (see [1,5,9,11,14]).

The RED algorithm uses a weighted queue length as factor determining the probability of packet drop. As the average queue length grows, the probability of packets drop also increases (see (1)). The algorithm uses two threshold values of the average queue length to control drop function (Fig. 1):

$$p(\hat{Q}) = \begin{cases} 0, & 0 < \hat{Q} \leqslant Q_{\min}, \\ \frac{\hat{Q} - Q_{\min}}{Q_{\max} - Q_{\min}} p_{\max}, & Q_{\min} < \hat{Q} \leqslant Q_{\max}, \\ 1, & \hat{Q} > Q_{\max}. \end{cases} \tag{1}$$

Here $p(\hat{Q})$ — packet drop function (drop probability), $\hat{Q}$ — exponentially-weighted moving average of the queue size average, $Q_{\min}$ and $Q_{\max}$ — thresholds for the weighted average of the queue length, $p_{\max}$ — the maximum level of packet drop.

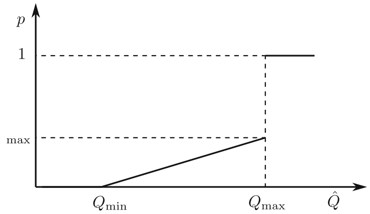

Fig. 1. RED packet drop function

The RED algorithm is quite effective due to simplicity of implementation in the network hardware, but it has a number of drawbacks. In particular, for some parameters values there is a steady oscillatory mode in the system, which negatively affects Quality of Service (QoS) indicators [10,15,19]. Unfortunately there are no clear selection criteria for RED parameters values, in which the system does not enter in self-oscillating mode.

To describe the RED algorithm we will use the following continuous model

$$\begin{cases} \dot{W}(t) = \frac{1}{T(Q,t)} - \frac{W(t)W(t-T(Q,t))}{2T(t-T(Q,t))} p(t - T(Q,t)); \\ \dot{Q}(t) = \frac{W(t)}{T(Q,t)} N(t) - C; \\ \dot{\hat{Q}}(t) = -w_q C \hat{Q}(t) + w_q C Q(t). \end{cases} \tag{2}$$

(see [4,6,7,12,13,16,17,20]) with some simplifying assumptions:

- the model is written in the moments;
- the model describes only the phase of congestion avoidance for TCP Reno protocol;
- in the model the drop is considered only after reception of 3 consistent ACK confirmations.

In (2) the following notation is used:

- W— the average TCP window size;
- Q— the average queue size;
- $\hat{Q}$— the exponentially weighted moving average (EWMA) of the queue size average;
- C— the queue service intensity;
- T— full round-trip time; $T = T_p + \frac{Q}{C}$, where T_p — round-trip time for free network (excluding delays in hardware); $\frac{Q}{C}$ — the time which batch spent in the queue;
- N — number of TCP sessions;
- p— packet drop function.

3 Harmonic Linearization Method

The method of harmonic linearization is an approximate method. It is used for study of start-oscillation conditions and determination of the parameters of self-oscillations, for the analysis and evaluation of their sustainability, as well as for the study of forced oscillations. Harmonically-linearized system depends on the amplitudes and frequencies of periodic processes. The harmonic linearization differs from the common method of linearization (leading to purely linear expressions) and allows to explore the basic properties of nonlinear systems.

We will use the block-linear approach in control theory [3]. According to this approach, the original nonlinear system is linearized and divided into blocks. These blocks are characterized by the transfer function linking the input and output values. The method of harmonic linearization is used for systems of a certain structure (see Fig. 2). The system consists of linear part H_l and the nonlinear part, which is set by function $f(x)$. It is generally considered a static nonlinear element.

For the harmonic linearization method free movement mode (input $g(t) = 0$) is assumed. The free harmonic oscillations are applied to the input of the nonlinear element:

$$x(t) = A\sin(\omega t). \tag{3}$$

On the output of the nonlinear element $f(x)$ we get a periodic signal. Let's expand it in a Fourier series:

$$f(x) = \frac{a_0}{2} + \sum_{k=1}^{\infty}(a_k \sin(k\omega t) + b_k \cos(k\omega t)), \tag{4}$$

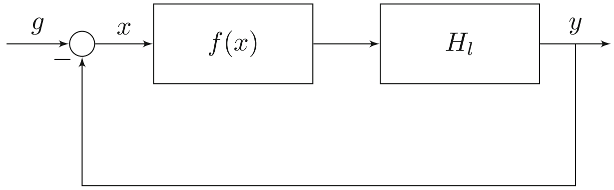

Fig. 2. Block structure of the system for the harmonic linearization method

where the coefficients of the Fourier series have the following form:

$$a_k = \frac{1}{\pi} \int_0^{2\pi} f(A \sin(\omega t)) \sin(k\omega t) \mathrm{d}(\omega t);$$
$$b_k = \frac{1}{\pi} \int_0^{2\pi} f(A \sin(\omega t)) \cos(k\omega t) \mathrm{d}(\omega t); \quad k = \overline{1, \infty}.$$

In this case we assume that in (4) $a_0 = 0$, in other words the constant component is absent.

The linear element is a low-pass filter, that is, when k is increasing the linear elements suppress higher harmonics. We will consider only the first harmonics. Then (4) will be presented in the form:

$$f(x) = a_1 \sin(\omega t) + b_1 \cos(\omega t), \tag{5}$$

where

$$a_1 = \frac{1}{\pi} \int_0^{2\pi} f(A \sin(\omega t)) \sin(\omega t) \mathrm{d}(\omega t);$$
$$b_1 = \frac{1}{\pi} \int_0^{2\pi} f(A \sin(\omega t)) \cos(\omega t) \mathrm{d}(\omega t).$$

From (3) you can write:

$$\begin{aligned} \sin(\omega t) &= \frac{x}{A}; \\ \cos(\omega t) &= \frac{1}{A\omega} \frac{\mathrm{d}x}{\mathrm{d}t} = \frac{1}{A\omega} \frac{\mathrm{d}}{\mathrm{d}t} x. \end{aligned} \tag{6}$$

Then we may rewrite (5) with respect (6):

$$f(x) = [\varkappa(A) + \frac{\varkappa'(A)}{\omega} \frac{\mathrm{d}}{\mathrm{d}t}] x = H_{nl}(A, \partial_t) x, \tag{7}$$

where $H_{nl}(A, \partial_t)$ — approximate transfer function of the nonlinear unit, $\varkappa(a)$ and $\varkappa'(a)$ are the harmonic linearization coefficients:

$$\begin{aligned} \varkappa(A) &= \frac{a_1}{A} = \frac{1}{A\pi} \int_0^{2\pi} f(A \sin(\omega t)) \sin(\omega t) \mathrm{d}(\omega t); \\ \varkappa'(A) &= \frac{b_1}{A} = \frac{1}{A\pi} \int_0^{2\pi} f(A \sin(\omega t)) \cos(\omega t) \mathrm{d}(\omega t). \end{aligned} \tag{8}$$

After finding the coefficients of harmonic linearization for given nonlinear unit, it is possible to study the parameters of the oscillation mode. The existence of oscillation mode in a nonlinear system corresponds to the determination of oscillating boundary of stability for the linearized system. Then A and ω can be found by using stability criteria of linear systems (Mikhailov, Nyquist–Mikhailov, Routh–Hurwitz). Thus, the study of self-oscillation parameters can be done by one of the methods of determining the limits of stability of linear systems.

3.1 The Nyquist–Mikhailov Criterion

This criterion belongs to analytical and graphic criteria. It has remarkable graphical representation of the system behavior and regions of existence of the oscillatory mode.

The Nyquist-Mikhailov criterion – [18] allows to judge about the stability of the open-loop automatic control system by using Nyquist plot (amplitude-phase characteristic) of the open-loop system.

Make the substitutions $\partial_t \to \mathrm{i}\omega$ and $s \to \partial_t \to \mathrm{i}\omega$ in the transfer function. Undamped sinusoidal oscillations with constant amplitude are determined by passing the amplitude-phase characteristics of the open-loop system through the point $(-1, \mathrm{i}0)$.

The characteristic function of the system is:

$$1 + H_o(\mathrm{i}\omega) = 0,$$
$$H_o(\mathrm{i}\omega) := H_l(\mathrm{i}\omega) H_{nl}(A, \mathrm{i}\omega).$$

where H_o — the transfer function of the open-loop system.

Thus:

$$H_l(\mathrm{i}\omega) H_{nl}(A, \mathrm{i}\omega) = -1. \tag{9}$$

Given by (7) from (9) the equality is obtained:

$$H_l(\mathrm{i}\omega) = -\frac{1}{\varkappa(A) + \mathrm{i}\varkappa'(A)}. \tag{10}$$

The left part of the Eq. (10) is the amplitude-phase characteristic of the linear unit, and the right part is the inverse of the amplitude-phase characteristic of the first harmonic non-linear level (with opposite sign). And the Eq. (10) is the equation of balance between the frequency and the amplitude.

This type of criterion is also called as a Goldfarb method.

Sometimes it is more convenient to write the Eq. (10) in the following form:

$$\varkappa(A) + \mathrm{i}\varkappa'(A) = -\frac{1}{H_l(\mathrm{i}\omega)}. \tag{11}$$

This type of criterion is also called as a Kochenburger method.

4 Harmonic Linearization of the Linearized RED Model

To rewrite the model (2) in the block-linear approach we need to linearize it. We will follow the article [6].

Let's write linearized system:

$$\begin{cases} \delta W(s) = -\frac{1}{s+\frac{N}{CT_f^2}(1+\mathrm{e}^{-sT_f})}\frac{C^2T_f}{2N^2}\mathrm{e}^{-sT_f}\delta p(s); \\ \delta Q(s) = \frac{1}{s+\frac{1}{T_f}}\frac{N}{T_f}\delta W(s); \\ \delta \hat{Q}(s) = \frac{1}{1+\frac{s}{w_q C}}\delta Q(s); \\ \delta p(s) = P_{\mathrm{RED}}\frac{1}{1+\frac{s}{w_q C}}\delta Q(s), \end{cases} \tag{12}$$

where the balance point is denoted by f index, variation is denoted by δ, and

$$P_{\mathrm{RED}} := \begin{cases} 0, & 0 < \hat{Q} \leqslant Q_{\min}, \\ \frac{p_{\max}}{Q_{\max}-Q_{\min}}, & Q_{\min} < \hat{Q} \leqslant Q_{\max}, \\ 0, & \hat{Q} > Q_{\max}. \end{cases}$$

Based on (12) the block representation of the linearized RED model (Fig. 3) is constructed.

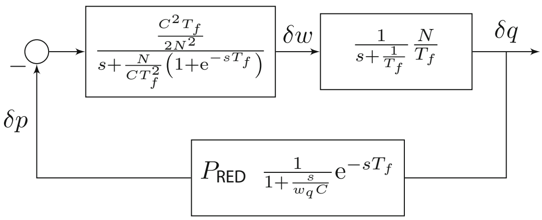

Fig. 3. Block representation of the linearized RED model

Let's reduce the block diagram of linearized model (Fig. 3) to the form required for harmonic linearization.

As a static nonlinear function we will use P_{RED}. The linear part is follows:

$$\begin{aligned} H_l &= \frac{1}{s+\frac{N}{CT_f^2}(1+\mathrm{e}^{-sT_f})}\frac{C^2T_f}{2N^2}\mathrm{e}^{-sT_f} \times \frac{1}{s+\frac{1}{T_f}}\frac{N}{T_f} \times \frac{1}{1+\frac{s}{w_q C}} \\ &= \frac{1}{s+\frac{N}{CT_f^2}(1+\mathrm{e}^{-sT_f})}\frac{1}{s+\frac{1}{T_f}}\frac{1}{1+\frac{s}{w_q C}}\frac{C^2}{2N}\mathrm{e}^{-sT_f}. \end{aligned} \tag{13}$$

In the block representation the diagram from Fig. 3 will be as shown in Fig. 4.

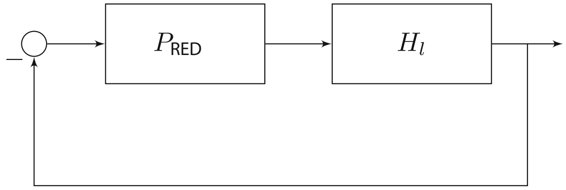

Fig. 4. Block representation of the linearized RED model for harmonic linearization

Let us compute the coefficients of harmonic linearization $\varkappa(a)$ and $\varkappa'(a)$ (8) for the static nonlinearity P_{RED}:

$$\varkappa(A) = \frac{4}{A\pi}\int_0^{\pi/2} P_{\mathrm{RED}}(A\sin(\omega t))\sin(\omega t)\mathrm{d}(\omega t);$$
$$\varkappa'(A) = \frac{4}{A\pi}\int_0^{\pi/2} P_{\mathrm{RED}}(A\sin(\omega t))\cos(\omega t)\mathrm{d}(\omega t).$$

We will get:

$$\begin{aligned}\varkappa(A) &= \frac{4}{A\pi}\frac{p_{\max}}{Q_{\max}-Q_{\min}}\int\limits_{\alpha_{\min}}^{\alpha_{\max}}\sin(\omega t)\mathrm{d}(\omega t)\\ &= \frac{4}{A\pi}\frac{p_{\max}}{Q_{\max}-Q_{\min}} - \cos(\omega t)\Big|_{\alpha_{\min}}^{\alpha_{\max}}\frac{4}{A\pi}\frac{p_{\max}(\cos\alpha_{\min}-\cos\alpha_{\max})}{Q_{\max}-Q_{\min}};\end{aligned} \tag{14}$$

$$\begin{aligned}\varkappa'(A) &= \frac{4}{A\pi}\frac{p_{\max}}{Q_{\max}-Q_{\min}}\int\limits_{\alpha_{\min}}^{\alpha_{\max}}\cos(\omega t)\mathrm{d}(\omega t)\\ &= \frac{4}{A\pi}\frac{p_{\max}}{Q_{\max}-Q_{\min}}\sin(\omega t)\Big|_{\alpha_{\min}}^{\alpha_{\max}} = \frac{4}{A\pi}\frac{p_{\max}(\sin\alpha_{\max}-\sin\alpha_{\min})}{Q_{\max}-Q_{\min}}.\end{aligned} \tag{15}$$

The values of sin and cos from integration limits $\alpha_{\min}$ and $\alpha_{\max}$:

$$\begin{aligned} x = A\sin\alpha_{\min} = Q_{\min}, \quad \sin\alpha_{\min} = \frac{Q_{\min}}{A}; \quad \cos\alpha_{\min} = \sqrt{1-\frac{Q_{\min}^2}{A^2}};\\ x = A\sin\alpha_{\max} = Q_{\max}, \quad \sin\alpha_{\max} = \frac{Q_{\max}}{A}; \quad \cos\alpha_{\max} = \sqrt{1-\frac{Q_{\max}^2}{A^2}}.\end{aligned} \tag{16}$$

Thus, from (14) and (15) with the help of (16) we will get:

$$\begin{aligned}\varkappa(A) &= \frac{4}{A\pi}\frac{p_{\max}}{Q_{\max}-Q_{\min}}(\sqrt{1-\frac{Q_{\min}^2}{A^2}} - \sqrt{1-\frac{Q_{\max}^2}{A^2}});\\ \varkappa'(A) &= \frac{4}{A\pi}\frac{p_{\max}}{Q_{\max}-Q_{\min}}\frac{Q_{\max}-Q_{\min}}{A} = \frac{4p_{\max}}{A^2\pi}.\end{aligned} \tag{17}$$

Thus, from (10), (13) and (17) we may derive:

$$\frac{1}{\mathrm{i}\omega + \frac{N}{CT_f^2}(1+\mathrm{e}^{-\mathrm{i}\omega T_f})}\frac{1}{\mathrm{i}\omega + \frac{1}{T_f}}\frac{1}{1+\frac{\mathrm{i}\omega}{w_q C}}\frac{C^2}{2N}\mathrm{e}^{-\mathrm{i}\omega T_f}$$
$$= -\frac{A\pi}{4p_{\max}}[\frac{1}{Q_{\max}-Q_{\min}}(\sqrt{1-\frac{Q_{\min}^2}{A^2}} - \sqrt{1-\frac{Q_{\max}^2}{A^2}}) + \mathrm{i}\frac{1}{A}]^{-1}. \tag{18}$$

For clarity, it is possible to plot parametric graphs on the complex plane separately for left $H_l(\mathrm{i},\omega)$ and right $-1/H_{nl}(A)$ parts of the Eq. (18) (of ω and A respectively) (see Figs. 5 and 6). The intersection of the curves gives the point of emergence of self-oscillations.

For the example of the calculation we have chosen the following parameters: $Q_{\min} = 100$ [packets], $Q_{\max} = 150$ [packets], $p_{\max} = 0.1$, $T_p = 0.0075$ s, $w_q = 0.002$, $C = 2000$ [packets]/s, $N = 60$ (the number of TCP sessions). As a result we obtained the following values for the amplitude and the cyclic frequency: $A = 1.89$ [packets], $\omega = 16.55s^{-1}$.

The traffic behavior can be demonstrated by using the standard computer networks simulation software NS-2 [2,8]. For selected parameters we will get the

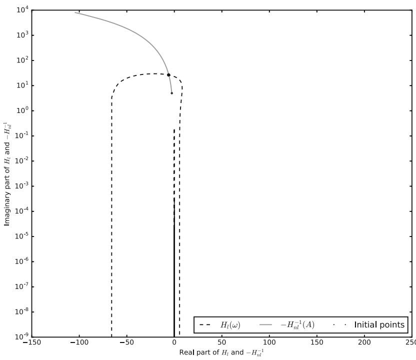

Fig. 5. Nyquist plot for system (18)

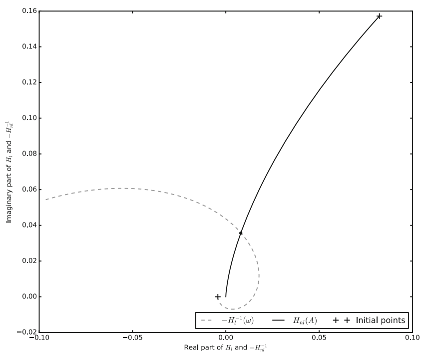

Fig. 6. Nyquist plot for system (11)

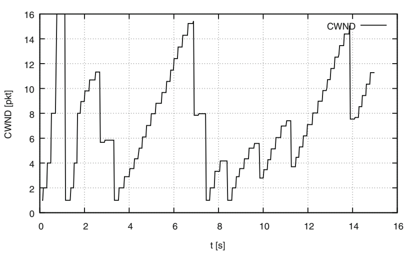

Fig. 7. A sliding window size changes at the source

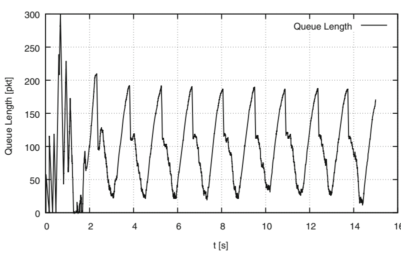

Fig. 8. A router's queue oscillation under RED control

graph of the window size change (at the traffic source) (Fig. 7) and oscillations of the instantaneous queue length at router under RED control (Fig. 8).

5 Conclusion

The authors demonstrated the technique of research of oscillatory modes of the systems with control. We tried to explain this technique for mathematicians unfamiliar with the formalism of the control theory. We plan to apply this technique to the study of a wide range of algorithms of traffic active control. Also it is interesting to compare these results with the previous results obtained for self-oscillation systems with control.

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References

1. Adams, R.: Active queue management: a survey. IEEE Commun. Surv. Tutorials **15**(3), 1425–1476 (2013). doi:10.1109/SURV.2012.082212.00018
2. Altman, E., Jiménez, T.: NS simulator for beginners. Synth. Lect. Commun. Netw. **5**(1), 1–184 (2012). doi:10.2200/S00397ED1V01Y201112CNT010
3. Aström, K.J., Murray, R.M.: Feedback Systems: An Introduction for Scientists and Engineers, p. 408, USA (208)
4. Brockett, R.: Stochastic analysis for fluid queueing systems. In: Proceedings of the 38th IEEE Conference on Decision and Control (Cat. No. 99CH36304), vol. 3, pp. 3077–3082. IEEE (1999). doi:10.1109/CDC.1999.831407
5. Floyd, S., Jacobson, V.: Random early detection gateways for congestion avoidance. IEEE/ACM Trans. Netw. **1**(4), 397–413 (1993). doi:10.1109/90.251892
6. Hollot, C.V.V., Misra, V., Towsley, D.: A control theoretic analysis of RED. In: Proceedings of IEEE Conference on Computer Communications. Twentieth Annual Joint Conference of the IEEE Computer and Communications Society, INFOCOM 2001 (Cat. No. 01CH37213), vol. 3, pp. 1510–1519. IEEE (2001). doi:10.1109/INFCOM.2001.916647
7. Hollot, C.V.V., Misra, V., Towsley, D.: On designing improved controllers for AQM routers supporting TCP flows. In: Proceedings of IEEE Conference on Computer Communications. Twentieth Annual Joint Conference of the IEEE Computer and Communications Society, INFOCOM 2001, (Cat. No. 01CH37213), vol. 3, pp. 1726–1734. IEEE (2001). doi:10.1109/INFCOM.2001.916670
8. Issariyakul, T., Hossain, E.: Introduction to Network Simulator NS2. Springer, New York (2012). doi:10.1007/978-1-4614-1406-3. 9781461414
9. Jacobson, V.: Congestion avoidance and control. ACM SIGCOMM Comput. Commun. Rev. **18**(4), 314–329 (1988). doi:10.1145/52325.52356
10. Jenkins, A.: Self-oscillation. Phys. Rep. **525**(2), 167–222 (2013). doi:10.1016/j.physrep.2012.10.007

11. Korolkova, A.V., Kulyabov, D.S., Chernoivanov, A.I.: On the classification of RED algorithms. Bull. Peoples' Friendship Univ. Russ. Ser. "Math. Inf. Sci. Phys." (3), 34–46 (2009)
12. Korolkova, A.V., Kulyabov, D.S., Sevastianov, L.A.: Combinatorial and operator approaches to RED modeling. Math. Model. Geom. **3**(3), 1–18 (2015)
13. Korolkova, A.V., Velieva, T.R., Abaev, P.A., Sevastianov, L.A., Kulyabov, D.S.: Hybrid simulation of active traffic management. In: Proceedings 30th European Conference on Modelling and Simulation, pp. 685–691 (2016). doi:10.7148/2016-0685
14. Kushwaha, V., Gupta, R.: Congestion control for high-speed wired network: a systematic literature review. J. Netw. Comput. Appl. **45**, 62–78 (2014). doi:10.1016/j.jnca.2014.07.005
15. Lautenschlaeger, W., Francini, A.: Global synchronization protection for bandwidth sharing TCP flows in high-speed links. In: Proceedings of 16th International Conference on High Performance Switching and Routing, IEEE HPSR 2015, Budapest, Hungary (2015)
16. Misra, V., Gong, W.B., Towsley, D.: Stochastic differential equation modeling and analysis of TCP-windowsize behavior. In: Proceedings of Performance 1999 (1999)
17. Misra, V., Gong, W.B., Towsley, D.: Fluid-based analysis of a network of AQM routers supporting TCP flows with an application to RED. ACM SIGCOMM Comput. Commun. Rev. **30**(4), 151–160 (2000). doi:10.1145/347057.347421
18. Nyquist, H.: Regeneration theory. Bell Syst. Techn. J. **11**(1), 126–147 (1932). doi:10.1002/j.1538-7305.1932.tb02344.x
19. Ren, F., Lin, C., Wei, B.: A nonlinear control theoretic analysis to TCP-RED system. Comput. Netw. **49**(4), 580–592 (2005). doi:10.1016/j.comnet.2005.01.016
20. Velieva, T.R., Korolkova, A.V., Kulyabov, D.S.: Designing installations for verification of the model of active queue management discipline RED in the GNS3. In: 6th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), pp. 570–577. IEEE Computer Society (2015). doi:10.1109/ICUMT.2014.7002164