REVIEW
of the Official opponent for thesis by Marat V. Yuldashev
« Nonlinear Mathematical Models of Costas Loops »,
submitted for the degree of PhD SPbSU

The PhD thesis by M.V. Yuldashev is devoted to the problem of non-linear mathematical models for classic Costas loop derivation and finding the variants of solution to this problem for a wide range of the signal parameters. Development of the numerically efficient methods for simulation of the Costas circuits is also addressed in the thesis.

At the beginning of the thesis an analytical survey of the existing approaches of the Costas loops investigation is presented. It is demonstrated that, despite of the existing wide bibliography in this field, the problem of nonlinear analysis Costas loops is still relevant.

The novelty of the research work by M.V. Yuldashev is that the characteristics of the phase detector for classic Costas loop for a broad class of signals and QPSK Costas loop are obtained, which allows deriving the non-linear mathematical model of Costas loops for the considered classes of signals. On the basis of autonomous differential equations, the efficient simulation tools and software are developed for studying dynamics of the classic Cotas loop and QPSK Costas loop.

The theoretical results, obtained by M.V. Yuldashev, made it possible developing the device, method, and software, protected by patents and copyright certificates.

All the analytical results of the thesis are new, have been presented and discussed at international conferences and published in several journal papers (in such magazines as Doklady Mathematics, IEEE Transactions On Circuits And Systems II), presented in the patent application, two patents and two certificates for the computer programs.

For my opinion, the thesis by M.V. Yuldashev is a complete research work, which contains new important results on the topical problem.

Professor Boris R. Andrievsky
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REVIEW

of the official opponent on Ph.D thesis entitled

«Nonlinear Mathematical Models of Costas Loops»

by Marat V. Yuldashev

submitted for the Ph.D degree of St.Petersburg State University

The models of the Costas loops are widely used in telecommunications for recovering the phase and data as well as determining the carrier.

From the invention to the present time the classic Costas loop remains one of the basic circuits used for demodulating signals in telecommunication systems. The thesis contains a fairly comprehensive literature review on the Costas loops and methods of their study, the merits and shortcomings of the most common approaches to analysis of Costas loops.

The present thesis introduced new mathematical model of the classic Costas loop for typical classes of signals, suggested the appropriate differential equations in the phase space and signal space. The assumptions and estimates suggested for derivation of the models are substantiated by practical engineering applications. A method of describing the QPSK Costas loop in the phase space is developed and the corresponding differential equations are developed. The numerical simulations are carried out and the effectiveness of the proposed methods is proved. Furthermore, it is shown how the suggested method can be used for digital Costas circuits.

A large part of the dissertation consists of the attached articles which are published on the topic of the dissertation in refereed international journals. This is a recognition of the results and the positive evaluation of the work carried out by experts in the field. The presence of patent applications and patents suggests the practical relevance and novelty of the study.

I believe that the thesis by Marat V. Yuldashev is a completed scientific work which contains important results on the topical subject of research.

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Report on the Thesis

Nonlinear Mathematical Models of Costas Loops

submitted by Marat V. Yuldashev
to the Saint Petersburg state University
for the Degree of Doctor of Philosophy

The standard amplitude modulation method uses a signal with a sinusoidal component at the carrier frequency that conveys no information message, though needs energy to be generated. This component is used to create an envelope that permits easy de-modulation by simple and inexpensive envelope detectors. In the 1950s Dr. John Costas at General Electric convincingly demonstrated advantages of the phase modulation over amplitude modulation. He also invented an outstanding system, called the Costas Loop, for phase de-modulation. This system recovers the carrier phase and frequency information from suppressed-carrier modulation signals, exemplified by double-sideband suppressed carrier signals. This invention is now recognized as having a profound effect on modern digital communications. The primary application of Costas loops is in wireless communication of digital data. It is well suited to serve phase-shift keying, which scheme of digital communication now finds widespread use in e.g., wireless communication systems, deep space programs and satellite communication and navigation systems, terrestrial microwave radio links, and telemetry applications.

The permanent demand for higher communication quality, including noise and interference resistance, higher data rates and frequency of operation, combined with increase of the level of miniaturization, the need for improvement of the cost-efficiency performance, and the use of various types of phase-shift keying provide real challenge for designers of modern Costas loops. Due to the nonlinearity and complexity, 'direct 'mathematical models of the loop that provide meticulous account for all details and relevant physical laws often appear to be nearly intractable for theoretical analysis. In the context of high-frequency signals, their utility for numerical analysis is undermined by the need to essentially minify the step size. This promotes accumulation of computational errors over time and thus challenges the accuracy and reliability of the result. At the same time, a popular hint of linear approximation often results in models that are unable to account for essential dynamic phenomena.

A way out of these troubles was proposed by F. Gardner and A. Viterbi as early as 1960. The idea was to model Costas loop circuits in the space of signal phases, thus neglecting the details of high-frequency oscillations by focusing attention on a slow time scale of the signals phases. However, this approach heavily depends on availability of a relatively simple and trustworthy models of the basic element of the circuit, i.e., the phase detector. For many typical signal waveforms and modifications of the classic Costas loop employed in the modern equipment, these models basically lie in uncharted territory.

The main contribution of the thesis consists in introduction, mathematically rigorous justification, and validation of such models for a wide range of typical signal waveforms and for two modifications of the Costas loop. As a background for theoretical analysis, the thesis first lays down mathematically rigorous and rather non-restrictive assumptions about the investigated signals. For signals with a general time-invariant waveform, the author introduces a novel model of the phase detector and provides its mathematically rigorous justification. Then this model is specified for a series of typical waveforms. The theoretical results were also validated via extensive numerical analysis, where simulation software developed by the author was employed. According to this analysis, the overall output of the proposed models is in harmony with that of 'direct'nonlinear mathematical models. At the same time, the proposed models impressively outperform the 'direct'models. This provides an evidence that the proposed models carry visible potential benefits for designers of Costas loops, which may be converted into a competitive advantage of manufactures.

The results of the thesis have been properly reported to scientific community through 22 peer reviewed journal and conference publications, including 8 papers indexed by Scopus. The practical relevance of the research is highlighted by 5 patents. The thesis provides a good motivation for the undertaken research, which is based on relevant references and fairly extensive knowledge of the area.

Overall this is a well presented and researched thesis. It provides a sufficiently comprehensive study of the topic and employs and properly applies techniques that are appropriate to the subject matter.

All main results of the thesis are novel, and their mathematically rigorous justification is provided. Overall, the thesis presents a completed scientific research and addresses an issue of real importance.

Professor Alexey S. Matveev

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REVIEW

of the official opponent on thesis of

Yuldashev Marat

«Nonlinear Mathematical Models of Costas Loops»,

submitted for the Ph.D. degree at SpbSU

The reviewed thesis is devoted to deriving and analysis of nonlinear mathematical models for Costas loops. Costas loop is one of the key circuits in the systems of satellite navigation (GPS, GLONASS). Development of nonlinear mathematical models of Costas loops is an actual and practically important task since such models might decrease numerical simulations time cost and simplify application of analytical methods. This very task is being solved in the current thesis.

The feature of Costas loop is dependence between the characteristic of nonlinear units (phase detector characteristic) on the class of the signals used. Consequently, such important features as capture range, holding range and synchronization time essentially depend on the signal class. The novelty of the work is in obtaining of the phase detector characteristics which are necessary for construction of nonlinear differential equations of Costas loops in the phase space for a broad range of signals. On the base of these theoretical results developed are effective methods and programs for numerical simulation of Costas loops in the phase space.

The results of numerical simulations show that the obtained characteristics allow to conduct modeling of Costas loops in the phase space more than hundreds times faster than in the time space (signal space) for relatively low frequencies. Since modeling in the phase space does not require reduction of the step while the frequency is increased, time of modeling for higher frequencies does not demand more resources, which situation differs from modeling in the time space where the time step is proportional to the signal period. This demonstrates the practical and theoretical significance of the results.

The results of the thesis might be considered as justification and generalization of the classical results of A. Viterbi and F. Gardner. All the obtained results are strictly mathematically proven, the obtained charactristics of the phase detectors coincide with the classical results in a particular case of sinusoidal signals, which demonstrates their reliability. The publications correctly reflect the content of the thesis. The main results are formulated in the form of two theorems which allow to construct nonlinear models in the phase space. Besides that are obtained the consequences which explicitly define the characteristics of the phase detector for typical classes of signals.

I believe that the thesis is a all-sufficient study containing important results on an actual topic of Costas loops investigation.

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Institute of Applied Physics of the Russian Academy of Sciences,

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Vladimir Nekorkin

Opponent's Report on the thesis
Nonlinear Mathematical Models of Costas Loops
by Marat V. Yuldashev
submitted as a PhD thesis of St. Petersburg University

In the thesis, the Costas loop and schemes developed on its basis are studied. Their main purposes are carrier recovery and data demodulation applied in many applications, including telecommunication devices, global positioning systems, medical implants, etc.

In the usual study of the Costas loop by engineers, mostly the method of linearization and direct numerical modeling were applied. Since the Costas loop contains nonlinear elements, proper models of its dynamics must include nonlinear systems of differential equations; for this reason, its study by linearization is either impossible or requires additional justifications. High-frequency signals used in the modern devices complicate the application of direct numerical simulation to the Costas loop since such a simulation requires long computations. Hence, it is very important both for theory and applications to construct nonlinear mathematical models of the Costas loop which can be studied in detail on the theoretical level and can be numerically simulated at reduced time.

To construct nonlinear mathematical models of the Costas loop described by autonomous systems of differential equations, one has to find phase-detector characteristics of the schemes. These characteristics depend on the type of the signal; thus, for nonharmonic signals which are often applied in practice, one has to determine phase-detector characteristics separately.

The novelty and originality of results of M. Yuldashev's thesis is mostly related to the found phase-detector characteristics for a wide class of signals both for the classical Costas loop and for its modification. Quadrature Phase Shift Keying (QPSK) Costas loop, now widely used in practice. An effective numerical procedure for simulation of Costas loops based on the phase-detector characteristics has been proposed by the author.

The results obtained in the thesis allowed the author to essentially reduce the time of computer modeling for the considered schemes, which emphasizes the practical importance of this research.

The results are formulated in the form of theorems. Corollaries of these theorems allow one to determine phase-detector characteristics of the Costas loop for a wide class of signals applied in practice.

The thesis also contains results of numerical modeling of Costas loops in signal space and in phase space; these results are compared with the corresponding physical model. It is shown that the suggested method is highly effective and gives reliable results.

The contents of the thesis is properly reflected in author's publications (the list of publications contains 21 items, 8 of them are in Scopus database). The author gave talks at various international conferences of high level. Based on this results, the author got several patents and certificates for realized computer software.

In my opinion, the thesis "Nonlinear Mathematical Models of Costas Loops" by Marat V. Yuldashev is a **completed scientific research containing new and deep results in the study of mathematical models of data transfer and important applications to practical devices.**

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REPORT

of the official opponent to the PhD thesis

Marat V.Yuldashev

« Nonlinear Mathematical Models of Costas Loops »,

Presented for the obtaining the degree of Ph.D. of SPbSU

This work is devoted to construction of nonlinear mathematical models of Costas loop. The Costas loop is a classic PLL-based circuit for carrier recovery. Nowadays various modifications of Costas loop circuit are used in many applications: wireless receivers, mobile phones, satellite-based systems and others.

The thesis gives a survey of the literature on this subject, both "classical" (that is 40-50 years old) up to the most recent contributions – including those of the author. According to this survey, simulation is one of the key elements in designing and testing Costas loop based circuits. However, Costas loop is essentially a nonlinear circuit and operates with high-frequency signals, therefore simulation of Costas loops is a very difficult, especially time consuming. Simulation in time domain is a time/power consuming task and does not allow one to estimate important characteristics of the corresponding circuit in reasonable time. Phase detector characteristics obtained by the author of the thesis, M. V. Yuldashev gives a solution of this problem, allowing one to perform simulation in a very effective manner and significantly enhance the circuit design process. Therefore, these results are novel and have a practical applicability and usefulness.

This work is funded by scholarship of president of Russia for PhD Students. Its main results are published in the best international journals on mathematics and engineering. Methods for simulation and design of Costas loops received positive feedback from one of the leading companies in the industry and became well-known in engineering community. From the purely scientific point of view, I appreciate the rigorous proofs in order to give a sound mathematical basis to the existing engineering receipts. This deductive part of the thesis is in a good relation with its inductive (inference) part of the thesis which is reflected in the patents it generated.

I consider that the examined thesis contains a comprehensive original research on a modern topic. It is sustained by an important number of publications in prestigious journals and important conferences hence the necessary dissemination of the results has been achieved.

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Reviewer statement on:
Nonlinear Mathematical Models of Costas Loops
by Marat V. Yuldashev for a PhD degree at Saint Petersburg State University

The work of the candidate is focused on mathematical and numerical analysis of so called Costas loops that are multi component electronic circuits based inherently on utilizing the so called phase-locked loops (PLL). The circuits are studied in the context of high frequency operation. The topic is of great practical significance as Costas loops are basic structural components in many communication devices.

Mathematically Costas loops are modeled with a nonlinear system of ordinary differential equations. The challenge and difficulty comes mainly from the presence of different time scales. The ODE system has one small parameter, the wave length (or inverse of the frequency) of the payload signal. However, the real interest in the modeling is in the synchronization process that takes place in much longer time scale. Analyzing and designing the long time characteristics of the circuits has been a difficult issue as direct brute force simulation is overly expensive and different simplifications proposed by the engineering community have lacked theoretical foundation.

The main contribution of the thesis is systematic development and rigorous formal justification of asymptotic models for Costas loops for a variety of different wave forms. The author derives a general formula for the asymptotic model (as a function of the wave forms in question) and proves an asymptotic error majorant for the modeling error as a function of the base frequency. The work has clearly been made in collaboration with a colleague working on similar issues for a simpler PLL circuit. The Costas loops present an additional difficulty as the different Fourier components of the waveforms interact (unlike for PLLs). This adds new terms and technicalities both in derivation of the asymptotic formulae and in carrying out the convergence estimates. The feasibility of the asymptotic model for numerical simulation of PLLs is demonstrated both from the point of view of the computational cost of solving as well as by visualizing the modeling error compared to the full physical model.

As already stated above the problem in question is highly relevant and subject to many studies from the engineering side. These are summarized extensively in the literature review as well as are the mathematically oriented works on stability that underline the need for rigorous approach (instead of engineering heuristics) to the problem. The main contribution provides a rigorously justified solution to a very common and much studied engineering problem and is as such a valuable contribution to the body of scientific knowledge. This being said, the problem is far from being fully resolved from the mathematical and numerical point of view. It is obvious that this has not even been the goal as the literature review is comparably thin on materials on asymptotic and numerical analysis that would be beneficial when proceeding with the study.

The results are very practical, adding simple tools to the engineering toolboxes. The fact that several patents have been issued based on the results speaks also for the potential practicability and relevance. As the results will be actively used by professionals with limited mathematical background it will be of importance to explore in depth the properties and limitations of the new results, both from the mathematical and numerical points of view. The thesis provides a good start for this, but only a start.

All the actual contributions have been published on international level, mainly in well established conferences in electronics and control theory which are very appropriate forums for dissemination and getting feedback on practicability. For a reader with mathematical or numerical background it would have been nice to have also treatise that covers the mathematical model and the numerical implementation/experiments in more detail. Now these have been presented in very concise style due to space limitations in the articles. In the Finnish culture one way to treat this kind of situations would have been to write the summary more as a tutorial that discusses the background knowledge and numerical results in more detail that has been possible/needed in the actual articles that are directed to special audiences.

To summarize: the thesis is a solid contribution to a long studied problem of major engineering relevance. The theoretical part is rigorous as such and meets the major needs of the engineering community. The thesis opens several directions for continuation. The most immediate is systematic numerical verification of the asymptotic result (the material presented gives no indication about the real asymptotic rate - is the proven error rate optimal or subject to improvement). As the Costas loop (based on the derived asymptotic formulae) mixes the different length scales present in the waveforms it is natural to ask how the behavior of the loop (stabilization property) depends on the used wave forms, and how the quality of the approximation by asymptotic model behaves depending on the waveforms.

In Jyväskylä, Finland on June 17th 2013,

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