REVIEW

of the Official opponent for thesis by Renat V. Yuldashev

«Nonlinear Analysis and Synthesis of Phase-Locked Loops»,

submitted for the degree of PhD SPbSU

The so-called «timing jitter» phenomenon is one of the problems, frequently occurring during transmission and receiving data over communication channels. This phenomenon appears in changing the signal period. This kind of distortion can not be eliminated by means of the signal multiplication or restriction, even in the case of a binary signal. It is well known that the phase-locked loop (PLL) is an electronic device, which has many practical applications, such as sync generators, division and multiplication of the signal frequency, signal modulation and demodulation, amplification of phase-modulated signals, etc. PLL may be also used for elimination of timing jitter effect. This confirms relevance of the problem under consideration.

For a numerous applications, multiplication of a periodic signal frequency is required. For example, the frequency of a motherboard clock oscillator may be restricted owing to the parasitic capacitances and other effects, while the frequency of the CPU clock register should be significantly higher. As another example, one may mention wireless transceivers that use low-power electrical oscillations generator which frequency should be varied by small prescribed steps, e.g. from 900MHz up to 925MGts in 200kHz step size. These challenges may be also effectively addressed through the use of PLL systems.

In the PhD thesis by R.V. Yoldashev, the approaches to the strict numerical analysis of the classical analogue PLL system are described and an efficient analytical method for computation of the performance index of the phase detector/multiplicator is proposed. For various classes of high-frequency signals, new types of characteristics of the phase detector are obtained and the model of the PLL system dynamics is presented.

The commonly used approach to the analysis of PLL systems consists of a numerical solution of differential equations. However, the high frequency (up to tens of gigahertz) of the inner loop PLL signals causes serious difficulties for numerical analysis of PLLs. For instance, the sample rate should be chosen significantly small to describe adequately the generator output signal, which causes difficulties, or even impossibility, to observe transients over a long period of time. In the reviewed thesis an alternative approach is proposed, which employs the special state space versions of PLL models. Such a kind of models may be simulated with a significantly increased time step, which allows reducing the calculation time of the system transients in hundreds of times or more.

The PhD thesis «Nonlinear Analysis and Synthesis of Phase-Locked Loops» by R.V. Yuldashev is a complete research work, which contains a new solution to the problem of PLL systems analysis. The results are new and significant both for the theory and applications.

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REVIEW
of the official opponent on Ph.D thesis entitled
«Nonlinear Analysis and Synthesis of Phase-Locked Loops»
by Renat V. Yuldashev
submitted for the Ph.D degree of St.Petersburg State University

The submitted thesis is concerned with the study of phase detector of analog system of the Phase-Locked Loop control (PLL). The focus is on computation of the phase detector characteristics. The paper utilises the asymptotic analysis of high-frequency oscillations which is known as the Krylov-Bogolyubov averaging method. The main result of the research is the characteristics of the phase detectors of the classical PLL and the PLL with squarer. The derived formulas allows one to greatly speed up the numerical simulation which is of crucial importance for designing new devices.

The thesis by Renat V. Yuldashev consists of an introduction, a single chapter and 8 included articles. The introduction consists of 8 items which describe the relevance of the study, presented the main problems associated with analysis and synthesis of PLL, the approaches to the solution in the literature, the purpose of work, the methods of research, the validity of the results, the novelty, the practical value and contribution of the author in joint publications.

The thesis is mainly composed of the articles included into the body of thesis which are published in well-reputed journals. For this reason it contains only a short chapter to the main content. This chapter deals with the concept of asymptotic equivalence of the PLL model and the PLL model with a squarer in the frequency-phase space and the time space. The author derived the conditions for signals to possess the property of high frequency and high stability. It enables formulation and proof of the asymptotic equivalence of the corresponding models. The tables of characteristics of the phase detector are presented for the typical classes of signals. These characteristics are matching with the classical results for sine and square-wave signals, whereas for other types of signals they are new.

The accompanying articles provide the reader with the complete proofs of theorems formulated in the main content chapter and a description of the method of modeling of PLL in the frequency-phase space by using the characteristics of the phase detector.

All the obtained results are new and valuable from both practical and scientific perspective.

The list of references in the work evidences of erudition of the author and focus on contemporary and historical background of the problems tackled in the paper.

The content of the thesis is sufficiently reflected in several scientific publications. The main results of the work were reported at many scientific conferences and explained in details in the work itself and in the author's papers.

To my mind, the thesis by Renat V. Yuldashev is a completed scientific work which contains importamt results on the topical subject of research.

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Report on the Thesis

Nonlinear Analysis and Synthesis of Phase-Locked Loops

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

Phase-locked loops (PLLs) refer to control systems whose objective is to bring certain parameters (mainly phase or frequency) of a generated signal into (phase, frequency) lock with an input 'reference ' signal. Nowadays, PLL's have myriad digital and mixed analog-digital applications to regulation, demodulation, synchronization, frequency multiplication/division, de-noising of noisy reference signals, regeneration of chopped signals, clock and data recovery and clock de-skewing, and are utilized as hosts of other special applications, e.g., motor speed controls. The usefulness of PLL's is highlighted by the fact that many of them are manufactured in the form of a one-chip integrated circuit.

During the early period of PLL's usage, they typically operated at relatively low frequencies, but gradually, high frequency versions become extremely vital. The PLL method is now ubiquitous in producing high frequency signals in modern communication hardware, as well as in other equipment that needs stable high frequency oscillations. Today's demand for higher communication quality, data rates, and frequency of operation, combined with increase of the level of miniaturization, the need for low power consumption and improvement of the cost-efficiency performance, makes the overall design of modern PLL's, including component evaluation, quite challenging.

A substantial trouble in analysis and synthesis of PLL's stems from the fact that their 'out-of-lock' dynamics are essentially nonlinear, whereas the overall complexity of nonlinear systems highly exceeds that of linear ones and requires much more sophisticated research methods. Nevertheless, to overcome this trouble, practical engineers traditionally rely on simplified linear models that are based on a series of simplifying assumptions. For example, it is typically assumed that the essentially nonlinear basic component of a PLL, called the phase detector, is fed by constant frequency signals and generates an output that is linearly proportional to the difference in phase between its inputs (modulo a subsequent filtering of the output). However in fact, those frequencies evolve over time during a transient period, though not rapidly, and the linear proportion approximately holds only in 'close vicinity of zero'. Outside it, the above relationship between the inputs and the output of the detector is more complicated and nonlinear. These imperfections of the linear models become a very serious concern as the requirements to the performance of PLL's are increased. On the other side, complete nonlinear models in the signal-time space appear to be too bulky for not only theoretical but also numerical analysis, especially whenever high frequencies are concerned. A remedy may be found in the form of adequate nonlinear models of PLL circuits in the phase-frequency space. However up to now, they were basically proposed only for signals with sinusoidal and square waveforms, whereas their actual variety is much wider.

To fill this gap, the thesis studies signals with general time-invariant waveforms but time-varying frequencies, which is inherent in many real-world scenarios. It also lays down mathematically rigorous and rather realistic assumptions about the signals as a background for the subsequent theoretical analysis. The main theoretical contribution of the thesis is introduction and mathematically rigorous justification of nonlinear models of PLL circuits in the phase-frequency space that deal with the afore-mentioned general waveforms. These models were also validated via extensive computer simulations. These demonstrated that the proposed models impressively outperform the previous models, both linear and nonlinear. In turns, this provides an evidence that the proposed models have a potential to serve as effective tools for analysis and synthesis of modern PLL's.

The thesis renders a fair critical judgement of the proposed approach, thus outlining the recommended domain of its applicability. It also contains relevant references to previous research and demonstrates an extensive knowledge of the area. The author properly relates his work with that in the area and provides convincing motivation for the research presented in the thesis. The thesis research has been properly disseminated to scientific community through 22 peer reviewed journal and conference publications, including 8 papers indexed by Scopus.

Overall this is a well presented and well researched thesis. It provides a sufficiently comprehensive study of the topic and employs and properly applies techniques that are entirely appropriate to the subject matter. I can hardly consider myself as an expert in English. Nevertheless, it seems that the quality of English contained in the thesis is good.

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.

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REVIEW

of the official opponent on thesis

"Nonlinear Analysis and Synthesis of Phase-Locked Loops"

by Renat Yuldashev

submitted for the Ph.D. degree at SpbSU

Devices in which the rate of quasi-periodic processes adjusts automatically to achieving a certain phase relationship between them (electric generators and motors, synchrotrons, device of controlling the cardiac rhythm activity, etc.) are important in modern science and technology.

In electronic systems, similar problems occur in radiolocation, television, computer architectures, in radio-navigation, when using coherent reception methods, in frequency generators, in servomechanisms, when receiving the modulated signals, in hard disk drives, etc. A technical solution of these problems is the use of automatic phase control (APC) systems.

After implemented in a separate chip, APC systems are widely used in modern telecommunication equipment and distributed computer architectures. In particular, APC is used for synchronizing the signals which come to the processors (CPU cores) working on a common bus. Unlike applications in electronics, there arises a problem of synchronization between generators not only in frequency but also in phase. This allows to eliminate delays in the implementation of parallel algorithms and reduce the power of generators that are on the motherboard.

These new applications for APC requires rigorous mathematical models in the frequency-phase space for different classes of non-sinusoidal high-frequency signals. To address this problem the conditions of high-frequency and high-stability signals are formulated in the thesis. Methods of asymptotic analysis of oscillations with a discontinuous waveform are also developed. The result is the formulas for the characteristics of the phase detector (PD) APC and APC with a quad in new classes of signals that allow to write down differential equations for APC. A table with the characteristics of PD is given for typical signals. Also the asymptotic equivalence is proved in the paper of the corresponding models at the level of implementation and in the frequency-phase space.

A major focus of studying the APC systems in modern engineering literature is the numerical simulation of circuits. This approach is usually very time-consuming because of the high frequency of signals under consideration, which can amount to tens of gigahertz. Therefore the simulation step is chosen to be sufficiently small for a clear observation of the dynamics of nonlinear APC elements. Frequency (phase) adjustment time of the controlled generator may be several seconds or minutes depending on an application, which makes it difficult to monitor the entire system transients together with the high frequency of signals. An approach proposed in the thesis to solving this problem is based on the transition to asymptotically equivalent APC models in the frequency-phase space for a wide range of signals. This allowed the use of a large sample rate, which reduced the time of the numerical analysis of hundreds or more times. The results of computer simulations presented in the thesis confirm the theorems obtained and PD characteristics and can be used for the synthesis of specific APC systems and APC systems with a quad.

The thesis is a complete research on a current topic. It contains new results in the field of nonlinear analysis and synthesis of automatic phase control systems

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Opponent's Report on the thesis
Nonlinear Analysis and Synthesis of Phase-Locked Loops
by Renat Yuldashev
submitted as a PhD thesis of St. Petersburg University

In the last decades, systems of phase synchronization are widely used for correction of phase shifts in clock generators for circuits which are bases for systems of digital signal processing, computers, and other similar devices. The joint feature of such circuits is the general principle of phase synchronization: The difference of phases of the reference generator and adjusted generator (AG) is transformed to a control signal, which, in turn, changes the frequency and the phase of AG.

One of the basic approaches in the study of such circuits is based on application of methods of linear analysis to differential equations of the models on the level of electronic realization (V. Shakhgil'dyan, E. Viterbi, W. Lindsey). These methods are effective in the study of phase-locked loops (PLL) if the differences of phases of the generators are small. Nevertheless, it must be noted that methods of linear analysis do not allow one to study transition processes at the phase locking regime. At the same time, nonlinear PLL models on the level of phase relations do not have such disadvantages but they were applied only for sinusoidal and impulse signals.

In his thesis, R. Yuldashev develops the methods suggested by G. A. Leonov and S. M. Seledzhi to derive systems of differential equations modeling PLL in the phase-frequency domain for various types of signals. In addition, he proves their asymptotic equivalence to models on the level of electronic realization (in the signal space).

One of the most important problems in data transfer is the carrier recovery. A classical scheme devoted to the solution of this problem is realized by a PLL with a squarer. Such a system includes an additional element, a squarer, which allows one to separate the data signal from the carrier signal. At the same time, the presence of this block leads to change of the class of signals and requires construction of a model in the phase space which is different from PLL. In the R. Yuldashev's thesis, a model of PLL with a squarer is suggested for a new class of signals; it is shown that this model is asymptotically equivalent to the system on the level of electronic realization.

The contents of the thesis is properly reflected in author's publications (the list of publications contains 22 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 4 patents and several certificates for realized computer software.

In my opinion, the thesis "Nonlinear Analysis and Synthesis of Phase-Locked Loops" by Renat Yuldashev is a **completed scientific research containing new and important results in the field of nonlinear analysis of dynamical system which are applicable in data transfer.**

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REPORT

of the official opponent to the thesis

«Nonlinear Analysis and Synthesis of Phase-Locked Loops»,

presented for the degree of PhD of SPbSU

The Phase Locked Loop (PLL) systems start with the invention of Henri de Bellescize of 1932 and since then a permanent development of these systems occur, due to such engineering applications as automatic control of the phase and/or frequency in communication systems, control systems, measurement a.o. Besides the engineering applications, it has been established that PLL may be used in modeling biological oscillators as heart or lungs.

The PLL device is a strongly nonlinear device. While a rather large amount of publications dedicated to PLL exists, the nonlinear theory – the only one able to give a comprehensive explanation of the PLL operation – is not enough developed yet. It has to be mentioned however that this absence of a good nonlinear theory was not considered a serious problem since in most cases the PLL are operated at high frequencies while the frequency deviations are relatively small. This “small” error signal – which justifies (at the physics and engineering levels of rigor) the analysis by the first approximation made linear analysis sufficient for the studies and limited the interest for the development of a nonlinear (“large signal”) theory.

There are nevertheless new, contemporary requirements in the communication systems, new applications of the PLL within computer architectures, network synchronization and in electrical machinery control which boosted the development of a more completed theory since the standard linear (by the first approximation) theory proved to be not sufficient. In this way the attempts to develop a comprehensive PLL theory got a serious practical support.

The first chapter of the dissertation contains a description of the actuality of the research as well as of its state of the art. There are given also the main aim of the dissertation and the novelty of the scientific results. In particular, the section «Appraisal of the work and publications» contains the list of the conferences and meetings (workshops) where the results of the author have been subject of debate. In the same section there is presented the contribution of the author of the thesis to those papers where he is co-author.

The main novelty of the thesis consists in the application of the asymptotic analysis to the high frequency oscillations. On this basis it is solved the problem of the construction of the characteristics for the phase detector both for the classical PLL and for the PLL with squaring device. It is also proved the equivalence of the phase detector models at the electronic realization level and also in the phase-frequency state. In the attached papers there are given complete proofs of the theorems on asymptotic equivalence and the description of a modeling approach for PLL. The obtained results are useful and can be applied for the analysis of the specific models for standard PLL and for PLL with squaring device, also for the stability analysis of the aforementioned devices. At the same time it appears that the approach of the thesis is a good illustration of what may be called nonlinear signal processing for oscillatory (in particular, periodic) signals.

I consider that the examined dissertation represents an accomplished scientific research containing important new original results in a very actual research field.

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Reviewer statement on:
Nonlinear Analysis and Synthesis of Phase-Locked Loops
by Renat V. Yuldashev for a PhD degree at Saint Petersburg State University

The work of the candidate is focused on mathematical and numerical analysis of the so called phase-locked loops (PLL) in the context of high frequency operation. The topic is of great practical significance as PLLs are basic structural components in many current electronic devices.

Mathematically PLLs 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 PLLs 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 PLLs 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 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 and justifying the existing ones. 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, mainly in conferences of famous international societies in electronics and control theory (IEEE, IFAC) 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). Also the exact characterization of the spaces of wave forms for which the result is valid would be needed (the space of piecewise differentiable functions with finite amount of discontinuities meets the engineering needs but use of classical function spaces might be interesting also). The same applies to the norm used to measure the error between the full model and its asymptotic approximation - is uniform pointwise error of the output the most/only natural criterion.

In Jyväskylä, Finland on June 17th 2013,

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