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Peer Review

Review of: "Modeling and Analysis of Phase-locked loops: a non reductionist approach"

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The authors study a nonlinear state-space model of a phase-locked loop (PLL) node that takes into account the phase-detection process with higher inter-modulation products, the loop filter transfer function, and the response of the VCO. Compared to existing work, the manuscript presents results for the case that higher order inter-modulation products that arise during the phase-detection process of the PLL are not omitted or assumed to be ideally filtered. Furthermore, the authors study the effects of noise in the input signal of the PLL and frequency fluctuations of the VCO.

Abstract: is written clearly and concisely.

Introduction:

1. The authors state on page 2: "...the PLL is a vital element to detect clocks signals..." What exactly is meant by that? To my understanding, the classical use case of a PLL is to be entrained by a precise clock signal, e.g., originating from a (temperature stable, high quality) quartz oscillator and then to distribute that clock signal to a local recipient.
2. In the section about the "Other motivations" on page 2, please explain with some more detail point ii). A phase model is in principle also valid for large phase errors, as long as the coupling function is not linearized. Or does that remark refer to the small error approach during linear-stability analysis?
3. The authors state on page 3: "A PLL (Fig. 1) is composed of a phase detector (PD) where the input signal, u(t), and the voltage controlled oscillator (VCO) feedback output, z1 , are added and multiplied by a gain Kd, resulting in the filter input vd."

   Please explain in more detail here. For analog signals, the PD may be a multiplier, and for digital

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signals, it could be an XOR gate. Why do the authors state that the signals u(t) and z1 are "added"? In Eq. (5) in the derivation of the state-space model, this is considered as expected.

4. Remark on the caption of Fig. 1: also phase models and the derivations of those show such block diagrams of PLLs, i.e., take into account all the parameters and properties of a PLL as shown in Fig. 1.

Contributions:

1. Nonlinear effects of the phase detection are also studied in "reductionist models," maybe not in [13], however, there is a vast body of literature out there.
2. Also, this point can be addressed by the "reductionist models," see e.g., Network Synchronization Revisited: Time Delays in Mutually Coupled Oscillators.
3. This is a valid point and of great interest when studying the dynamics of phase-locked loops.
4. Agreed.
5. Higher order loop filters can also be addressed in "reductionist models." There, they lead to modified Kuramoto models of higher order.

State space model:

1. What is the "instant frequency" on page 4? It seems the authors refer to the intrinsic or free-running (no external forces) frequency of the oscillator, given that a harmonic oscillator is considered. Ok, given the definition of the VCO, it becomes apparent that the $\omega_\texrm{inst}$ refers to the instantaneous frequency of the VCO and the intrinsic frequency is given by ω_0. Wouldn't it be preferable to use ω_0 in Eq. (1) of the unperturbed oscillator?
2. Are the authors aware of the works of C. Hoyer et al. that also consider higher order loop filters in a very similar modeling approach as shown in this manuscript, see e.g., Basin Stability of Mutual Synchronization with 24 GHz Oscillators in Theory and Experiment, Mutual Synchronization of Spatially Distributed 24 GHz Oscillators up to Distances of 500 m, and Entrainment of Mutually Synchronized Spatially Distributed 24 GHz Oscillators, to mention only a few papers.
3. It would be nice to formulate the final state-space model for general loop-filter transfer functions. That would enable engineers to directly study the LFs in use.
4. Small typo on page 5: "In Example 1 it will **be** shown that..."

5. “The latter alternative is likely to improve the filter performance but also to deteriorate the PLL performance as the increase of phase-lag in the loop is known to be deleterious.” Please provide a reference here, or explain in more detail for the reader.
6. Does “reductionist model” only refer to the model in [13]? If not, then the same observations as shown in Fig. 3 can also be made in phase models, particularly Kuramoto-like phase models, see the aforementioned papers.
7. The results in Fig. 6 are nice. It raises the question of how synchronization has to be defined. The phases are not entirely locked, yet are strongly correlated and hence show some type of synchronization behavior. In Synchronization in the presence of time delays and inertia: Stability criteria, see Fig. 12, it has been shown that such solutions with a modulated PLL output frequency are stable and arise when there is inert response in a system, i.e., introduced by the loop filter and leading to a higher order Kuramoto model.
8. The authors state on page 8: “Observing the example, non-reductionist strategy to model PLL dynamics provides the possibility of having the temporal evolution of the periodic signals through the loop, complementing the reductionistic strategy that gives only corresponding phase and frequency errors and their trajectory to equilibrium states. Besides, Figures 4, 5, and 6 show signals that have counterparts in real electronic circuits, differently from the reductionist strategy where instead of voltage signals they directly provide the phase error.” This is a strong statement. The definition of “reductionist model” needs to become clearer, and proper citations to other works and existing results should be provided.

Performance of the PLL node:

1. The authors state on page 11: “The simulation time for each case was tf =10000 and the values in (12) were computed in the second half of the data to reduce transient effects.”
2. Would it not be preferable to introduce a measure to detect that transient dynamics have decayed? This could be done using an order parameter or measure that detects the frequencies have settled to their asymptotic values, e.g., using some type of moving window within which the analysis is performed.
3. In Fig. 10 on page 11, there are the green islands in the blue basin that represent the best sync, i.e., the smallest frequency differences in the entrained state. Do the authors have an idea what causes them?

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Noisy Scenarios:

1. The authors write on page 12: "In the present study noise is added to the VCO central frequency and to the input signal and to see how this affects performance and synchronization boundaries as the gains are varied." It would be great to show the equations again at this point, including the noise terms. One of them refers to frequency noise, which often is assumed to be Lorentzian in PLL literature. The other noise term, added to the input signal, presumably (it is not clear where the noise is added exactly, to the amplitude, to the argument of the periodic function?) represents an amplitude noise that will cause amplitude fluctuations and therefore also affect the phase, see e.g., works by Demir et al.: Phase noise in oscillators: a unifying theory and numerical methods for characterization.
2. What motivated the choice of noise strength?
3. The section on the noisy scenarios could address the question of how the noise affects the quality. As known from classic PLL literature, see e.g., the book by Best, the input clock signal quality will increase the quality of the PLL output signal, which can be seen by a power spectrum narrowing. Applying the same noise with the same strength to the input/reference signal and the output signal may not be helpful to investigate these known results. If that could be added, the paper would gain strength by relating more closely to known results in PLL theory.

Conclusions:

1. The novelty of the manuscript is presented mainly by point ii) raised by the authors on page 15. This part and the investigation of the noisy PLL should be put into focus.
2. The authors write on page 16: "By comparison with studies reported in the literature in seems that abrupt transitions in the performance diagrams are closely related to bifurcations obtained using reductionist models that include second-order harmonics." Please provide a few citations to such models and relate your results to those presented in these works. As mentioned before, second-order Kuramoto models, which may fall into this manuscript's definition of "reductionist model," introduce the physical property of inert responses of an oscillator, i.e., compared to first-order classical Kuramoto models, there is no instantaneous frequency response to the input but a characteristic time-scale (the loop filter's integration constant and the VCO's response time) associated with the response dynamics. Apart from the higher inter-modulation products, or high-frequency components of the phase-detection process, the state-

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space model is the basis on which second-order Kuramoto models for PLL studies have been derived and have therefore been studied before.

3. It would be great if the authors pushed forward on their discussion of measures for synchronization performance, especially in the light of weak synchronization with strongly correlated (time-dependent) phase relations.

Declaration of competing interest:

The reviewer declares no competing interests with the authors of this manuscript.

References: (numbering refers to reference identifier)

1. nice, original paper cited
2. ok
3. ok
4. nice
5. nice – in addition a reference to recent works on synchronization of mutually coupled PLLs with new results and the analysis of delayed-coupling and inert response could have been added
6. nice – see 5.
7. ok
8. ok
9. ok
10. ok – self
11. ok
12. ok – self
13. ok
14. ok – self
15. ok
16. ok
17. ok
18. ok
19. ok – self
20. ok
21. ok

22. ok
23. ok
24. ok

Declarations

Potential competing interests: No potential competing interests to declare.

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