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I declare, I confirm, I certify and I sign that I received substantial, important, line by line peer review with several and substantial comments, important remarks and hints from, at least, 3 Reviewers and the Assistant Editor for my paper: "**Possibility of Quenching of Limit Cycles in Multi Variable Nonlinear Systems with Special attention to 3X3 Systems**"

With Authors:
(1) Kartik Chandra Patra
(2) Asutosh Patnaik

I would like to thank all the reviewers for their thoughtful comments and efforts towards improving our manuscript. We revised the manuscript with special attention to the comments that we received from **Three (3)** reviewers that were experts, specialists in the area of my paper.
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Compliance to Editor / Representative of Editor: Elena Triantafyllou

Comment 1: The English must be absolutely correct as well as the references.

Compliance 1: Utmost care has been taken with the best of our ability to present the English correctly. The text has been passed via auto-grammar correction such as via Gmail.

Comment 2: Pay high attention in references. Every reference inside the text must be reported in the list of the references, and every reference in the list of the references be connected inside the main text properly.

Compliance 2: Proper attention has been given to literature survey and so also in references. All the references cited in the text have been included in the list of references, and to confirm, every reference in the list of references placed at the end has been connected inside the main text properly.

Comment 3: The general Policy of WSEAS in the references is that the authors dedicate a maximum 10% of their previous publications with a maximum number 5.

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i. Reference [21] PATRA, K.C. of 1986 is replaced by [21] ELISABETH, T.M and SENG,C.C of 2020.
ii. Reference [28] PATRA, K.C., SWAIN, A.K. and MAJHI, S, of 1992 is replaced by KERAN,S, XIAOLONG,W and RONGWE I,G of 2023.
iii. Reference [35] PATRA, K.C., et al of 1997 is replaced by HABIB, G and KERSCHEN, G of 2015.
iv. Reference [36] PATRA, K.C., PATI, B.B. of 1998 is replaced by LIM, L. H and LOH, A.P of 2005.
v. Reference [38] PATRA, K.C., et al of 1999 is replaced by RAJGOPALAN, P.K and SINGH, Y.P of 1969.
vi. Reference [52] PATRA, K.C., and KAR, N, of 2020 is replaced by ZEINEB, R, CHEKIB, G. and NACEUR, B.B, of 2021.

Comment 4: Also you must sign and upload from the same link the certification.

Compliance 4: We have signed and uploaded from the same link the certification.

Compliance to Reviewers

Compliance to reviewer 1:

Comment 1: Please, the authors must give the Technical and Mathematical details in the 3. Signal Stabilisation in 3x3 nonlinear systems.

Compliance 1: In case of 2x2 nonlinear systems the concept of Signal Stabilisation is as under:

If a 2x2 Nonlinear system exhibits limit cycles (L.C.), in the autonomous state, the possibility of quenching the limit cycling oscillations by injecting a suitable high frequency signal, preferably at least 10 times of limit cycling frequency [8],[21], [28], [35], [51]. The process is also termed as forced oscillations which have also been extensively discussed by several researchers [35], [38]. Under the forced oscillation process the phenomena of Synchronization and De-synchronization have been addressed thoroughly in [51] for 2x2 nonlinear systems. Such phenomena have been realized / observed by injecting a sinusoidal input $B_1 \sin \omega_f t$ /$B_2 \sin \omega_f t$ at any one or both input points of two subsystems S_1 and S_2 respectively. When the amplitude B_1 of forcing signal $B_1 \sin\omega_f t$ gradually increased keeping the amplitude B_2 of forcing signal $B_2 \sin \omega_f t$ fixed, the system would continue to exhibit a limit cycle. The variables at various points in the system would be composed of signals of the input frequency (ω_f), the frequency of self oscillations (ω_s) and the combination of frequencies, $k_1\omega_f + k_2\omega_s$ where k_1, k_2 assume various integer values. At this condition the system exhibits complex oscillations. In the process of gradual increase of B_1, the frequency of oscillations w_s would also gradually change and for a certain value of B_1, the synchronization would occur, the self-oscillation would be quenched and the system would exhibit forced-oscillation at frequency ω_f. On the other hand if subsequently the magnitude B_1 is reduced gradually, a point would arrive at which the self oscillations would reappear which is termed as de-synchronization phenomenon. It may be noted that the synchronization value of B_1 is larger than the De-synchronization value of B_1 [51].

Similar facts have been observed in 3x3 nonlinear systems. The forced oscillation can be realized by feeding deterministic or random signals of high frequency, at least greater than 10 times the limit cycling frequency at any one/all input points of subsystems S_1, S_2 and S_3.

If the amplitude B of the high frequency signal is gradually increased, the system would exhibit complex oscillations before the synchronization takes place. On the reverse operation, if the amplitude B is gradually reduced at certain values of B the self oscillations i.e. the Limit cycle would reappear and the system would reappear and the system would exhibit complex oscillations again which can be called the de-synchronisation.

The phenomena of synchronization and de-synchronization can be observed / identified analytically using Incremental input Describing function (IDF).

However the forced oscillation can also be analyzed using the Equivalent Gain/ Dual input Describing Function (DIDF) [21], [38] in case of a deterministic forcing signal in particular with a sinusoidal signal. Similarly Equivalent Gain (Random input Describing Function-RIDF) [9],[10],[11] in case of random forcing signal, in particular with Gaussian Signal.

The complexity arises in the structures [1], particularly for implicit non-memory type or memory type nonlinearities, it may be extremely difficult to formulate and simplify the expressions even using the harmonic linearization method [53]. Hence an attempt has been made to develop a graphical technique using the harmonic linearization / harmonic balance method for prediction of limit cycles in 3x3 nonlinear systems by extension of the procedure as presented in [33]. The method uses the simultaneous intersection of two straight lines and one circle in three combinations.

The analytical / mathematical observation of synchronization and de-synchronization of complex oscillation in the process of signal stabilization would be quite involved and time-consuming. Hence the digital simulation (Using our developed programme) opted for demonstration of signal stabilization with deterministic / Gaussian signals which have been validated through use of SIMULINK ToolBox of MATLAB Software.

But in case of suppression of the limit cycle in 3x3 nonlinear systems, Pole Placement technique has been adopted which has been developed mathematically / analytically and validated by digital simulation.

However the analytical method for signal stabilization in case of 3x3 nonlinear systems may be taken up in future work which is also a formidable task.

Comment 2: Your reference has some old References. Add many references from the years 2015-2023:

Compliance 2:

i. Reference [21] PATRA, K.C. of 1986 is replaced by [21] ELISABETH, T.M and SENG, C.C of 2020.

ii. Reference [28] PATRA, K.C., SWAIN, A.K. and MAJHI, S, of 1992 is replaced by KERAN, S, XIAOLONG, W and RONGWE I,G of 2023.

iii. Reference [35] PATRA, K.C., et al of 1997 is replaced by HABIB, G and KERSCHEN, G of 2015.

iv. Reference [36] PATRA, K.C., PATI, B.B. of 1998 is replaced by LIM, L. H and LOH, A.P of 2005.

v. Reference [52] PATRA, K.C., and KAR, N, of 2020 is replaced by ZEINEB,R, CHEKIB,G. and NACEUR, B.B, of 2021.

Comment 3: Improve the English language.

Compliance 3:

Utmost care has been taken with the best of our ability to improve the English Language. Moreover our text has been passed via auto-programmer correction such as via Gmail.

Comment 4: It will be useful in the conclusion to provide to the audience some directions for future research.

Compliance 4:

1. There is an ample scope of extending the present work for signal stabilization as well as for suppression of LC in 3x3 memory type nonlinear systems.
2. The present work has the brighter future scope of adopting the techniques like Signal Stabilization [51],[52] and suppression of limit cycles for 3x3 or higher dimensional systems through an exhaustive analysis.
3. Analytical / Mathematical procedures may also be developed for signal stabilization using both deterministic and random signals based on DIDF and RIDF respectively.
4. The phenomena of synchronization and de-synchronization can be observed / identified analytically using Incremental input Describing function (IDF).

Comment 5: How can you implement the control here?

Compliance 5:

Backlash is one of the nonlinearities commonly occurring in physical systems that limit the performance of speed and position control in robotics, automation industry and other occasions of modern applications, [2], [3]. The proposed method of suppression of Limit cycle in 3x3 nonlinear system by pole placement either with arbitrary selection or optimal selection of feedback gain K (matrix),which can completely eliminate the limit cycle, thereby control/mitigate the difficulty of poor performance in speed and position control in modern application of robotics, automation industries.

<u>Compliance to Reviewer 2:</u>

Comment 1: The authors must discuss some possible applications and must give at least one more example after the 3.2 using Gaussian signal.

Compliance1:

Until [52] the method of Signal Stabilization with random signal for multivariable nonlinear system has not been reported and not available even for 2x2 systems. In the present day practice the researcher focused more on the robust control design which is a combination of modern state space and classical frequency domain technique. However robust design addresses the uncertainties means the randomness. The idea goes back to 1970s and 1980s [56]. In recent days people prefer to have H_∞ control as in [52].

The phenomenon of introducing/injecting an external signal at sufficiently high frequencies (deterministic/random) at a convenient point in the loop to stabilize a nonlinear feedback system in a state of self sustained oscillations is termed as “Signal Stabilization” with external or stabilizing signal of sinusoidal one , the nonlinearity is represented as an Equivalent Gain [8]. An analogous term Equivalent Admittance has been used in [10], [11] for representing the nonlinearity in the presence of a pure Sine wave together with Gaussian noise. The Equivalent Admittance is an analogous term for negative reciprocal of Describing Function under dual inputs (a sinusoidal and another Gaussian signal) which is otherwise known as Random input Describing Function (RIDF). The forced oscillations with Random signal can be analyzed in a similar way as have been discussed with Deterministic sinusoidal signal using DIDF. The analytical treatment would be very complex and may be taken up in future study.

Two examples have been used to illustrate the signal stabilization with random signal where the result /the images obtained using the SIMULINK are shown in Fig10 and Fig.11.

Example 3: Consider a system whose linear elements are represented by their transfer functions G(s) and the nonlinear elements are dead zone with saturation whose input output characteristic is shown in Fig.12 and represented by describing function N: Where $G_1(s) = \frac{2}{s(s+1)^2}$, $G_2(s) = \frac{1}{s(s+4)}$, $G_3(s) = \frac{1}{s(s+2)}$

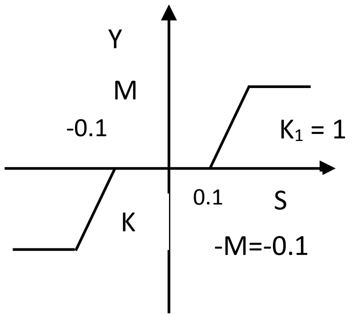

Fig. 12: The nonlinear elements used in the system of example 3 (the same nonlinear elements are used for three sub systems, S_1, S_2 and S_3.)

The result / images obtained from digital simulation, using Gaussian signals are shown in Fig.13 for Example 3.

Fig.13 (a) shows the limit cycling oscillation in the absence of the forcing signal and Fig 13(b) shows the forced oscillation with Gaussian signal of mean 300 and variance 0.025 for the Example 3.

Comment 2: The authors should pass their paper via auto-grammar correction:

Compliance 2: The text of the paper has been passed via auto-grammar correction.

Comment 3: The authors ought to provide more details in the conclusion.

Compliance 3: In addition to the three passages presented in the clause 5. In the conclusion section of our manuscript, the following facts are added:

The present work has the brighter future scope of adopting the techniques like signal stabilization [51], [52] and suppression of limit cycles [53], in the event of the existence of limit cycling oscillations for 3x3 or higher dimensional systems through an exhaustive analysis.

Analytical/Mathematical procedures may also be developed for signal stabilization using both deterministic and random signals applying DIDF and RIDF respectively.

Backlash is one of the nonlinearities commonly occurring in physical systems which are an inherent characteristic of Governor, more popularly used for load frequency control (LFC) in power systems. The LFC shows poor performance due to the backlash characteristic of the governor. Similarly, the backlash characteristic limits the performance of speed and position control in the robotics, automation industry. The poor performance of LFC, speed and position control in robotics and in automation industries are happening since these systems exhibit limit cycles due to their backlash type of nonlinear characteristics. The proposed method of suppression of L.C. can be *extended and developed* for backlash type nonlinearity in 3x3 systems and can be used to completely eliminate the limit cycle to mitigate such problems.

Comment 4: What are the directions of their future research?

Compliance 4: We have planned to work on signal stabilization and suppression of LC in 3x3 memories type nonlinear systems such as rectangular and backlash type. If possible we may extend our method for n x n multivariable nonlinear systems.

Comment 5: Please, authors remove all the material (Paragraphs) that you have published in previous Journals.

Compliance 5:

As per as practicable we have removed the material (Paragraphs) that we have published in previous Journals.

Comment 6: Do not forget the example after 3.2 using Gaussian signal

Compliance 6:

In addition to examples 1 and 2 a new example 3 is added with a dead zone of nonlinearities whereas ideal ray and ideal saturation are used in Ex.1 and 2 respectively.

Compliance to Reviewer 3:

Comment 1: Why do the authors believe that this article is an important contribution in Control Theory?

Compliance 1: The novelty of the work / method claims in:

i. Quenching of Limit Cycles exhibited in nonlinear 3x3 systems by signal stabilization with deterministic as well as random (Gaussian) signals.

ii. Suppression of L C in a 3x3 nonlinear systems by pole placement using state feedback with arbitrary selection as well as optimal selection (using Riccati Equation) of feedback gain matrix K. In particular suppression of LC by pole placement with optimal selection of feedback gain matrix K in 3x3 nonlinear system, using Riccati Equation has not been reported elsewhere and hence the article is an important contribution in Control Theory. The results /images shown in Fig. 17 confirm the suppression of L C, which has been exhibited before the pole placement.

Comment 2: I want to know. What is the originality here? What is the originality and novelty?

Compliance 2:

It has been reported in [1] regarding the exhibition of limit cycles in three dimensional nonlinear systems such as a boiler turbine unit and some chemical processes. No literature available which addresses the quenching or suppression of such self sustained oscillations in 3x3 nonlinear systems. In the present work it has been attempted to quench the limit cycling oscillations applying signal stabilization technique, using both deterministic and random signals in 3x3 systems. The work here also presents suppression of limit cycles by pole placement technique with selection (arbitrary and optimal) of feedback gain matrix K. In particular the optimal selection of feedback gain matrix K, used for suppression of LC claims to be the originality and novelty.

Comment 3: The author should not have references inside the text that are not at the end of your text in the list of references and vice versa.

Compliance 3:

As per the instruction, all the references inside the text are at the end of the text in the list of references and vice versa.

Comment 4: The author should include paragraphs (copy-pasted) from other publications. Our turn-tin tool will block the publication.

Compliance 4: We have removed all the material (paragraphs) that we have published in previous journals.

Comment 5: Authors must add more references from the recent years 2020-2023.

Compliance 5:

i. Reference [21] PATRA, K.C. of 1986 is replaced by [21] ELISABETH,T.M and SENG,C.C of 2020.

ii. Reference [28] PATRA, K.C., SWAIN, A.K. and MAJHI, S, of 1992 is replaced by KERAN,S, XIAOLONG,W and RONGWE I,G of 2023.

iii. Reference [35] PATRA, K.C., et al of 1997 is replaced by HABIB, G and KERSCHEN, G of 2015.

iv. Reference [36] PATRA, K.C., PATI, B.B. of 1998 is replaced by LIM, L. H and LOH, A.P of 2005.

v. Reference [52] PATRA, K.C., and KAR, N, of 2020 is replaced by ZEINEB,R, CHEKIB,G. and NACEUR, B.B, of 2021.

Comment 6: The authors must make necessary corrections in the English literature.

Compliance 6:

Entire text has been passed through G-mail and the necessary corrections have been made in the English language.

Comment7: After the corrections, the authors must send us back file in .docx format (only Word for Windows in the revised versions, please). The authors are kindly requested not send us PDF:

Compliance7:

According to the instruction, we have submitted the revised manuscript in the word F not PDF.

Comment 8: Check also if the in-text citations exist in the reference list also check if all the articles in the reference list exist in – text citations.

Compliance 8:

Accordingly it has been checked.

Comment 9: Check also if the in text citations for Tables, Equations and Figures are connected with Tables Equations and Figures properly.

Compliance 9:

Accordingly it has been checked and Tables, Equations and Figures are cited in text and also properly connected.

3.1 Using Deterministic signal

In case of 2x2 nonlinear systems the concept of Signal Stabilisation is as under:

If a 2x2 Nonlinear system exhibits limit cycles (L.C.), in the autonomous state, the possibility of quenching the limit cycling oscillations by injecting a suitable high frequency signal, preferably at least 10 times of limit cycling frequency [8], [21], [28], [35], [51]. The process is also termed as forced oscillations which have also been extensively discussed by several researchers [35], [38]. Under the forced oscillation process the phenomena of Synchronization and De-synchronization have been addressed thoroughly in [51] for 2x2 nonlinear systems. Such phenomena have been realized /observed by injecting a sinusoidal input $B_1 \sin \omega_f t$ /$B_2 \sin \omega_f t$ at any one or both input points of two subsystems S_1 and S_2 respectively. When the amplitude B_1 of forcing signal $B_1 \sin \omega_f t$ gradually increased keeping the amplitude B_2 of forcing signal B2 $\sin \omega_f t$ fixed, the system would continue to exhibit a limit cycle. The variables at various points in the system would be composed of signals of the input frequency (ω_f), the frequency of self oscillations (ω_s) and the combination of frequencies, $k_1\omega_f + k_2\omega_s$ where k_1, k_2 assume various integer values. At this condition the system exhibits complex oscillations. In the process of gradual increase of B_1, the frequency of oscillations ωs would also gradually change and for a certain value of B_1, the synchronization would occur, the self-oscillation would be quenched and the system would exhibit forced-oscillation at frequency ωf. On the other hand if subsequently the magnitude B_1 is reduced gradually, a point would arrive at which the self oscillations would reappear which is termed as de-synchronization phenomenon. It may be noted that the synchronization value of B_1 is larger than the De-synchronization value of B_1 [51].

Similar facts have been observed in 3x3 nonlinear systems. The forced oscillation can be realized by feeding deterministic or random signals of high frequency, at least greater than 10 times the limit cycling frequency at any one / all input points of subsystems S1, S2 and S3.

If the amplitude B of the high frequency signal is gradually increased, the system would exhibit complex oscillations before the synchronization takes place. On the reverse operation, if the amplitude B is gradually reduced at certain value of B the self oscillations i.e. the Limit cycle would reappear and the system would reappear and the system would exhibit complex oscillations again which can be called the de-synchronisation. The phenomena of synchronization and de-synchronization can be observed/identified analytically using Incremental input Describing function (IDF).

However the forced oscillation can also be analyzed using the Equivalent Gain/Dual input Describing Function (DIDF) [21], [38] in case of a deterministic forcing signal in particular with a sinusoidal signal. Similarly Equivalent Gain (Random input Describing Function-RIDF) [9], [10],[11] in case of random forcing signal, in particular with Gaussian Signal.

The complexity arises in the structures [1], particularly for implicit non-memory type or memory type nonlinearities, it may be extremely difficult to formulate and simplify the expressions even using the harmonic linearization method [53]. Hence an attempt has been made to develop a graphical technique using the harmonic linearization / harmonic balance method for prediction of limit cycles in 3x3 nonlinear systems by extension of the procedure as presented in [33]. The method uses the simultaneous intersection of two straight lines and one circle in three combinations.

The analytical /mathematical observation of synchronization and de-synchronization of complex oscillation in the process of signal stabilization would be quite involved and time-consuming. Hence the digital simulation (Using our developed programme) opted for demonstration of signal stabilization with deterministic/random (Gaussian) signals which have been validated through use of SIMULINK ToolBox of MATLAB Software.

It is established that the system shown in Fig1 with Numerical Example 1 exhibits a limit cycle in the autonomous state. The possibility of quenching the self-sustained oscillations has been explored by injecting suitable high frequency preferably more than ten times of ω_s signals [8] at any one/all three input points (U_1, U_2, U_3) .

However taking the second option i.e. all three inputs are same as B sinω_f t at 3 input points U_1, U_2, & U_3, shown in Fig.7. Amplitude B is gradually increased, the frequency of self oscillation, ω_s would gradually change, the system will synchronize to forcing frequency i.e. the self oscillation would be quenched and the system would exhibit forced oscillations at frequency ω_f.

3.2 Using Gaussian signal:

The concept of signal stabilization with random inputs for SISO nonlinear systems were discussed [9], [10],[11]. Current research gives importance on robust design and analysis which considers uncertainty/ randomness. Until [52] signal stabilization with random signal for multivariable nonlinear systems was not available even for 2X2 systems.

The authors in [52] focused on robust and non fragile stabilization of nonlinear systems described by multivariable Hammerstein model. The method illustrates a general procedure which addresses the general multi variable nonlinear systems. Of course the method considers uncertainties and the most importantly control is adopted for stabilization which fells to project insight into the problem. However the present work shows a simple method to quench the limit cycling oscillations exhibited in a class of 3x3 nonlinear systems and stabilize the systems using random signals in particular a Gaussian Signal. The signal stabilization refers to the possibility of quenching the self sustained oscillations by injecting a suitable high frequency preferably more than ten times of ω_s (the frequency of LC) signal at any point of the system [8]. The random signal having Gaussian distribution contains infinite components of frequency. The Gaussian Signals are passed through a high pass filter, so that the high frequency signal quenches the limit cycles and stabilizes the system. This has been illustrated through examples 1 and 2 revisited again. This method projects a clear and lucid insight into the problem.