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Designing optimal fuzzy controller for chaotic spur gear systems using NSGAII extended genetic algorithm

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Extended Abstract

Chaos is an unpredictable phenomenon that have been drawn attention in nonlinear dynamic systems. precise studies and experimental analysis on spur gear dynamic response have been shown nonlinear bifurcation phenomena occurrence and chaos in some system parameters, therefore the controlling of chaos phenomenon in spur gear as a nonlinear dynamic system have been investigated. Spur gear role have been selected to be analyzed due to be as an important component in industrial rotating machine and also as a power transmission systems. Chaotic behavior that been recognized as an uncommon and unpredictable manner in system response have been considered as an unfavorable phenomenon in spur gear system vibrations. Designing optimal spur gear system, controlling or removing the said behaviors are significant. Smart fuzzy controllers have been used in order to control the chaos and keeping the stability of system. In order to optimize the proposed controlling system and providing the fuzzy control requirement, the educated expert information on systems is needed and also the NSGAII extended genetic algorithm has been added to controlling structure. The simulation results in MATLAB software have been revealed that optimal combinational controlling strategy could remove chaos and achieve the spur gear to determined condition and place in a proper time after conducting the inputs

Introduction

The chaotic behavior is general phenomenon that have been observed in many nonlinear systems. The chaos phenomenon have been introduced by Edward Norton Lorenz and since then have been drawn interest by many other scientists. Chaos have been drawn attention more lately in engineering and mostly considered like a noise phenomenon. The chaotic behaviors have been reveled in 1990 for the first time that are controllable. Also the first safe transmission system based on chaos theory have been invented by electricity engineering [1].

Chaos means in state of complete confusion and lack of order and turbulence as a word [2]. The word itself describes accidental situation in philosophy. Chaos is synonym of turbulence or vortex in mechanic science. One of the most comprehensive qualitative definition that bring for chaos is in "the order and rhyme in disorderliness" statement; this definition has been achieved from natural phenomena observation calling chaotic. Indeed if we pay close attention to many natural phenomena regarding as a regular phenomenon apparently, looking deeply into these phenomena makes us to believe that there are apparent disorderliness in their details. In another means, there are many natural phenomena calling regular and systematic in microscopic viewpoint but there have been shown disorderliness and chaos in their details in microscopic viewpoint [3].

One of the main features of chaotic systems is that they shall not repeat their previous behaviors (even approximately). The other feature for dynamic systems showing chaotic behaviors is that these systems must include one nonlinear statement that could show chaotic behavior for special parameters. The other feature is having strange attractor [4]. The strange attractors are those kind of attractors that phase trajectory attract toward them and taking far simultaneously.

The most significant properties of chaotic systems are high sensitivity toward initial condition and parameters. Any subtle changes in initial condition of two similar

Doi:

chaotic systems, the phase trajectory of these two systems taking far exponentially from each other. nevertheless, this property could be intruder to coupled oscillators control, but this high sensitivity is advantageous in many applications [5]. For instance, this feature lead to usage of chaotic systems in transmission systems with high sensitivity that lead to four generation of chaotic transmission systems. The most important issue in safe chaotic transmission is synchronization of transmitter (starter system) and receptor (response system) [6].

Many researchers for novel chaotic systems introduction and chaotic behavior analysis in these systems have been conducted in last two decades. Two new research area base on chaos have been introduced due to widespread chaos applications in systems engineering. These two novel area including chaos control and the other is chaos synchronization [7].

The optimal control for chaotic systems have been proposed using linear and dynamic programming and Riccati algebraic equations by Merat et al in 2004 [8] .The optimal control for nonlinear systems could not be conducted by linear systems methods, therefore the “SDRE” (state dependent Riccati Equation) have been used for optimal control in nonlinear systems in this study. This method has high stability, proper performance and being resistant in broad range from nonlinear systems.

The adaptive control is proper solution for systems controls with non-probability parametric. There is no need for precise model from systems and only knowing system model and structure could design stabilizing control that approximate the system parameters adaptively. Adaptive control have been proposed for special chaotic categories of chaotic systems by Ruihong and Lee in 2015 [9]. In this study, some derivatives related to optimal controllers have been modified to some extent for chaotic systems based on Pontryagin minimum principle. The reference model used in said study, the proper response properties presented as a reference model in adaptive control method and the aim of the controller is to control the system output based on reference model.

Backstepping control compromised in nonlinear control methods. This method have been used for control and synchronization of chaotic systems. Combination of backstepping method and slipper mode is nonlinear control and resistant one for chaotic systems that have been designed by Wang et al in 2010 [10]. Backstepping control using bee’s optimization algorithm have been proposed by Gholipour et al in 2015 [11]. Multiobjective cost function have been proposed for error tracking optimization and control effort improvement, therefore, the optimal system parameters using optimization algorithm could be achieved in a way that lead to minimum cost function.

Chaos controlling have been considered in permanent magnetic synchrony motor studied by Li and Wu in 2016 [12]. For achieving favorable target, the nonlinear slipper for slipper mode controller with limited convergence have been designed. In this method, despite the resistance, it has very fast convergence. In a study by Khanzadeh and Pourgholi in 2016, this viewpoint using nonlinear slippage level and variance within time, the resistant controller have been proposed for chaotic systems [13].Singularity of sliding surface is one of the major issues in some conditions in this method.

Fuzzy systems are general approximators, in fact they could approximate every soft nonlinear function with proper precise. Fuzzy systems have used this property in controlling and characterization science. Fuzzy controllers are nonlinear control methods that have been used as nonlinear system function approximators or used for optimal controller approximation. The controlling method using fuzzy method have been proposed for some chaotic systems by Shirkhani et al in 2016 [14]. In this method, nonlinear function of chaotic system approximated using fuzzy systems and then using this nonlinear functions in controller for compensation and feedback linearization. In this method, the controller itself is nonlinear control (linearized based on feedback) and fuzzy systems have been used for nonlinear function approximation. In a study by Zheng et al in 2015, a fuzzy system plays system controller role (direct control method) and the fuzzy system output is same as controller output that have been conducted to chaotic system and stabilized that [15].

There is chaotic behavior in mechanic system control that have been drawn attention in recent researches. These systems including servopneumatic system, vehicle suspension system, magnetic suspension system, autonomous systems [16]. There are various controlling methods for some mechanic systems. One of these systems is spur gear transmission. Spur gear transmission systems have various application in industrial machineries, aerospace, robotic and comprehensive applications in power systems. The existing vibrations in these systems directly affect the system performance. Many researches and works have been investigated on this research area [17] .The results showed chaotic behavior in special ranges of vibration. These vibrations are harsh and unpredictable and could damage and make intruding noise in spur gear. The investigation and analysis on spur gear systems and various effective factors on that could help to reduce the intruding noise and therefore improve the spur gear quality.

In this paper, the modelling and Chaotic systems control have been conducted due to significance of spur gear role as important component in industrial rotating machine and also the power transmission systems. In order to investigate on recent years researches in nonlinear system modelling and chaotic spur gear, the mathematical model have been presented for this system. For keeping the system stability, improved fuzzy controllers using NSGAII algorithm have been used.

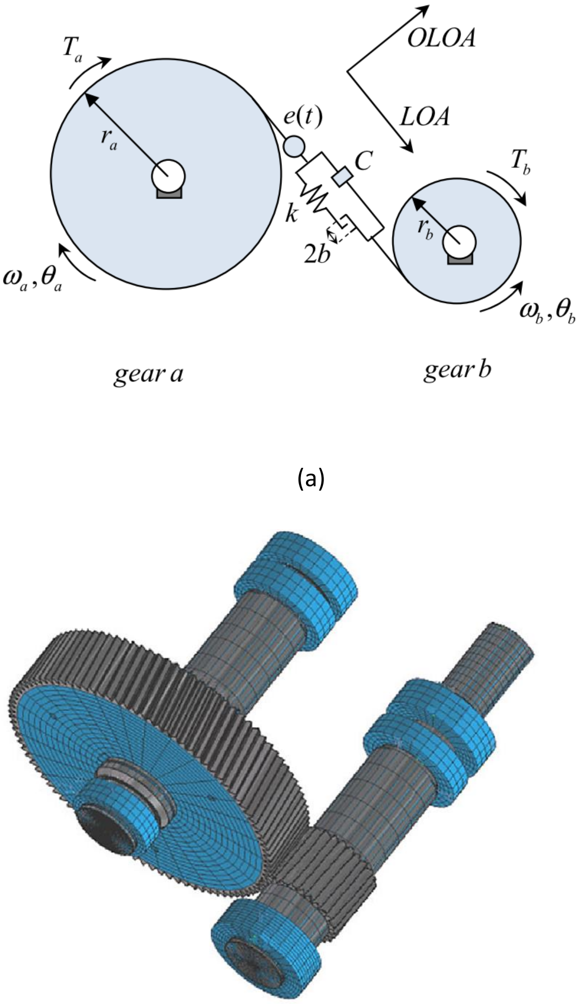
The present paper have been published in five chapters. Novel and valid articles in recent years have been analyzed, and the nonlinear model for chaotic spur gear have been extracted in second chapter. The proposed controller structure have been investigated in third chapter. Finally, the results from improved fuzzy controller simulation using NSGAII algorithm have been presented on spur gear system model and the conclusion brought in fifth chapter.

I. Nonlinear model presented for chaotic spur gear system

In this chapter, a novel dynamic model have been presented for spur gear systems and dynamic equation on them have been extracted [18]. The general perspective of industrial system for modelling looks like figure 1(a). based on spur gear vibrational model analyzed on figure 1(b), the spur gear system generally has been modelled by two discs revealing the two spur gear inertia. The damper and spring system have been presented to express the involvement of two spur gear. In this model, the spur gear of a and b introduced with $r_a$and r_b radii respectively. I_a and $I_b$demonstrating the two spur gear inertia moments and km and cm are involvement hardness and damping coefficient of involved spur gear. The conducted torque on spur gears symbolized with Ta and Tb respectively. Backlash function $f_h$and displacement $e(t)$ defined for looseness and static transmission system respectively. According to these hypothesis, the displacement equation of spur gear system shall be as follows:

$$
\begin{aligned}
I_a \frac{d^2\theta_a}{dt^2} + c_m \left(r_a \frac{d\theta_a}{dt} - r_b \frac{d\theta_b}{dt} - \frac{de(t)}{dt}\right) r_a \\
+ r_a k_m f_h\big(r_a\theta_a - r_b\theta_b \\
- e(t)\big) = T_a
\end{aligned}
\qquad (1)
$$

$$
\begin{aligned}
I_b \frac{d^2\theta_b}{dt^2} - c_m \left(r_a \frac{d\theta_a}{dt} - r_b \frac{d\theta_b}{dt} - \frac{de(t)}{dt}\right) r_b \\
- r_b k_m f_h\big(r_a\theta_a - r_b\theta_b \\
- e(t)\big) = -T_b
\end{aligned}
$$



(a)

(b)

Figure 1: (a) the modelled industrial spur gear system perspective (b) vibrational model for spur gear transmission system.

The both spur gear require the looseness to some extent for better lubrication and the reduction of interaction design. Also the fabrication errors and friction are the main factors of this looseness. Therefore the backlash function f_h have been defined for both spur wear looseness and expressed as piecewise linear function as follows:

$$
f_h = \begin{cases} r_a\theta_a - r_b\theta_b - e - (1-\alpha)b & . \\ \alpha\,(r_a\theta_a - r_b\theta_b - e) & . \qquad -b \le (\\ r_a\theta_a - r_b\theta_b - e + (1-\alpha)b & . \qquad b < \end{cases} \qquad)\,2\,(
$$

With novel parameter definition of $\tilde{x} = r_a\emptyset_a - r_b\emptyset_b - e(t)$ showed that the relative linear displacement was for involvement and expressing the transmission error of system, the vibrational equation (1) simplified to equation (3) as follows:

$$m\frac{d^2\tilde{x}}{dt^2}+c_m\frac{d\tilde{x}}{dt}+k_m f_h(\tilde{x}) = \hat{F}_m+\hat{F}_e(t) \qquad (3)$$

There is

$$f_h(\tilde{x}) = \begin{cases} \tilde{x}-(1-\alpha)b & , \quad b<\tilde{x} \\ \alpha\,\tilde{x} & , \quad -b\leq\tilde{x}\leq b \\ \tilde{x}+(1-\alpha)b & , \quad b<-\tilde{x} \end{cases}$$

$$m=\frac{I_a I_b}{I_b r_a^2+I_a r_b^2} \;,\; \hat{F}_e(t) = -m\frac{d^2e}{dt^2} \;,\; \hat{F}_m = m\left(\frac{T_a\,r_a}{I_a}+\frac{T_b\,r_b}{I_b}\right) \qquad (4)$$

Static transmission error $e(t)$ defined as the most effective parameters of vibrational spur gear systems. Static transmission error due to changes in cogs and deformation is one of the most sources of vibration in spur gear. In modelling, the transmission error has been considered as a periodic displacement excitation due to both involved cogs during the contact cycle. Therefore, the static transmission error is function of involved frequency and input as an equation (5) in the system [19].

$$e(t)=e\left(t+\frac{2\,\pi}{\omega_e}\right)=e\,\cos(\omega_e t+\emptyset_e) \qquad (5)$$

In order to achieve the dimensionless form of displacement equation of the system, the following parameter (6) is defined as (6)

$$x=\frac{\tilde{x}}{b} \;,\; \omega_n=\sqrt{\frac{k_m}{m}} \;,\; \tau = \omega_n t \;,\; \Omega_e = \frac{\omega_e}{\omega_n} \;,\; \tilde{\mu}=\frac{c}{2m\omega_n} \;,\; \tilde{F}_e = \frac{e}{b} \;,\; \tilde{F}_m = \frac{\hat{F}_m}{b\,k_m} \qquad (6)$$

According to definition of equation (6), the dimensionless form of the equation of displacement system shall be as follows (7)

$$\frac{d^2x}{d\tau^2}+2\tilde{\mu}\frac{dx}{d\tau}+f_h(x) = \tilde{F}_m + \tilde{F}_e\,\Omega_e^2\cos(\Omega_e\tau+\emptyset_e) \qquad (7)$$

There is:

$$f_h(x)=\begin{cases} x-(1-\alpha) & , \quad 1<x \\ \alpha\,x & , \quad -1\leq x\leq 1 \\ x+(1-\alpha) & , \quad 1<-x \end{cases} \qquad (8)$$

Considering $a=0$ and $f_h$function approximation with third order function shall be as $f_h\,(x)=-0.1667x+0.1667x^3$, the equation (7) shall be rearrange to equation (9):

$$\frac{d^2x}{d\tau^2}+2\tilde{\mu}\frac{dx}{d\tau}+(-0.1667\,x+0.1667\,x^3) = \tilde{F}_m + \tilde{F}_e\,\Omega_e^2\cos(\Omega_e\tau+\emptyset_e) \qquad (9)$$

In order to convert the second order equation (9) to first order differential equations (the state demonstration of dynamic systems), the equation (10) is presented:

$$\tilde{F}_e=\varepsilon\,f_e \;,\; \tilde{F}_m = \varepsilon\,f_m \;,\; \tilde{\mu} = \varepsilon\mu \qquad (10)$$

That $0<\in\leq1$, in state and considering the undesirable conducted inputs to the system shall be expressed as (11):

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -2\,\varepsilon\,\mu\,x_2+(0.1667\,x_1-0.1667\,x_1^3) + \varepsilon\,(f_m+f_e\,\Omega_e^2\,cos(\Omega_e\tau+\emptyset_e)) + \Delta f(x.t)+d(t)+u(t) \end{aligned} \qquad (11)$$

The space state of (11) analyzed the chaotic equation of spur gear system in this paper that x=[x_1 , x_2]T with state vector of $\Delta f(x,t)$ indefinite model, d(t) and u(t) are internal disturbance and input control respectively. The state equation parameters of (11) have been considered as follows for chaotic behavior investigation:

$$\varepsilon=0.01 \;\;.\;\; f_m=1 \;\;.\;\; \mu = 9 \;\;.\;\; \Omega_e = 0.5 \;\;.\;\; f_e=30 \qquad (12)$$

The MATLAB software have been used for simulation in order to getting familiar with modelled spur gear fuzzy-surface diagram. The presented values from equation (12) and initial condition of $(x_1\,(0),x_2\,(0))=(-2,1)$ have been used for this simulation.

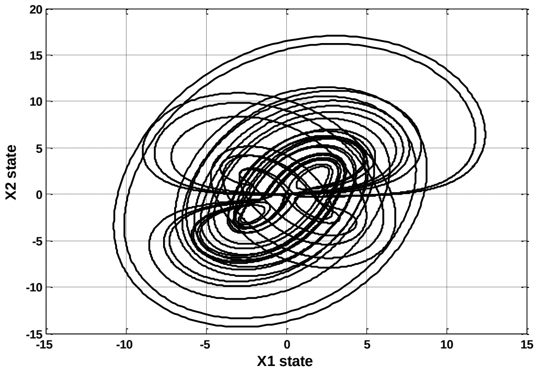


Figure 2: chaotic spur gear system of fuzzy- surface diagram

According to figure 2, the attractor picture of the fuzzy space (x_1, x_2) is chaotic and weird representing the chaotic condition of analyzed system that must taking proper strategic controls to alleviate the condition.

II. Fuzzy-PID controlling structure improved with genetic algorithm

Fuzzy control improved with NSHAII genetic extended algorithm have been the proposed controlling structure in this paper. The first step in controlling structure implementation is fuzzy control design. The general perspective of implemented fuzzy controller has been used to stabilize the spur gear system in figure 3.

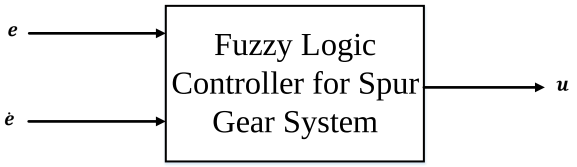


Figure 3: the general structure of designed fuzzy controller

As can be seen in figure 3, the designed fuzzy controller has two inputs (error signal and its derivative) and one output (conducted controlling signal to the system) that must define membership functions for each of them. According to researches in [20] is trimf function and defined as follows.

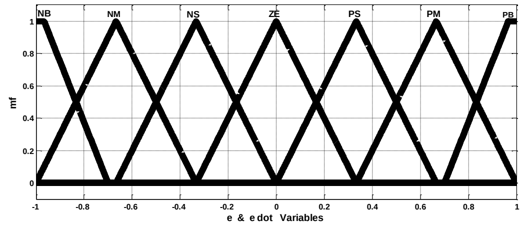


Figure 4: membership functions related to error inputs and its derivative in designed fuzzy control structure

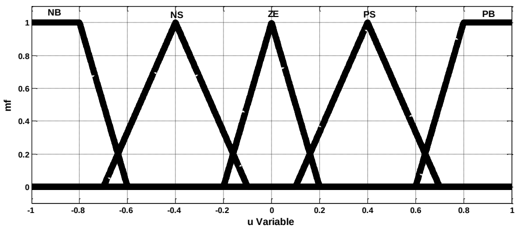


Figure 5: the membership function related to fuzzy controller output (signal u)

After the membership function specification related to fuzzy control inputs and outputs, in second step, the rules base that linked this membership function together must be calculated. One of the design requirement for fuzzy control is access to precise information of optimal design. There is no information access to modelled chaotic spur gear systems in this paper, therefore the designed fuzzy control is imperfect and does not show the optimal performance. Many research sources have been analyzed to overcome this issue and all lead to NSGAII extended genetic algorithm addition to fuzzy control structure. The second reason for NSGAII algorithm is the same direction of random search nature in issue space, because the produced random chromosomes by means of algorithm are starting point in parts of issue state space and the research must take simultaneously in all parts. Moreover there is no limitation in research path and the selection of random responses. The main goal from NSGAII algorithm implementation is to specify rules related to fuzzy control design that makes this controller independent from expert information to run optimally.

The tables for fuzzy controller's rules have been considered for error and derivative inputs in order to implement fuzzy control algorithm improved with NSGAII innovational algorithm.

Table 1: Making fuzzy control rules for NSGAII genetic extended algorithm for improvement

		$\boldsymbol{e(t)}$						
$\frac{d}{dt}e(t)$		B	M	S	E	S	M	B
	B	C	$C_{1.2}$	$C_{1.3}$	$C_{1.4}$	$C_{1.5}$	$C_{1.6}$	$\boldsymbol{C_{1.7}}$
	M	C	$C_{2.2}$	$C_{2.3}$	$C_{2.4}$	$C_{2.5}$	$C_{2.6}$	$\boldsymbol{C_{2.7}}$
	S	C	$C_{3.2}$	$C_{3.3}$	$C_{3.4}$	$C_{3.5}$	$C_{3.6}$	$\boldsymbol{C_{3.7}}$
	E	C	$C_{4.2}$	$C_{4.3}$	$C_{4.4}$	$C_{4.5}$	$C_{4.6}$	$\boldsymbol{C_{4.7}}$
	S	C	$C_{5.2}$	$C_{5.3}$	$C_{5.4}$	$C_{5.5}$	$C_{5.6}$	$\boldsymbol{C_{5.7}}$
	M	C	$C_{6.2}$	$C_{6.3}$	$C_{6.4}$	$C_{6.5}$	$C_{6.6}$	$\boldsymbol{C_{6.7}}$
	B	C	$C_{7.2}$	$C_{7.3}$	$C_{7.4}$	$C_{7.5}$	$C_{7.6}$	$\boldsymbol{C_{7.7}}$

According to table1, seven membership function have been considered for each error inputs and its derivatives in fuzzy control structure. The fuzzy control optimization using NSGAII algorithm, these membership function convert into binary numbers presented in equation (13).

$$Inputs\ \&\ Output:$$

$$\begin{cases} NB & \rightarrow & 1111 \\ NM & \rightarrow & 1011 \\ NS & \rightarrow & 1001 \\ ZE & \rightarrow & 0000 \\ PS & \rightarrow & 0001 \\ PM & \rightarrow & 0011 \\ PB & \rightarrow & 0111 \end{cases} \qquad (13)$$

As can be observed in (13), all the fuzzy controller membership substitute with four-bit binary numbers. It is worth to mention that the first bit in this number expressing the sign that fi the number was one, the number is negative and the zero means the number is positive. The presented structure in equation (14) have been shown in fuzzy control membership function.

$$NM: \underbrace{1}_{sign\ bit} \quad 0 \quad 1 \quad 1 \qquad (14)$$

That is inevitable that combination of fuzzy control membership functions leads to fuzzy rules. For instance, the first rule from fuzzy control could be defined in equation (15):

$$if\ \ (e(t)\ \ is\ \ NB)\ \ and\ \ \left(\frac{d}{dt}e(t)\ \ is\ \ NB\right)\ \ t \quad \begin{matrix}1)\\(5\end{matrix}$$

Each of fuzzy rules could be expressed in a binary numbers. For example, the fuzzy rule in (15) could turn into (16) equation:

$$\underbrace{1111}_{e(t)(NB)} \quad \underbrace{1111}_{\frac{d}{dt}e(t)(NB)} \quad \underbrace{1111}_{output(NB)} \qquad (16)$$

Each of fuzzy rules that could be expressed in Fuzzy-NSGAII combinational control design defined in one chromosome in order to implement smart innovational NAGAII algorithm design. Therefore, the 7× 7 × 7=343 chromosomes defined in equation (17). In fact, the chromosome numbers, constituted the initial random population in NSGAII optimization algorithm.

$$\begin{cases} chromosome\ 1 = [1111 \quad 1111 \quad 1111]_{1:} \\ chromosome\ 2 = [1111 \quad 1011 \quad 1111]_{1:} \\ \vdots \\ chromosome\ 343 = [0111 \quad 0111 \quad 0111] \end{cases} \quad \begin{matrix}17)\\(\end{matrix}$$

According to equation (17), there are 3 binary numbers in each 12-bit chromosome expressing the input and output variants in fuzzy controller.

In each optimization problem, the goal is to find proper optimal values for the problem variants in order to contact with existing phrases and minimize and maximize the target function.

The fitness function have been selected for optimization using innovational NSGAII algorithm in this paper, and target will be the minimization of this function. In fact, the control rule specification is to minimize the cost function with lowest possible effort. The general cost function form in this paper shall be as follows (18):

$$\begin{aligned} Optimize \quad y = f(k) & \\ = (w_1 \times MP) & \\ + (w_2 \times Ts) & \\ + (w_3 \times SI) & \qquad (18) \end{aligned}$$

$$s.t. \begin{cases} |w_1| \le 100 \\ |w_2| \le 100 \\ |w_3| \le 10 \end{cases}$$

As can be seen in cost function structure, this function including all the significant criterion of design that being weighted. The criterions compromised of the maximum Peak (MP), the settling time(Ts) and the stability index (SI). The w1 to w3 are the weights of these criterions.

The second step after getting familiar with cost function is Crowding distance controlling parameter calculation in NSGAII optimization algorithm structure. This parameter have been calculated for each initial random population member and expressing the closeness of sample to the other population member. It must be noticed that the large value for this parameter lead to divergence and proper dispersion in population members. Therefore the present paper, the parameter have been considered as (19).

$$d_j(k) = \sum_{i=1}^{n} \frac{f_i(k-1) - f_i(k+1)}{f_i^{max} - f_i^{min}} \qquad (19)$$

The algorithm performance related to genetic family in simulation is in a way that after achieving the results for each chromosome, the best of them including the chromosome with the fast response as an expert transmit to next generation and the other combine with combination or mutation methods and makes the next generation.

The results from simulation

The chaotic spur gear model implemented in open circle without controlling usage in Matlab Simulink software in order to getting familiar with system state variants behavior in time passage, the results have been demonstrated in figure 6.

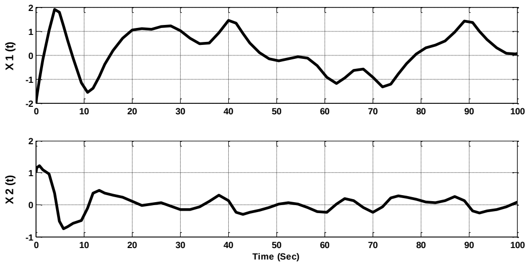


Figure 6: the time response of chaotic spur gear state variants in open circle simulation

The results from figure 6 showed that the modelled system state variants changed in an unsteady way and open circle study could not provide the requirements the designer of this system. It is inevitable that chaos existence in spur gear system is the main reason for this unfavorable results. The MATLAB software have been used for fuzzy controller implementation improved with NSGAII extended genetic algorithm. The initial random population based on total numbers of the rules for fuzzy control (chromosome number in NSGAII algorithm structure) have been taken into account in this paper. The other parameters of table 2 have been conducted using the information in [21] or the trial and error method.

Table 2: design parameters in NSGAII optimization algorithm

Parameters	Symbol	Value
N_g	Number of selected random population	343
N_c	Number of selected parents from the random population	15
iteration	Maximum number of iterations for the algorithm	100
N_p	Number of mutations	10
p_c	Crossover probability	0.7
p_m	Mutation probability	0.3

In this paper, the maximum numbers have been 100 for optimization trend that is similar to figure (7). According to this figure, the cost function value shall be reached to the minimum level in one hundredth repetition revealing the NSGAII algorithm in optimization. The result of this proper performance is fuzzy control rules specification without the expert person information.

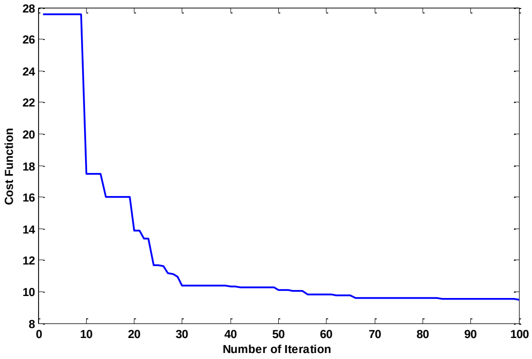


Figure 7: optimization trend in NSGAII for chaotic spur gear system in 100 repetition

After NSGAII optimization algorithm implementation, 22 rules related to fuzzy control as an expert and algorithm output have been achieved that all the rules demonstrated in table 3.

Table 3: optimal fuzzy rules achieved for combinational fuzzy-NSGAII controller

	e	$\dot{e}$		u
If	NB	ZE	**Then**	NS
	NB	NB		NB
	NB	PS		ZE
	NM	NM		NS
	NM	PB		PS
	NS	NS		NS

	NS	NB		NS
	NS	PS		PS
	ZE	PM		PS
	PS	NM		ZE
	PS	ZE		PS
	PS	NB		NS
	PS	PB		PB
	PM	NB		NS
	PM	NS		PS
	PM	ZE		NS
	PM	PS		PB
	PM	NM		ZE
	PM	PM		PS
	PB	NS		NS
	PB	PM		PS
	PB	PB		PB

Implementing optimal results from NSGAII optimization algorithm in designed fuzzy control structure, we expect the improvement in system controlling goals. Various strategies have been taken to prove this claim. As a first step, the various external disturbance inputs have been inserted into the system. These signals have been shown in figure 8.

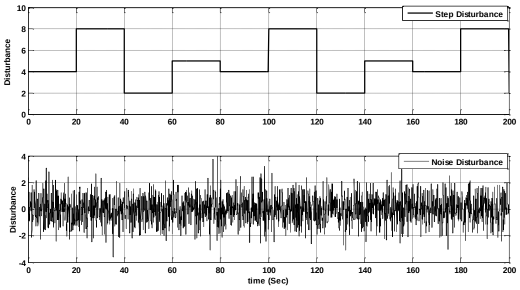


Figure 8: external step disturbance signal inputs and implemented noise to chaotic spur gear system.

Step disturbance and noise of figure 8 have been implemented in the system and the results from this paper have been compared with the fuzzy control method and have been shown in dual state variants from figure 9 to figure 12.

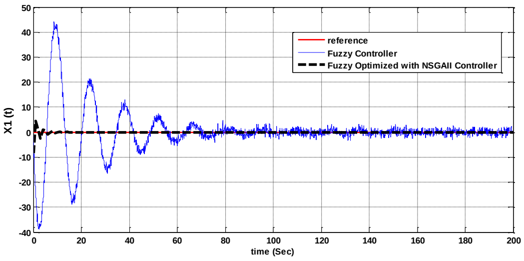


Figure 9: the state variant x1(t) in step external disturbance, fuzzy control improved with NSGAII innovational algorithm.

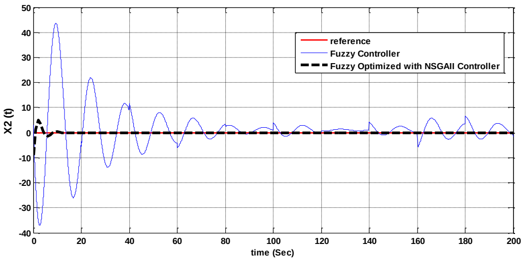


Figure 10: the state variant x2(t) in step external disturbance, fuzzy control improved with NSGAII innovational algorithm.

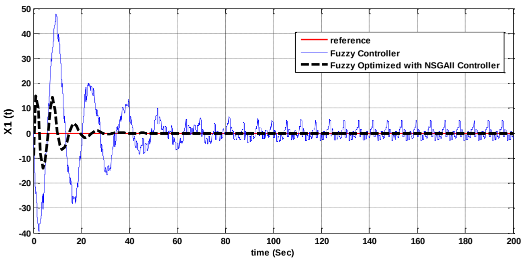


Figure 11: the state variant x1(t) in external noise disturbance presence, fuzzy control improved with NSGAII innovational algorithm.

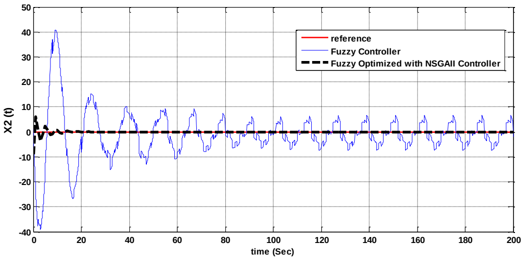


Figure 12: the state variant x1(t) in external noise disturbance presence, fuzzy control improved with NSGAII innovational algorithm.

As mentioned before, the goal of control in chaotic system together with external disturbance input is system state variants stabilization and providing the requirements of the designer. According to figure 9 to 12, we can claim that designed controlling strategy in this paper could provide the goals. The other point is, system state variants stabilization without the need for expert information for fuzzy control design. Therefore we came into conclusion that the proposed NSGAII algorithm did its task properly.

These results have been compared with previous works for precise evaluation. The subject of this project is "nonlinear controller design for stabilization of chaotic spur gear state, therefore the similar strategic subjects have been selected for comparison [22] one of the selection could be the ones that the controlling variants conducted with the help of the Melnikov nonlinear strategy. The proposed controlling advantages have been shown in figure 13 and figure 14.

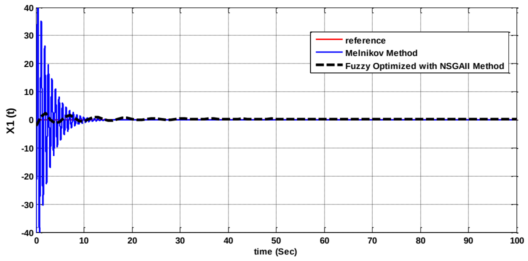


Figure 13:the comparison of achieved diagrams for state variant stabilization x1(t) in chaotic spur gear system using fuzzy combinational controller based on NSGAII optimization algorithm (the black broken diagram) and the control based on Melnikov strategy (solid blue line diagram)

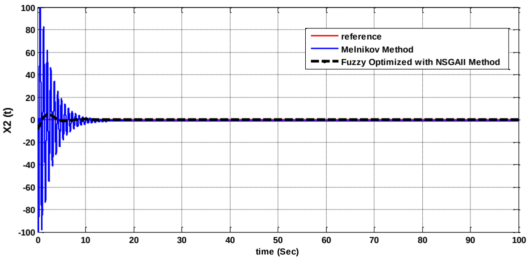


Figure 14: the comparison of achieved diagrams for state variant stabilization x1(t) in chaotic spur gear system using fuzzy combinational controller based on NSGAII optimization algorithm (the black broken diagram) and the control based on Melnikov strategy (solid blue line diagram)

Conclusion

The combinational fuzzy controlling improved with NSGAII extended genetic algorithm have been used in industrial systems to overcome the destructive chaos phenomenon in this paper. The proposed controlling strategy have been implemented in industrial spur gear sample. The surface –fuzzy diagram of chaotic spur gear have been shown before and the after the fuzzy-NSGAII excitement in figure 15. According to this figure after the fuzzy controller optimized with NSGAII genetic extended algorithm, the periodic response shall be as fixed limit cycle. These results validate the proper performance of the controlling of the chaos.

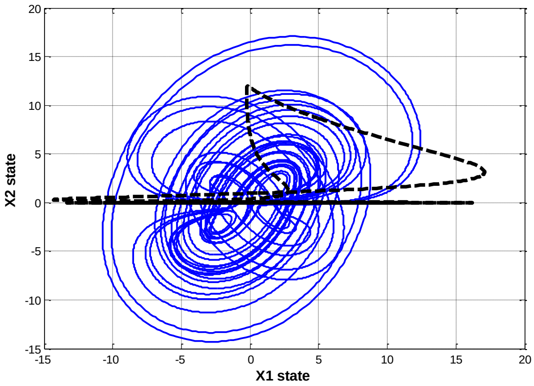


Figure 15: fuzzy-surface diagram for chaotic spur gear system before implementing the fuzzy controller optimized with NSGAII algorithm (solid blue diagram) and after that (inconsistent black line diagram)

One of the disadvantages of the proposed method shall be high volume of calculation, the lagging trend of simulation in comparison with previous works that could be due to proposed combinational algorithm. The novel smart algorithm such as evolutionary multiobjective optimization have been proposed to overcome in this phenomenon for future works in this research area.

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