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An Experimental Study on Fuzzy Controller Robustness Augmented by Fuzzy Supervisor for Cutting Force Control of End-Milling

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ABSTRACT: In this paper, the robustness of controlling the cutting force of an end-milling process using a supervisory fuzzy controller has been experimentally investigated. In the proposed controller an ordinary fuzzy controller is augmented by implementing a fuzzy supervisor. The ordinary controller is the highly-used cutting force fuzzy controller due its advantages. However, because of participating only one cutting parameter in its structure, i.e. mostly feed-rate, the ordinary controller is suitable only when other parameters like depth of cut, spindle speed and etc. have small amount of variations. Since in practice this assumption is not valid, ordinary controller needs to be augmented. This augmentation has had suggestions in the literature. However, these suggestions never have been on the basis of the fuzzy logic; while fuzzy being is the major advantage of ordinary controller for controlling cutting force. Due to this deficit, in this paper a supervisory fuzzy controller has been added to the system. The designed fuzzy supervisor, inspects the dynamic behavior of the cutting force, estimates a pre-defined 'sensitivity' parameter and cancels the output fluctuations arisen with this parameter's variation. The numerous experiments conducted in different cutting situations, proved that this supervisory structure increases the robustness and applicability of the fuzzy controller with respect to an ordinary one. These experiments are conducted on two different end-milling machines to confirm the efficiency of the presented method.

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1- Introduction

Computerized numerical control (CNC) has played probably a significant role in the progress of machining technology. In a CNC machine cutting parameters such as feed-rate, spindle-speed and so on, should be determined before the process execution. To avoid tool breakage and work-piece damage, machining parameters must be selected conservatively based on the most severe conditions expected. Hence, the resulted safe condition, cause a CNC technology to has a low efficiency. The cutting force is the most important parameter that endangers a cutting process with breaking tools, roughing surfaces and so on. Thus, by regulating peak forces in cutting operations, one can protect the system from damages. On the other hand, by maximizing the feed-rate to increase the cutting force up to an allowable peak value, the productivity of a process can reach to its greatest extent. There have been several works in the cutting force control area done by researchers. These works generally can be divided into two categories: model-based controllers[1-5] and model-free controllers [6, 7]. In the model based controllers, the method of modeling the cutting force is an important object beside the controller design. Artificial neural networks (ANNs) have been favorable methods for modeling cutting force because of their advantages [8-10]. U. Zuperl et al.[11] used ANNs approach to evolve a generalized model for the prediction of cutting forces. Moreover, mathematical and mechanistic approaches have been other popular methods utilized in this realm. Hamdi Aouici et al. [12] and Filho [13] applied the response surface methodology for modeling cutting force that was a mathematical approach and determined a relationship between independent input process parameters and output data. M.C. Yoon et al. [14] suggested a mechanistic model for the cutting force and showed that this parameter is proportional to the uncut chip thickness. Then, it was concluded that this model could be used in on-line controlling. On the other hand, in the model based controllers, the control algorithms are another aspect that should be taken into consideration. Sudan Huang [1] presented a model-based robust control approach for the cutting force controlling. The model utilized has been based on the experimental data and was comprised of a dominant model and an uncertain part. Park et al. [2] considered a linear model and identified its parameters from the step response. Then, a sliding mode controller was utilized for controlling the cutting force. Rodolfo Haber-Haber et el. [3] controlled the cutting force of drilling process by a PID controller. In this work the cutting force was modeled by using a first ordered dynamic model extracted from a step response. Paolo Gallina et el. [4] presented a delayed-

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reference force control and applied it on a CNC machine. Then the cutting force was approximated by a power of the feed-rate. This approach also utilized by Paulo Pascutto et el. [6] but different model for tool support modeling was applied. Min-Yang Yang [7] presented a hybrid adaptive control algorithm to regulate the spindle current. For this purpose, variations of steady state spindle current, time constant and time delay were examined through experiments performed in step end milling under various cutting conditions.

On the other hand, in a cutting phenomenon because several factors engage with each other, the extract of a comprehensive model that simulates the cutting process for all conditions is somewhat impossible. Therefore, model-based controllers are appropriate only for specific situations that the model is reputable. Due to this limitation model free controllers are desirable for controlling cutting force. In addition, since cutting processes, despite the complexity, is well understandable by human experiences, model free fuzzy controllers would be much suitable for this reason [15]. Rodolfo Haber was of the first researchers raised this idea [16]. Then, a basic fuzzy control strategy in the intelligent system was developed by U.Zuprel et el. [17] which effectively regulated the peak cutting forces. Nevertheless, due to utilize a fixed structure fuzzy controller, these works lacked a reasonable robustness. Because many variables, like depth of cut, angle of tool, work-piece hardness, etc., have not been directly contributed in controller's structure. These variables, so called non-control variables (NCV), experience big variations in general cutting process, while a fixed structure fuzzy controller is not sensitive with them.

In order to remedy the above limitation, a supplemented part has been coupled with the above fuzzy controller in the literature. This solution has been executed through two approaches thus far. In the first of them, the supplemented part has been an artificial neural network (ANN) predicting the surface roughness [15, 18, 19]. This coupling forms a neural-fuzzy controller targeted on the surface quality improvements. In the second approach, the supplemented part has been a mathematical model that changes the width of fuzzy sets according to process situations. Therefore, the base fuzzy controller becomes a variable structure one adapting itself to the cutting conditions. An idea for doing this approach has been the utilization of correlations as performance factors that tuned input and output gains of fuzzy controller. [20, 21]. Another idea has been the development of analytical models for cutting process that predicted conditions ahead thereby adapting the base fuzzy controllers [22, 23]. This methodology also has had heritages in non-fuzzy controllers [24].

Overall, the last plan addressed, that is the implementation of a supplemented part (mathematical model or ANN) on the ordinary fuzzy controller, shows a more efficient performance in practice. However, the supplemented part, despite being targeted on compensating NCVs' disturbing effects, has never been fuzzy, yet. In fact, NCVs' action, like cutting processes, better understandable by humane experiences. Thus, similarly with limitations quoted for model-based controllers, the present supplemented parts also show a restricted effect.

Due to above limitations, in this paper the utilization of a fuzzy supplement to an ordinary fuzzy controller is aimed. This supplement is a fuzzy supervisor that estimates and compensates NCVs' disturbing effects. For this reason, NCV's influences are linguistically described by defining a new factor, "sensitivity". The fuzzy rule base, established in the fuzzy supervisor, adopts commands based on the sensitivity. These commands modify the width of the input fuzzy sets of the ordinary fuzzy controller to compensate NCV's effects. This procedure augments the robustness of the control system and makes it applicable for a wide variety of cutting conditions. To prove this ability, different experimental tests is carried out on two CNC machine namely Hexaglide and Kefa. The acceptable performance of the proposed controller on these machines with thoroughly different structures satisfies the claim about system robustness.

2- Structure of a fuzzy controller for cutting force

A cutting operation is a phenomenon that is properly describable by human knowledge and experiences while cannot be mathematically formulated well. Therefore, fuzzy controllers would be suitable alternatives for this application. Due to this advantage, in this paper a new scheme of fuzzy controllers is presented. This controller is a fuzzy supervisory one wherein an ordinary fuzzy controller (OFC) is augmented by applying a fuzzy supervisor. Ordinary and supervisory sections are explained in detail in the following.

2- 1- Ordinary fuzzy controller

The OFC is designed on the basis of human knowledge about cutting processes. The inputs of this controller are force error and its derivative. Error is calculated from $F_e(k) = F_{ref} - F(k)$ at each sampling instant k, where F is cutting force measured by sensors and F_{ref} is its desired value. Force derivative is calculated by $\delta F = F(k+1) - F(k)$. The defined fuzzy sets on the inputs and output domains are shown in Fig.1. In this figure the abbreviated titles of the fuzzy sets are introduced as: S: small, LN: large negative, LP: large positive, LI: large increase, LD: large decrease, MI: medium increase, MD: medium decrease, NC: no change. These fuzzy sets are regular for the cutting force control (for example [17]) but their tuning is fulfilled through experimental tests. In addition, the fuzzy sets of OFC output, f, is indicated in the figure whose domains are tuned through conducting several experimental tests. It is noted that f is a non-dimensional number multiplied to the current feed-rate at each step thereby calculating the next step feed-rate.

The fuzzy rule base is established on the basis of the following principles: 1) if force is far from the desired value, feed-rate changes such that the force approaches the set point, meaning feed-rate increases when force is greater than the desired value and vice versa. 2) When force approaches desired value and is near to that, feed-rate changes such that force derivative to be lessened; then, feed-rate decreases when force is greater than the desired value and vice versa. Accordingly, the fuzzy rule base is established as indicated

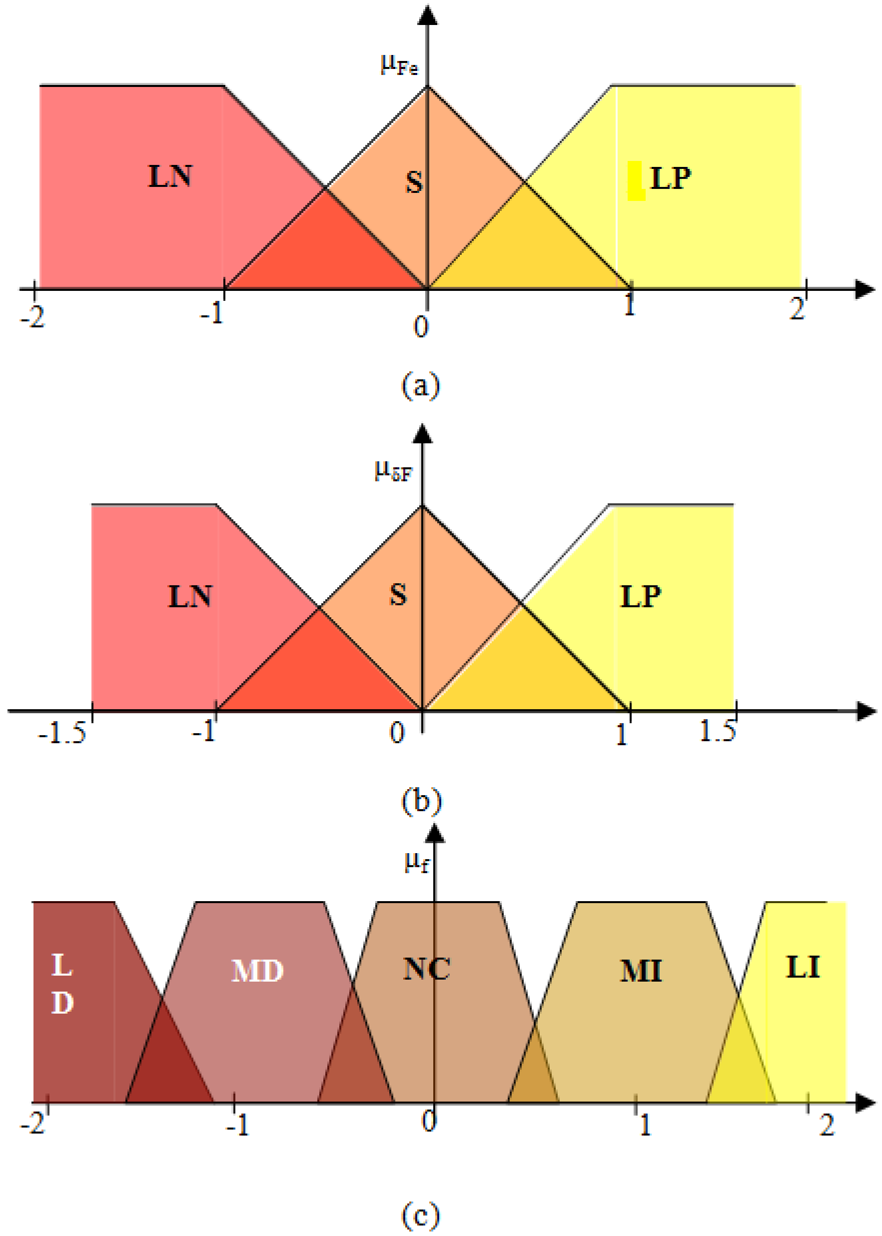

Fig. 1. Fuzzy sets on (a) cutting force error (b) cutting force derivative (c) control output

in Table 1. It is noted that fuzzifier, defuzzifier and inference engine are singleton, center average and the Mamadani, respectively.

Table 1. Fuzzy rule base of OFC

		F_e		
		LN	S	LP
δF	LN	LI	MI	NC
	S	MI	NC	MD
	LP	NC	MD	LD

2- 2- Fuzzy supervisor

During a machining process, various parameters, so called "cutting parameter", determine cutting conditions. These parameters consist of feed-rate, spindle speed, depth of cut, rake angle and so on. In OFC, the feed-rate, as the control law, was tuned for the regulation of the cutting force. Hence, feed-rate was the lone cutting parameter directly contributing to the control loop. Therefore, the rest of these parameters have variations not handling by OFC. These parameters are called "non-control variables" (NCV). In simple milling operations, the variation of NCV is not so high that disturbs the control performance. Thus, in these situations, OFC would function properly. However, in more complex processes, variations of

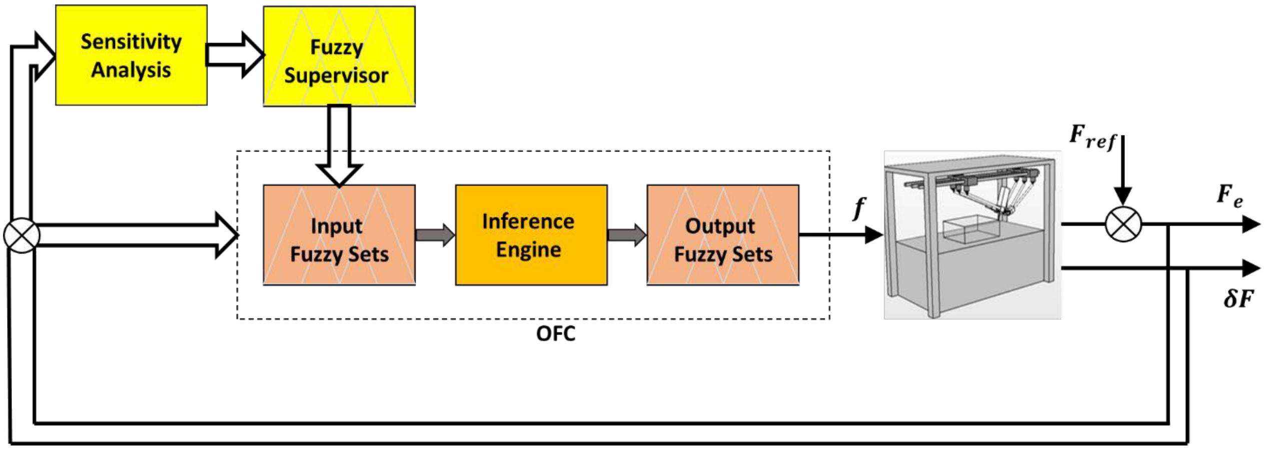

Fig. 2. structure of the supervisory fuzzy controller (SFC)

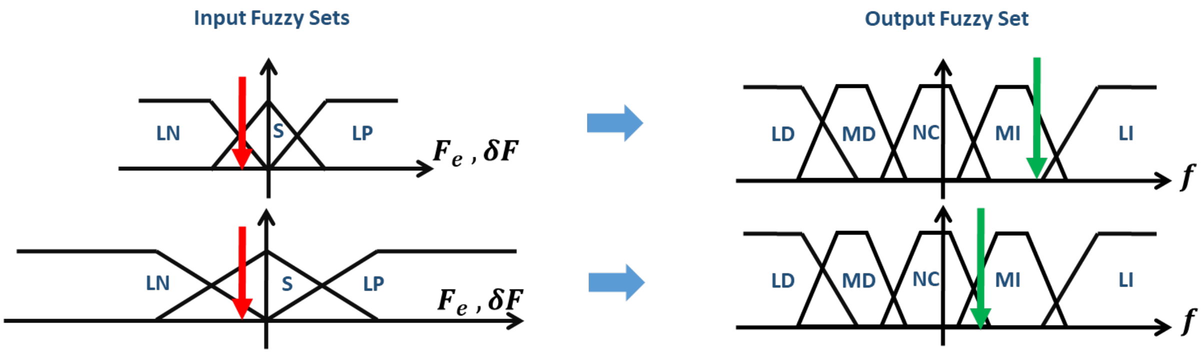

Fig. 3. the change of OFC's output for the same inputs by expanding and contracting the input fuzzy sets

NCV become noticeable that impact controller performance. Then, the cutting force cannot be regulated well and fluctuates extensively around its set point. To compensate this effect, the fuzzy supervisor is applied that makes the OFC as a variable structure controller.

In order to understand the function of fuzzy supervisor, the effects of NCV are scrutinized. To simplify this inspection, suppose that the depth of cut is the lone NCV contributing in an operation. Since OFC does not sense the depth of cut, it may adopt the same outputs in two different depths, which is for example, a same increasing command in feed rate. However, this increase causes a sharper rise in cutting force at deeper positions because of increasing the cutting surface. This shows, OFC is unable to predict the effect of changing the depth. Other NCVs have the similar influences on OFC performance. Therefore, it can be generally stated that the contribution of NCVs in a process causes the system to show different reactions to the same control signals. In other words, NCVs vary the ''sensitivity'' of the cutting force with respect to the control law. Therefore, the so called parameter, sensitivity, is considered as the factor thereby describing the effects of the NCVs on the cutting process.

In order to compensate the sensitivity variations during the process, OFC should be modified to a variable structure controller. This goal is met by expanding and contracting the input fuzzy sets that is fulfilled by the supervisor. In other words, the mentioned supervisor by specifying the sensitivity, changes the fuzzy sets width to cancel the NCVs effects. This scenario is illustrated in Fig.2. In this scenario by expanding or contracting the input fuzzy sets, the OFC's output decreases or increases, respectively, that is indicated in Fig.3.

In order that supervisor performs the above procedure properly, the required fuzzy rules should be obtained based on the sensitivity parameter. For this reason, the sensitivity should be quantifiably expressed, first. Since NCVs are not measurable by sensor, their numerical values are unknown.

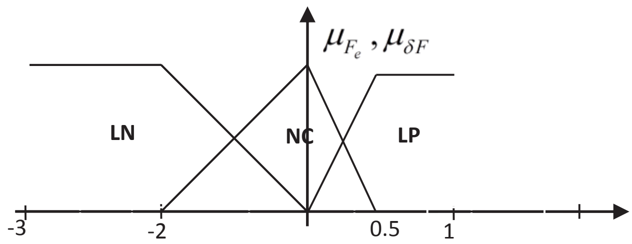

Fig. 4. Expanding and contracting of input fuzzy sets of OFC by the supervisor near to the set point

Table 2. Fuzzy rule base of fuzzy supervisor

		F_e		
		LN	**S**	**LP**
δF	**LN**	-	D(f>0)/I(f<0)	-
	S	I	NC	I
	LP	-	I(f>0)/D(f<0)	-

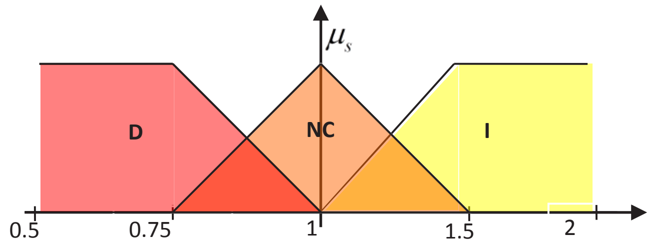

Fig. 5. Fuzzy sets of the supervisor

Instead, the sensitivity can be linguistically expressed based on the NCVs' effects. In fact, this parameter illustrates the ratio of the cutting force changes with respect to the feed-rate changes which is proportional to the OFC's output, 'f'. Thus, regarding to the previous section, when cutting force is near to the set point, that the control law is small, the large value of force derivative means that the sensitivity is large. With the same reason, for the force far from the set point, small force derivative shows that the sensitivity is low. According to these definitions, the large and low sensitivities are expressed based on the linguistic values of F_e and δF . Then, large sensitivity means small F_e and large (negative/ positive) δF and low sensitivity means large (negative/ positive) F_e and Small δF .

The fuzzy rules of the supervisor are obtained on the basis of the above extreme sensitivity. This rule base is indicated in Table 2. The abbreviated terms in this table stand for: I: increase D: decrease NC: no change. The corresponding fuzzy sets are illustrated in Fig.5. Regarding to above table, the supervisor is quantified for extreme sensitivities. Specifically, for the low sensitive conditions, supervisor take 'I' command that amplifies OFC's output through contracting its input fuzzy sets (according to Fig.3). In addition, in large sensitive conditions the supervisor commands depend on the 'f' sign that tends to damp force variations and regulate it on the set point. Therefore, in these conditions, the supervisor action makes the input fuzzy sets of OFC asymmetric as shown in Fig.4.

It is noted that fuzzifier, defuzzifier and inference engine are similar to OFC.

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3- Experimental setup

As it is previously claimed, the SFC is a model free controller. To prove this claim, SFC was implemented on two CNC milling machines with thoroughly different structures. The first one was a three axis Kefa machine manufactured by Ofogh Company. A photograph of this device is indicated in Fig.6. In this machine the three degree of freedom is provided by three rails positioned perpendicularly to each other. The spindle is an AC motor moved through the mentioned rails by the action of the driving system. This driving system consists of three stepper motor coupled with gearbox individually put on each rails to obtain the required linear motion.

The second machine was a 6 DOF CNC Hexaglide machine manufactured by Sharif University of technology. This machine is illustrated in Fig.7. Hexaglide is a parallel robot used for high speed complicated machining. Six servo motors with their corresponding ball screws provide the linear motion for the basis to which the robot's linkage is connected. This motion through the linkage, causes three linear and three angular movement of the end effecter.

Cutting force measurement is fulfilled differently in two above machines. For the Kefa machine, due to the space restriction, we preferred to use the spindle current instead of the cutting force because of their correlation [23]. The current is transuded to the voltage by a high power 4.7Ω resistor

Fig. 6. Three axes Kefa CNC machine

Fig. 7. Six axes CNC Hexaglide machine

placed on the null power line of the spindle. In Hexaglide machine we directly measured the force by a 5kg load-cell mounted on the work-hold. The output voltage of the load-cell is transferred to the computer by a 1711 PCI DAQ. In Kefa machine data transferring was performed via the com port. The fuzzy control algorithm presented in previous sections is implemented in LabVIEW software. For transmitting the control commands from LabVIEW to the Hexaglide and Kefa machines, USB 4711 and ISA port are utilized, respectively

4- Experimental results and discussion

To examine the performance of the supervisory fuzzy controller on canceling the NCVs effects, several tests are performed on wooden work-pieces by Hexaglide and Kefa CNC machines.

At the first step, the OFC was used for machining a predefined ramp that the depth of cut increases as shown in Fig.8. The cutting force variations for Kefa and Hexaglide machines are indicated in Fig.9 and Fig.10. In regard to this figure the OFC has a good action at the beginning of the operation, but in the proceeding, the noticeable peak forces are appeared when the depth is increased. This event is so that the sensitivity is varied during the operation but OFC cannot adapt itself to the encountered conditions because of having invariant structure. In fact, a specific increase in feed rate near the force set point, causes a sharper increase of cutting force in more depth of cut. This behavior is coincident with the large sensitive situation defined in the previous section. Thus, the invariant structure of OFC disables this controller to compensate the sensitivity changes during cutting process as

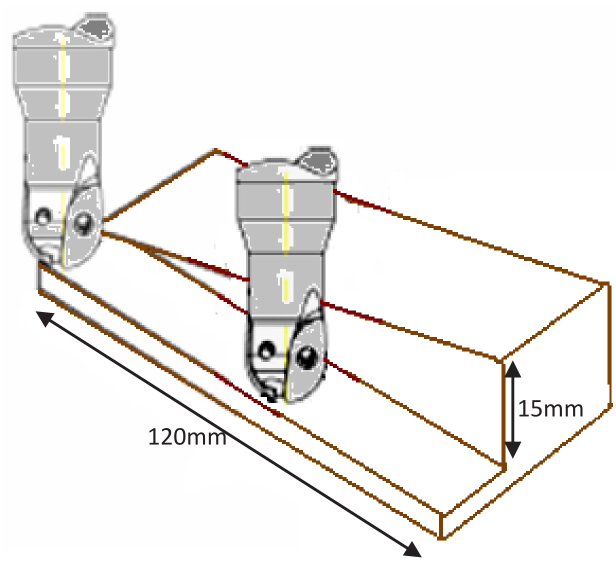


Fig. 8. The ramp path of the machining

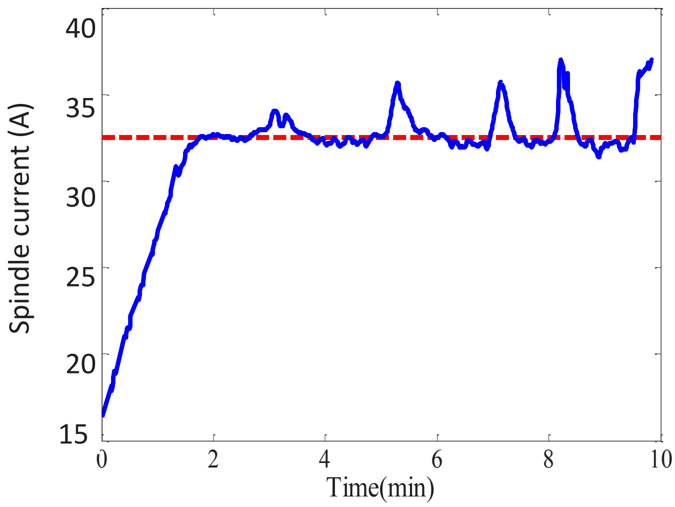


Fig. 9. Response of the system in the OFC for the ramp path in Kefa machine

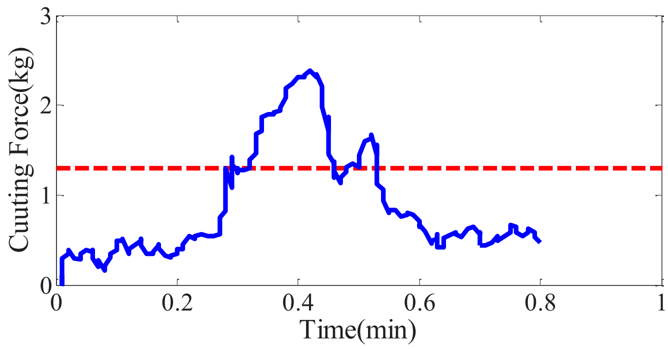
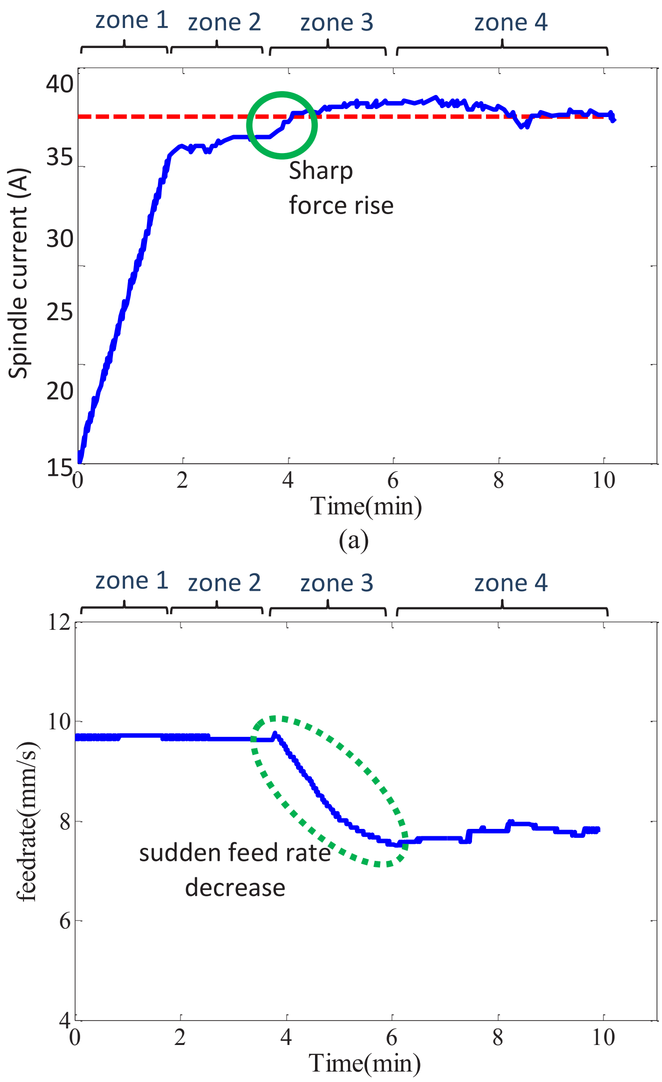


Fig. 10. Response of the system in the OFC for the ramp path in Hexaglide machine



(b)

Fig. 11. Response of the system in the supervisory fuzzy controller for the ramp path in Kefa machine(a) cutting force (b) federate

claimed before. This disability can be physically justified that in deeper positions the cutting surface increases. Then, by the same tool's displacement, the more material should be cut in more depth of cut. Since OFC cannot sense this phenomenon, by taking the same feed rate increasing commands, the greater force rising would be obtained in deeper positions. This procedure leads to the force peaks shown in the figure.

In the next step, to check whether the fuzzy supervisor is capable of eliminating the above OFC's deficit, the supervisory fuzzy controller was exposed to the same examination. Fig.11 and Fig.12 shows the response of the systems together with the control effort. As it is obvious, the force peaks have been well eliminated and cutting force is regulated on the set point. This outcome shows that the fuzzy supervisor has been able to estimate the sensitivity variations and by which compensate the disturbing effects of NCVs. In addition, attending to the trend of the control law, feed rate experiences four distinct zones during the process. At the beginning step (zone 1) the feed rate saturates on its maximum value; because the depth of cut starts from zero and gradually increases. Therefore, the cutting force would be small and the controller tries to raise that via increasing the feed rate until reaching the maximum allowable value. Moreover, in zone 2, the depth of cut is in a range that the cutting force becomes near to the set value. However, the sensitivity is so low that the supervisor still prevents the feed rate decreasing. After that, the depth of cut may reach to a level that causes a sharp rise of cutting force near the set point that is recognized as the large sensitive condition according to the previous sections definition. Therefore, by the action of the supervisor, the feed rate suddenly decreases thereby damping the force sharp variations (zone 3). Hence, the intensive peak forces, being impressive in the OFC actions, are moderated and make force regulate on the set point. After this sudden decrease of feed rate, its variations is considerably mitigated because the SFC intelligently recognizes the large sensitivity condition and

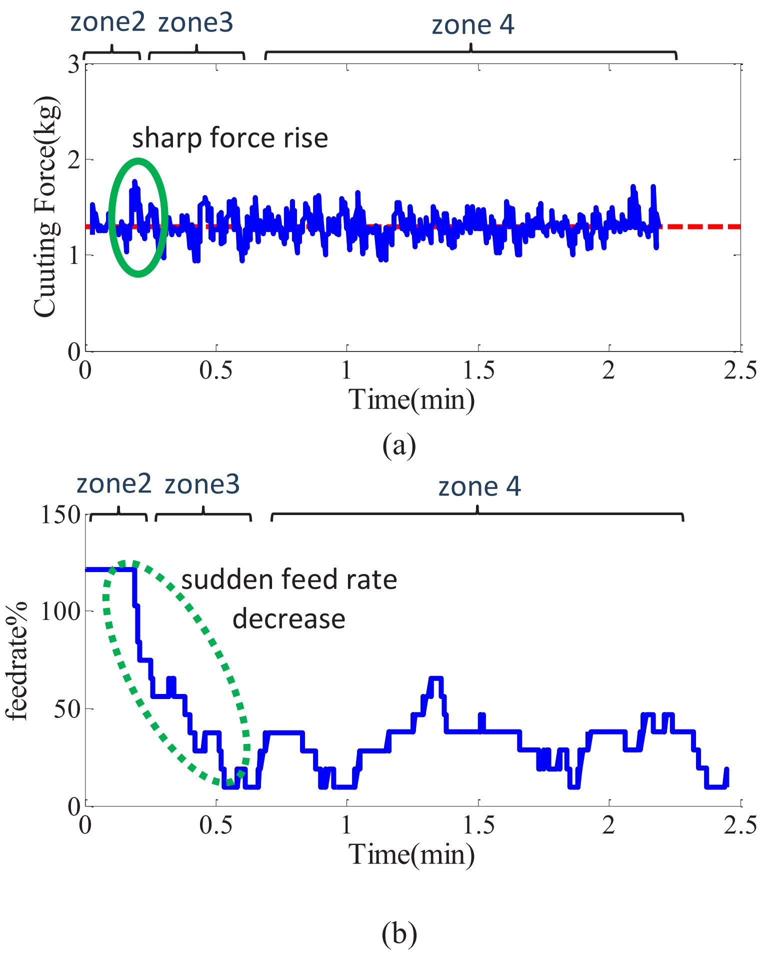


Fig. 12. Response of the system in the supervisory fuzzy controller for the ramp path in Hexaglide machine(a) cutting force (b) feed rate

controls the cutting force by slight changes of the feed rate (zone 4).

In the next stage, the independency of the SFC from the model is examined. For this reason, a work-piece with a quite uneven surface is considered for machining. This work piece is shown in Fig.13. The response of the system in this examination is illustrated in Fig.14 and Fig.15. In this test, the systems encountered with random and unexpected depth variations and thus the robustness of the controller was extremely tested. This examination is a strict test for evaluating controller robustness while in other works predefined paths or depth of cut were usually utilized [16, 17, 22]. The proper action of the controller in two machines confirmed the above claim.

The last examination was only performed on the Hexaglide machine because of being a 6-axis device. Indeed, in this test a general motion of an end milling machine was performed that the tool's angle also varied beside the depth of cut. This variation was fulfilled in two directions: aligned with and perpendicular to the feed direction. Therefore, the most NCVs were contributed in the process and the ability of the SFC in canceling their disturbances was perfectly examined. The depth variations were the same as the first test and tool's angle in perpendicular direction varies from -10^{o} to 5^{o} and in parallel direction was from -5^{o} to 10^{o}. The result of this test is indicated in Fig.16 that the supervisory controller could properly damp the cutting force variations.

5- Conclusion

A supervisory fuzzy controller is presented in this paper for controlling the cutting force. In this controller an ordinary fuzzy controller is augmented by a fuzzy supervisor. The reason for applying this supervisor was to regulate the disturbing effects of cutting parameters not contributing directly in control structure (NCVs). Fuzzy based being

Fig. 13. A workpiece with a ruined surface, the specified area is demanded to be smoothed

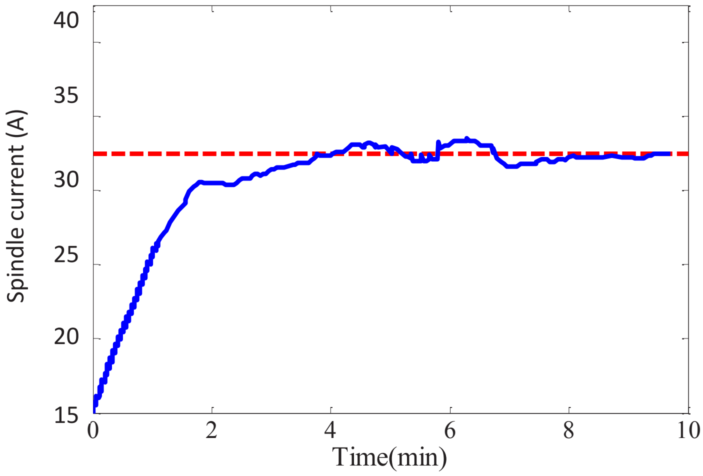


Fig. 14. Response of the plants by the supervisory fuzzy controller in machining of a uneven surface work-piece in Kefa machine

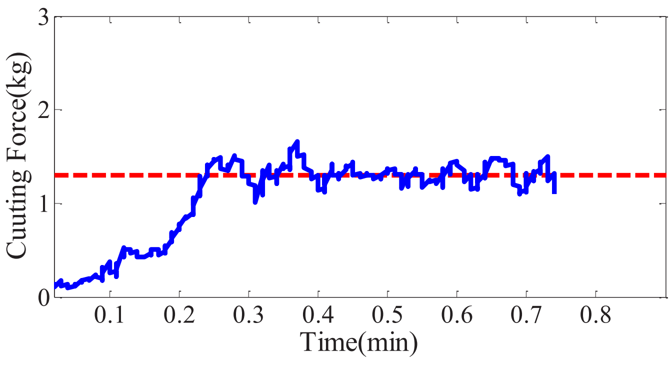


Fig. 15. Response of the plants by the supervisory fuzzy controller in machining of a uneven surface work-piece in Hexaglide machine

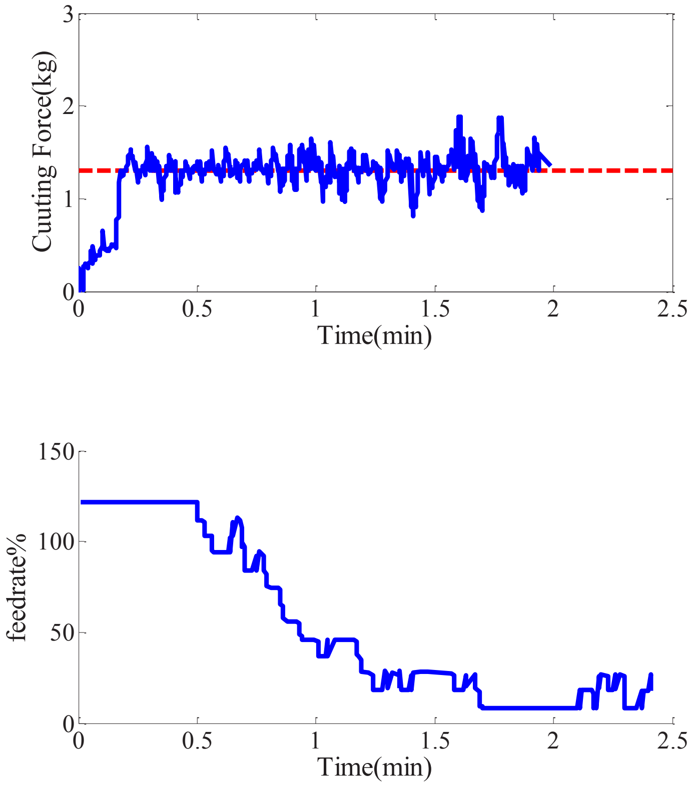


Fig. 16. response on the CNC Hexaglide machine for a general milling motion with 15cm depth variation and -10o to 5o and -5o to 10o changes for perpendicular and parallel tool orientations respectively

is the superiority of the proposed supervisor over similar researches .This superiority helps that NCVs' effect, despite being indescribable with mathematical formulation, is felt in a so called 'sensitivity' parameter. By this means, a fuzzy rule base is defined to relieve the disturbing effects of NCVs. Then, different experimental tests are carried to examine the efficacy of the proposed scheme. The variety of these tests was huge with respect to the similar works that proved how the robustness of the proposed controller is high in a wide range of cutting conditions. These tests were conducted in the following conditions:

- The controller is examined experimentally on two distinct CNC machines, namely Hexagalide (6 DOF) and Kefa (3 DOF).

- Testing on a 6DOF CNC machine makes the process more complicated because of participating further cutting parameters in the process.

- The test case with random change of cutting depth is examined instead of utilizing a predefined test case

Having a good performance in the above experiments proves the independency of the controller to the type and number of NCVs.

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