A Fuzzy Regulator for the Speed Control of Ultrasonic Motors

Sheng-Huang Yen [#1], Truong Son Nguyen [#2]

Department of Mechanical and Automation Engineering, I-Shou University
#1,Sec.1 Hsieh-Cherng Rd. Ta-Hsu Hsiang,Kaohsiung County, Taiwan

[1]shyen@isu.edu.tw

[2] homebeejsc@gmail.com

***Abstract*—In this paper, a calibrated fuzzy regulator was designed to control the rotary speed of a Shinsei USR60-E3 ultrasonic motor (USM). From the manufacturer's manual, the driving voltage to the USM controller was linearly related with the desired rotary speed. However, the linear mathematical relation generated from the characteristics in manual produced a speed gap practically. A calibrator was designed to compensate the speed gap first. Moreover, The operating temperature rise was unavoidable because of the friction in USM operation. It caused a significant model variation and degraded the rotary speed under constant driving voltage. A calibrated fuzzy regulator was then constructed in Matlab Simulink to balance the variations in the operating conditions and preserve the desired rotary speed.**

***Keywords*—Fuzzy regulator, calibrator, ultrasonic motor, , rotary speed, driving voltage**

1. INTRODUCTION

The inner structure of a Shinsei USR60-E3 ultrasonic motor was shown in Fig.1.

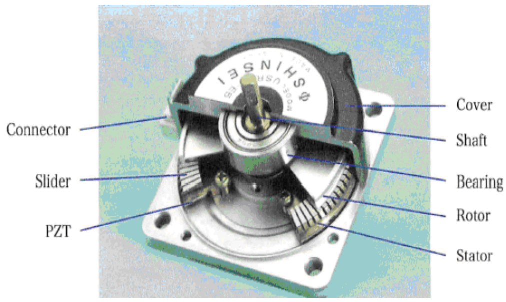


Fig.1 Inner Structure of USM （USR60-E3）

The rotor and stator conducted the ultrasonic vibrations when 2-phase driving voltages with 90^0 phase shift were applied to produce a relative rotational motion. According to the characteristics in the manufacturer's manual originally, the USM rotary speed was linearly related to the driving voltage applied to the controller. However, we found that there existed a speed gap between the desired and the practical cases. It denoted that this mathematical relation was not precisely linear and needed to be calibrated. A calibrator was used in the govering equation to adapt to the practical output speed.

Moreover, the friction between the rotor and the stator caused an ascending operating temperature which affected the nonlinear USM model unavoidably. The rotary speed then degraded gradually as the operating temperature rised for the variations in the nonlinear model characteristics. It was not easy to obtain a precise model in the traditional control process because of the nonlinear USM properties. A fuzzy control scheme may provide a solution on this issue for the lacking of system modeling process. Hence, we developed a calibrated fuzzy regulator to compensate the driving voltage. This fuzzy regulatiion compensated the operating variations and achieved a more stable rotary speed.

2. SYSTEM CONFIGURATIONS

We presented the system configuations for three cases as follows and compared their experimental results in the succeeding section.

2.1. Original Linear Case

The DC voltage－rotary speed characteristics in the manual was shown in Fig.2.

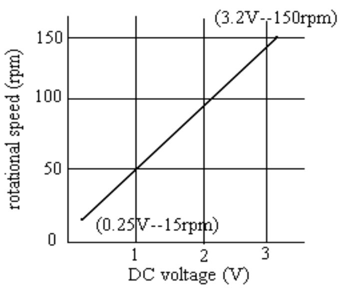
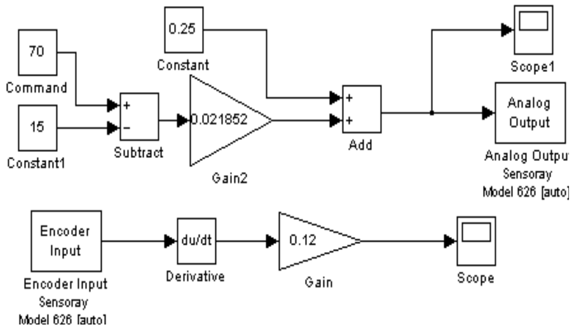


Fig.2 DC volage－rotary speed characteristics

The linear relation generated from the foregoing characteristics was described as follows:

$$V = 0.021852(\omega - 15) + 0.25 \qquad \text{(Equ. 1)}$$

where V is the controller voltage and ω is the rotary speed in rpm. The Simulink model with a 70-rpm speed setting for this original linear characteristics was configured in Fig.3.



. Fig.3 Simulink model of original linear case

2.2. Calibrated Linear Case

Investigating the result of the original case, there existed a speed gap between the desired and the practical. It denoted that the characteristics was not precisely linear. A constant calibrator was utilized to compensate first the speed gap as shown in Fig.4.

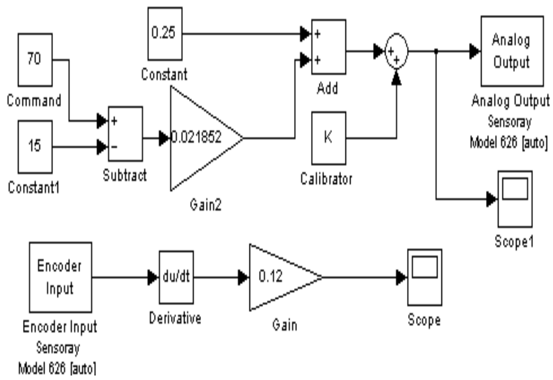


Fig.4 Simulink model for the calibrated linear case

This model configuration corresponded to the following linear equation:

$$V = 0.021852(\omega - 15) + 0.25 + \mathrm{K} \qquad \text{(Equ. 2)}$$

2.3. Calibrated Fuzzy Regulator Case

The friction between the rotor and the stator caused an ascending operating temperatur. The rotary speed degraded gradually as the operating time went on.

We utilized Matlab Fuzzy Toolbox and Simulink to develop a calibrated fuzzy regulator model in real-time windows target mode as shown in Fig.5. It was expected that a more stable rotary speed could be achieved under system variations.

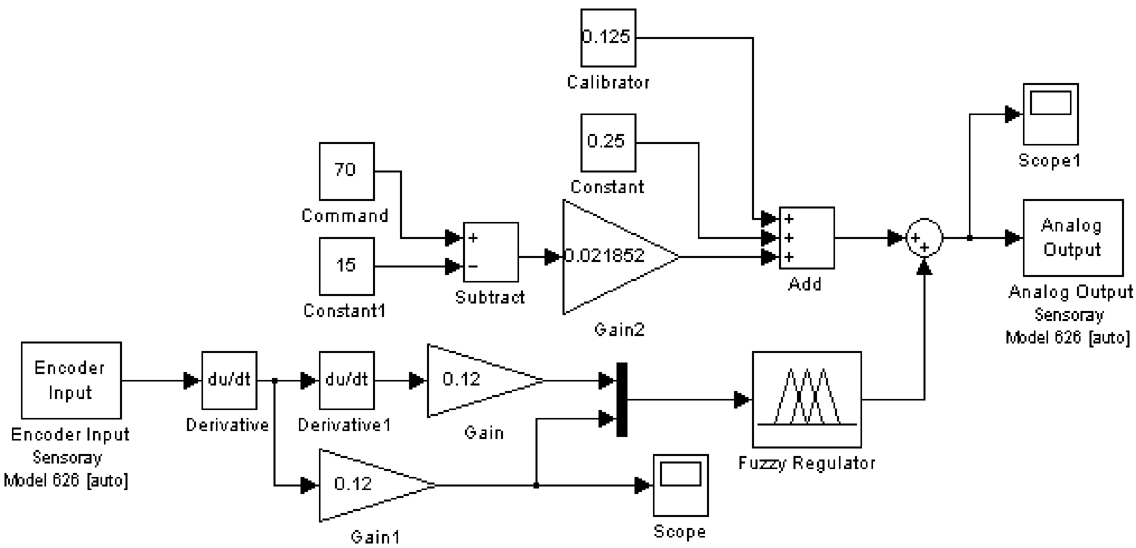


Fig.5 Simulink model of the calibrated fuzzy regulator

The software configurations of the calibrated fuzzy regulator were presented in the following sections.

2.4. Fuzzy Core

The rotary speed and its derivative were defined as the fuzzy input variables. We set their membership functions as shown in Fig.6. and Fig.7, respectively.

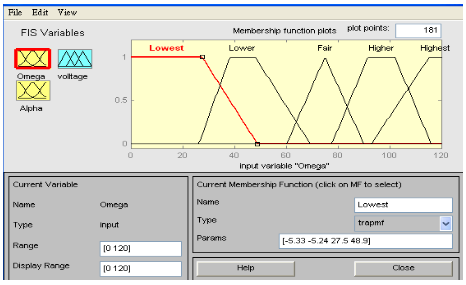


Fig.6 The membership function of ω

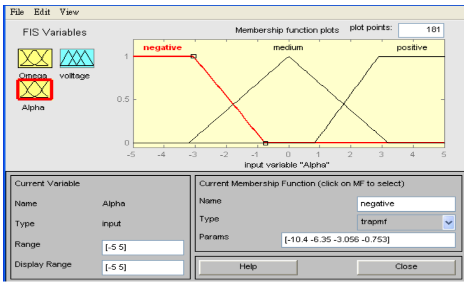


Fig.7. The membership function of $d\omega/dt$

The membership function of the driving voltage modifier was defined as Fig. 8.

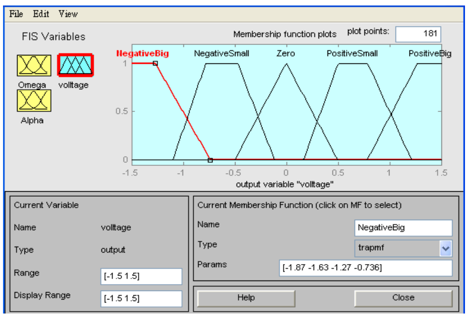


Fig.8 The membership function of the output voltage modifier

The fuzzy rule base used “AND” as the input variable connective to formulate the “IF-THEN” inference rules. The rule base was shown in Table1.

TABLE 1
Fuzzy rule base

	Inputs		Output
	Omega	Alpha	Voltage
1	Lowest	Negative	PositiveBig
2	Lowest	Medium	PositiveSmall
3	Lowest	Positive	PositiveSmall
4	Lower	Negative	PositiveSmall
5	Lower	Medium	PositiveSmall
6	Lower	Positive	NegativeSmall
7	Fair	Negative	Zero
8	Fair	Medium	Zero
9	Fair	Positive	Zero
10	Higher	Negative	PositiveSmall
11	Higher	Medium	NegativeSmall
12	Higher	Positive	NegativeSmall
13	Highest	Negative	NegativeSmall
14	Highest	Medium	NegativeSmall
15	Highest	Positive	NegativeBig

The USM encoder signal acted as the omega input variable. Executing the fuzzy inference and the centroid defuzzification, the fuzzy regulator generated a driving voltage modifier which adjusted the output driving voltage to the USM controller in order to preserve a stable rotary speed.

2.5. Simulink Model

The fuzzy Simulink model was constructed in Matlab environment as shown in Fig.5. The rotary speed setting was transformed first to the driving voltage, according to the calibrated linear relation (Equ.2). This transformed voltage was combined with the modifier from the fuzzy regulator to obtain the integrated driving voltage. This executing driving signal was transferred to the USM driver controller through the analog output port of Sensoray 626.

The calibrated fuzzy regulator played in real-time mode, receiving rotary speed feedback from the USM encoder. The encoder signal and its derivative were fed into the fuzzy regulator as input signals. The fuzzy inference engine determined the modifier based on the fuzzy rules.

3. EXPERIMENTAL RESULTS

We first present the results of the control system with a constant driving voltage and then show the results of the system with a fuzzy regulator in order to compare the difference between these two control schemes.

3.1. The Results of Original Constant Driving Voltage

.The model of the control system with a constant driving voltage is shown in Fig.6.

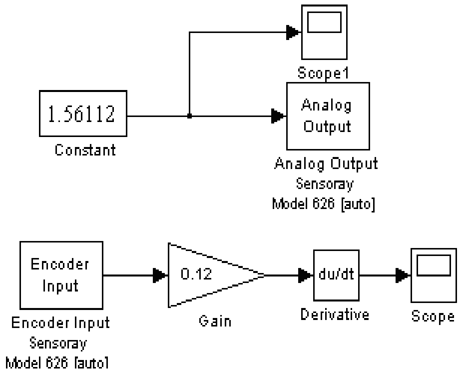


Fig.6. Model with a constant output voltage

According to Equ.1, the rotary speed setting of 75 rpm is transformed to the constant driving voltage of 1.56112 volts. The rotary encoder of USM delivers the pulse signal which is transformed to the rotary speed in rpm. The response is shown in Fig.7. However, we find that the linear relation (Equ.1) defined from the USM manual may not be precisely linear. Practically, the driving voltage of 1.56112 volts corresponds to the rotary speed of 70 rpm. Fig. 7 shows the rotary speed downgrades from 70 rpm at t = 0 second to 65.2 rpm at t = 100 seconds.

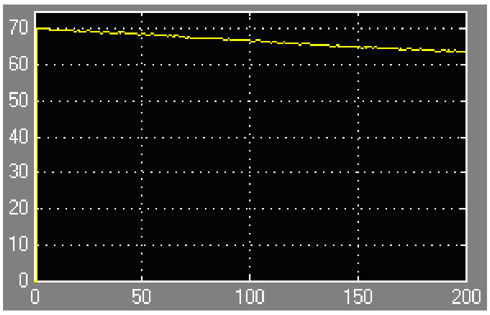


Fig.7. Rotary speed with constant controller voltage

The zoomed responses within the time ranges of [0,50] and [150,200] are shown in Fig. 8 and Fig.9, respectively. The constant control effort is shown in Fig.10.

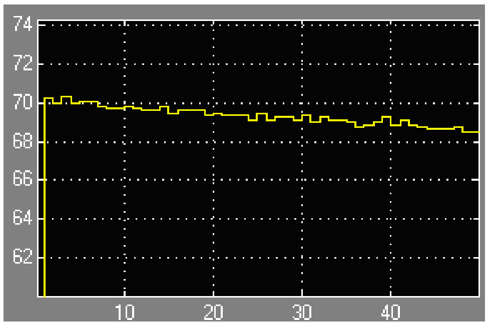


Fig.8 The response within [0,50]

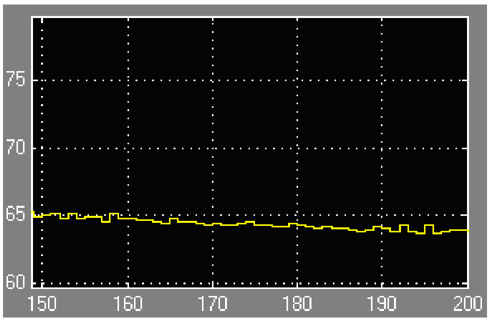


Fig.9 The response within [150,200]

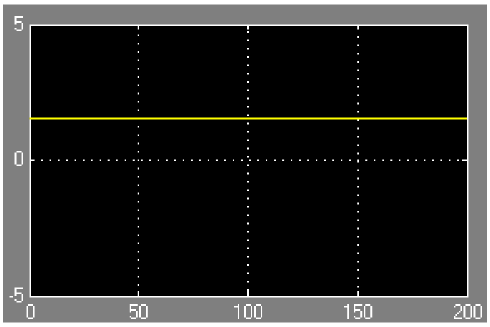


Fig.10 The output controller voltage

We can view the zoomed result within the time range [0,50] in Fig.8 which shows the rotary speed degrades from 70 rpm to 68.2 rpm and Fig.9 shows that it degrades from 65 rpm to 63.8 rpm within the time range [150,200]. Moreover, It proves the fact that the rotary speed degrades as the operating temperature rises under constant control effort.

3.2. The Results of the Fuzzy Regulator

The configuration of the fuzzy control system is shown in Fig.2. The membership functions and fuzzy rules are defined in Section 2.3. The response under fuzzy environment is shown in Fig.11. The regulated response within the time ranges of [0,50] and [150,200] are shown in Fig. 12 and Fig.13, respectively. The regulated fuzzy control effort is shown in Fig.14.

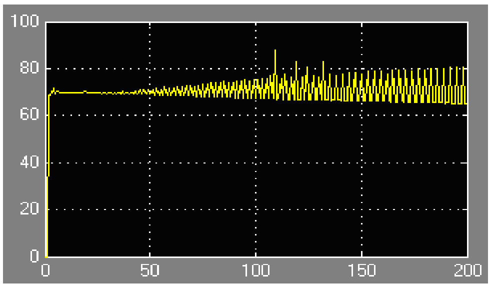


Fig.11 The response with a fuzzy regulator

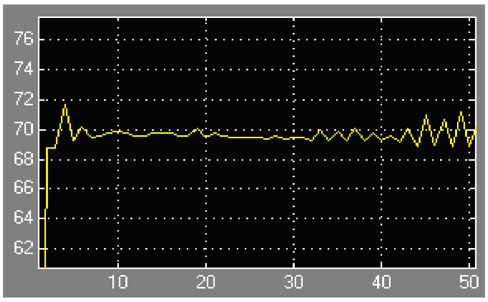


Fig.12 The regulated response within [0,50]

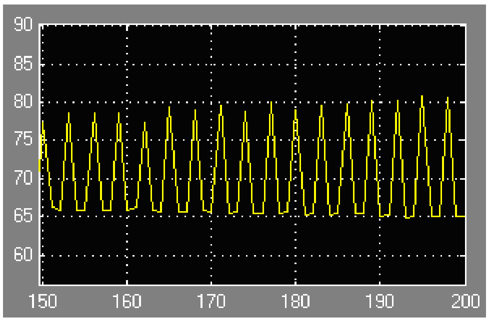


Fig.13 The regulated response within [150,200]

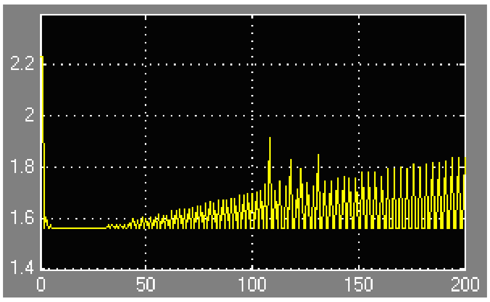


Fig.14 The regulated driving controller voltage

3.3. The Comparison of Constant Response and Regulated Response

From the response figures above, it is obvious that the linear relation (Equ.1) may not be precisely linear. This equation is generated from the DC voltage-rotational speed characteristics in the USM manual. The setting voltage of 1.56112 volts corresponds to a rotary speed of 70 rpm, not 75 rpm. Hence, there exist speed deviations in both cases of constant driving voltage and fuzzy regulator. A more accurate mathematical relation would be necessary for controlling the rotary speed.

On the other hand, we can treat the constant of 0.25 in Equ.1 as an offset voltage to compensate the output speed level. From this concept, if the rotary speed was at a lower level, we can adjust the offset voltage from 0.25 to 0.4, and contrarily we can change it from 0.25 to 0.2 for a higher level case, etc..

The constant driving voltage causes the rotary speed to degrade as the operating temperature rises. This tendency is irreversible since the temperature gets higher and higher during the USM operation and the speed deviation expands worse and worse. However, in the fuzzy case, the regulator puts the speed deviation under control. During the initial time interval as in Fig.12, the rotary speed stays quite stable. Although it becomes more and more fluctuant as the operating temperature rises, the fuzzy regulator engages effectively in maintaining a stable rotary speed. Even though it goes up and down, we find the tendency of keeping the centered speed around a stable value. Investigating the regulated control effort, we think it is reasonable that for a higher operating temperature, the regulator needs more control action to balance the deviation. Furthermore, with a divergent-like aspect in performance, we can say that the speed system is still stably controlled.

4. Conclusions

The ultrasonic motor reveals its highly nonlinear characteristics and behaves sensitively with the environmental conditions such as the operating temperature. According to the manufacturer’s manual, there exists a linear mathematical relation between the supplied driving voltage and the rotary speed of the ultrasonic motor. However, the rotary speed seems to degrade gradually in the practical applications when the operating temperature gets higher because of friction. In this research, we develop a fuzzy regulator to preserve a stable rotary speed no matter how the environmental conditions may alter.

The rough resolution (500P/R) of the embedded rotary encoder on the Shinsei USM causes the serious fluctuant performance. It is expected that a high-resolution rotary encoder will provide effectively pulse signals to reduce the fluctuation in the regulated response and achieve a more stable control.

By adjusting the membership functions of the fuzzy variables and constructing an efficient rule base, we can promote the effectiveness of the fuzzy regulator system. Hence, there possibly exists an alternative fuzzy regulator configuration which possesses a better control performance.

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