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Mechatronics Application Using Characteristics Polynomial Control Approach With Case Study: Development of A Simulated Air Speed Indicator for Helicopter Simulator

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Abstract

A helicopter simulator has to be built to fully resemble the real cockpit environment including its instrument indicating air speed. This paper is aimed to apply mechatronics technology in development of a Simulated Air Speed Indicator (SASI) that can be used for a helicopter simulator. This indicator has a pointer which indicates a certain value at the dial depending on the simulated air speed signal sent by the host computer. The driving mechanism of this mechatronics system is composed mainly of dc motor, reduction gear, pointer and potentiometer. An analog positioning controller has been developed based on characteristics polynomial control approach. The performance of the developed instrument was validated through step response and precision repetitive experiments. From the experimental results, it is obtained that the controller with proportional gain of K_p =30 gives steady state error of 0.14% and repetition error of 0.3 (knots).

Keywords: mechatronics, Simulated Air Speed Indicator, helicopter simulator, positioning control, dc motor, characteristics polynomial.

Introduction

Mechatronics is a Japanese English expression associated with a technological field which combines mechanical engineering and electronic-electrical engineering. In the process of pursuing technology that makes a machine can move in higher speed and higher precision with more functional flexibility Japanese industries found their solution in what they called mechatronics in early 1970s. Nowadays, mechatronics becomes a key technology to win the world wide severe industrial competition since this technology provides advantages in: production cost reduction, high quality product, and energy saving.

Servo system can be thought as the heart of mechatronics. According to the Japan Industrial Standard (JIS) servo system is defined as "a control system that makes position, orientation or posture follow the desired reference value" [1]. Figure 1 shows a block diagram of a servo system incorporating: a plant to be controlled P, sensor to monitor necessary variables S, electronic controller C, power amplifier A and actuator Ac.

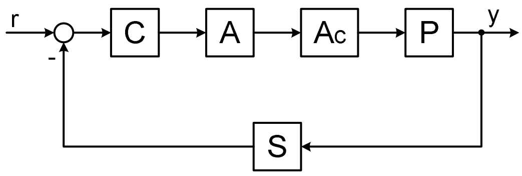


Figure 1: Block diagram of a servo system.

This paper is aimed to apply mechatronics technology in development of a Simulated Air Speed Indicator (SASI). The Simulated Air Speed Indicator is used for helicopter simulators. Because such a simulator is used for training pilots, the simulator has to be built to fully resemble the real cockpit environment including its instruments indicating air speed, vertical speed, altitude, and other flight variables. The Simulated Air Speed Indicator has a pointer which rotates above the dial indicating air speed of 0 to 220 knots [2]. The air speed information is sent from the host computer where the dynamical model of the helicopter is calculated. The pointer shall point position as precisely as the air speed information. In this sense, the Simulated Air Speed Indicator should be designed having high precision positioning and fast response positioning specifications.

Development of SASI

The Simulated Air Speed Indicator (SASI) is functionally intended to indicate the simulation of the helicopter air speed, in standard temperature and pressure condition. It operates in the range from 0 to 220 knots with one pointer which gives air speed indication in one rotation. Physically, the case of the SASI shall be the same as the original standard helicopter part. The case shall be 20 cm maximum in length. The front face of the case shall be the same as the standard helicopter part. Rear face of the SASI comprises an electrical connector, ensuring the electrical connection of the unit with the external interface to enable air speed indications. Electrically, the SASI shall be operated on 28 VDC power with nominal range of 24 VDC to 32 VDC and maximum 3 A load. Two power input lines with a common ground are required i.e. Primary 28 VDC and Secondary 28 VDC. In the event no power on the primary power line, the SASI shall automatically switch to the secondary power line. It shall be operated on 28 VDC lighting power with nominal range of 24 VDC to 32 VDC and maximum 1 A load.

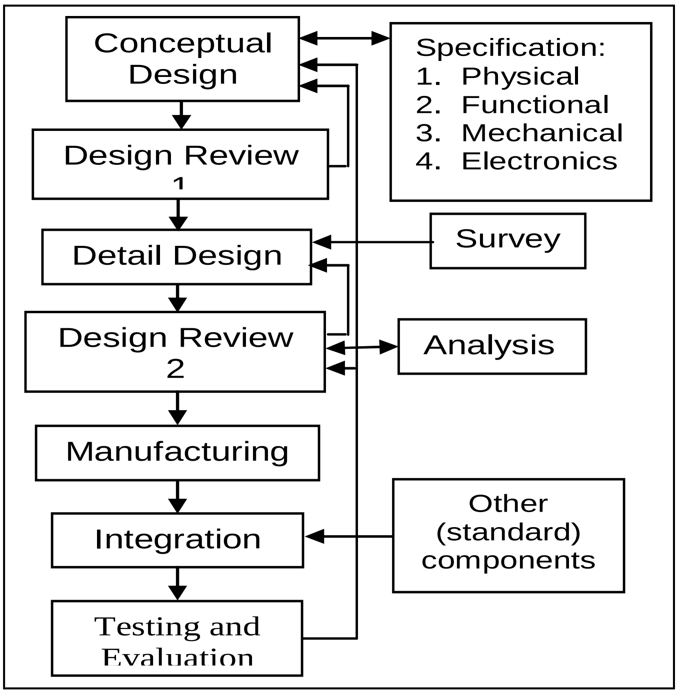


Figure 2. Development procedure.

According to experience, the development procedure shown in figure 2 is used to develop SASI. It starts with conceptual design where ideas are explored to meet designated specifications. Computer Aided Design (CAD) is mainly used at this step. In Design Review (DR) 1 the ideas are compared and evaluated to select the most appropriate conceptual design. Relevant veiw points in this step are: specification fulfillment, parts manufacturability, and availability of standard components. In detail design step the selected conceptual design is broken down into detail technical drawings to obtain mechanical drawing used for manufacturing mechanical parts and electronics drawing used for making printed circuit board (PCB). In design review 2 the detail technical drawings are thoroughly and deeply checked to ensure that all parts can be manufactured properly and that all parts are compatible to each other to build the overall system in purpose. After passing design review 2, all parts are ready to be manufactured. In manufacturing step Computer Aided Manufacturing (CAM) is used for manufacturing high precision mechanical parts and PCB. In integration step, all parts are integrated together to build the overall system. Testing is then carried out to evaluate whether it satifsfies the specification or not. When the system satisfies the specification the procedure finishes. Otherwise, the procedure is repeated from the beginning.

In order to satisfy the above mentioned specification (functional, physical, electrical), a conceptual design of driving mechanism has been drawn as shown in figure 3. This design locates in the center one solid shaft where the pointer is attached.

The pointer shaft is rotated by a dc motor through a reduction gear, while the position of the shaft is monitored by a potentiometer to construct a servo mechanism. The body of the designed SASI is constructed by plats and spacers. The plats hold actuators, sensors, and rotating parts, while the spacers link the plats to each other. Figure 4 shows the exploded drawing of the indicator mechanism and the body. This design has 4 plats i.e. head plat, bushing plat, gear plat, and motor plat. Below the motor plat, there is a compartement for electronics circuit.

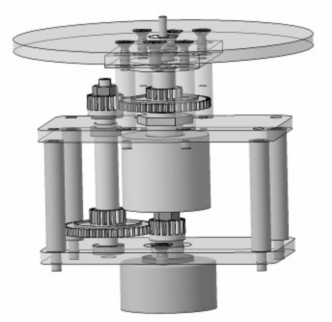


Figure 3: Conceptual design of SASI driving mechanism.

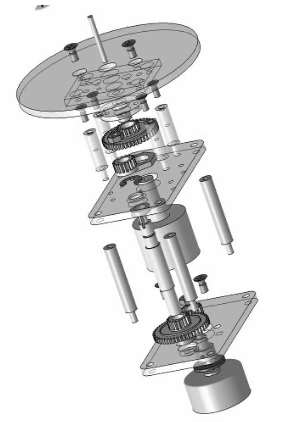


Figure 4: Exploded drawing of SASI.

The head is mainly constructed by a bezel, a rubber ring seal, glass, dials, and a gasket. The driving mechanism is attached to the head by screwing the head plat to the gasket. The pointer and the dial are set above the gasket. These parts are then covered by the glass which is sandwitched between the gasket and the bezel. The rubber ring seal is set between the glass and the bezel to fixed the glass firmly and safely. Figure 5 shows the front view of the original air speed indicator (ASI). In the original ASI, the speed of an air craft relative to air is obtained by differential measurement of static pressure and total pressure. The pressure differential is a function of speed. It is measured with the help of an aneroid capsule, amplified and mechanically transmitted to the pointer. The dial shows 220 knots per 360 ˚ divided by strips. The scale between two strips at the dial varies with angular position. It means that the value of the air speed in knots is a non-linear function of rotational position of the pointer. It is also equipped with 3 seven segment LEDs to digitally display the monitored air speed.

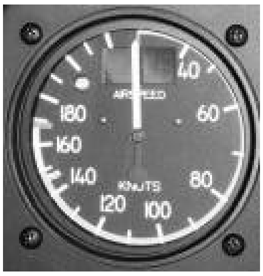


Figure 5. Front view of the original ASI.

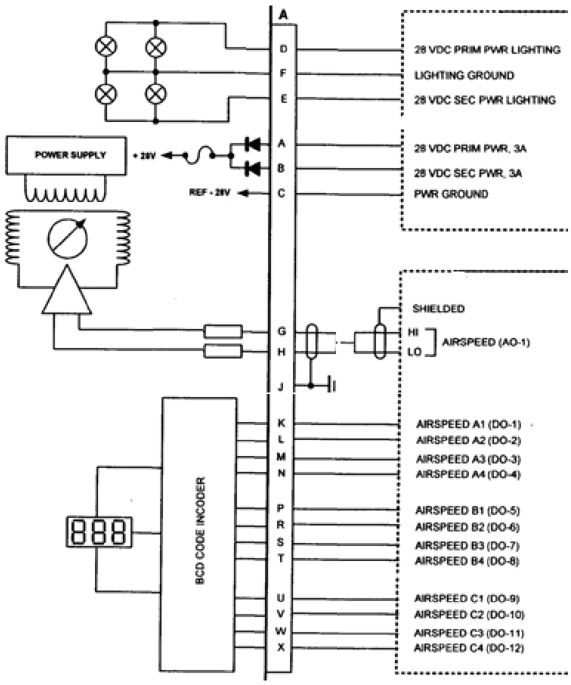


Figure 6. Wiring diagram of SASI.

Figure 6 shows the wiring diagram of the designed SASI. Pin A, B and C are used for Primer, Secunder and Ground of power supply 28VDC. Pin D, E, and F are connected to Primer, Secunder and Ground of lighting power supply 28 VDC. Pin G and H are used for air speed analog signal, while pin J is alocated for shielded these signals to protect from noise effect. Three seven segment LEDs are used to digitally display the air speed. These LEDs are controlled by the host computer through pin (K,L,M,N), (P,R,S,T), and (U,V,W,X).

A dc motor is basically constructed by a rotor, a stator and carbon brush. Pairs of permanent magnet are attached to the inner side of the stator and conductor wire is wound to the rotor shaft. The winding is supplied with dc current by external electrical power source through the carbon brush. The voltage equation of a dc motor is given as follows.

$$L_m \frac{di}{dt} + R_m i = u - K_e \omega_m \tag{1}$$

where: u , i , and ω_m denote voltage applied to the winding terminal, current flowing in the winding, and rotational velocity of the rotor respectively. R_m is winding resistance, L_m is winding inductance, and K_e is back electro motive force coefficient.

The motion equation of the pointer driving mechanism is given by:

$$J\ddot{\theta} + D\omega = G_r K_t i - \tau_f \tag{2}$$

where: ω , $\ddot{\theta}$ and τ_f express the angular velocity, angular acceleration and friction torsion respectively. J is the total moment inertia, D is the damping coefficient, K_t is the torque coefficient, and G_r is the gear rasio. Note that $\theta_m = G_r\theta$.

In this paper a positioning controller has been developed to make the pointer indicate precisely the simulated air speed. It is designed using characteristic polinomial control approach. According to this control approach the transfer function from the reference signal to the controlled variabel is designed so that its characteristic polinomial parameters' value be the same (nearly equal to) as the desired reference model ones'. The desired reference model has the following form.

$$M(s) = \frac{a_0}{a_0 + a_1 s + a_2 s^2 + a_3 s^3 + \cdots + a_n s^n} = \frac{a_0}{\sum_{n=0}^{n} a_i s^i} \tag{3}$$

where $\sum_{i=0}^{n} a_i s^i$ is the characteristics polynomial.

Taking into account equations (1), (2) and (3), the positioning control system shown in figure 7 is developed. Parts inside the block represent the mechanical system and the dc motor. It is the plant to be controlled. Parts ouside the block constitute controller. The variable s is Laplace variable. Parameters K_i and τ_i constructs a feedback current controller. The feedback current controller reads current signal i, compares it with the current reference signal V_i , and then delivers the calculated controller ouput signal to power amplifier A. According to this control system, the transfer function from current reference signal V_i to the current i is given by:

$$P_i = \frac{i}{v_i} = \frac{\left(\frac{AK_i}{R_m}\right)}{\tau_i s + 1 + \left(\frac{AK_i}{R_m}\right)} \tag{4}$$

Since R_m is small enough compared to AK_i then the above transfer function can be represented using time constant of the current control system T_1 as follows

$$P_i == \frac{1}{T_1 s + 1} \tag{5}$$

where $T_1 = \frac{\tau_i R_m}{AK_i}$.

Parameter K_v constructs a rotational velocity feedback controller. It reads rotational velocity signal ω, compares it with rotational velocity referece signal ω_r, and then delivers the calculated velocity controller output signal to the current control system. The transfer function from rotational velocity reference signal ω_r to the rotational velocity ω is obtained as follows.

$$P_\omega = \frac{\omega}{\omega_r} = \frac{K_v}{JT_1 s^2 + Js + K_v} \tag{6}$$

Parameter K_p constructs a rotational position feedback controller. It reads rotational position signal θ, compares it with rotational position referece signal θ_r, then delivers the calculated position controller output signal to the velocity control system. The transfer function from the rotational position reference signal to the rotational position is given by:

$$P_p = \frac{\theta}{\theta_r} = \frac{K_p K_v}{JT_1 s^3 + Js^2 + K_v s + K_p K_v} \tag{7}$$

In the above sense, the positioning control system in figure 7 is merely a cascade control system.

It is obvious that each transfer function in equations (5), (6) and (7) has the form of the reference model. Determination of the controllers' parameter value in equation (5), (6) and (7) can be conducted using appropriate types of model reference, i.e.: Butterworth [3], Bessel [3], ITAE (Integrated Time Absolute Error) [4], or α parameter method [5].

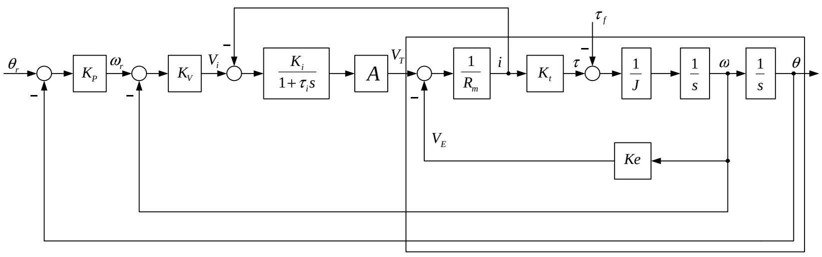


Figure 7: Positioning control system based on characteristic polynomial control approach.

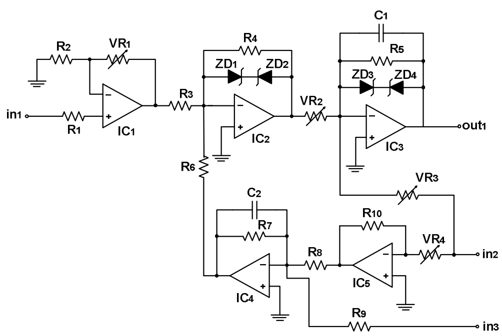


Figure 8. Analog positioning controller.

In this paper, the controller in figure 7 is realized using analog controller shown in figure 8. Operational amplifier 1 (IC 1) represents proportional gain K_p , IC 2 represents proportional gain K_v , and IC 3 represents the current controller. Input signals in 1, in 2 and in 3 denote error signal between rotational reference position and measured rotational position, electrical current flowing in the dc motor rotor winding, and terminal voltage of the dc motor, respectively. The ouput signal out 1 constitutes control input signal delivered to the power amplifier A. The terminal voltage is used to estimate rotational speed according to equation (1) while IC 4 and IC 5 are used to realize the rotational speed estimator. Zener diodas ZD1 and ZD2 set the upper limit and the lower limit of the velocity controller output signal, respectively. Simillary, zener diodas ZD3 and ZD4 set the upper limit and the lower limit of the current controller output signal, respectively. Relationship between input signal and output signal of each operational amplifier circuit can be derived using operational amplifier circuit theory [6]. IC 1 acts as a non-inverting amplifier which gives the relation between input signal v_i and output signal v_o as follows

$$v_o = \left(\frac{VR_1}{R_2} + 1 \right) v_i \tag{8}$$

IC 2 acts as a summing amplifier with the realtionship between input and output signals given by the following equation.

$$v_o = R_4 \left(\frac{v_{i1}}{R_3} + \frac{v_{i2}}{R_6} \right) \tag{9}$$

where v_{i1} is output signal from IC 1 and v_{i2} is output signal from IC 4.

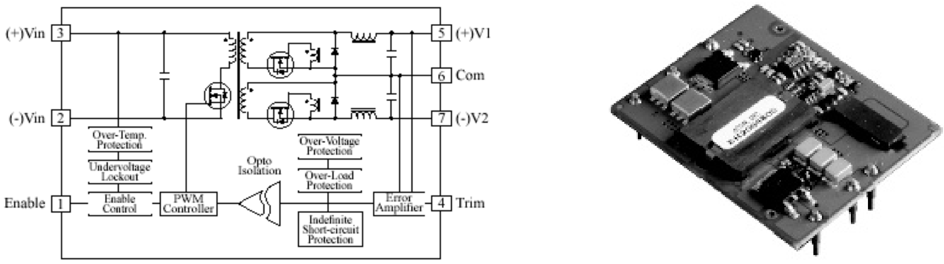
IC 3 acts as a phase lag compensator having input-output relationship as follows.

$$v_o = R_5 \left(\frac{v_{i1}}{VR_2} + \frac{v_{i2}}{VR_3} \right) \left(\frac{1}{1 + sR_5C_1} \right) \tag{10}$$

Note that the gain of this phase lag compensator is determined by R_5, VR_2, and VR_3 while the time constant is defined by R_5 and C_1. IC 4 performs the similar action as IC 3, while IC 5 performs inverting amplification having input-output relationship as follows.

$$v_o = -\left(\frac{R_{10}}{VR_4} \right) v_i \tag{11}$$

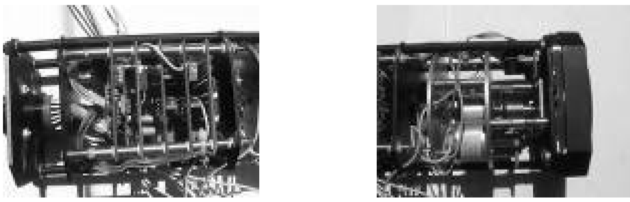
The SASI is equipped with a digital display using 3 seven segments Light Emitting Diodas (LEDs). Integrated ciruit HC4511 is used to drive common catode 7 segments LED. The operational amplifiers used in the controller circuit require bipolar power supply (+15, Gnd, -15 VDC). Because of the space restriction a small dimension dc-dc converter module is used. Figure 9 shows the dc-dc converter with the following specification [7]: input voltage 18 to 36 VDC, reverse input voltage protection (internal shunt diode), +15 VDC output voltage (ripple & noise 120mV$_{p\text{-}p}$, current +0.2 A to +2 A), -15 VDC output (ripple & noise 120mV$_{p\text{-}p}$, current -0.2 A to -2 A), total output power 50 Watts (maximum), overload protection 60 Watts, efficiency at full load 89%, isolation voltage input to output 1500 VDC, switching frequency 500 KHz, transient response 25% step load change less than 200 μsec. Its dimension is 52.8 mm x 37.6 mm x 13.45 mm.



(a) Circuit illustration of dc-dc converter (b) Photo of DC-DC converter

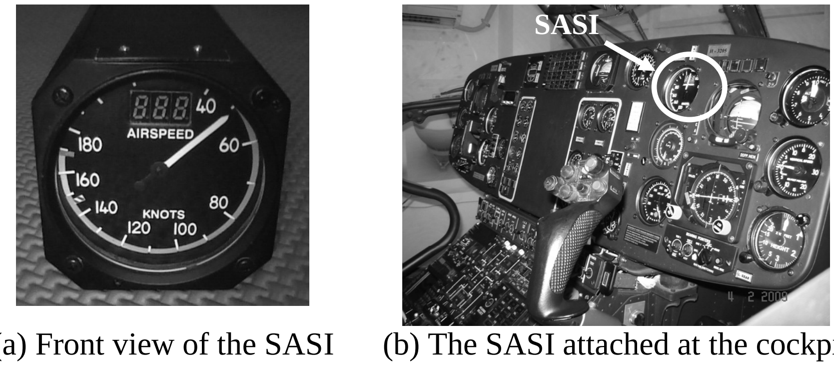
Figure 9: DC-DC conveter used in the SASI.

Figure 10 and figure 11 show physical appearance of the developed Simulated Air Speed Indicator (SASI). Photos in figure 10 demonstrate how ready on the self components can be used to construct a Simulated Air Speed Indicator which is a mechatronics system. The plats have been made of aluminum and the spacers of bronse. Polymer gears are used because of 3 reasons: load torque is small, no need for lubrication, and low aquistic noise. Photo in the left side of figure 11 exhibits physical outside view of the SASI where the pointer, dial with its scale and LEDs display can be seen covered by the glass in the bezel. By comparing the SASI in figure 11 and the original ASI in figure 5, concerning the front side appearance, it is clear that the SASI resembles well the original ASI. Photo in the right side of figure 11 shows the developed SASI attached at the cockpit of a helicopter simulator.



DC motor controller Driving mechanism

Figure 10: Inside view of the SASI.



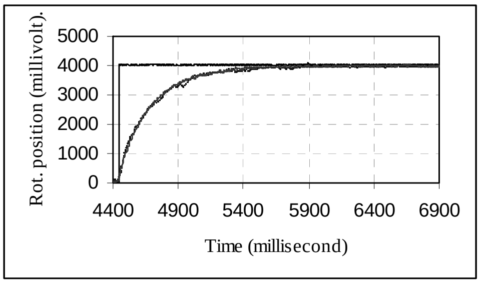
(a) Front view of the SASI (b) The SASI attached at the cockpit

Figure 11: Ouside view of the SASI

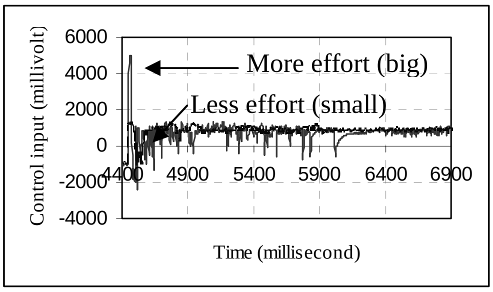
Experimental Results

The performance of the developed instrument was validated through step response experiment and precision repetition experiment. The step response experiment was conducted to evaluate time response performance of the instrument. It was carried out by applying a step like signal simulating air speed and recording the pointer rotational position which is measured by the potentiometer. Figure 12 shows step response experimental results using two controllers with different values of the proportional gains K_p. One controller has small gain value (K_p=10) and the other controller has big gain value (K_p=30).

The simulated air speed signal is 4000 millivolt, and the experimental data was recorded from time 4400 milisecond through 6900 millisecond with interval time 5 millisecond. Figure 12 (a) shows the rotational position of the pointer while figure 12 (b) shows the control input produced by the controller to move the pointer. The black line is the result using the small gain controller and the dark gray line is the result using the big gain controller. Both controllers qualitatively give the similar rotational position time responses. However, at the starting time the big gain controller uses more effort than the small gain controller.



(a) Rotational position of the pointer



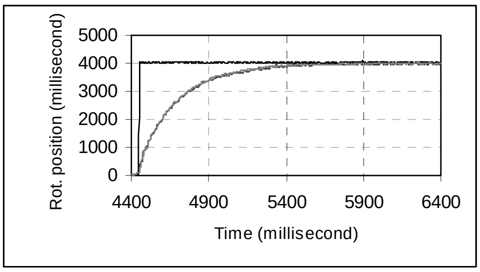
(b) Control input

Figure 12: Step response experimental results.

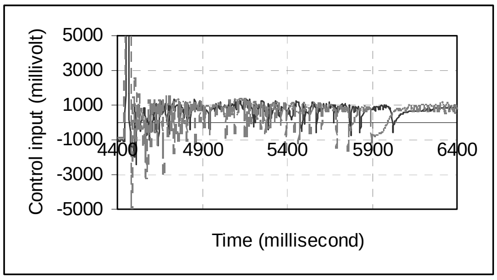
Some experiments were also conducted to evaluate controllers having gain value bigger than 30. Such controllers in this paper named very high gain controllers. A representative result of a very high gain controller having gain value K_p=50 is plotted in figure 13. For comparison purpose in figure 13 is also plotted the experiment results of the big gain controller with K_p=30. In order to more expose important parts of the experimental results, the time is limitted form 4400 millisecond to 6400 millisecond. The dark gray line is the result using the big gain controller while the light gray broken line is the result using the very high gain controller.

From figure 13 (a) qualitatively the step responses of the pointer rotational position are similar for both the big gain controller and the very high gain controller. However, from visual observation during experiment it was realized that when the very high gain controller was used the driving mechanism including the reduction gear moved roughly and vibrated all the time even when the pointer rotational position had already settled at the desired position. From figure 13 (b) it is clear that the control input of the very high gain controller moves up and down with larger variation than the big gain controller during transient periode as well as during steady state periode. In order to further clearly expose this difference, in figure 13 (c) the control inputs are plotted during time 5400 millisecond to 6400 millisecond during which is considered that the response has already reached steady state condition.

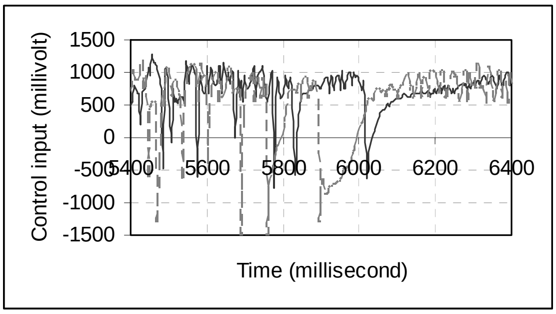
From other experiments conducted in this research, it was obtained that controllers having gain value larger than the one of the big gain controller did not provide substantial better step response performance, but even make the mechanical system including reduction gear be suffered by mechanical load because the system becomes very sensitive against high frequency noise. This justifies that controllers having gain larger than 30 are rejected. Only controllers having gain value 30 or less are considered for further evaluation.



(a) Rotational position of the pointer.



(b) Control input.



(c) The closed up control input.

Figure 13: Step response experimental results using the very high gain controller.

Figure 14 shows the closed up of the pointer rotational position signals during time 5900 millisecond to 6900 millisecond when the pointer position reaches steady state condition using the big gain controller and the small gain controller. The light gray broken line is the simulated air speed (reference) signal, the gray dotted line is the result using the small gain controller and the black solid line is the result using the big gain controller. The steady state error of 1.33% is obtained by the small gain controller and 0.14% by the big gain controller.

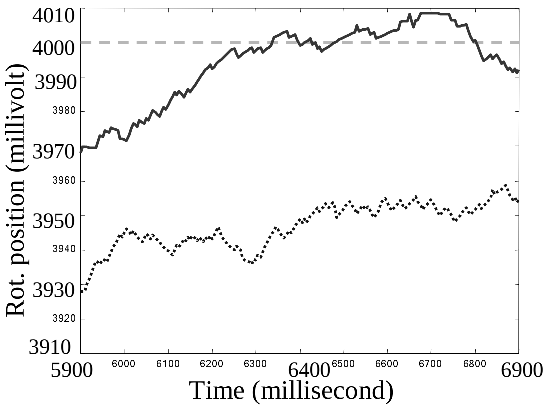


Figure 14: Steady state error.

Tabel 1: Precision repetition experimental result (6 times repeated).

Dial Memory (knots)	**Reference signal (volt) under different temperature**					
	25˚C	**25˚C**	**25˚C**	**55˚C**	**55˚C**	**55˚C**
0	0.504	0.517	0.514	0.511	0.516	0.506
40	1.363	1.316	1.353	1.358	1.362	1.354
50	1.916	1.92	1.939	1.928	1.907	1.926
60	2.648	2.599	2.653	2.646	2.633	2.656
70	3.376	3.384	3.372	3.447	3.413	3.417
80	4.10	4.15	4.15	4.17	4.16	4.14
90	4.77	4.77	4.78	4.80	4.81	4.80
100	5.30	5.34	5.34	5.35	5.33	5.33
110	5.81	5.83	5.82	5.82	5.83	5.81
120	6.28	6.33	6.33	6.30	6.31	6.30
130	6.73	6.77	6.78	6.74	6.77	6.74
140	7.14	7.16	7.18	7.16	7.16	7.14
150	7.54	7.54	7.57	7.55	7.56	7.53
160	7.89	7.93	7.94	7.89	7.92	7.90
170	8.28	8.28	8.32	8.26	8.27	8.29
180	8.62	8.66	8.60	8.60	8.62	8.61
190	8.94	8.98	8.96	8.79	8.95	8.94
200	9.30	9.31	9.30	9.30	9.27	9.25
210	9.59	9.62	9.61	9.58	9.58	9.59
220	9.92	9.91	9.89	9.86	9.93	9.90

From the step response experimental results, the big gain controller was selected to be used to conduct precision repetition experiment. This experiment is done to observe how good the instrument repeats consistently the desired position. It was conducted by applying simulated air speed (reference) signal 6 times under temperature variation (25˚C and 55˚ C), and recording rotational position of the pointer after settling steady state condition each time. Reference signal was then varied to obtain experimental results thoroughly from dial memory 0 to dial memory 220 knots. Table 1 lists this experimental result.

Figure 15 plots the result listed in table 1. It can be seen that for each reference signal the pointer position repeats precisely the (almost) same value. From this set of data, in the interval air speed from 40 knots to 160 knots, the following estimation function ca be derived.

$$\left.\begin{aligned} m &= -3.3089 + 48.0803r - 15.6132r^2 + 3.1259r^3 - 0.2788r^4 - 0.0098r^5 \\ m &= f(r) \end{aligned}\right\} \quad (8)$$

where m and r denote dial memory (knots) and reference signal (volt), respectively. The bold line plots this function. It demonstrates that this function expresses the relationship very well.

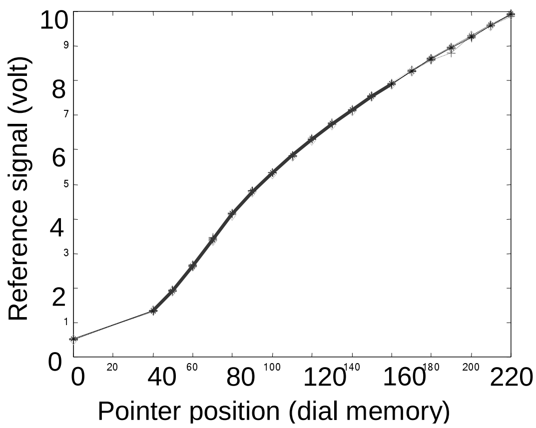


Figure 15: Repetition experiment result

From calculation of average absolute error, repetition error of 0.3 knots is obtained. This implies that given a certain value of reference signal r (volt) then the pointer will indicate dial memory according to the following formulae:

$$m = f(r) \pm 0.3 \text{ (knots)} \quad (9)$$

For example, reference signal $r = 4$ volt will rotate the pointer to indicate dial memory $m = 77.95 \pm 0.3$ (knots).

Conclusion

From the experimental results the following conclusion can be drawn:

(1) The developed Simulated Air Speed Indicator (SASI) functionally works well in indicating air speed signal using both pointer and 3 seven segment LEDs.

(2) The developed SASI performs good step response with quite low steady state error, i.e.: 0.14%.
(3) The developed SASI gives very good repetition performance with repetition error of 0.3 (knots).
(4) The developed SASI has physically the same front view appearance with the original air speed indicator (ASI).

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