International Journal of Computer Techniques – IJCT Volume 12 Issue 5, October 2025
Open Access and Peer Review Journal ISSN 2394-2231 https://ijctjournal.org/

RESEARCH ARTICLE OPEN ACCESS

Autonomous Human Body Control, Part XV: Intradialytic Hypotension Control during Hemodialysis using First-order and D-P Compensators Compared with a PD Controller

Galal Ali Hassaan
Department of Mechanical Design and Production, Faculty of Engineering, Cairo University, Egypt
Email: galalhassaan@ymail.com

--************************----------------------------------

Abstract:

This paper is the fifteenth in a series of research papers presenting the control of an autonomous human body. It handles the control of the intradialytic diastolic blood pressure in human hemodialysis operations using a first order and a D-P compensators from the second generation of control compensators. Some tuning techniques for the proposed controller/compensators are proposed based on zero/pole cancellation and fulfilling some time-based characteristics for the closed-loop control system. The step time response of the control system using the investigated controller/compensators is presented and compared with that of a conventional PD controller from the first generation of PID controllers tuned by the author. The comparison reveals the best controller/compensator among the three ones presented depending on a graphical and quantitative comparison study for reference input tracking.

Keywords — Autonomous human body control, hypotension control, first order compensator, D-P compensator, PD controller, controller/compensators tuning.
.

--************************----------------------------------

I. INTRODUCTION

Low blood pressure (*hypotension)* is associated with some patients undergoing hemodialysis. Intradialytic '*Hypotension*' makes patients suffer from some symptoms including: muscle cramps, back, chest or abdominal pain, headache, nausea, vomiting, yawing, sighing, fainting and anxiety [1]. These symptoms are common and clarify the need to accurate and efficient control strategy to achieve blood purification without '*hypotension*'. '*Hypotension*' is regulated during hemodialysis in an open-loop control manner dialysate scheduling [2], [3], [6], [12]. We start by presenting a literature review about some '*intradialytic hypotension*' aspects since 2001:

Dheenan and Henrich (2001) outlined that intradialytic hypotension is a common adverse event of hemodialysis. They investigated the application of five different protocols in 10 hemodialysis patients with prior history of intradialytic hypotension based on using dialysate sodium. They compared high sodium and cool temperature protocols with standard protocol of 138 mEq/L dialysate sodium. They recommended the use of high sodium dialysate and cool temperature protocols as they were effective [2]. Kariazis et al. (2002) outlined that low dialysate calcium concentration was used to treat induced '*hypercalcemia*' during hemodialysis and intradialytic hypotension was resulted in some patients. They described a dialysate protocol based on the use of low dialysate calcium of 1.25 mmol/L, high dialysate calcium of 1.75 mmol/L and medium dialysate calcium of 1.5 mmol/L with a specific time profile during hemodialysis [3]. Manap, Papadimitrion et al. (2005) outlined that the most frequent cause of death in patients on regular dialysis treatment is cardiovascular. They investigated the impact of hypotension on lift ventricular mass index (LMDI) parameter. They concluded that the LDMI < 130 g/m^3 for male and < 100 g/m^3 for female were considered normal [4]. Gabutti et al. (2009) investigated the changes in systemic hemodynamics induced by bicarbonate and calcium concentrations. They concluded that both high bicarbonate and high calcium concentrations in the dialysate improved the hemodynamic pattern during dialysis [5].

Shahgholian, Ghafourifard and Shafiei (2011) outlined that one of the most prevalent side effects of hemodialysis is intradialytic hypotension and its symptoms and using sodium profiles, ultra filtration and cold dialysate are the ways to overcome this problem. They found that there was a significant difference in the mean blood pressure in three groups and in a combination group, drop of systolic and diastolic blood pressure was less than groups using each method alone [6]. Soliman et al. (2014) outlined that intradialytic hypotension remains to be a major complication of hemodialysis occurring in about 25 % of dialysis sessions. They concluded that patients with chronic kidney disease and regular hemodialysis who practiced moderate or severe intradialytic hypotension had higher prevalence of myocardial ischemia and stress induced myocardial dysfunction than those who had no or mild intradialytic hypotension [7].

Khan et al. (2016) reviewed published data on the role of hyper and/or hypotension in cardiovascular associated morbidity and mortality in patients on hemodialysis. They concluded that both intradialytic hypertension/hypotension episodes were major risk factors for cardiovascular mortality [8]. Aunon et al. (2018) outlined that 5 to 10 % of hemodialysis patients have chronic hypotension representing great comorbidity for them. They concluded that the identification of those patients could be of vital importance to implement therapeutic measures to improve the treatment result [9]. Pulido et al. (2021) outlined that patient's hypotension during hypodialysis represent a proven factor of possible mortality. They investigated the appearance of prediction of hypotension during a dialysis session using predictive model trained from large size dialysis database. The predictive model considered 22 clinical parameters, gender and age of the patients. They used machine learning classifiers to train the model providing prediction success above 80 % [10].

Davenport (2023) outlined that intradialytic hypotension remains the most common complication associated with dialysis sessions leading to episodes of transitory organ ischemia and repetitive episodes lead to permanent organ damage. He investigated the exercise during dialysis and its effect on intradialytic hypotension [11]. Arasneshad et al. (2024) studied the effect of the ascending/descending ultrafiltration along with linear sodium profiles on hemodialysis patients with hypotension. They concluded that this technique contributed to the stability of blood pressure levels among hemodialysis patients [12]. Fahmy, Abdel Moez and Mohammed (2025) conducted a study aiming to assess intradialytic hypotension in chronic kidney disease patients on chronic hemodialysis. They concluded that predictors of intradialytic hemodialysis were females [13].

II. THE CONTROLLED BLOOD PRESSURE AS A PROCESS

- Gabutti et al [5] investigated the use of bicarbonate and calcium dialysate concentrations to increase the hypotension during the intradialytic process of hemodialysis patients. They presented the dynamic change of systolic and diastolic blood pressure for a time span from 0.5 to 4 hours. I have considered only one of their diastolic profiles for calcium dialysate of 1.25 mmol/L concentration having pressure increase from 67 mmHg at 0.5 h to 73.42 mmHg at 4 hours. Then I normalized the blood pressure profile to work with changes from the starting value at 0.5 h for purpose of transfer function identification of the diastolic blood pressure variation. Considering the normalized time response of the blood pressure its changes start with zero at 0.5 h and ends with 6.42 mmHg at 4 h. From the experience of the author in system dynamics it was decided to consider this time response as a step time response of a first-order plus integrator process without time delay giving a process transfer function $G_p(s)$ as:

$$G_p(s) = K_p / [s(T_p s + 1)] \quad (1)$$

Where the K_p is the process gain and T_p is its time constant. Using the ITAE performance index [14] and the MATLAB optimization toolbox [15], the time data and normalized diastolic blood pressure (DBP) data, the parameters of the DBP process in Eq.1 are given by:

$$K_p = 0.40416 \;,\; T_p = 1.0204 \text{ h} \quad (2)$$

- The unit step time response of the DBP process defined by Eqs.1 and 2 is shown in Fig.1 as generated by the step command of MATLAB [16].

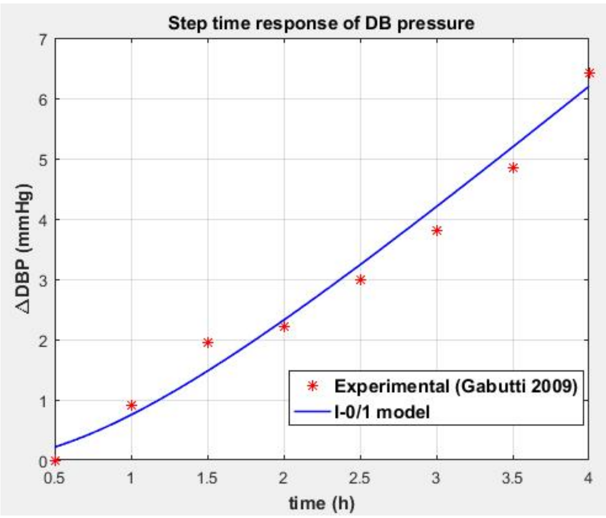


Fig.1 Step time response of the DBP change as a process.

The step time response of the DBP process as shown in Fig.1 is an unstable process which represents great challenge for control engineers to select controllers/compensators to stabilize the process and provide good performance.

CONTROLLING THE DBP PROCESS USING A PD CONTROLLER

- The conventional PD controller is one of the controllers of the first generation of PID controllers. It is still in use in some engineering applications such as second-order processes [17], systems with fuzzy differential equations [18] and industrial processes with delay time [19]. A PD controller has a transfer function, $G_{PD}(s)$ given by:

$$G_{PD}(s) = K_{pc1} + K_{d1}s = K_{pc1}[(K_{d1} / K_{pc1})s + 1] \quad (3)$$

- The PD controller has two gain parameters: proportional gain K_{pc1} and a derivative gain K_{d1} tuned as follows:
- The open-loop transfer function of a single-loop block diagram control system, $G_{PD}(s)G_p(s)$ comprises a simple zero $(K_{d1}/K_{pc1})s+1$ and a simple pole T_ps+1.
- Using the zero/pole cancellation technique [20], The time constant of the simple zero cancels the time constant of the simple pole giving:

$$K_{d1} = T_p K_{pc1} \quad (4)$$

- The closed-loop transfer function, $M_1(s)$ of the control system structure with a single control loop incorporating the PD controller defined by Eq.3 and the DBP process defined by Eq.1 is derived and given by:

$$M_1(s) = 1/(T_1 s + 1) \;;\; T_1 = 1/(K_p K_{pc1}) \quad (5)$$

- Eq.5 reveals the fact that the control system in this case is a standard first-order one characterised by its time constant T_1.
- The settling time of the control system step time response T_{s1} is related to T_1 through the relationship [21]:

$$T_{s1} = 4T_1 \quad (6)$$

- Let the desired settling time of the control system step time response is 0.5 h. Then, Eq.6 gives the time constant T_1 as: T_1 = 0.125 h.
- Now, with T_1 known, Eq.5 gives the proportional gain K_{pc1} as:

$$K_{pc1} = 19.7941 \quad (7)$$

- Now, Eq,4 gives the derivative gain Kd1 as:

$K_{d1} = 20.1989$ (8)

- With the PD controller tuned, Eq.5 is used to plot the step time response of the DBP control system using the controller gain parameters in Eq.4 and MATLAB step and plot commands [16] providing the step time response shown in Fig.2 for a desired DBP change of 10 mmHg (corresponding to 75 mmHg absolute value). The upper limit of 35 and 80 mmHg (absolute values) [1] is shown in the plot.

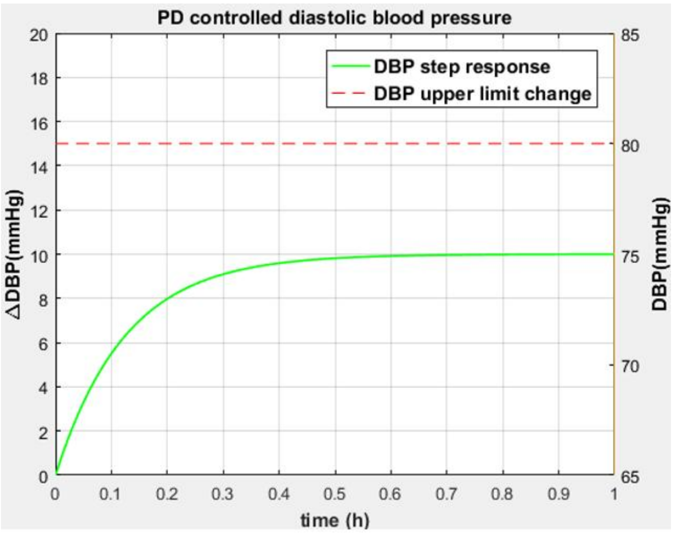


Fig.2 Step time response of a PD controlled DBP.

COMMENTS:

- Maximum overshoot: zero
- Settling time to ± 2 % tolerance: 0.489 h
- Delay time: 0.092 h
- Rise time: 0.275 h
- Steady-state error: zero

III. CONTROLLING THE DBP USING A FIRST ORDER COMPENSATOR

- The first-order compensator is one of the first generation of control compensators introduced before 2014. The author used the first-order compensator to control very slow second-order process [23] and a delayed double integrating process [24]. It has the transfer function $G_{1st}(s)$ given by [23]:

$G_{1st}(s) = K_{c2}(T_{z2}s+1)/(T_{p2}s+1)$ (9)

Where:

K_{c2} = compensator gain
T_{z2} = time constant of the compensator zero
T_{p2} = time constant of the compensator pole

- The first-order compensator is set in a single-loop control system block diagram just before the process and after the error detector receiving the error signal and as input.
- The three parameters of the first-order compensator are tuned as follows:

- The zero/pole cancellation technique [20] is applied to the open-loop transfer function of the block diagram loop for the DBP control. The compensator zero (in Eq.9) is chosen to cancel the simple pole (T_ps+1) of the DBP process (in Eq.1) providing the value of the compensator zero as:

$T_{z2} = T_p = 1.0204$ h (10)

- The transfer function of the closed-loop control system, $M_2(s)$ is deduced using Eqs.1 and 9 in a unit feedback single loop control system. It is given by:

$M_2(s) = \omega_{n2}^2 /(s^2+2\zeta_2\omega_{n2}s+ \omega_{n2}^2)$ (11)

Where:

$\omega_{n2}^2 = K_pK_{c2}/T_{p2}$, $2\zeta_2\omega_{n2} = 1/T_{p2}$ (12)

- It is known from the dynamics of second-order control systems that critical damping provides dynamics without any maximum overshoot. Therefore, for a critical damping design ($\zeta_2 = 1$).
- The settling time T_{s2} of a second order control system is related to ω_{n2} through the relationship [25]:

$T_{s2} = 5.8355/\omega_{n2}$ (13)

- For a desired settling time of (say) 0.5 h, Eq.13 provides the control system natural frequency, ω_{n2} for critical damping condition as:

$\omega_{n2} = 11.6718$ rad/h (14)

- Now, Eq.12 gives the value of the compensator pole time constant, T_{p2} for a critical damping dynamic second-order control system as:

$T_{p2} = 0.0428$ h (15)

- Now, with Tp2 known, Eq.12 gives the compensator gain Kc2 as:

$K_{c2} = 14.43859$ (16)

- The step time response for reference input tracking using the compensator transfer function in Eq.11 and the natural frequency in Eq.14 for critical damping characteristics is obtained using the command 'step' of MATLAB [16] as shown in Fig.3 for a desired DBP change of 10 mmHg.

COMMENTS:

- Maximum overshoot: zero
- Settling time to ± 2 % tolerance: 0.5000 h
- Delay time: 0.1438 h
- Rise time: 0.2878 h
- Steady-state error: zero

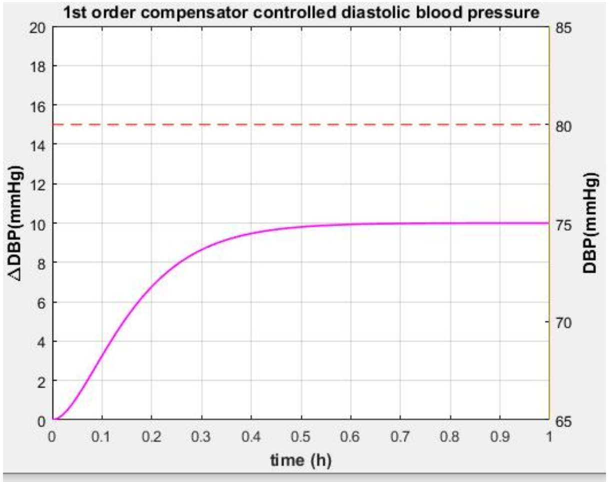


Fig.3 Step time response of a first-order compensator controlled DBP.

IV. CONTROLLING THE DBP USING A D-P COMPENSATOR

- The D-P compensator is a novel compensator design belonging to the second generation of control compensators introduced by the author since 2014. A D-P compensator consists of two control elements: A D-control mode, $G_{D3}(s)$ in the forward path just after the error detector and before the controlled process and a P-control mode, $G_{P3}(s)$ in the feedback path of the single-loop control system proposed to control the DBP process. It has the transfer function equations:

$$G_{D3}(s) = K_{d3}s \;\; ; \;\; G_{P3}(s) = K_{pc3} \qquad (17)$$

Where:

K_{d3} = compensator derivative gain
K_{pc3} = compensator proportional gain

- The two parameters of the D-P compensator are tuned as follows:
- The zero/pole cancellation technique [20] is applied to the open-loop transfer function of the block diagram loop for the DBP control. The compensator zero at origin (s) (in Eq.17) will cancel the pole at origin (s) of the process (in Eq.1). This step results in producing a closed-loop transfer function, $M_3(s)$ given by:

$$M_3(s) = K_p K_{d3} / (T_p s + 1 + K_p K_{pc3} K_{d3}) \qquad (18)$$

- Eq.18 will generate a control system dynamic having non-zero steady state error. To have a zero steady-state error, the following condition exists from Eq.18:

$$K_p K_{d3} = 1 + K_p K_{pc3} K_{d3} \qquad (19)$$

- The condition in Eq.19 reveals a mathematical expression for the proportional gain K_{pc3} as:

$$K_{pc3} = (K_p K_{d3} - 1) / (K_p K_{d3}) \qquad (20)$$

- Now, combining Eqs.18 and 19 reveals the transfer function equation of the control system incorporating the D-P compensator having the same equation as Eq.5 with T_3 instead of T_1 where the time constant of the first-order control system, T_3 is given by:

$$T_3 = T_p/(K_p K_{d3}) \qquad (21)$$

- The settling time of the control system step time response T_{s3} is related to T_3 through the relationship [21]:

$$T_{s3} = 4T_3 \qquad (22)$$

- Let the desired settling time of the control system step time response is 0.5 h. Then, Eq.22 gives the time constant T_3 as: T_3 = 0.125 h.
- Now, Eq.21 gives K_{d3} and Eq.20 gives K_{pc3} as:

K_{d3} = 20.1980 , K_{pc3} = 0.8775 (23)

- Now, using the transfer function in Eq.5 with $T_1 = T_3 = 0.125$ h, the step time response is the same as that in Fig.2 with same comments as in the PD controller.

V. COMPARISON ANALYSIS

- To evaluate the effectiveness of using the proposed controller/compensators, the step time response for a desired DBP is compared with that using a PD controller tuned in this research work.
- A graphical comparison is presented in Fig.5.
- A quantitative comparison for the time-based characteristics of the control systems proposed to control the human DBP during hemodialysis is given in Table 1 for reference step input tracking (desired DBP).

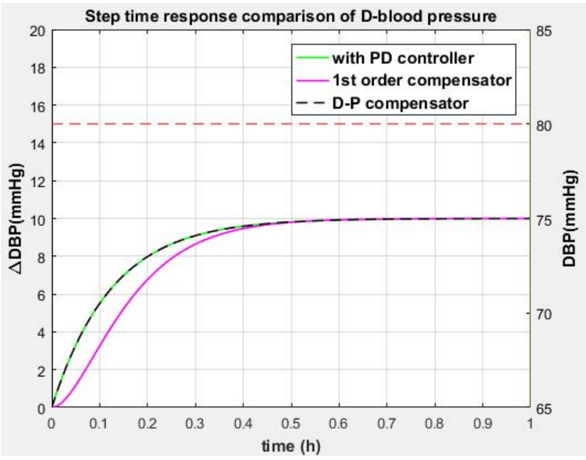


Fig.5 serum DBP control using one controller and two compensators.

TABLE 1
CHARACTERISTICS COMPARISON FOR DBP CONTROL

Characte-ristics	Without control	PD controller	First-order compensator	D-P compensator
OS_{max} (%)	∞	0	0	0
$T_{s2\%}$ (h)	∞	0.4890	0.500	0.4890
T_d (h)	∞	0.0920	0.1438	0.0920
T_r (h)	∞	0.2746	0.2878	0.2746
e_{ss}(mmHg)	∞	0	0	0

OS_{max} = maximum percentage overshoot
$T_{s2\%}$ = settling time to 2 % tolerance.
T_d = delay time.
T_r = rise time.
e_{ss} = steady-state error.

VI. CONCLUSIONS

- This research paper investigated the use of first order and D-P compensators from the second generation of control compensators compared with a PD controller from the first generation of PID controllers to control the diastolic blood pressure a human body during hemodialysis.
- The process under control was identified as an unstable process having a first order + an integrator process transfer function without time delay.
- The performance of the proposed controller/compensators was assigned through the investigation of the step time response of the control system comprising the controller/compensator and the DBP process.
- The tuning technique used to optimize the controller/compensator parameters was based on the zero/pole cancellation technique and fulfilling specific requirements for the settling time and the steady state of the control system.
- The three proposed controller/compensators succeeded to eliminate completely the maximum percentage overshoot of the closed-loop control system for reference input tracking.
- The settling time of the step input tracking time response (for 2 % tolerance) was assigned to be only half an hour for the three controller/compensators indicating fast time response compared with infinity for the uncontrolled DBP process.
- With the proposed controller/compensators it is possible to select any value for the settling time where the controller/compensator parameters will change accordingly.
- The three proposed controller/compensators succeeded to provide a step time response having a delay time less than 0.144 h.
- The three proposed controller/compensators succeeded to provide a step time response having a rise time less than 0.288 h.

- Through the tuning approaches used it was possible for the proposed controller/ compensators provided step time response to step input tracking without steady-state error.
- The PD controller and the D-P compensator proved in this application to be the best controller/compensator because of their ideal step shape without any overshoot, undershoot or steady-state error.
- However, the D-P compensator was selected as the best controller/compensator because of its simple design without summing point electronic circuit.

REFERENCES

[1] V. Chauhan, “Low blood pressure from hemodialysis: Signs and prevention”, https://www.verywellhealth.com/complications-at-hemodialysis-low-blood-pressure-3954431 ,February 2025.

[2] S. Dheenan and W. Henrich, “Prevention dialysis hypotension: A comparison of usual protective maneuvers”, *Kidney International*, vol.59, pp.1175-1181, 2001.

[3] J. Kariazis et al., “Dialysate calcium profiling hemodialysis: Use and clinical implications”, *Kidney International*, vol.61, pp.276-287, 2002.

[4] M. Papadimitrion et al., “Hypertension and left ventricular mass index in patients on regular hemodialysis”, *Hemodialysis International*, vol.9, issue 1, p.86, 2005.

[5] L. Gabutti et al., “Hemodynamic consequences of changing bicarbonate and calcium concentrations in hemodialysis fluids”. *Nephrol Dial Transport*, vol.24, pp.973-981, 2009.

[6] N. Shahaholian, M. Ghafourifard and F. Shafiei, “The effect of sodium and ultrafiltration profile combination and cold dialysate on hypotension during hemodialysis and its symptoms”, *IJNMR*, vol.16, 3, pp.212-216, 2011.

[7] R. A. Soliman et al., “Assessment of hypotension during dialysis as a manifestation of myocardial ischemia in patients with chronic renal failure”, *The Egyptian Journal of Critical Care Medicine*, vol.2, pp.12-18, 2014.

[8] A. Khan et al., “Management of patient care in hemodialysis while focusing on cardiovascular disease events and the typical role of hyper and/or hypotension: A systematic review”, *Biomedical Research International*, vol.2016, issue 1, 10 pages, 2016.

[9] P. Aunon et al., “Chronic hypotension in dialysis is a prognostic factor in the evaluation of kidney transplantation”, *Transplantation*, vol.102, 2018.

[10] J. A. Pulido et al., “Predicting the appearance of hypotension during hemodialysis sessions using machine learning classifiers”, *International Journal of Environmental Research and Public Health*, vol.18, issue 2364, 17 pages, 2021.

[11] A. Davenport, “Why is intradialytic hypotension the commonest complication of outpatient dialysis treatment?”, *Kidney International Reports*, vol.8, pp.401-418, 2023.

[12] M. Arasneshad et al., “The effect of ascending-descending ultrafiltration and sodium profiles on blood pressure in hemodialysis patients: A randomized cross-over study”, *BMC Nephrology*, vol.25, issue 128, 9 pages, 2024.

[13] M. Fahmy, F. Abdel Moez and E. Mohammed, “Intradialytic hypotension in hemodialysis patients and its relation to duration of hemodialysis”, *Journal of Current Medical Research and Practice*, vol.10, issue 3, 8 pages, 2025.

[14] A. Shuaib and M. Ahmed, “Robust PID control system design using ITAE performance index (DC motor model)”, *International Journal of Innovative Research in Science Engineering and Technology*, vol.3, issue 8, pp.15060-15067, 2014.

[15] C. P. Lopez, “MATLAB optimization techniques”, *Springer*, 2014.

[16] Mathworks, “Step response of dynamic system”, https://www.mathworks.com/help/ident/ref/dynamicsystem.step.html , 2023.

[17] G. A. Hassaan, “Tuning of a PD controller used with second-order processes”, *International Journal of Engineering and Technical Research*, vol.2, issue 7, pp.120-122, 2014.

[18] N. R. Castro et al., “Modeling PD closed-loop control problems with fuzzy differential equations”, *Automatika*, vol.47, issue 4, pp.960-967, 2016.

[19] P. Aryan and G. Raja, “Equilibrium-optimized IMC-PD double-loop control strategy for industrial processes with dead time”, in G. Manik et al. (Editors), “Recent advances in mechanical engineering”, Springer, Singapore, 2023.

[20] M. C. Campi, “The problem of pole-zero cancellation in the transfer function identification and application to adaptive stabilization,” *Automatica*, vol.32, issue 6, pp. 849-856, 1996.

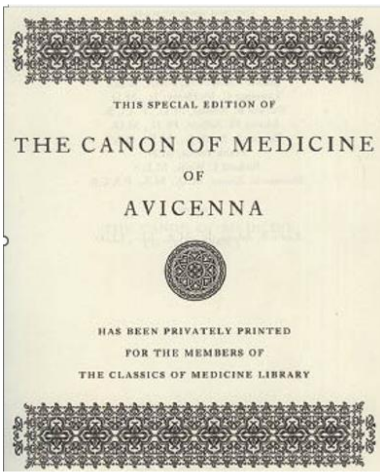
[21] Electrical for You, "Settling time: What is it?", https://www.electrical4u.com/settling-time , 25 April, 2024.

[22] Heart, “Understanding blood pressure readings”, https://www.heart.org/en/health-topics/high-blood-pressure/understanding-blood-pressure-readings , 2025.

[23] G. A. Hassaan, “Tuning of a first-order lag-lead compensator used with a very slow second-order process”, *International Journal of Advances in Engineering and Technology,* vol.7, issue 4, pp.1786-1791, 2015.

[24] G. A. Hassaan, "Tuning of a feedforward lag-lead first-order compensator used with a delayed double integrating process", *International Journal of Recent Engineering Science,* vol.11, issue 5, pp.3-7, 2015.
[25] G. A. Hassaan, "Novel characteristics evaluation of critically damped second-order-like dynamic systems", International *Journal of Computer Techniques*, vol.12, issue 5, pp.167-174, 2025.
[26] M, Nasser, A. Tibi and E. Smith, "Ibn Sina's canon of medicine: 11th century rules for assessing the effects of drugs", Journal of the Royal Society of Medicine, vol.108, pp.78-80, 2009.
[27] R. Hajar, "The air of history (part V) Ibn Sina (Avicenna): The great physician and philosopher", Heart View, vol.14, issue 4, pp.196-201, 2013.

DEDICATION


THIS SPECIAL EDITION OF
THE CANON OF MEDICINE
OF
AVICENNA
HAS BEEN PRIVATELY PRINTED
FOR THE MEMBERS OF
THE CLASSICS OF MEDICINE LIBRARY

IBN SINA, The Great Physician [26], [27]

- Ibn Sina was one the great physicians in Islam.
- He was also one of the greatest thinkers and medical scholars in history.
- He was born in 980 AC near Bukhara and died in 1037 AC in Iran.
- He began his medical studies at the age of 13.
- He wrote 100 books including the 'canon of medicine' which became the standard textbook of medicine in European medical schools after translation to Latin in the 12th century.
- Before an age of 16, he mastered physics, mathematics, logic and metaphysics.
- He wrote his famous book 'the canon' book when he was 21 year old.
- His 'canon' book was translated to Latin, Persian, Chinese, Hebrew, German, French and English languages.
- He specified 7 rules to assess the effects of drugs.

BIOGRAPHY

GALAL ALI HASSAAN

- Emeritus Professor of System Dynamics and Automatic Control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, EGYPT.

- Research on Automatic Control, Mechanical Vibrations, Mechanism Synthesis and History of Mechanical Engineering.
- Published more than 360 research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Honourable Chief Editor of the International Journal of Computer Techniques.
- Reviewer in some international journals.
- Scholars interested in the authors publications can visit:

  http://scholar.cu.edu.eg/galal