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Power Turbines Control, Part I: Al-Jazari Turbine Control using I-PD, PD-PI, 2DOF-3 and PI-PD Controllers Compared with a PI Controller

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ABSTRACT

This research paper is the first in a series of research papers aiming at the investigation of an efficient control of hydraulic turbines. It starts with the control of Al-Jazari's turbine invented during the end of the 12th century AC. The paper proposes I-PD, PD-PI, PI-PD and 2DOF-3 controllers from the second generation of PID controllers to control the turbine speed. The controllers are tuned using the MATLAB optimization toolbox and an ITAE performance index. The performance of the control system using the proposed controllers is compared with the performance using a PI controller from a previous work applied to the same turbine. The comparison takes the form of quantitative form revealing the best controller suitable to control the speed of the turbine considering both reference and disturbance inputs.

Keywords: A-Jazary turbine, turbine speed control, I-PD controller, PD-PI controller, PI-PD controller, 2DOF-3 controller, controller tuning, control system performance.

Introduction

This research is devoted to the study of the control of hydraulic turbines. As a start, the paper handles Al-Jazari impulsive turbine invited before 1200 AC [1]. Ibn Ismail Al-Razzaz Al-Jazari was a genius mechanical engineer lived in '*Amed*' of Iraq serving the rulers of the Artuqid state up to 1206 AC. He used his impulsive turbine to drive hydraulic clocks, automatic music bands and other applications. Fig.1shows his design of the impulsive turbine used in a hydraulic clock [2]. The turbine receives water jet from a nozzle through a hydraulic timer and drives a gear train. Unfortunately, this impulsive turbine was related to the American L. A. Pelton who built his first water wheel in 1878 [3]. i.e. before Al-Jazari by about 680 years but the west didn't refer it to him even his book about ingenious devices was known since 1206 and translated to English in 1974. First of all let us review some of the research work about Al-Jazari water wheel (turbine).

Eisenring, 1991 handled the layout, design, manufacture and installation of very small Pelton (Al-Jazari) turbine plants. He provided necessary theoretical background, designs and hints on manufacturing and procedures of installation. He wrote a section about turbine control handling hints about needle position control to control the water flow through the nozzle. He quoted some the applications of Pelton turbines such as in: centrifugal pump drive, electrical power generation, drinking water supply systems [4]. Pennacche, Chatterton and Vania, 2011 presented a numerical model for the dynamics of a Pelton turbine installed in a hydroelectric plant. Their model considered the turbine, speed governor, controller, nozzle servo-actuator and electric generator. The electrohydraulic plant had a rated speed of 500 rev/min and the turbine had 6 jets and its rotor had 21 buckets. They used a 2/2 transfer function model for the speed controller, a 0/1 transfer function model for the spoolvalve controlling the nozzle-actuator position, turbine model and a 0/1 transfer function model for the load [5]. Chouhan, Kisheorey and Shah, 2017 outlined that for high speed power projects, Pelton turbine is the first choice and the turbine material affects speed and efficiency of the system. They used a turbine wheel with 20 split bucket. Their finite element analysis showed the results: speed from 117.8 to 172.1 rev/min, power output from 1.17 to 1.55 Watt and efficiency from 49 to 64 % [6].

Santos, Lescano, Rose and Laporte, 2017 presented the dynamic modeling, simulation and control of a Pelton hydraulic turbine in a laboratory scale. They used MATLAB toolbox to identify the model parameters and plotted the efficiency curve of the turbine against running speed showing maximum efficiency at 600 rev/min for three levels of the water flow rates. They used a 0/1 transfer function for the turbine and used a PI-controller to control the turbine speed with 600 rev/min reference input (optimum turbine speed). They tuned the controller using the PID tuner of MATLAB and simulated the step time response using of the control systems showing no overshoot and about 5 s settling time [7]. Theint and Myo, 2018 presented the design of a Pelton turbine, its regulating mechanism and its speed control system for a 25 kW power output at a turbine speed of 1000 rev/min. They calculated the governor specifications required to run the generator at a constant speed [8]. Ducard, 2018 presented an introduction to the Pelton turbine including invention and modern wheels, hydroelectric power plants using Pelton turbines, electromagnetic systems, electromechanical systems (DC motor modeling) [9]. Hamilton and Sjogien, 2021 investigated three generator speed control strategies and two dead-time strategies to assign the best strategy for the selected wave fields to maximize the efficiency of the turbine. They outlined that the local averaging method and the adaptive control method resulted in the highest system efficient. They presented two cascaded controllers: current controller with 0/1 transfer function and a PI controller. They tuned a PID controller for current and speed control [10].

Mehmet and Altinkaya, 2022 presented the design, manufacture and automation of a micro hydroelectric power plant prototype. The setup contained three 1 KW generators, 3 Pelton turbines with a single nozzle, a one ton water tank, 5.5 kW pump providing flow and head conditions and a pump speed controller. They applied conventional PID and ANN-PID controllers for frequency and voltage control. They displayed frequency and voltage graph under different load conditions [11]. Sandmaier, Meusburger and Benigni, 2023 investigated a 6-nozzle Pelton turbine prototype with 19 buckets using 3D CFD simulation. They assigned the operating conditions of the turbine: 382 m head, 5.5 m3/s flow rate, 75 % nozzle opening and 600 rev/min speed [12].

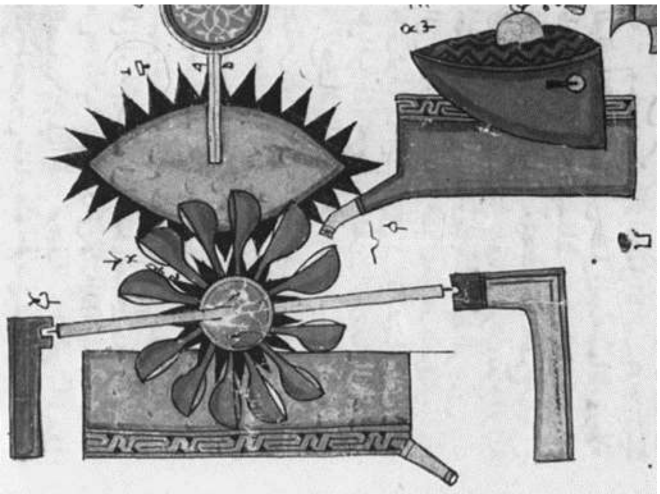


Fig.1 Impulsive turbine of Al-Jazari [2].

Nomenclature	
C(s)	Laplace transform of the control system output
D(s)	Laplace transform of the disturbance input of the control system
$G_c(s)$	Controller transfer function
$G_p(s)$	Process transfer function
$G_{PDPI}(s)$	Transfer function of the PD-PI controller
I-PD	Integral-proportional derivative controller
K_d	Derivative gain parameter
K_i	Integral gain parameter
K_{pc}	Proportional gain parameter
PD-PI	Proportional Derivative – Proportional Integral controller
PI	Proportional Integral controller
PI-PD	Proportional integral – proportional derivative controller
R(s)	Laplace transform of the reference input of the control system
s	Laplace operator
2DOF	Two Degree of Freedom controller

Controlled Al-Jazari Turbine Speed

Santos et al., 2017 modeled a laboratory Pelton turbine for its control for speed regulation using a PI controller [7]. The model they derived was an un-delayed first-order one having the form [7]:

$$G_p(s) = 214.2/(2.743s+1) \qquad (1)$$

The step time response of Kaplan (Al-Jazari) turbine speed process reveals the dynamic characteristics of this process without any control. Its unit step time response is generated by the MATLAB command step [13] and shown in Fig.2.

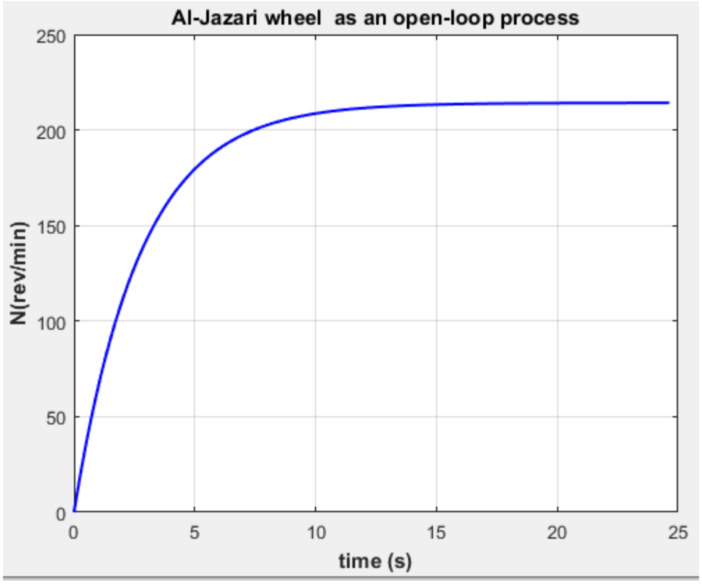


Fig.2 Unit step time response of Al-Jazari turbine.

Comments:

- Al-Jazary turbine speed as a process is stable.
- It shows no overshoot nor undershoot.
- It has – 213.173 rev/min steady-state error.
- It has a settling time of 4.49 s.
- Any good proposed control system has to overcome the large steady-state error and provides better settling time.

Controlling Al-Jazari Turbine using an I-PD Controller

The I-PD controller was introduced by the author in 2014 as one of the controllers of the second generation of the PID controllers. The author tested the performance of the I-PD controller through its use in controlling a highly oscillating second-order process [14], delayed double integrating process [15], third-order process [16], liquefied natural gas tank level [17], furnace temperature control [18], mold temperature of an injection molding machine (IMM) [19], cavity gate pressure of an IMM [20], mold packing pressure of an IMM [21] and ram velocity of an IMM [22].

The block diagram of a control system incorporating an I-PD controller and the cavity gate pressure process is shown in Fig.3 [22].

- The transfer function of the control system for reference input tracking [C(s)/R(s)] is obtained using the block diagram in Fig.3 and Eq.1 for the process transfer function $G_p(s)$.
- The I-PD controller gain parameters are:

K_i = integral gain of the I-control mode.

K_{pc} = proportional gain of the P-control mode.

K_d = derivative gain of the D-control mode.

- The three controller gain parameters have to be tuned to optimize the performance of the control system.
- The three I-PD controller parameters are tuned using the transfer function of the closed loop control system in Fig.3 and the MATLAB optimization toolbox [23] to minimize an ITAE performance index [24].
- The tuned I-PD controller parameters are:

$K_i = 5016.8628$; $K_{pc} = 693.6714$; $K_d = 0.0000258$ (2)

- The unit step time responses of the cavity gate pressure for reference and disturbance inputs are plotted using the transfer functions derived from the block diagram in Fig.3 and the tuned controller parameters in Eq.2 using the MATLAB command ‘*plot*’ and shown in Fig.4.

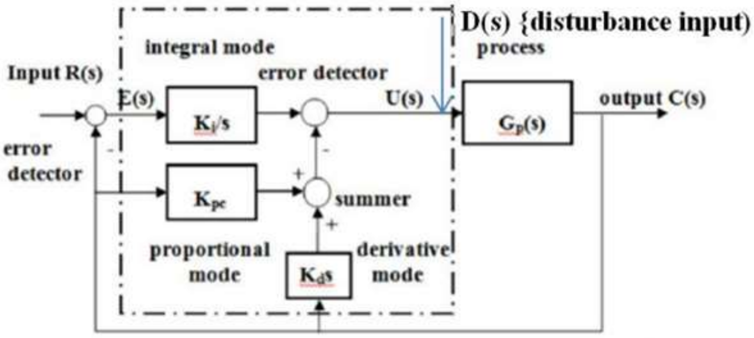


Fig.3 Al-Jazari turbine speed control using I-PD controller [22].

Comments:

- For a reference input tracking:
- Maximum percentage overshoot: zero
- Settling time: 0.612 ms
- Steady-state error: zero
- For a disturbance input with second order high-pass filter:
- Maximum time response: 0.0035 rev/min
- Minimum time response: -0.0008 rev/min
- Settling time to zero: 0.4 ms
- The I-PD controller succeeded to eliminate completely the maximum overshoot and steady-state error of the controlled Al-Jazary turbine speed.

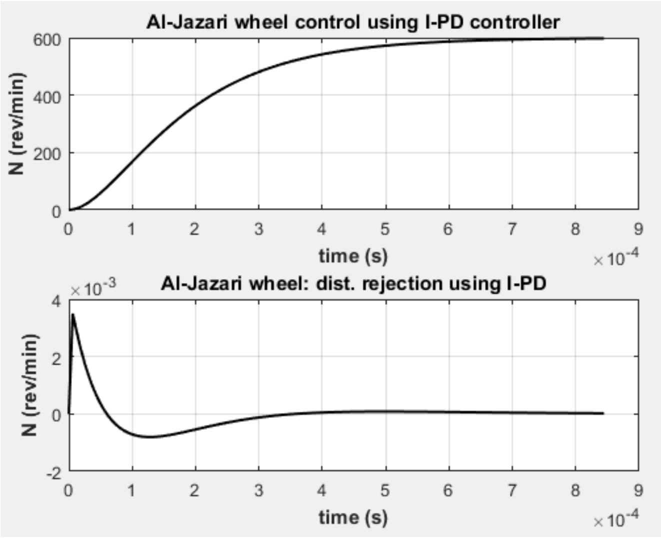


Fig.4 Al-Jazari turbine speed control using an I-PD controller.

Controlling Al-Jazari Turbine Speed using a PD-PI Controller

The PD-PI controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation of PID controllers. The author used PD-PI control to control a variety of industrial processes with bad dynamics such as: first-order delayed process [25], highly oscillating second-order process [26], integrating plus time delay process [27], delayed double integrating process [28], third-order process [29], internal humidity of a greenhouse [30], boost-guide rocket [31], electro-hydraulic drive [32], rolling strip thickness [33], furnace temperature [18], mold temperature of an IMM [19], barrel temperature of an IMM [35], cavity gate pressure of an IMM [20], mold packing pressure of an IMM [21] and ram velocity of an IMM [22].

- The two elements of the PD-PI controller (PD and PI control modes) are set in cascade in the forward path of the block diagram of the barrel temperature control system just after the error detector.
- The transfer function of the PD-PI controller is given by [22]:

$$G_{PDPI}(s) = [K_d K_{pc2} s^2 + (K_{pc1} K_{pc2} + K_d K_i)s + K_{pc1} K_i]/s \qquad (3)$$

Where:

K_{pc1} = proportional gain of the PD-control mode

K_d = derivative gain of the PD-control mode

K_{pc2} = proportional gain of the PI-control mode

K_i = integral gain of the PI-control mode

- The four PD-PI controller parameters are tuned using the transfer function of the control system as derived from its block diagram and the MATLAB optimization toolbox [23] is used to minimize the ITAE performance index [24].
- The tuned PD-PI controller parameters are:

$K_{pc1} = 230.49873$; $K_d = 0.7001666$

$K_{pc2} = 0.7548541$; $K_i = 0.0322040$ (4)

- The unit step time responses of Al-Jazari turbine speed for reference and disturbance inputs using the PD-PI controller are plotted using the MATLAB command ‘*plot*’ [13] and shown in Fig.5.

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: zero
  - Settling time: 0.5 ms
  - Steady-state error: zero
- For a disturbance input (to improve the performance of the control system regarding the rejection of the disturbance using a high pass second-order filter added after D(s):
  - Maximum step time response: 0.00022 rev/min
  - Minimum time response: -7×10^{-6}rev/min
  - Settling time to zero: 0.5 ms

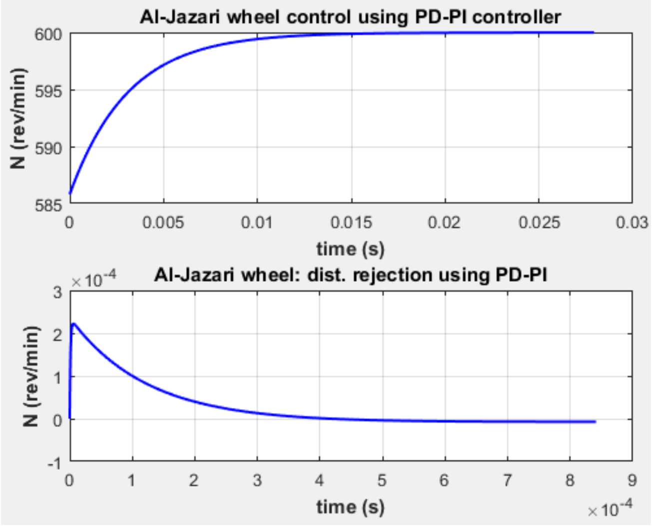


Fig.4 Al-Jazari turbine speed control using a PD-PI controller.

Controlling Al-Jazari Turbine Speed using a 2DOF-3 Controller

Several 2DOF controllers were introduced by the author as members of the second generation of PID controllers introduced by him starting from 2014 to overcome the problems associated with the use of the conventional PID controller. The author used 2DOF controllers to control a number of processes having bad dynamics such as: highly oscillating second-order process [35], delayed double integrating process [36], gas turbine speed control [37], boost-glide rocket control [31], liquefied natural gas tank level control [17], furnace temperature [18], electro-hydraulic drive [32], rolling strip thickness [33], mold temperature of an IMM [19], barrel temperature of an IMM [34], cavity gate pressure of an IMM [20], mold packing pressure of an IMM [21] and ram velocity of an IMM [22]. The structure of the 2DOF-3 controller used to control Al-Jazari turbine speed is shown in Fig. 5 [22]. It comprises two sub-controllers: PD-control mode in the feedforward path receiving the reference input signal and another PD-control mode in a feedback loop receiving an output signal of the control system. The transfer functions of the two control modes are as follows:

$$G_{c1}(s) = (K_{pc1}+K_{d1}s)$$

$$G_{c2}(s) = (K_{pc2}+K_{d2}s) \qquad (5)$$

Where: K_{pc1} and K_{d1} are the proportional and derivative gains of the first PD-mode of the 2DOF-3 controller. K_{pc2} and K_{d2} are the proportional and derivative gains of the second PD-mode.

The transfer functions of the closed-loop control system for both reference and disturbance inputs using the 2DOF controller are derived from the block diagram in Fig.5.

- The PD control is the second simplest control mode after the proportional mode. However, depending on the structure of the controlled process it may result in a non-zero steady-state error. In the application of the PD-mode as an element of the 2DOF-3 controller, the transfer function of the control system for reference input tracking was investigated and a gain-constraint was derived to produce a zero steady-state error.
- The 2DOF-3 controller structure proposed in the present work has four gain parameters to be tuned to provide accepted performance for the control system for both reference input tracking and disturbance rejection with a specific constraint on its gain parameters.
- The four 2DOF-3 controller parameters are tuned using the transfer function of the control system for reference input tracking and the MATLAB optimization toolbox [13] to minimize the ITAE performance index [24].

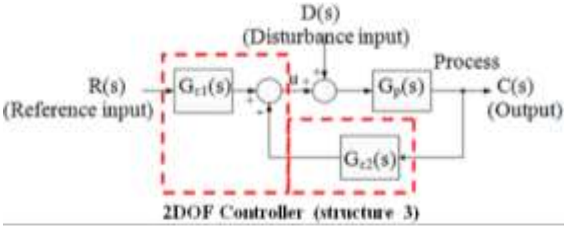


Fig.5 Al-Jazari turbine speed control using 2DOF-3 controller [22].

- The tuned 2DOF-3 controller parameters are:

$K_{pc1} = 0.330555$; $K_{d1} = 0.0626599$

$K_{pc2} = 0.330555$; $K_{d2} = 0.0507391$ (6)

- The unit step time responses of Al-Jazari turbine speed for reference and disturbance inputs using the 2DOF-3 controller are plotted using the transfer functions of the control system for both reference and disturbance inputs, the tuned controller parameters in Eq.6 and the MATLAB command ‘*plot*’ [13] and shown in Fig.6.

Comments:

- For a reference input tracking:
- Maximum percentage overshoot: zero
- Settling time: zero
- Steady-state error: zero
- For a disturbance input [to improve the performance of the control system regarding the rejection of the disturbance, a high pass second-order filter is added after D(s)]:
- Maximum time response: 0.001895 rev/min
- Minimum time response: zero
- Settling time to zero: 0.6 ms

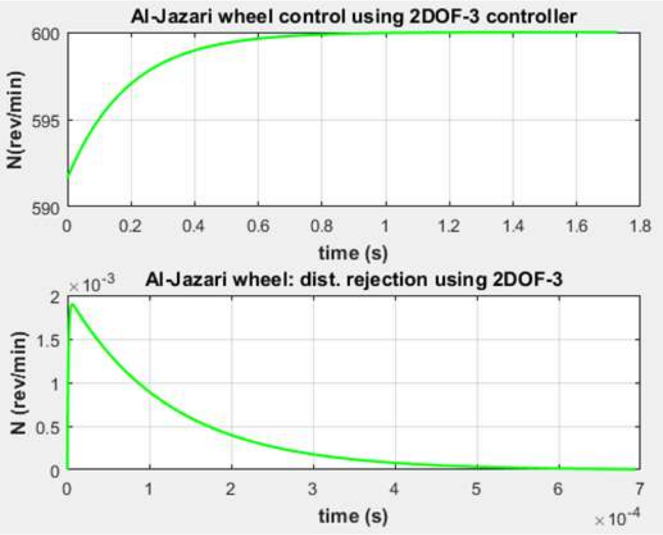


Fig.6 Al-Jazari turbine speed control using a 2DOF-3 controller.

Controlling Al-Jazary Turbine using a PI-PD Controller

The PI-PD controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used PI-PD control to control a variety of industrial processes with bad dynamics such as: highly oscillating second-order process [38], third-order process [39], greenhouse humidity [30], fourth-order blending process [40], boost-glide rocket engine [31], BLDC motor [41], boiler drum water level [42], electro-hydraulic drive [32], rolling strip thickness [33], IMM barrel temperature [34], IMM cavity gate pressure [20], IMM packing pressure [21] and IMM ram velocity [22].

The block diagram of a control system incorporating a PI-PD controller controlling Al-Jazari turbine speed is shown in Fig.7 [22].

The PI-PD controller is composed of two elements: PI-control-mode in the forward path receiving its input from the error detector of the control system and a PD-control-mode in the feedback path of an internal loop with the controlled process.

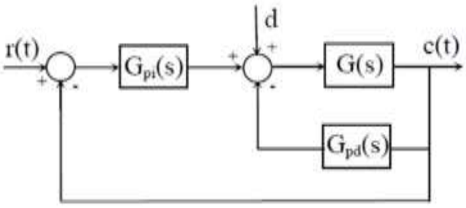


Fig.7 Block diagram of a PI-PD controlled process [22].

- The PI-PD controller elements have the transfer functions:

$G_{PI}(s) = K_{pc1} + (K_i/s)$

And $G_{PD}(s) = K_{pc2} + K_d s$ (7)

- K_{pc1}, K_i, K_{pc2} and K_d are the four controller parameters gains to be tuned to adjust the performance of the closed-loop control system.
- The transfer functions of the closed-loop control system in Fig.7 are derived from the block diagram using Eqs.1 for Al-Jazari turbine speed and 7 for the PI-PD controller for both inputs R(s) and D(s).
- The unit step time response of the control system, n(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [13].
- The ITAE performance index [24] is minimised using the MATLAB optimization toolbox [23].
- Minimizing the error function ITAE reveals the following optimal gain parameters of the PI-PD controller:

$K_{pc1} = 37.481591$; $K_i = 0.0012501$

$K_{pc2} = 0.0049190$; $K_d = -0.0128057$ (8)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [13] using the PI-PD controller tuned gain parameters in Eq.8 and shown in Fig.8.

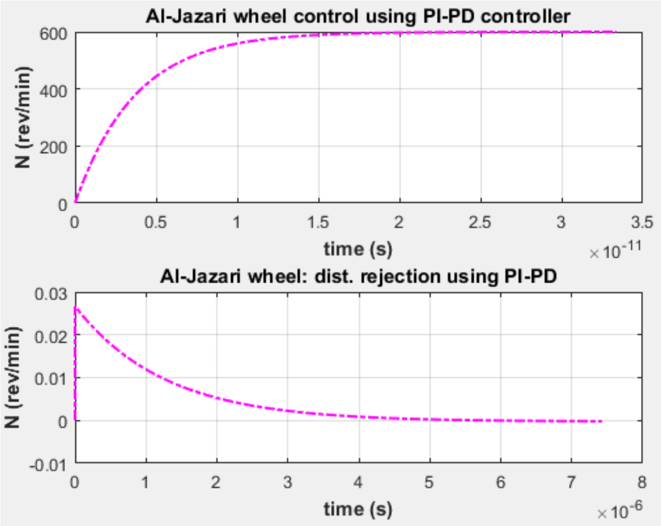


Fig.8 Al-Jazari turbine speed control using a PI-PD controller.

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: zero
  - Settling time: $1.46\text{x}10^{-11}$ s
  - Steady-state error: zero
- For a disturbance input:
  - Maximum time response: 0.026 rev/min
  - Minimum time response: $7.08 \text{ x } 10^{-4}$ rev/min
  - Settling time to zero: 6 μs

Comparison with a PI Controller

The performance of the control system used for Al-Jazari turbine speed control is compared graphically and numerically with that of the control system for the same process using a PI controller used and tuned by Santos et al. [7]. The step time responses of the control system using the PI controller were generated by the author for both reference and disturbance inputs using the step command of MATLAB [13] according to the presentation of Santos et al. [7] for reference input tracking. They are presented in Fig.9.

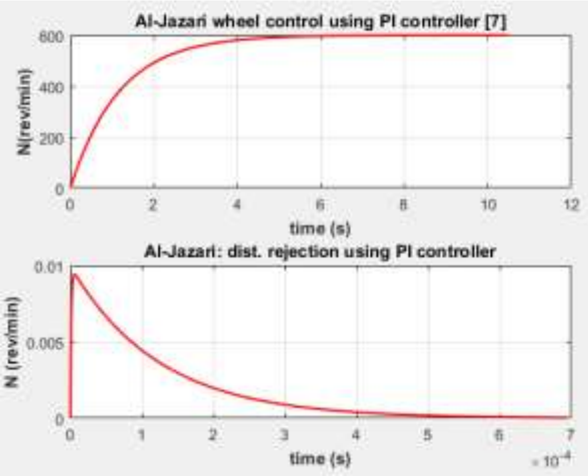


Fig.9 Al-Jazari turbine speed control using a PI controller.

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: zero

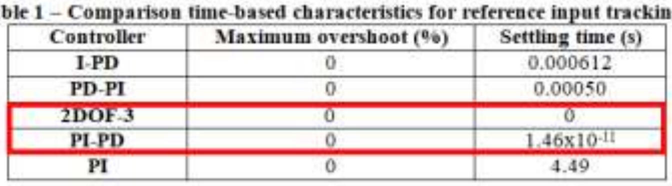
- Settling time: 4.49 s
- Steady-state error: zero

- For a disturbance input:

- Maximum time response: 0.0094 rev/min
- Minimum time response: zero
- Settling time to zero: 0.6 ms

A quantitative comparison for the time-based characteristics of Al-Jazari turbine speed control systems is shown in Table 1 for reference input tracking.

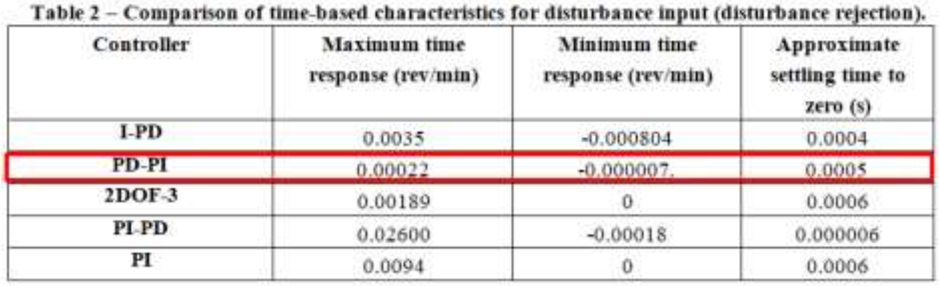
Table 1 – Comparison time-based characteristics for reference input tracking.



Controller	Maximum overshoot (%)	Settling time (s)
I-PD	0	0.000612
PD-PI	0	0.00050
2DOF-3	0	0
PI-PD	0	1.46×10^{-11}
PI	0	4.49

The time-based characteristics of the disturbance step time response (disturbance rejection) are compared in Table 2.

Table 2 – Comparison of time-based characteristics for disturbance input (disturbance rejection).



Controller	Maximum time response (rev/min)	Minimum time response (rev/min)	Approximate settling time to zero (s)
I-PD	0.0035	-0.000804	0.0004
PD-PI	0.00022	-0.000007	0.0005
2DOF-3	0.00189	0	0.0006
PI-PD	0.02600	-0.00018	0.000006
PI	0.0094	0	0.0006

Conclusions

- The paper investigated the control of Al-Jazari impulsive turbine using four controllers from the second generation of PID controllers introduced by the author since 2014.
- The controllers proposed for this purpose were the I-PD, PD-PI, 2DOF-3 and PI-PD.
- The four controllers were tuned using the MATLAB optimization toolbox and an ITAE error-based performance index.
- The performance of the control system was evaluated through the maximum percentage overshoot and the settling time for reference input tracking.
- For the disturbance input, the control system was evaluated through the maximum step time response, minimum step time response and settling time to zero.
- The four proposed controllers were compared with a PI controller from previous research work used to control the same process.
- The controlled Al-Jazari impulsive turbine as a process to be controlled had bad dynamics when excited by a step input in terms of a large steady-state error.
- The I-PD controller could eliminate completely the maximum overshoot of the control system and could generate a step time response of the turbine speed having only about 0.6 ms settling time (compared with 4.49 s using the PI controller).
- The PD-PI controller could eliminate completely the maximum overshoot of the control system and could generate a step time response of the turbine speed having only about 0.5 ms settling time (compared with 4.49 s using the PI controller).
- The 2DOF-3 controller could eliminate completely the maximum overshoot of the control system and could generate a step time response of the turbine speed with zero settling time within the ± 2 % band around the steady-state time response (compared with 4.49 s using the PI controller).
- The PI-PD controller could eliminate completely the maximum overshoot of the control system and could generate a step time response of the turbine speed having only 0.146 ps (0.146×10^{-12} s) settling time (compared with 4.49 s using the PI controller).

- Regarding reference input tracking of Al-Jazary turbine reference input, the 2DOF-3 and PI-PD controllers are the best choice for the control engineer when controlling Al-Jazari impulsive turbine speed.
- Regarding disturbance rejection, all the proposed controllers provided very small maximum and minimum step time responses with a special concern to the PD-PI controller where it provided good characteristics regarding disturbance rejection.

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DEDICATION

Genius Engineer Ibn Ismail Al-Razzaz Al-Jazari:

Automatic music band of Al-Jazari [2]

- I dedicate this work to one of the great mechanical engineers in the Arabic World during the Medieval Centuries: Ibn Ismail Al-Razzaz Al-Jazari.
- He was born in 1136 AC, lived and served during the '*Artuqid Dynasty*' at '*Al-Jazira*' of '*Iraq*'.
- He died in 1206 AC.
- He acted as a '*Chief Engineer*' in the Palace of the '*Artuqid Rulers*'.
- He wrote his famous book about '*Knowledge of engineering tricks*' describing 50 mechanical devices with detailed instructions about their construction and production. This was between 1200 and 1206 AC.
- He is the father of '*robotics*', '*hydraulic clocks*', '*positive displacement pumps*' and '*dynamic fountains*'.
- He invented the '*digital lock*'.
- He invented a '*mechanical mechanism*' to control the speed of a turbine wheel ('*first mechanical speed controller*').
- He invented '*segmental gears*' and used them to drive some of his '*positive displacement pumps*'.
- He invented '*camshafts*' to operate some automata such as '*automatic music bands*'.
- He invented the '*two-cylinder positive displacement pump*' with "*non-return valves*' and '*reciprocating pistons*'.
- He invented '*water supply systems*' to supply mosques and hospitals with water.
- He invented a large number of '*mechanical clocks*' some of them equipped with '*musical bands*'.
- He used '*flow control valves*' in the design and control of some of his '*robotics*'.
- This is the genius mechanical engineer '*Al-Jazary*'. I invite the "*Iraqi Government*' to honor Al-Jazary and make a permanent exhibition for his inventions and publish his book in various languages to help the whole world to know this great engineer.