CONSTRUCTION AND EVALUATION OF AUTOMATIC PIVOT WEIR CONTROL SYSTEM

CONSTRUCTION ET EVALUATION DU SYSTEME DE COMMANDE DE DEVERSOIR PIVOT AUTOMATIQUE

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ABSTRACT

Water losses in irrigation canals are large, but they could be substantially reduced by improving the control systems. On the other hand, irrigation canals are complex hydraulic systems difficult to control. In recent decades, many control models have already been developed. In the present study, a physical control system based on PID algorithm was designed and constructed in a laboratory flume in Tarbiat Modares University. The control parameters were determined experimentally and the control system was tested under sudden flow variations. The results showed that the constructed control system was appropriate for water level tuning in a short time with a little fluctuation.

Key words: *Weir control, Canal system, Laboratory flume, Control system hardware, PID controller.*

RESUME ET CONCLUSIONS

En raison de mauvaise performance des réseaux d'irrigation et faiblesse de la productivité de l'eau dans la section agricole, il est nécessaire d'introduire des méthodes efficaces pour l'exploitation optimale des réseaux d'irrigation. Pour améliorer la performance des réseaux d'irrigation, fournir une plus grande flexibilité et l'amélioration des méthodes de distribution d'eau, application des systèmes de contrôle automatiques sont proposées. Processus d'introduction de système de contrôle automatique comprend développement de son modèle mathématique. Après évaluation favorable du modèle mathématique, modèle physique à l'échelle du laboratoire devraient être développés après ses essais, il pourrait être introduit pour l'application en condition réelle. Beaucoup de recherches sont présentés résultats des modèles mathématiques et de physique des systèmes de contrôle de l'irrigation dans le monde entier. Cependant, seulement quelques modèles mathématiques et presque pas de modèle physique sont étudiés en Iran.

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Différents algorithmes de contrôle pour l'automatisation des canaux d'irrigation ont été développés. Le régulateur PID, qui se compose d'éléments proportionnelle, intégrale et dérivée, est largement utilisé dans le contrôle des procédés industriels. L'algorithme PID, tenter de diminuer écart de niveau d'eau de profondeur de la cible, avec de la mode stable et dans un temps acceptable.

En raison de plusieurs avantages de Pivot Weir y compris les automatisations faciles, conception simple et ayant une caractéristique de débordement, il est structure adaptée à la régulation du niveau d'eau et est considérée comme une structure de contrôle. Dans cette recherche, modèle physique de déversoir pivot automatique basée sur la logique de contrôle PID a été construit en canal hydraulique au laboratoire d'hydraulique de l'Université Tarbiat Modares. Le canal avait une longueur de 10 m, 30 cm de large et 45 cm de hauteur. Un déversoir pivot installée à 6 m de distance de l'entrée de canal, et relié à un moteur pas à pas pour ses mouvements. Il y avait deux capteurs à ultrasons de la profondeur de l'eau sens en amont et en aval du déversoir avec 0,2 cm de précision. Le déversoir pivot automatique programme a été écrit en MATLAB sur un PC. Les données entre le PC et le matériel (capteurs et moteurs) a été transmis par une carte électronique.

Les performances optimales de l'algorithme de contrôle PID est une fonction de ses paramètres de contrôle (proportionnelle, intégrale et dérivée coefficients). Dans cet article, les paramètres de contrôle ont été déterminés expérimentalement et le système de contrôle a été testé dans les variations de débit soudaines. Le modèle a été évalué à l'aide des indices de performance comme MAE (maximum absolu d'erreur) et de l'IAE (Intégrale de la magnitude absolue d'erreur), et l'analyse des variations de profondeur de l'eau en fonction du temps. Les résultats ont montré que l'erreur maximale dans les pires conditions était de 10%, ce qui est pratiquement acceptable, et les déviations d'eau ont été contrôlés en moins de trois minutes. Par conséquent, le prévu système de contrôle Il est suggéré d'appliquer dans les canaux d'irrigation.

Mots clés : *Commande de déversoir, système du canal, canal hydraulique, matériel du système de commande, régulateur PID.*

(Traduction française telle que fournie par les auteurs)

1. INTRODUCTION

As water is becoming precious, there is a growing interest for advanced management methods that prevent wastage of this vital resource. Irrigation is acknowledged as being the largest water consumer in the world and many irrigation systems are still being managed manually, which leads to a low efficiency in terms of water delivered versus water taken from the resources. Automation is recognized as an effective means to increase this efficiency (Goussard, 1993).

The development process of a control system consists of three steps: appropriate performance of mathematical model, assured performance in physical model, and applying in real condition in field. The delivery and distribution schedules in irrigation networks are very complex, therefore, a mathematical model of irrigation control system can help irrigation experts to comprehend the complexity without interfering with the real field system. In the other hand, there is no analytical solution for many complex hydraulic problems like unsteady flow equations and the model can be provided with some simplifications. Therefore, the mathematical model would be acceptable when a physical model approves it, so, in the next step, system performance has to be tested in physical model and after its assured operation can be applied in real condition.

Each control system includes software and hardware. Success of a control system depends on the ability of the control algorithm in tuning of controlled variables. Regulator structures performance under various algorithms are different. Each of these algorithms that are selected based on the objectives and features desired design are to be scrutinized for their advantages and disadvantages The PID controller, which consists of proportional, integral and derivative elements, is widely used in industrial control process. Because of several advantages of pivot weir including easy automation, simple design and having overflow characteristic, it is a suitable structure for water level regulation and is considered as a check structure.

Several mathematical models have been developed in Iran, but little physical models have been tested. In this research, physical model of automatic pivot weir based on PID control logic was constructed in hydraulic laboratory in Tarbiat Modares University, and tested under different operation scenarios. At first, PID algorithm will be explained. Then, pivot weir and its equations will be expressed. Next, the laboratory experiment and finally conclusions and recommendation will follow.

2. PID ALGORITHM

PID controller was marketed in 1939 in industry. PID controller has been the most commonly used controller (Araki, 2009). Its algorithm acts as a feedback control. The controlled variables (water depth, y) are measured, then, in order to close controlled variable and target depth (y_c), their difference is returned to control algorithm to correct the control action (check adjustment, u). Figure.1 shows a feedback control system. In feedback control, perturbations (P) are monitored indirectly, through their effects on the output (y).

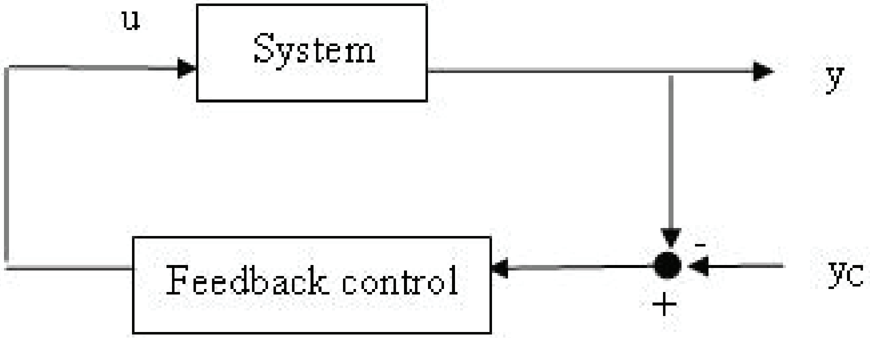

Fig. 1. Feedback control (Le contrôle par rétroaction)

PID control tries to minimize the error between actual and target depth. The proportional term is related to the water depth deviation from target depth, the integral term is related to the summation of water depth from admissible band of depths during operation period and the derivative term is related to water depth changes rate. The sum of three above elements gives the movement of check structure as Equation 1.

$$u(t) = K_p e(t) + K_d \frac{de}{dt} + K_i \int_0^T e(t)dt \tag{1}$$

Where u(t) is the control action, *e*(*t*) the deviation of the controlled variable from the desired set point and k_p, k_i, and k_d are proportional, integral and derivative gains, respectively. Many researches on PID algorithm application in irrigation control systems have been done like using decentralized PI controller on 6th canal in Coleambally in Australia (Ooi and Wayer, 2008), application of PI controller in EASET Bench district in Montana (Stringam et al,. 2006), and classic PI control system on a experimental canal in Portugal (Litrico et al,. 2005).

3. PIVOT WEIR

Recently, pivot weir has become increasingly popular for controlling water levels in open channels. This popularity is partly due to the ability of weirs to handle flow surges with limited depth changes, easy automation, simple design and having overflow characteristic.

The pivot weir consists of a rectangular panel that is hinged to the bottom of the canal. Usually, two cables connect the top of the panel to a hoisting mechanism that can then be used to raise and lower the weir to the desired height to control the upstream depth for various flow rates (Wahlin and Replogle, 1994). Figure. 2 shows a pivot weir.

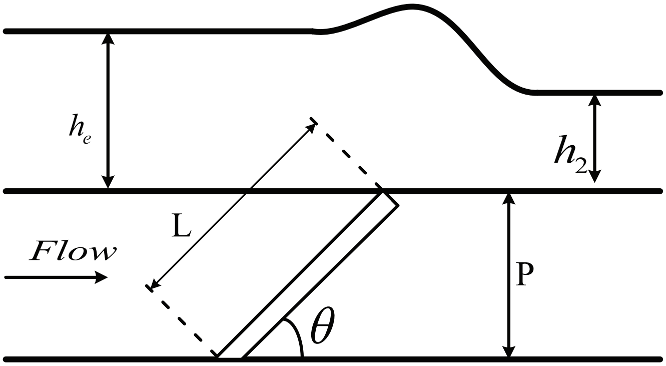

Fig. 2. A pivot weir (Un déversoir pivot)

The first experiment on the pivot weir was done by USBR on the Boulder Canyon Project (1948). The results showed that the discharge estimate error was 0.94 in free flow condition (USBR, 1948). Then, Wahlin and Replogle (1994) tested pivot weir in free and submerge flow condition in laboratory. Results showed that the error in the equation for pivot weir was 6.4% for free flow condition and 10% for submerge flow condition (Wahlin and Replogle, 1994). Recently, pivot weir has been applied as check structure in Haughtan Main Canal in Australia (Wayer and Eurénand, 2007).

3.1 Hydraulic Equation

Identifying of sharp crested weir is necessary to study pivot weir hydraulic behavior. Then, the weir angle effects as a discharge coefficient. Kindsvater and Carter (1957) presented Equation 2 for sharp crested weir under free flow condition.

$$Q = \frac{2}{3}\sqrt{2g}C_e b_e h_1^{1.5} \qquad (2)$$

Where C_e : effective discharge coefficient

b_e : effective width of the weir

and h_e : effective water head on the weir

The value of C_e is assumed to be of the form Equation 3.

$$C_e = m\frac{h_1}{p} + b \qquad (3)$$

Where m and b are experimental constants.

After, considering weir angle effect Equation 4 presented for pivot weir under free flow condition.

$$Q = \frac{2}{3}\sqrt{2g}C_a C_e b_c h_1^{1.5} \qquad (4)$$

where C_a : correction factor for angle of the weir (Kindsvater and Carter (1957)).

Villmonte (1947) developed the following useful Equation 5 to estimate the discharge over a submerged rectangular sharp crested weir.

$$Q = C_{df} Q_0 = Q_0\left[1 - \left(\frac{h_2}{h_1}\right)^{1.5}\right]^{0.385} \qquad (5)$$

Where C_{df} : drowned flow reduction factor

Q_o : discharge under free flow condition with upstream head h_1

h_1 : upstream head

and h_2 : downstream head (Villmonte, 1947).

For pivot weir, drowned flow reduction factor based on angle of weir is calculated from Equation 6.

$$C_{df} = A\left[1-\left(\frac{h_2}{h_1}\right)^{1.5}\right]^n \tag{6}$$

Where *A* and *n* are experimental constants.

4. LABORATORY EXPERIMENT

4.1 Flume and pivot weir

Physical model of automatic pivot weir based on PID control logic was constructed in hydraulic flume at hydraulic laboratory of Tarbiat Modares University. The flume was 10 *m* long, 30 *cm* wide and 45 *cm* tall. There was an inlet tank at the upstream of the flume that water is pumped in canal through it. Figure 3 shows the laboratory flume.

Fig. 3. Laboratory flume (Canal de laboratoire)

A pivot weir was installed at 6 *m* distance from flume entrance, and connected to a step motor for its movement. Bed and sides of weir were equipped with rubber seal so that there's no leak from sides and negligible leak from bed. Figure 4 shows pivot weir. At the end of flume, there is a manual pivot weir to regulate downstream depth. Finally, water sheds in reservoir. The laboratory water system is rotational. Discharge can be changed and measured by a digital flow meter. Figure 5 shows flow meter.

Fig. 4. Pivot weir (Déversoir Pivot)

Fig. 5. Flow meter (Débitmètre)

4.2 Control System Hardware

Figure 6 shows various parts of hardware equipments that each of them will be explained:

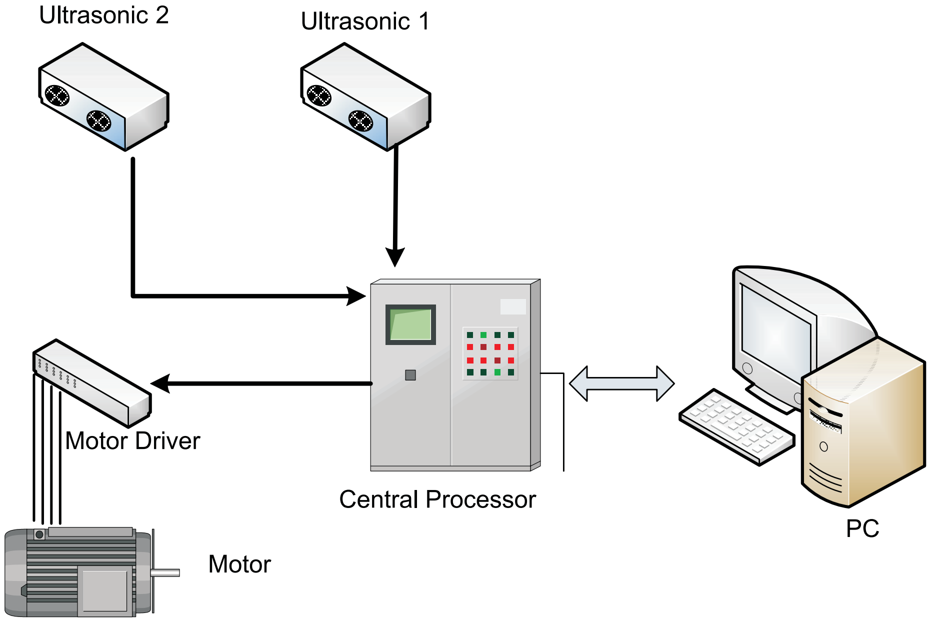

Fig. 6. Hardware of control system (Matériel du système de contrôle)

- Sensors: There were two ultrasonic sensors to sense water depth in upstream and downstream of the weir with 0.2 *cm* precision which sense water depth each 100 *ms*. Then, water depth data was sent to computer. Figure 7 shows an ultrasonic sensor.

Fig. 7. Ultrasonic sensor (Capteur à ultrasons)

- Computer (PC): The automatic pivot weir program was written in MATLAB on a PC. The program included a GUI (Graphical User Interface) through which requirement gains could be entered and some results like water depth changed and pivot weir height could be seen through it.
- Central Processor: Central processor connected different parts of hardware. It consisted a ATMEGA 32 microcontroller which analyzed data and interpreted PC commands.
- Motor: There was a stepper motor to move the weir. The motor rotated 1.8 *degree* with each step. Figure 8 shows used motor.

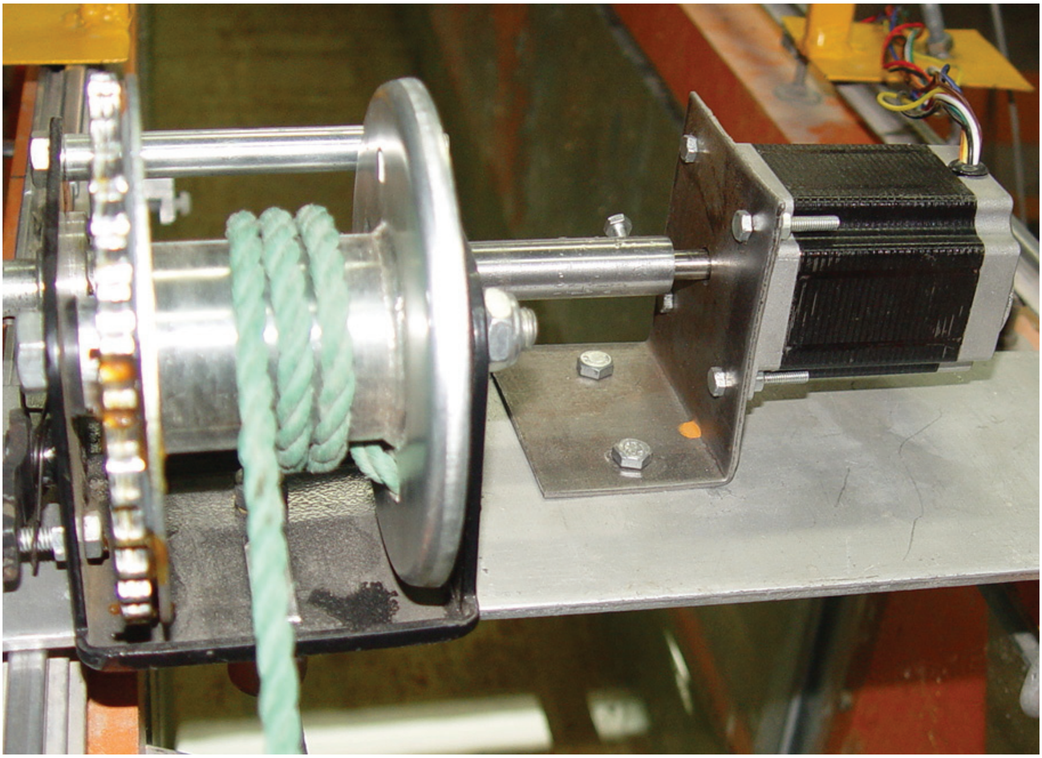

Fig. 8. Step motor (Moteur pas à pas)

4.3 Control System Software

The automatic and manual operation programs of pivot weir were written in MATLAB. Each program had a GUI through which the required data could be entered or water depth changes could be seen.

4.4 Relation Between Hardware And Software

After running the automatic operation program, the reading sensors command is sent to microcontroller. Then, the ultrasonic sensors act and send a pulse to microcontroller which transforms it to water depth in number format. Next, the water depth data are sent to PC through USB interface. The movement of the weir is calculated by using water depth data based on PID algorithm on PC and is sent to the motor. The explained process will continue until the water depth equals target depth.

4.5 Operation Scenarios of Physical Control System

Physical PID control system tested under increasing and decreasing of inlet discharge. At first, the flume flow regulate on 5 *lit/s*. Next, the automatic program was run and the target depth set 20 *cm*. Then, the flow increased to 15 *lit/s*. After water depth stabilization on target depth the flow was decreased to 5 *lit/s*. The water depth and pivot weir height were saved to analysis the control system performance.

5. CONCLUSIONS AND RECOMMENDATIONS

One of the most difficult stages in PID control algorithm is to determine control coefficients (k_p, k_i, and k_d). At first, the recommended values were assumed k_i (0.0001) and k_p (0.0001) and the k_p value was determined with try and error method so that the depth deviation from target depth and the system response time (SRT) were minimum. After, the k_p value set on determined value and recommend value was assumed for k_d (0.0001), and the k_i coefficient was determined with try and error. At last, the determined values were set for k_p and k_i, and k_d was determined with try and error. The appropriate control coefficients, k_p, k_i, and k_d were specified 0.4, 0.0001, and 0.0001 respectively. Figure 9 and figure 10 show the water depth and weir height changes during operation.

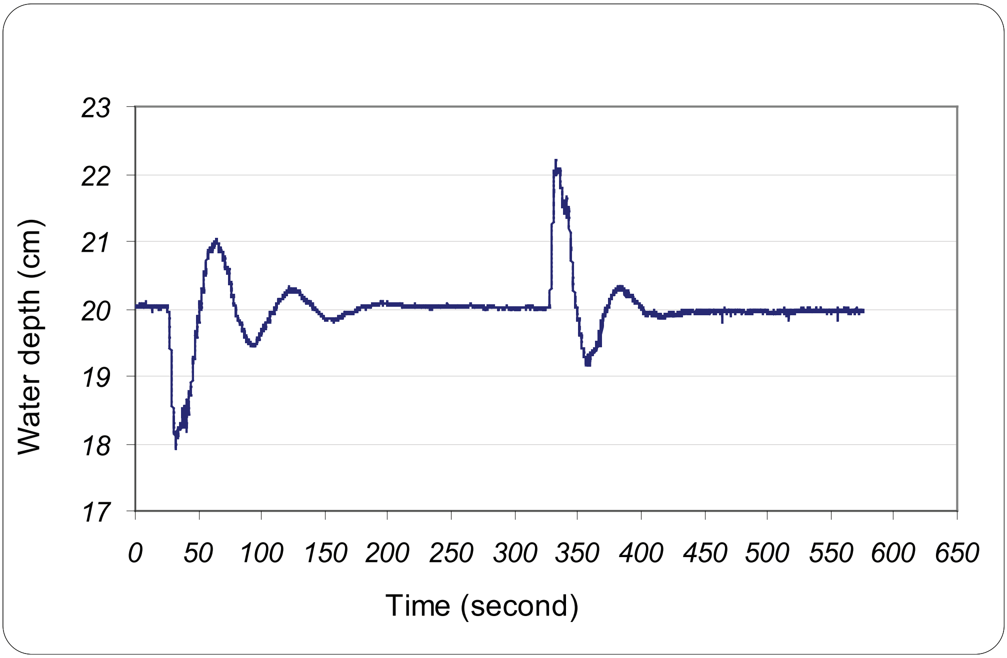

Fig. 9. Water depth changes versus time (Les changements de profondeur de l'eau en fonction du temps)

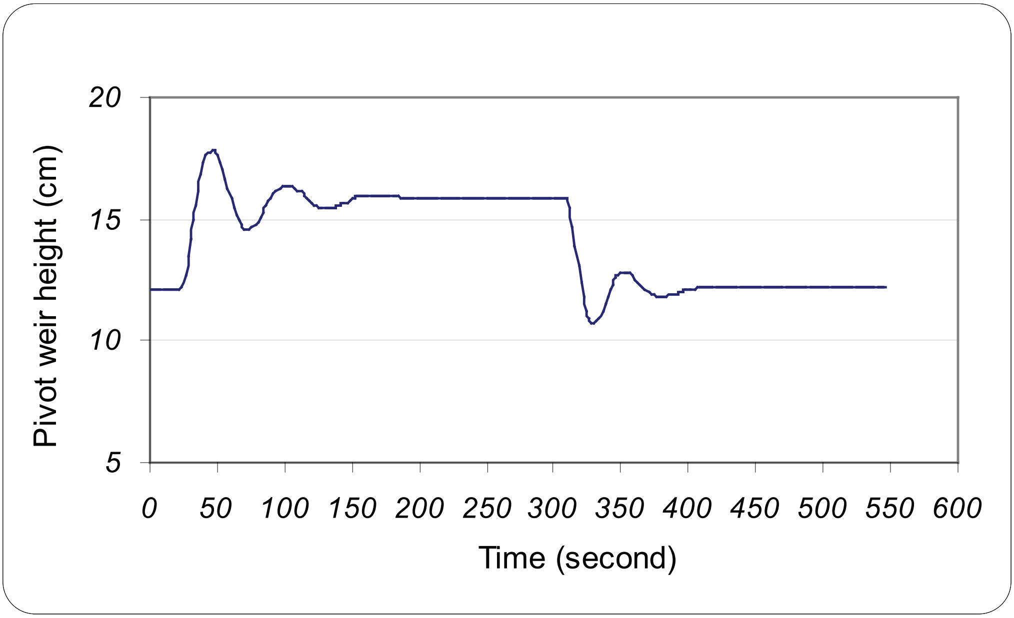

Fig. 10. Pivot weir height changes versus time (Changements Pivot hauteur du déversoir en fonction du temps)

There are many ways to examine the amount of error in the water levels. In this paper were used following three indicators: (Clemmense et al., 1998)

1. Maximum Absolute Error (MAE): It idicates the mamaximum error between absobserved and target water depth which can be calculated from Equation 7.

$$MAE = \frac{\max\left|y_m - y_t\right|}{y_t} \tag{7}$$

Where y_m and y_t are observed and target water depth, respectively.

2. Integral of Absolute Magnitude of Error (IAE): It shows the average deviation of water depth from target depth during operation that could be calculated from Equation 8.

$$IAE = \frac{\frac{\Delta t}{T}\sum_{t=0}^{T}\left|y_m - y_t\right|}{y_t} \tag{8}$$

Where Δt and T are regulation time step and time period for test, respectively.

3. System Response Time (SRT): System response time is the time duration which water depth is out of admissible band. The admissible band is a range around the target depth

that defined as $y_t \pm 0.5 \times x \times y_t$ where x is defined by user. The less SRT is appropriate for a system.

Afer control soefficients detemination, MAE, IAE and SRT were calculated for two scenarios that Table 2 shows them.

Table 1. The assessment indicators for increase and decrease inlet discharge

Assessment indicator	Increase inlet discharge (5 to 15 lit/s)	Decrease inlet discharge (15 to 5 lit/s)
Max diviation from target depth (cm)	2.22	2.21
MAE	0.11	0.1
IAE	0.09	0.12
SRT(10%) Second	0	9
SRT(5%) Second	1.5	16.1
SRT(2.5%) Second	19.5	19.1

Following results can be obtained from Figure 8, Figure 9, and Table 1:

- When inlet discharge is decreased the upstream water depth decrease rapidly.control system acts so that the pivot weir hieght increase and discharge over the weir decrease untill the upsream water depth reaches the target depth.
- When inlet discharge increased the upstream watre depth increase rapisly. In order to maintain water depth in target depth, the control system decrease the pivot weir hieght and the discharge over the weir increase untill the upstream water depth gets the target depth.
- There is no difference in inlet dischrage increase and decrease in MAE point of view, but the IAE values show that the control system can regulate the water depth in increase changes better than decrease changes.
- The SRT values in 10, 5, and 2.5 % levels show that the control system is able to regulate the upstream water depth in appropriate duration. Moreover, it can be seen control system can control the increase of inlet discharge better.

Next, in order to test the specified control coefficients, tow inlet discharge increase and decrease in exprimental discharge range (5-15 lit/s) were done and the water depth and pivot weir height changes were drawn. Figure 11 and Figure 12 show the water depth and pivot weir height changes for increase and decrease change in 6-12 lit/s range (decrease discharge from 12 to 6 lit/s and increase it from 6 to 12 lit/s) and 8-13 lit/s range, respectively.

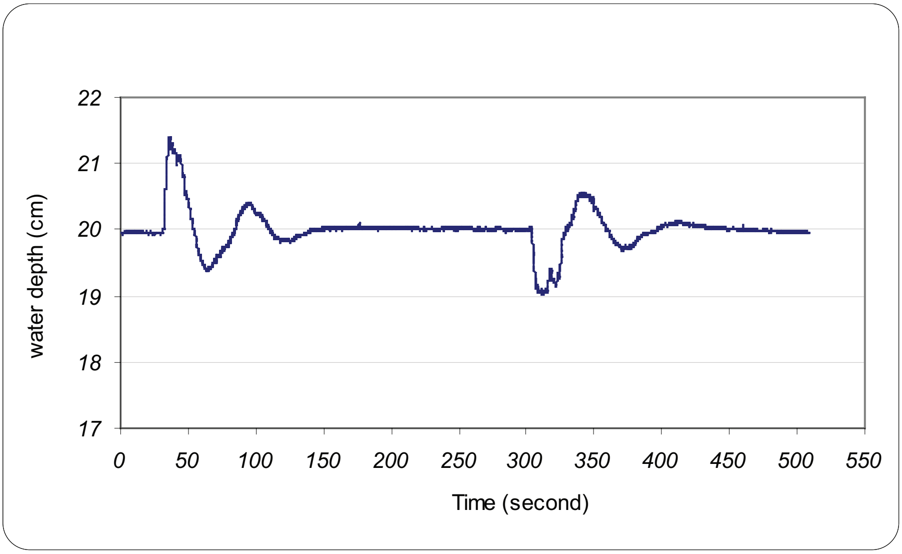

Fig. 11. The water depth deviation versus time for 6-12 lit/s (L'écart de profondeur d'eau en fonction du temps pour 6-12 lit/s)

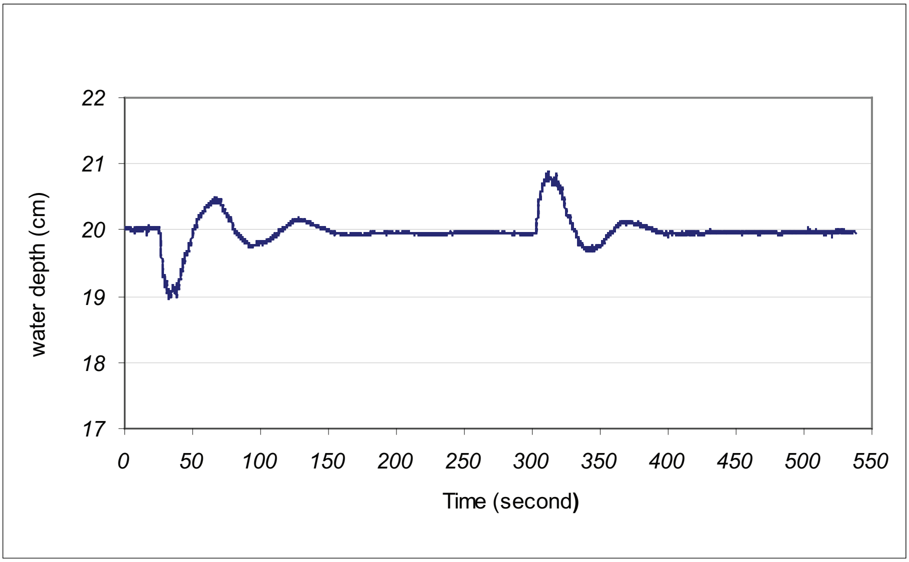

Fig. 12. The water depth deviation versus time for 8-13 lit/s (La profondeur de l'eau déviation en fonction du temps pour les 8-13 l / s)

Then, the assessment indicators were calculated for tow scenarios. Table 2 and Table 3 show the assessment indicators for 6-12 lit/s discharge range and 8-13 lit/s discharge range, respectively.

Table 2. The assessment indicators for increase and decrease inlet discharge (6-12 lit/s discharge range) (Les indicateurs d'évaluation pour la décharge d'entrée augmentent et diminuent (6-12 lit /s de décharge s)

Assessment indicator	Increase inlet discharge (6 to 12 lit/s)	Decrease inlet discharge (12 to 6 lit/s)
Max diviation from target depth (cm)	0.62	0.55
MAE	0.07	0.05
IAE	0.07	0.064
SRT(10%) Second	0	0
SRT(5%) Second	11	0
SRT(2.5%) Second	15.8	15.8

Table 3. The assessment indicators for increase and decrease inlet discharge (8-13 lit/s discharge range) (Les indicateurs d'évaluation pour la décharge d'entrée augmentent et diminuent (8-13 lit / s de décharge s)

Assessment indicator	Increase inlet discharge (8 to 13 lit/s)	Decrease inlet discharge (13 to 8 lit/s)
Max diviation from target depth (cm)	0.88	1
MAE	0.04	0.05
IAE	0.05	0.066
SRT(10%) Second	0	0
SRT(5%) Second	0	2.3
SRT(2.5%) Second	16.4	15.4

Figure 11, Figure 12, Table 2, and Table 3 show that the provided control system can control discharge changes in 5-15 lit/s range appropriately.

This paper recommends that the other control logics should be tested on laboratory physical models first and may apply in real condition.

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