Modeling and regulation of irrigation canals: existing applications and ongoing researches

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ABSTRACT

The objective of this survey paper is to review the main methodologies used in the development of models and in the design of controllers for irrigation canal systems. These systems are characterized by time delays, non-linear features, strong unknown perturbations, and interactions among subsystems. Although a large part of these developments are still at the research stage, more and more of these techniques have successful field implementations.

MODELING

An irrigation canal is an open water hydraulic system, whose objective is mainly to convey water from its source (Dam, River) down to its final users (Farmers). Cross structures (mainly hydraulic gates) are operated in order to control the water levels, discharges and/or volumes along this canal (Fig. 1).

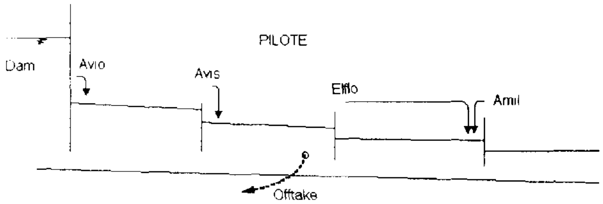

Fig. 1. Irrigation canal with cross regulators

Simulation models

The physical dynamics of such systems can be correctly approximated by Saint-Venant's equations [4] which are non-linear partial derivative hyperbolic equations (distributed model), combined with non-linear algebraic cross structure equations. These equations are:

$$\text{Mass} \qquad \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$$

$$\text{Momentum} \qquad \frac{\partial Q}{\partial t} + \frac{\partial Q^2/A}{\partial x} + g.A\frac{\partial z}{\partial x} = -g.A\,S_f$$

with: A = cross section area (m^2), t = time (s), Q = discharge ($m^3\ s^{-1}$), x = longitudinal abscissa (m), in the direction of the flow, q = lateral inflow or outflow ($m^2\ s^{-1}$), $g = 9.81\ m\ s^{-2}$, z = water surface absolute elevation (m), $S_f = \frac{n^2Q^2}{A^2R^{4/3}}$ friction slope, n = Manning coefficient, R = hydraulic radius (m).

These equations must be completed by external and internal boundary conditions at cross structures, where Saint-Venant's equations are not valid, and by initial conditions. Depending on the type of cross structure and hydraulic conditions, these equations can have different forms:

Weir - Free flow: $Q = C_{WF}\, L \sqrt{2g}\, h_1^{3/2}$
Weir - Submerged: $Q = C_{WS}\, L \sqrt{2g}\, (h_1 - h_2)^{1/2}\, h_2$
Gate - Free-flow: $Q = C_{GF}\, L\, w \sqrt{2g} \sqrt{h_1 - w/2}$
Gate - Submerged: $Q = C_{GS}\, L\, w \sqrt{2g} \sqrt{h_1 - h_2}$

with: L = device width (m), h_1 (resp. h_2) = upstream (resp. downstream) water depth (m), w = device opening (m), C_{ij} = discharge coefficients.

These separate equations are not sufficient, since a device can, during its operation, change from one hydraulic condition to another. Therefore, a continuous transition between hydraulic conditions is required [12].

Saint-Venant's equations have no known analytical solution in real geometry. In some simple cases (zero slope, no friction, constant rectangular cross section), the hydraulic behavior of such system can be studied through the method of characteristics. But, for further tests on real systems, these equations have to be solved numerically. Several finite difference numerical schemes are used, either explicit or implicit. One of the most used and well-known is the Preissmann implicit scheme [17].

Models for control

Complete non-linear model: The Saint-Venant's equations and the complementary internal and external boundary conditions can directly be used to design a controller as we will see in the next chapter [14]. But this is a very recent work, to be published, and on limited systems.

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Complete linearized model: A linearized version of these equations can also be used [58], [9]. This approach and the former non-linear one are powerful since they use the most complete version of the system model. But, the mathematical techniques required to design the controller are more complex, and can be used, for the moment, only on homogenous geometry.

Infinite order linear transfer function: Since the above described models are not very easy to use when designing a controller, some simplified models have been derived from the previous ones through some simplifications. A linearization, Laplace transform and integration of the above Saint-Venant's equations lead to a linear infinite order model [5], [6], of the following form (in the frequency domain):

$$\begin{pmatrix} Q'_{x^*} \\ Z'_0 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{22} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} Q'_0 \\ Z'_{x^*} \end{pmatrix}, \text{ with:}$$

where Q'_{x^*} is the discharge variation at distance x^*, Z'_{x^*} is the water depth at the same location, and Q'_0 and Z'_0 are the same values at the reference location $x^* = 0$. The m_{ij} are parameters obtained from the geometry and the hydraulic state of the canal system. This model has the advantage of keeping the distributed parameter system characteristics and therefore the infinite state space dimension. It supposes that the concerned system is homogenous and at the uniform flow conditions.

Finite order non-linear model: A discretized version of Saint-Venant's equations (in space, or time and space) can also be used [31]. A numerical approach is therefore used instead of a mathematical one. The main advantage is to simplify the control design and to allow this approach for almost any type of canal system, while keeping the non-linear features of the system. The main limitation is that these models, based on numerical schemes such as the Preissmann scheme require subcritical flow. The same approach can maybe be extended to supercritical flow, by using other schemes, but this was never tested according to the authors' knowledge. The numerical scheme introduces a discrepancy in the modelization, but this type of model can still be considered as very precise.

Remark: On systems with mainly supercritical flow, such as steep rivers, the Saint Venant's equations can be simplified (by removing the inertial terms). In this case the obtained model is a non-linear diffusive wave model. It can be solved numerically by a Cranck-Nicholson scheme. It can also be further simplified to a linear Hayami model.

Finite order linear model (state space model): The non-linear or the infinite order feature of the previous models reduce the spectrum of control theories that can be used. In particular, all the methodologies developed in the field of LQ optimal controllers cannot be used. To allow this, a linear finite-order state-space model is required and can be obtained (lumped model obtained from linearization and discretization of the Saint-Venant's equations). The form of this model is:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) + B_p p(k) \\ y(k) = Cx(k) \end{cases}$$

Where x is the state vector, y the controlled variable vector, p the perturbation vector, and A, B B_p and C matrices of appropriate dimensions.

In fact this model is the same as the previous one, except that the A, B, B_p matrices are constant (they do not depend on the time t nor on the state x). A similar model can also be constructed from the aggregation of different SISO transfer functions, between the different controlled and control action variables [26], [29].

Finite order linear model (transfer function): The advantage of the previous model is to be simple enough and to cope with the multivariable feature of the considered systems. But, on large systems, it can be costly in terms of required data, memory space, computation time. In order to overcome this difficulty, some simpler linear MIMO or SISO transfer function models can be used. These models can be first order, second order or second order with delay, depending on the size of the system and hydraulic conditions [32], [48], [49], [45].

Neural network model: Like in most industrial fields, neural network models and controllers were tested for irrigation canals or rivers [56], [55]. The identification phase is costly and difficult when the canal system is at the design stage. So far, these experiments have not been very successful.

Fuzzy model: This type of model and corresponding controllers have also been designed for irrigation canals [8], [57], [53], [52]. The advantage of this model is mainly to easily provide a non-linear model of the system. But its quality is not as good as the previous ones. Also, for MIMO systems this approach seems difficult.

Petri Net models: The first application of this type of models to irrigation canals have been presented recently [15]. The advantage of this type of models is to allow the use of many techniques and tools that proved to be efficient in systems bearing a close resemblance to canal network systems.

Measured, Controlled and Control Action Variables: Although not discussed in the above paragraphs, the choice of the variables manipulated by these models is also an important issue (levels, discharges, volumes, gate openings). The ***measured variables*** are almost always water levels at as few locations as possible. Usually these measurement points are the upstream and downstream level of cross devices. If the cross device is free flow the upstream level can be sufficient. Often these measurements allow, through the use of a calibrated rating curve, and the structure position, to compute the discharge at this location. The ***controlled variables*** can be levels, discharges, volumes, at different locations. This choice is important on a hydraulic point of view [35] (available storage volume, required bank elevations, etc.). The ***control action variable*** is also important. Some people use the gate opening, others use the discharge at the cross structure. Although advantages and drawbacks of both approaches have been quoted, a clear consensus does not exist on this point [35], [48].

CONTROLLERS

Different methodologies have also been used for the design of the controllers. The oldest and most popular ones, after some empirical methods, are the classical PID controllers. But due to the time delays inherent to these hydraulic systems, to non-linear features, and to interactions among subsystems, many other methods have been tested and are still under development. These methods are listed hereafter, with the basics references. For complete literature review, refer to [2], [11].

Heuristic monovariable methods have been developed based on hydraulics and not on control theory (e.g.: Zimbelman, CARDD). Although quoted in the literature they are hardly operational and too site specific. LittleMan is an empirical method based on a three position controller [42]. These methods have to be tuned on a complete simulation model, or on the real system, since no mathematical tool can enable this, nor prove their performances. This is one main drawback of heuristic methods.

PID: Most of the irrigation canal control methods based on control theory use the well-known linear monovariable PID controller. Examples of PID related methods are: P: AMIL, AVIS, AVIO; PI: ELFLO, BIVAL, Dynamic Regulation; PI: Sogreah; PID: UMA Engineering. Some are tuned using a simplified model of the process (Cf. previous chapter, e.g.: by pole placement on a SISO transfer function), some are tuned directly on the real process or on a full non-linear simulation model (e.g.: with the Ziegler-Nichols method).

Smith Predictor: Although very efficient in most cases, PID controllers do not explicitly take into account the characteristic canal time delays. In 1971, Shand [51] prospected the possibility to use a Smith Predictor in order to overcome this problem, when studying the automation of Corning Canal, California, USA. Developing an analog dead time model raised technological difficulties, at this time. Therefore, though less efficient, ELFLO method was eventually selected. Recently, the combination of a PI controller with a Smith Predictor was further developed [18], [45]. This controller is called PIR. Modern digital technology has solved problems faced by Shand.

Pole placement: Other linear controllers have been used on river systems with long time delays by CACG, [39]. High order transfer functions are used, and tuned with the pole placement technique.

Predictive control: The predictive control method, an usually monovariable optimization method, has been applied to canal systems by several authors [46], [41], [43], [38], [1]. It is not based on the desired closed-loop behavior, but on the minimization of a criterion J, weighting the control action variable and the error between the controlled variable and its targeted value. Predictive control method uses transfer function or state space models [36]. It can naturally incorporate an open-loop and a closed-loop.

Fuzzy control: Methods based on fuzzy control [8], [57], [53], [52], expert systems, or neural networks [47], [55] have been developed. Genetic Algorithms have also been tested on such systems. At least 3 successful field applications can be reported for fuzzy control, on SISO systems (T2, CPBS, and Roosevelt canals).

Model inversion: Different model inversion methods (also called Backward Computation) are described in the literature, leading generally to open-loop controllers [20], [37], [13], [30], [7], and more rarely to closed-loop controllers [31]. They are based on a finite-order non-linear model. Inverting such model including diffusive dynamics can generate oscillatory behavior. In order to prevent this, damper coefficients have to be introduced. They have to be tuned by try and error procedure since no mathematical tool can enable this.

Optimization methods have also been developed. These methods are, in essence, multivariable. Different methods exist: linear optimization [44], non-linear optimization [54], [25], [27], and LQR [16], [3], [24], [22], [21], [40], [32], [33]. The classical non-linear optimization leads solely to an open-loop, sensitive to errors and perturbations. In order to introduce a closed-loop, the optimization has to be processed periodically (for example at each time step). This complicates the method and limits its applications due to real-time constraints. Furthermore, the determination of real initial conditions, required for the optimization, is not easy. On the other hand, LQR methods, based on a state space representation, incorporate, in essence, an open-loop and a closed-loop. Recently H_2 norm minimization has been tested on canal systems. This approach has the advantage to allow the choice of the structure of the multivariable controller, and in particular to design a decentralized controller [50], [48]. When the order of the system is too large, or in order to design a decentralized controller, a decomposition-coordination approach can be used [26], [19].

Robust control: since some important characteristics of the considered systems are the strong unknown perturbations, and the model errors partly due to non-linear effects, robust control approaches are interesting and have been tested by several authors [48], [28].

Adaptive control: Non-linear features of the model can be taken into account by using adaptive linear controllers [10] or by using gain scheduling [45].

Non-linear control: A direct non-linear approach can also be used [14]. This latest method is probably the most difficult one, on the theoretical point of view. But if the non-linear effects are the main control difficulties, it can also be very powerful.

COMPARISON

Until recently it was very difficult to have an idea of the advantages and drawbacks of the different above quoted methods, and on their performances on canal systems. This was due to the fact that each author designed a new method on a new canal system, without comparing its method to others. Some synthesis work started to fill the gap [23], [34], [59]. A task committee of the ASCE proposed to push this effort further, and defined Test Cases. Some authors started to compare their methods on the proposed Test Cases, [2]. So far 3 methods have been tested on them: CLIS (Backward computation, [31]), PILOTE (LQG, [33]) and PIR (PI + Smith predictor, [45]).

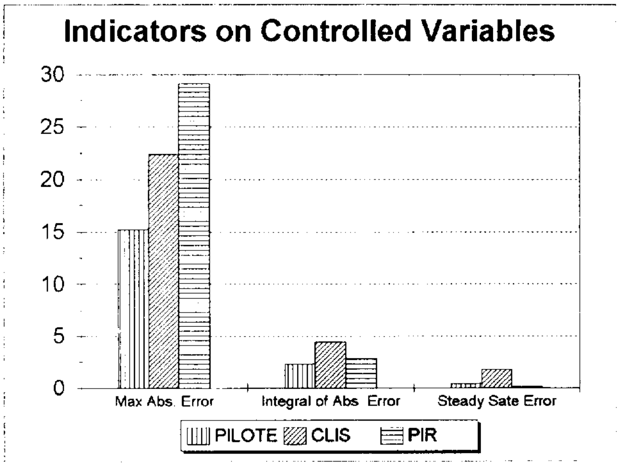

Fig. 2. Performance indicators on controlled variables

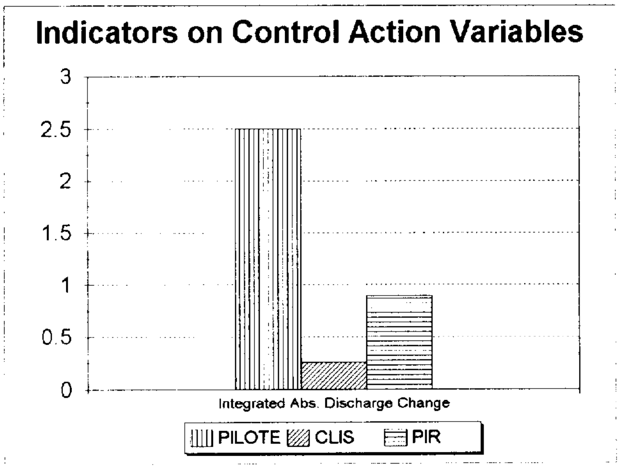

Fig. 3. Performance indicators on control action variables

Even though these results have been obtained from simulation on the same canal and scenarios, it is still difficult to make a definitive comparison. First of all, each author used its own simulation model, with some differences, since the Test Cases left some minor parameters undefined. Then, the objectives of the different authors were maybe different during the design and tuning process. We can observe that PILOTE obtains the best performances on the controlled variables (Fig. 2), but with more aggressive use of control action variables (Fig. 3). The ability of a multivariable controller to allow aggressive actions (in a reasonable domain), while staying stable and non-oscillatory is one of the best proof of its quality. But maybe all authors did not try to get this type of performance. This means that these Test Cases have probably to be improved in order to provide a better basis for comparison, which seems to be an interesting objective.

CONCLUSION

Control engineers have developed several monovariable and multivariable methods for irrigation canal or river systems. All of them have been developed and tested on simulation models. However, so far, only monovariable closed-loop methods or open-loop controllers have been applied to real systems. Pole placement technique in state space, multivariable PID, LQG controllers, closed-loop backward computation controllers, have never been applied to real irrigation canals. Important advances have been made recently as demonstrated in this paper, and in the quoted references. Still important efforts have to be made to improve the robustness of the algorithms (robust control, adaptive control, non-linear control), to improve the performance of monovariable controllers (decoupler, predictive controllers, internal model controllers), to reduce the computational efforts of the multivariable controllers (decentralized controllers), and to take into account possible defaults on sensors or devices. A close interaction of the different people working in this field, with different approaches, and the definition of a common basis of comparison of the developed methods such as the above quoted Test Cases will facilitate this work.

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