# CONTROL SYSTEMS FOR HYDRAULIC STRUCTURES AND EQUIPMENT

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## Contents

## Summary

A review is presented of the major aspects of control systems involved in the operation of hydraulic structures and equipment. Typical examples are given from water resources engineering practice. The principles of signal input and action output, and the mechanical and electrical devices involved in a wide variety of control systems, are outlined. The importance of fail-safe and sustainable operation of all components in a water supply or marine engineering system is emphasized. Examples of typical applications are given, such as water treatment plant operation, water power generation, pumping and conveyance of water, scheduling of irrigation water through automatic gates, and some hydraulic instability phenomena and their management.

## 1. Introduction

This article was compiled from many sources and gives an indicative, as well as representative, but by no means exhaustive, concept of control systems. In the operation of a water supply project, some form of human intervention or controlling action is necessary to achieve the objective from one instant to the next. The operation of a large power plant, a complex construction site, a production component for water resource development, or a water supply network, is an intricate undertaking, but involves a multiplicity of unit processes, as described below.

Control systems have a wide scope of useful application in the water supply industry. The purpose of control systems is to ensure the optimal functioning of the following types of installations:

- water treatment plants, including desalination plants;
- water power (hydroelectric) installations;
- dams and their operating equipment, including valves, spillway gates and handling equipment;
- canals, including sluice gates, off-takes and scheduling; and
- pipeline systems, including flow meters and pressure regulators.

The scope covered by this article includes the following:

- types of controls (hydraulic and fluidic controls, electrical and manual controls, including telemetry);
- control elements;
- methodological design principles;
- intuitive system design; and
- numerous examples in the water resources development field.

For smooth running and safe operation, all systems, components and subcomponents, must be under complete control at all times. Many safety and backup features are involved for the system to meet its purpose of life support, to be sustainable, to be economic, and not be liable to accidental malfunctioning. This is both a challenge, and an achievement that has been mastered many times over in the fields of water supply to cities, and hydropower supply to large consumer networks.

The principles and examples of control systems presented here are intended to be guidelines, but are not exclusive. Such systems are generally supplemented by so-called black boxes, or microprocessors, that prevail throughout the chemical and industrial engineering fields, and are linked in modern times to computers and databases. Control systems have been automated to a great extent, but should always have the capability to be manually overridden at the operator’s discretion.

## 2. Theory and Principles of Control

These guidelines to control systems for hydraulic structures and equipment are intended to be introductory. Distinction is necessary between manual control and automatic control. Manual control is cumbersome, nonuniform and needs training and detailed instruction manuals.

Human responsibility for actions taken can never be supplanted by automatic devices, no matter how sophisticated they might become, e.g., the automatic elevator system in a high-rise public building is efficient, fast and safe, but still needs periodic inspection and maintenance.

A heavy responsibility therefore lies on the decision makers and administrators of water-related life-support systems, which are by nature complex, to ensure that the operation and control of such technological wonders are reliable, sustainable and fail-safe, for the benefit of the population at large.

## 2.1 Theory of Control

The theory of control is an involved mechanical and electrical engineering subject and includes concepts such as exponential decay, critical damping, time constant, resonance, over- and under-correction, etc. For a control device to be able to function correctly, accurate knowledge, therefore measurement, is necessary, both of the desired output in the first place and also of the response time constant.

Sound mathematical principles underlie the philosophy of obtaining a desired output by means of a correctly selected input. This dictum is prevalent in the biological, the socioeconomic and the technological world, and dealing with the more abstract principles falls beyond the scope of the present article, but is well introduced elsewhere (see Elements of Control Systems).

## 2.2 Operational Sequence

In as much as control systems are part and parcel of any hydraulic structure and are intended to ensure smooth operation, there is always an operational sequence of events required. If a constant supply of water is the objective, then the hydraulic equipment which has to facilitate this action, is itself also subject to certain other control systems. For instance, in any control system, such as found in hydraulic water-supply equipment that involves an input signal and an output action, the following sequence of operations apply:

- A sensor detects the need for an action and generates a signal.
- The signal is then sent via a transmission system to an input control switch to an actuating mechanism.
- The actuating mechanism, activating a prime mover, operates the control element.
- The desired action (of the piece of equipment) then follows.

## 2.3 Operational Aids

Mechanical systems, telemetry, or online data transmission by hard-wire electrical, optical fiber, radio, telephone link, or satellite, to a processing base, are standard practice operational aids. These can be backed up by an information center, and an offline data processing center, equipped with computers, software and modem links for analyzing and predicting (forecasting) events such as progress of floods, flood routing, drought sequences, groundwater drawdown, reservoir status, and demand and supply scenarios (see chapter *Probabilistic Methods and Stochastic Hydrology*).

The extent of these operational aids varies greatly from modest farm, town and rural networks to elaborate city, regional and national/international grids in the water supply systems. A regional agricultural water supply network can be quite complex to operate, and these aids to automatic control can be invaluable (see chapter *Flow Measurement in Free Surface Flow*).

### 2.4 Safety Precautions

Before going into the finer details of the design and operation of an actuator control system for hydraulic equipment, such as used in water supply, a cardinal principle has to be outlined. A life-support system must be fail-safe in all respects, and must in itself not endanger lives. Failure of the water supply could do so, but any malfunction of the control system itself could cause fatal accidents.

Where large forces are held in balance and kept there by small actuators, and even smaller control elements, let alone minuscule sensors and push-button switches, the chances for component malfunction and human error are ever present. Items such as built-in safety interlocks should, therefore, be installed into the system, so that the gate or valve or piece of equipment would remain secure, even if the main power or the control-system’s own power should fail. Manual overrides, or the ignoring of warning indications, could be critical in an emergency. The time delay between signal and action is a very important factor and should be understood.

The importance of training personnel to cope correctly under all circumstances, beyond the normal operating conditions, is vital. Backup capability should be built in, and rehearsals and maintenance routines regularly exercised, to ensure that all such systems are indeed available when needed.

The design of a control system must only be done by qualified professionals, and the operation thereof by certified technical staff. All personnel involved must be familiar with all operating scenarios, safety routines, and time constants involved. The detailed design of a system could be done by the intuitive approach only based on experience, usually the more economical first case option. It could also, and preferably so, be designed by a rigid methodological approach, using standardized components, techniques and working drawings. The principles will be outlined in the following sections.

## 3. Design Principles

There are two ways to approach the design of control systems: methodological and intuitive. The first follows standard textbook procedures and ensures a uniform, intelligible layout that can readily be understood, operated and serviced by technically trained personnel. The second method is commonly known as Rube Goldberg “jerry rigs” or Heath Robinson “contraptions,” intelligible only to the inventor, but once standardized may be better than the first.

### 3.1 Methodological Design

The methodological approach would start with an idea, pursue with bench or laboratory tests, first establishing a pilot plant, then a full-scale production prototype, before going into standard practice and mass production.

There is a wide choice of control system working media and components, such as found in industrial applications, manufacturing, processing, etc. (electric—AC or DC;

hydraulics—oil; mechanics—gears and levers; and combinations of all of these), available through which the desired actions (force, stroke, motion—linear or rotary) can be executed. Likewise, there are a large number of control element media and components available (electrical, electronic, mechanical, pneumatic, hydraulic, magnetic, sound, light, chemical circuits and switches, etc.) to control the desired action.

For example, in the case of hydraulic (water control) equipment, the actions can be: the raising or lowering of a sluice gate; the opening or closing of a valve; the starting or stopping of a pump-motor set; the increasing or decreasing of system pressure; the handling of heavy equipment, such as stop-logs or trashrack-rakes; the taking on or casting off of load by a turbine-generator set; the charging or discharging of stored materials; and the lubrication of mechanical plants and mills, etc. The components to effect the action and its control are not designed from scratch, but are selected from manufacturers catalogs.

The most elementary action required is that of producing a linear motion or force against an opposing force (pressure or gravity), e.g., the raising of a heavy sluice gate. For producing a rotary motion against torque, (e.g., the opening or closing a spherical or butterfly valve) a lever/hand wheel/gear action is required. The operator normally selects the action desired by “push-button” switch control, after having obtained status information via sensors (optical, electrical, mechanical, thermal, magnetic, capacitance, inductance, resistance), in some cases automatically—e.g., the stopping and starting of a sump pump by water-level sensing controls. The switch (push button, knife, toggle, or rotary type) relays the signal to effect the desired action via the control element medium to the working actuation medium.

The control element could be a sliding or rotary valve, operated by a solenoid which then imparts direction to the motion of the actuator by admitting the working medium (e.g., compressed air or hydraulic oil) along the selected path into the output device (e.g., a double-acting cylinder). A feedback sensor is also needed, to return a stop or cancel action signal after the action is completed (and energize status lights or sound signals to convey information back to the operator that the desired action has been effected). The action completed is thus locked in and the control system for the time being deactivated or maintained in dormant mode, until needed again.

There are a number of considerations governing the design of a reliable control system for hydraulic equipment: ease of use and maintenance, safety, sustainability and affordable cost. The following criteria should, therefore, be applied when designing a control system of this nature:

- safety and reliability against power failure (interlocks, feedback sensors and signals);
- operating ease (controllability, low energy costs);
- sensitivity and service life (fail-safe and backup systems needed); and
- reliability (accessible, interchangeable, maintainable).

### 3.1.1 Typical Applications for Control Equipment in Water Systems

There are a great number and variety of controls in water systems, for controlling flow rate (discharge), pressure, pumps, prime movers, materials, etc. Some of these devices are the following:

- Pilot valve, service valve, main valve, adjustable control valve (active).
- Check valve, non-return valve, pressure release valve, float switches (flow control).
- Batching plants, door and hopper controls, weighing (process control).
- Skips, loaders, conveyors (materials transfer).
- Cranes, hoists (handling equipment).
- Earth movers, cableways (construction equipment).
- Pump-motor sets (start—stop).
- Turbine-generator sets (start—stop, governing).
- Feeders, aspirators, regulators (chemical dosing).
- Instrumentation (status-information, monitoring and data retrieval).

There are also some control system principles to be observed that have been proven superior in practice. For example, double-action cylinders are more efficient than single-action cylinders for positive opening and closure, while nonforce-reversible motions (screw and nut, worm and gear) are more effective for preventing back-fall than force-reversible motions (rack and pinion, cable hoist). Run-away or jamming may occur where the opposing force (gravity, springs or pressure) cannot overcome binding friction.

Reversed motion should, therefore, only be possible under reversed applied power for heavy hydraulic equipment in waterworks practice. In order that water control can be safely executed at all times, emphasis should also be placed on quality control in the construction of water-control structures, and not only on the control of the water itself.

The tabulated lists below give details of: (a) sensor types and processors, and signal outputs; (b) types of controls, actuators, switches, and power sources; (c) the causes and characteristics of types of action in control systems; and (d) the requirements for critical situations to be avoided with certainty.

(a)

| Types of Sensors and Processors, Signal Outputs | | | |
|---|---|---|---|
| Sensors: | photo-cell | Signal Outputs: | color lamps |
| | optical-fiber | | LEDs (light-emitting diodes) |
| | coaxial cable | | buzzers |
| | thyristors | | analog (dials) |
| | transducers | | digital (displays) |
| | solid-state processors | | printouts |
| | meters (flow, level, temperature, etc.) | | monitors (video) |
| | proximity type | | starters (e.g. standby power) |

| | | | |
|---|---|---|---|
| | video cameras (motion detectors) | | fans, sprinklers, cut-outs, etc. |

(b)

| Types of Controls, Actuators, Switches, Power Sources | | | |
|---|---|---|---|
| Controls: | limit stops | Switches: | “normally open” NO |
| | cams and rollers | | “normally closed” NC |
| | electromagnets | | “change-over” CO |
| | solenoids (hollow core) | | ganged, two-way, three-way, multiplex |
| | relays, selsyns | | float switches |
| | servo-mechanisms | | fuses |
| | stepping motors | | circuit-breakers |
| | linear motors | | earth-leakage |
| Actuators: | cylinders | Power: | electricity DC - 24V |
| | slide valves | | AC - 400V 3-phase |
| | rotary valves | | - 220V 1-phase |
| | electromagnets | | vacuum |
| | | | compressed air |
| | | | water power |
| | | | diesel generator set |
| | | | batteries (solar cell charged) |

(c)

| Types of Action in Control Systems have the following causes and characteristics: | | |
|---|---|---|
| undamped motion | positive feedback | synchronization |
| critically-damped motion | negative feedback | resonance |
| over-damped motion | manual override | natural and forced frequency |

(d)

| The following requirements are needed for critical situations to be avoided with certainty: | | | |
|---|---|---|---|
| needed: | backup control | to avoid: | system failure |
| | interlocks | | slam, overrun |
| | throttling | | accidental operation |
| | damping | | hunting, rebound |
| | fail-safe | | run-away |
| | limited-automation | | operator failure |

Table 1 below shows the various types of control elements, action media and examples in the broad field of industrial control systems, with particular application to water control structures and their operation and maintenance. It lists several examples of combinations of system components with their control elements and action media.

| Control Element | Action medium | Example |
|---|---|---|
| mechano- | mechanical | steam locomotive (Walschaerts-Gear) |
| electro- (AC.) | electrical (DC) | Ward-Leonard system (for variable speed) |
| electro- 3-phase AC. | mechanical | star-delta starter on crane winding-drums |
| mechano- | electrical (DC) | direct-on-line, knife starter on DC |
| electro-,<br>mechano- | hydraulic (oil) | gear pump, diesel drive, hydraulic cylinder operated hoist or earth-moving-machine |
| electro | pneumatic (compressed air)<br>pneumatic (vacuum) | pneumatic cylinder operating experimental wave-generator |

Table 1. Methodological control system components

For an example in more detail the following typical case is presented, using the last system listed in Table 1—an electro-pneumatic control system:

- The action signal travels forward on the pneumatic part of the system, controlling from the air reservoir to the action center.
- The sensor signal travels backward on the electrical part of the system, controlling from the mains supply to the energizer.

As an illustration of this typical control circuit in a schematic way, the following indicates how a pneumatic circuit to effect the desired action is achieved by means of an electric control circuit, sensing and controlling the action in its entirety. The route to follow is clockwise from top-left, horizontally to right, then down and to left, up again and so forth, according to the arrows.

***Pneumatic Circuit***

(air reservoir) → energizer ⇒ control element ⇒ activator
(solenoid) (slide valve) (position cylinder)

**POWER** **WORK**
**SOURCE** ↑ ↓
**EQUIPMENT**

***Electric Circuit***

(Mains) → energizer ⇐ input control ⇐ limit sensors reed
(solenoid) (switch) (magnetic switch)

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## Biographical Sketch

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