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Research and Evaluation on the Control Methods and Fault Detection of Flow Valves

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***Abstract*— In this paper flow control valves are studied. More specifically, an effort has been made to identify the methods used for flow control and to analyze the various functions of flow-control valves in order to suggest the most compatible method of flow control per case. Moreover, an analysis maintenance methods is given in order to establish when and where they should be applied.**

Keywords—Flow control; valve; maintenance; PID

I. INTRODUCTION

One of the most widespread pieces of equipment - in almost all production lines - are flow control valves.

Far too little has been done over the years to sustain the performance of control valves once they go into operation. Rather than considering control valves as assets to be preserved, many companies treat them as liabilities – frequently replacing valves in critical positions during shutdown or docking for no other reason than length of service. Maintenance departments often deal with costly emergency repairs, making it necessary for a company to monitor and manage its physical assets. In recent years model based diagnostics and prevention has been investigated to improve the operation and reliability of flow control valves.

II. FLOW CONTROL VALVES – OPERATION AND PRINCIPLES

"A control valve is a power operated device which modifies the fluid flow rate in a process control system. It consists of a valve connected to an actuator mechanism that is capable of changing the position of a flow controlling element in the valve in response to a signal from the controlling system" ISA S75.05 [1]

Flow control is achieved in a system when a liquid is passed through an orifice, creating a drop in pressure & increase in Velocity (Kinetic Energy). But the flowrate on inlet and outlet would be same. In this way pressure can be controlled keeping the flow constant. A flow control valve delivers a constant flow regardless of the pressure drop through the valve. The flow rate is the ratio between the pressure gradient between inlet and outlet and the fluidic resistance of the device. To get a constant flow, the fluidic resistance shall vary in linear format with the pressure gradient. In a simple orifice, the flowrate increases with the applied pressure.

Pressure control valves accommodate a mechanism that opens the valve when it reaches a predetermined pressure threshold, the pressure at the outlet remaining substantially constant while the flow increases dramatically after valve opening. Almost all passive valves on the market or valves in the human body (cardiac valves etc) are based on this principle. [2]

Flow control valves are special fittings designed for use in complex hydraulic and pneumatic systems. The control valve fittings are used to reduce the actual flow rate in a specific area of a pneumatic circuit.

III. HISTORIC DATA

The concept of a control valve goes at least as far back as the Roman Empire where bronze plug cocks were used in the aqua ducts.

The concept of a moving-stem valve was introduced by James Watt in the late eighteenth century as a part of his fly-ball governor, which was developed to regulate the speed of his steam engine.

In 1880, in Marshalltown, on Iowa, constant manual regulation was required because of the extreme demand made on the system to supply water to fight a fire. William Fisher invented the constant-pressure pump governor and was founder of the Fisher Controls Company. By 1907, these governors were installed in a number of power plants in the United States, Canada, and England.

In 1885, William B. Mason patented a steam pressure-reducing valve. The pressure-reducing valve was key factor to steam heat railroad cars and was used in that service for many years. In 1890, the regulator was introduced on U.S. Navy ships to secure the efficiencies of higher steam operating pressures.

The turn of the century was also ground breaking for the oil and gas industry. Due to the rapidly increased demand it became necessary to amplify production rates. At the same time, powerhouses became larger, requiring larger valve mechanisms. Larger valves called for more power in order to move a plug of greater area - although the pressure drop remained quite moderate.

In the early part of the twentieth century the individual oil well - with its individual tank and still - was replaced by collection tanks for a number of wells and continuous distillation. Pressure, temperature, and capacities increased, followed up by demand for larger valves, more powerful positioning mechanisms, and improved materials of construction. Oversizing combined with the quick-opening disks led to periodic instability and the need for some sort of a slow-opening characteristic. These developments were pioneered by the Hanlon-Waters Company of Tulsa, in Oklahoma. This company made many innovative contributions to valve technology in the refineries in the 1920s and 1930s.

IV. APPLICATIONS

Typical application includes regulating cutting tool speeds, spindle speeds, surface grinder speeds and the travel rate of vertically supported loads moved upward and downward by forklifts, and dump lifts.

Controlling the flow is a common requirement in standard industrial and process control applications.

V. PROCESS PLANTS

Process plants consist of hundreds, or even thousands, of control loops all networked together to produce a product to be offered for sale. Each of these control loops is designed to keep some important process variable, such as pressure, flow, level, or temperature, within a required operating range to ensure the quality of the end product.

The most common final control element in the process control industries is the control valve. The control valve manipulates a flowing fluid, such as gas, steam, water, or chemical compounds, to compensate for the load disturbance and keep the regulated process variable as close as possible to the desired set point.

VI. MEDICAL PRODUCT COATING & SPRAY ATOMIZING

In this application a proportional valve and a flow monitor can accurately control the flow of air in an atomizing spray and medical product coating application. The spray is used to coat medical products. The flow is measured and a second loop feedback signal is provided to either increase or decrease the flow. As the pressurized air combines with the coating material, the material is atomized for spraying. It coats consistently and accurately.

VII. PIG VELOCITY CONTROL WITH MASS FLOW CONTROLLER

Pipeline pigging is a vital and common process used in many industries. It is used to clean pipes, ensure proper flow and perform diagnostics on the pipe itself.

VIII. FUEL INJECTION SYSTEMS

The fuel injection system is one of the most important parts of a marine diesel engine. A fuel injection system provides the right amount of fuel to the engine cylinder at the right moment. It is also extremely important that the fuel injected inside the engine enters the cylinder at the right combustion situation for the highest combustion efficiency.

IX. FRESH WATER GENERATION

There are two things that are available in plenty on a vessel to produce fresh water –Seawater and heat-thus fresh water is produced by evaporating sea water using heat produced from the main engine. Fresh water is generally produced on board using the evaporation method. Heated seawater is used as feed water (brine) for the evaporating.

X. BALLAST WATER TREATMENT – VIA ELECTROLYSIS

Ballast Water Treatment System (BWTS) is a system designed to remove and neutralize biological organisms (zooplankton, algae, bacteria) from ballast water. The need to regulate and control the flow of the incoming (ballasting) water is essential.

XI. CLASSIFICATION OF FLOW-CONTROL VALVES

Flow control valves can be classified into pressure and non-pressure compensated.

Pressure compensated flow-control valves change the size of the orifice in relation to the changes in the system pressure.

Non-pressure compensated flow-control valves are used when the system pressure us relatively constant and the motoring speeds are not too critical. The operating principle behind these valves is that the flow through an orifice remains constant if the pressure drop across it stays the same.

XII. TYPES OF FLOW-CONTROL VALVES

There are eight different types of flow-control valves which are commonly used in hydraulic systems. From these eight, half are pressure compensated and the other half are non-pressure compensated. All these types control the speed of an actuator by regulating the flow rate.

Pressure compensated valve types include:

- Pressure-compensated, variable flow valves
- Pressure and temperature compensated, variable flow valves
- Priority valves
- Deceleration valves

Non-pressure compensated valve types include:

- Orifices
- Flow regulators
- By-pass flow regulators
- Demand-compensated flow controls

XIII. CONTROLLING VALVES

Proper operating control is the ability to control a variable at a given set point within an acceptable degree of accuracy, not an easy feat considering the dynamics of a control system.

Proportional Integral Derivative (PID) control is a form of closed loop control. In a closed loop control, the process variable is measured and compared to the set point. The controller changes its output (manipulated variable), until the measured variable meets the set point.

When setting up PID loop control the difficult part is to achieve proper operation, due to the complex setup parameters and the need to comprehend the sequence of implementing them.

PID controllers use three control modes:

- Proportional Control
- Integral Control
- Derivative Control

Each of these three modes reacts differently to the error. The amount of response produced by each control mode is adjustable by changing the controller’s tuning settings.

While Proportional and integrative modes are also used as single control modes, a derivative mode is rarely used on its own in control systems.

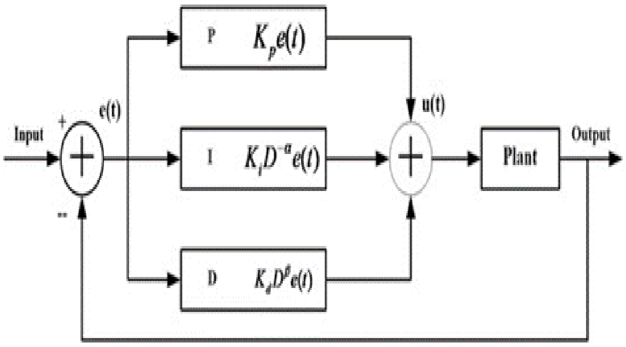


Fig. 1. *Working principle of PID controller*

PID controller maintains the output in such a way that there is zero error between process variable and set point/ desired output by closed loop operations.

XIV. PROPORTIONAL CONTROL MODE

This is the main driving force in a controller. It changes the controller output in proportion to the error. If the error increases, the control action increases proportionally. This is very useful, since more control action is needed to correct large errors.

The adjustable setting for proportional control is called the Controller Gain (Kc). A higher controller gain will increase the amount of proportional control action for a given error. If the controller gain is set too high the control loop will begin oscillating and become unstable. If the controller gain is set too low, it will not respond adequately to disturbances or set point changes.

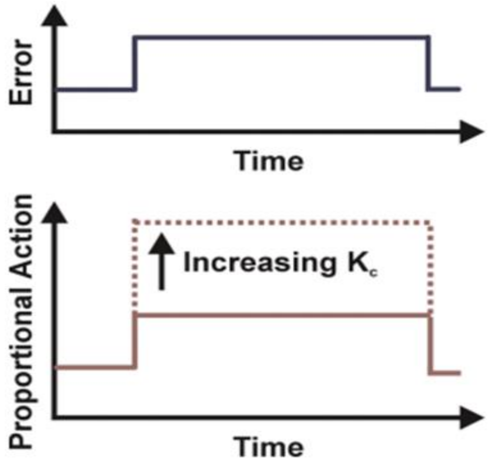


Fig. 2. *Proportional control action*

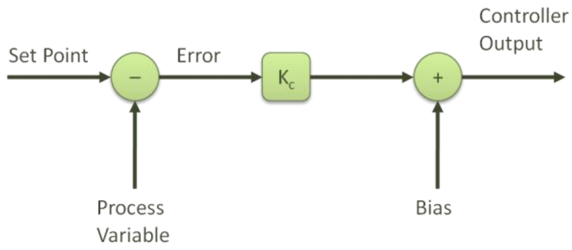


Fig. 3. *P-controller*

Proportional or P- controller gives output which is proportional to current error e (t).

XV. INTEGRAL CONTROL MODE

The function of the integral control mode is to increase or decrease the controller’s output over time to reduce the error, as long as there is any error present (process variable not at set point). Given enough time, the integral action will drive the controller output until there is no error.

If the error is large, the integral mode will increase or decrease the controller output at a fast rate; and if the error is small then the changes will be slow. For a given error, the speed of the integral action is set by the controller’s integral time setting (Ti). A long integral time (Ti) results in a slow integral action, and a short integral time results in a fast integral action.

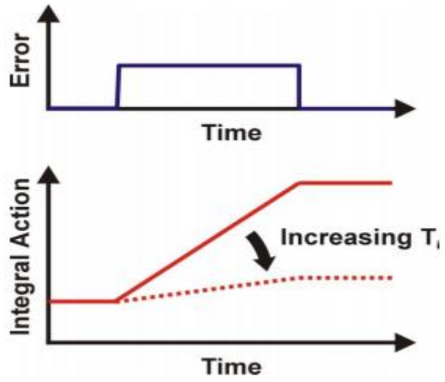


Fig. 4. *Integral control action*

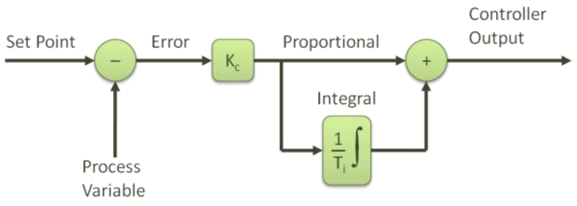


Fig. 5. *PI controller*

XVI. DERIVATIVE CONTROL MODE

I-controller provides necessary action to eliminate the steady state error. It integrates the error over a period of time until error value reaches to zero.

Derivative control is rarely used in controlling processes, although it is often used in motion control. It is very sensitive to measurement noise, and it makes error tuning more difficult, therefore it is not absolutely required for process control. Nevertheless, using the derivative control mode of a controller can make certain types of control loops respond a little faster than with PI control alone.

The derivative control mode produces an output which is based on the rate of change of the error. The derivative mode produces more control action if the error changes at a faster rate. If there is no change in the error, the derivative action is zero. The derivative mode has an adjustable setting called Derivative Time (Td). The larger the derivative time setting, the more derivative action is produced.

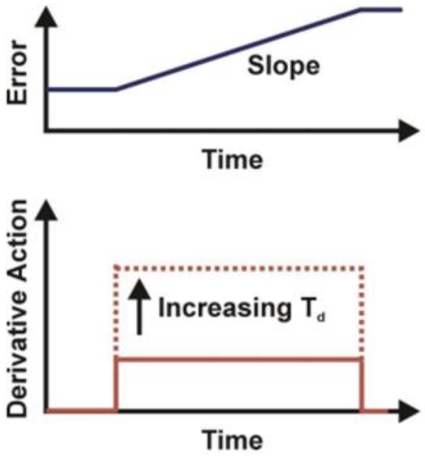


Fig. 6. *Derivative control action*

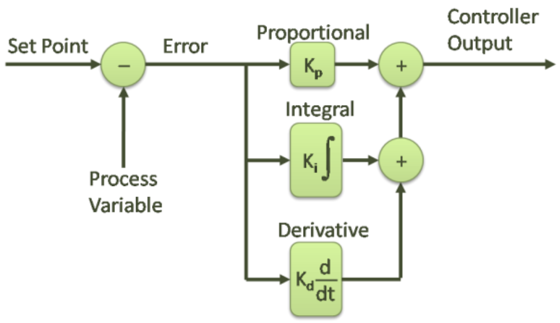


Fig. 7. *PID controller*

I-controller doesn't have the capability to predict the future behavior of error. So it reacts normally once the set point is changed. D-controller overcomes this problem by anticipating future behavior of the error. Its output depends on rate of change of error with respect to time, multiplied by derivative constant. It gives the kick start for the output thereby increasing system response.

XVII. TUNING METHODS OF PID CONTROLLER

Before the working of PID controller takes place, it must be tuned to suit with the dynamics of the process which is to be controlled. Even if the default values for P, I and D terms are given, these values couldn't give the desired performance - and sometimes they lead to instability and slow control performances.

Different types of tuning methods have been developed to tune the PID controllers and they require much attention from the operator to select the best values of proportional, integral and derivative gains.

XVIII. MAINTENANCE METHODS

In an ideal world, valves in a process would go unnoticed and remain problem-free throughout a line's entire functional lifetime.

An integrated approach to valve maintenance planning requires the consideration of many factors that may contribute to downtime, safety and environmental risks.

The right maintenance plan can save plants or vessels, both cost and downtime, thereby improving efficiency and allowing operations to run smoothly. The ideal maintenance program should be able to use a medley of different maintenance modes to make sure that the operation runs efficiently and effectively.

XIX. REACTIVE MAINTENANCE

This is a plan that essentially operates on run to failure strategy, a hands-off approach which keeps low routine maintenance costs, but can be costly in the long run. It focuses on restoring equipment to normal operation after a breakdown, by replacing or repairing faulty parts and components.

Reactive Maintenance requires minimal maintenance costs and fewer staff members but creates downtime, which can get quite expensive. This also drives up labor costs especially if there's need for overtime.

XX. PREVENTIVE MAINTENANCE

Preventive maintenance has been more popular in principle than in practice over the years. There's no argument that the idea of keeping equipment well maintained to extend its expected life and avoid future repair costs.

XXI. PREDICTIVE MAINTENANCE

Predictive maintenance is a data-driven approach, based on the results of monitoring and testing equipment performance, by routinely inspecting using various developments including infrared and ultrasound technology. This maintenance mode works to eliminate unexpected breakdowns and scheduled maintenance down time that would otherwise be used to inspect a valve piece by piece.

XXII. PROACTIVE MAINTENANCE

This mode differs from the other three, because it addresses much more systemic elements of a maintenance program, rather than examining the machine itself. This approach is much more diligent and looks to control the problems that can lead to machine wear and tear as opposed to the deterioration itself. It is based on the philosophy that supplants “failure reactive” with “failure proactive” by activities that avoid the underlying conditions which lead to fault and degradation. It aims at failure root causes and not failure symptoms.

XXIII. A BALANCED APPROACH

Balance is important to every part of life. The best maintenance plan is one that balances elements of each of these modes. There are reliability-centered maintenance programs which are largely less than 10 percent reactive, between 25 and 35 percent preventive and between 45 and 55 percent predictive.

The end goal of a maintenance program is making sure that facilities are constantly up and running. As a result, it is important to make sure that these plans account for the machines and facilities that are unique to a plant and its operations.

XXIV. DETERMINING THE ECONOMIC VALUE OF PREVENTIVE MAINTENANCE

In order to establish if it is worthy to invest in preventive maintenance when it comes to flow control valves, a study was executed. In order to determine the value of preventive maintenance the following aspects had to be identified:

- Actual cost of preventive maintenance
- Cost of repair maintenance
- Cost of replacing the valves
- Expected useful life of valves
- Effects of preventive maintenance on expected useful life
- Frequency of required repairs when valves are not maintained
- Effect of preventive maintenance on vessel’s idle time.

Supposing that a vessel has a ballast water treatment unit installed, and is operating it for five years. The unit is using flow control valves to regulate flow. Replacing these valves would cost 5.803€. Would an investment in preventive maintenance be justified?

With the information gathered, the valves will last approximately 10 years with proper preventive maintenance but only 6 without it. Repairing the valves will cost 654,50€ per incident. If maintained properly, it will need to be repaired once every 4 years. If they are not maintained they will need to be repaired every 2 years.

Given these variables, and assuming a time frame of 12 years, the results will prove if an investment in preventive maintenance is justified.

Applying preventive maintenance, the equipment will need to be repaired once every four years at a cost of 1.424,50€, a figure that translates to 356,13€ per year. . Lacking preventive maintenance, the valves can be anticipated to need repairs once every 2 years at a cost of 1.309€, with the annual cost of 654,50€.

With preventive maintenance (PM), the valves will need to be replaced in 10 years. Without PM they will have to be replaced twice, in year 6 and in year 12. Comparing the two cases indicates that the one with PM has the amount of 1.078€ in gain. If the time period is extended to 25 years, the valves will need to be replaced twice in the PM case, increasing the amount to 15.302€.

Three different scenarios were examined to further investigate if preventive maintenance has added value. For these scenarios, the following considerations were taken into account:

- All repairs will be made at the port of Shanghai.
- Cargo freight for a 20day voyage, on a 2016 built vessel
- The time-frame of the calculations will be 12 years

Scenario #1

It is assumed that the shipping company spends nothing on PM, reducing the PM cost to zero in this case. The cost of repair maintenance, the cost of downtime and the frequency of equipment replacement will increase, however, since the equipment will not be properly maintained. It is assumed that the frequency of repairs will increase in an amount similar to the expected-life degradation, which translates to an increase in downtime cost.

Scenario #2

In this case, the vessel carries stock of the sensitive components. PM cost remains zero, the cost of repair maintenance is reduced as well as the downtime cost. The frequency of equipment replacement is still increased but the cost of stocked items is added.

Scenario #3

This scenario assumes that the shipping company spends the industry benchmark amount on preventive maintenance activities. This scenario also assumes that the valves will last their full expected life and that downtime will be reduced to the zero.

Results

For each scenario the yearly cost of operating the valves was calculated, and a timeline of expenditures was built. The cost consisted solely of repair and preventive maintenance, stocked and replaced equipment.

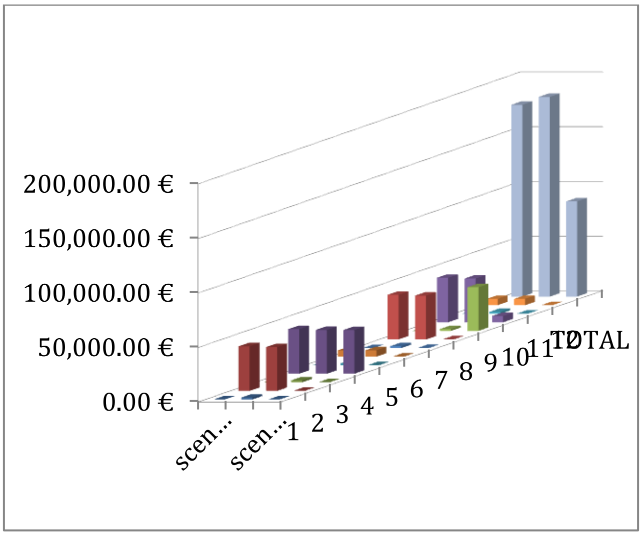
The average life of the valves was used in order to determine when the items would need to be replaced.

Cost estimation for 12-year period	Scenario #1	Scenario #2	Scenario #3
Equipment in stock cost	0,00 €	3.372,00 €	0,00 €
Preventive maintenance cost	0,00 €	0,00 €	1.620,00 €
Repair maintenance cost	2.848,00 €	3.972,00 €	1.424,00 €
Downtime cost	230.454,55 €	230.454,55 €	76.818,18 €
Equipment replacement frequency	6	6	3

The annual cost consisted of the following parameters:

- Equipment in stock
- Preventive maintenance
- Repair maintenance
- Downtime

Annual cost estimation for each scenario			
Years	**Scenario #1**	**Scenario #2**	**Scenario #3**
1	0,00 €	1.686,00 €	135,00 €
2	40.957,09 €	40.230,09 €	135,00 €
3	0,00 €	1.686,00 €	135,00 €
4	40.957,09 €	40.230,09 €	40.130,09 €
5	0,00 €	1.686,00 €	135,00 €
6	5.803,00 €	5.803,00 €	135,00 €
7	0,00 €	1.686,00 €	135,00 €
8	40.957,09 €	40.230,09 €	135,00 €
9	0,00 €	1.686,00 €	40.130,09 €
10	40.957,09 €	40.230,09 €	5.803,00 €
11	0,00 €	1.686,00 €	135,00 €
12	5.803,00 €	5.803,00 €	135,00 €
Total cost	**175.434,36 €**	**182.642,36 €**	**87.278,18 €**



XXV. CONCLUSION

The results of the analysis comparing the scenarios were overwhelmingly positive for performing preventive maintenance. Obviously, replacing equipment in later years is superior to replacing equipment earlier.

When it comes to shipping, one of the major problems is downtime cost. The analysis indicates that the expenses can be pushed out over time and can be programmed in such a way that the cost is reduced significantly.

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