Article

The trade-off between the controller effort and control quality on example of an electro-pneumatic final control element

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Featured Application: process control engineering practice. This paper shows that by the proper selection of the structure and parameters of the internal controller of the final control element, one can achieve two seemingly contradictory outcomes. On the one hand, better quality control, while on the other, simultaneous reduction of the controller effort, which in turn leads to a significant extension of the mean-time-between-failures of the final control element. This has a pertinent impact on functional safety and economy of the process.

Abstract: For many years, the programmable positioners have been widely applied in structures of modern electro-pneumatic final control elements. The positioner consists of an electro-pneumatic transducer, embedded controller and measuring instrumentation. Electro-pneumatic transducers that are used in positioners are characterized by a relatively short mean time-to-failure. The practical and economical method of a reasonable prolongation of this time is proposed in this paper. It is principally based on assessment and minimizing the effort of the embedded controller. For this purpose, were introduced: the control value variability, mean-time and the cumulative controller's effort. The diminishing of controller effort has significant practical repercussions, because it reduces the intensity of mechanical wear of the final control element components. On the other hand, the reduction of the cumulative effort is important in the context of process economy due to limitation of the consumption of energy of compressed air supplying the final control element. Therefore, the minimization of introduced effort factors has an impact on increasing the functional safety and economics of the controlled process. As a result of the performed simulations, the recommendations regarding the selection of the structure and tuning of positioner controller were elaborated. The simulations were performed in the Matlab-Simulink environment with the use of the liquid level control system in which a phenomenological model of a final control element was deployed. It has been proven that under appropriate conditions, it is possible to extend significantly the lifetime of the final control element and simultaneously enhance the control quality factors.

Keywords: final control element; electro-pneumatic transducer, controller effort, control quality factors, wear, mean-time-between-failures

1. Introduction

In the structures of the closed loop industrial automation systems, we can generally distinguish: controlled systems, controllers, measuring instrumentation and final control elements [1-3]. The general structure of a single-loop control system is depicted in Figure 1. The final control elements

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are physical units directly affecting the streams of energy and materials. In the structure of a control system, they simply play the role of adapters between controllers and controlled systems.

In fact, the final control elements are acting as energy or power converters that convert the low-energy or informative control value (*CV*) into a high-energy driving signal (*CV$_a$*). Clearly, due to the principle of energy conservation, the final control elements require an additional auxiliary power supply source.

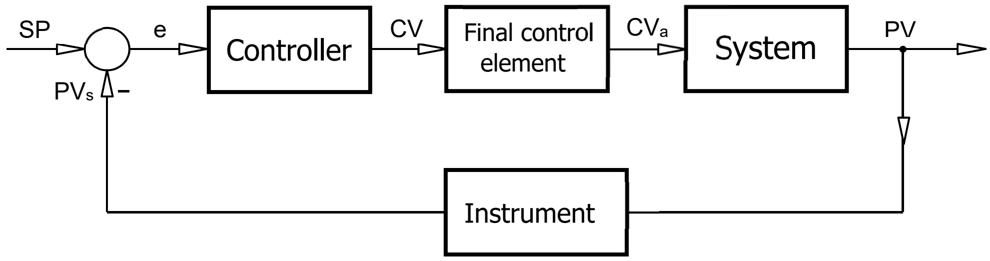

Figure 1. Block diagram of the structure of the closed loop automatic control system. Notion: SP – setpoint; PV$_s$ – measured value of process variable; e - control error; CV – controller output; CV$_a$ – final control element actuator output; PV- process variable.

The main interest of this paper is focused on the certain class of final control elements in which the compressed air is used as an auxiliary energy supply source. These elements are commonly used in automatic control systems used in the following industries: power, chemical, petrochemical, pharmaceutical and food.

A typical electro-pneumatic final control element consists of a pneumatic actuator with linear or rotational movement of its rod, a positioner and a control valve (Figure 2). By adjusting the position of the valve plug attached to the end of actuator's rod towards the valve seat, it is possible to control the flow rate of a medium passing through the valve.

The primary goal of the positioner is to follow-up the *CV*. In order to do it, the positioner has to control the pressure of the pneumatic actuator in such a way that the position of the valve plug will depend exclusively on *CV* and will suppress the influence of the disturbances such as: changes of operating temperature, supply pressure fluctuations, changes in the static and dynamic load of the actuator's rod, friction and the evolution of friction forces.

Figure 2. An example of an electro-pneumatic final control element and cross-section of its mechanical construction [4,5].

The final static and dynamic properties of the actuator are shaped by the positioner. In fact, the positioner is a specialized, autonomous control system of the rod position. The simplified block diagram of the final control element is shown in Figure 3.

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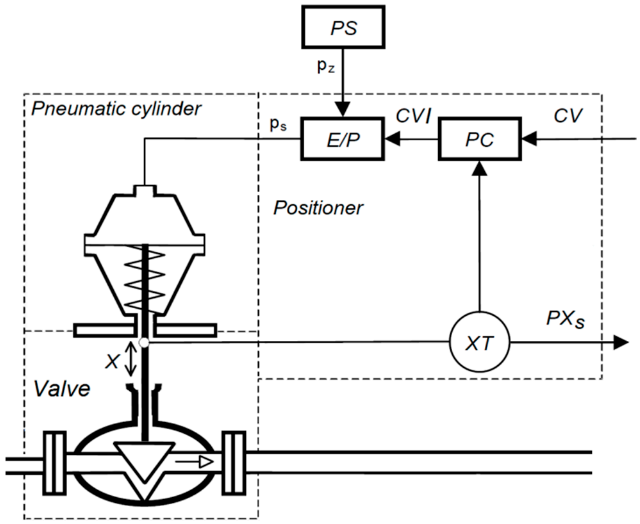

Figure 3. Block diagram of an electro-pneumatic final control element. Notions: *CV* – output of external controller; *CVI* – output of internal controller; *PC* – internal controller; *E/P* – electro-pneumatic transducer; *PS* – compressed air supply; p_z - supply air pressure; p_s - the output pressure of the *E/P* transducer; *X* - displacement of the valve plug; *XT* – displacement transducer of the actuator's rod; PX_s - measured displacement of the actuator's rod [6].

When applied, one requires from the final control element a repetitive non-hysteresis static characteristics, aperiodic step response and minimum control time. In principle, realisation of these requirements becomes realistic only due to the use of a positioner.

It should be noted that the final control elements are exposed to adverse environmental conditions such as thermal shocks, a wide range of operating temperatures, vibrations, humidity, dusty pollutants, corrosive working environment and electromagnetic interference. Therefore, the final control elements are classified as belonging to the group of elements of automation systems subjected to the most frequent failures. It is estimated that among instrumentation, actuators and technological components, the share of failures of final control elements exceeds 45%. The faulty final control element can lead to a deterioration of the quality of the final product, and can even lead to the process shut-down. All these factors influence the safety of the process and humans involved, as well as worsen the economic indices of the process. For this reason, the assurance of the most trouble-free operation of such devices becomes more important. In this context, the issues of fault prediction and diagnostics, as well as ways of prevention actions and fault tolerant control become particularly pertinent [7]. Most frequently, the electro-pneumatic transducer is subject to fail in case of electro-pneumatic final control elements. This component fails due to poor quality of supply air, friction wear of its mechanical components and material fatigue of its moving parts.

In this paper, a practical and economic approach to prolongation of final control element lifetime is proposed. It is based on appropriate shaping and tuning of the positioner controller in such a manner that it results in the limitation of the amplitude and of the number of cycles on its output. This directly influences the wear and fatigue of moving elements of the electro-pneumatic transducer. This type of approach, due to the conclusions drawn from the Wöhler's fatigue curve [8], has significant impact on mean-time-between-failures (MTBF), and therefore, reduces wear and increases functional safety of the controlled process.

The essence of the proposed approach is to change the structure and parameters of the positioner controller (*PC*) in order to minimize its effort, but not at the expense of worsening the control quality factors of the controlled system in which such an element is used.

The results of research of the proposed approach were obtained in the Matlab-Simulink simulation environment with the use of the final control element model [9] which is recognized widely in the field of diagnostics and process safety. This to some extent enhances trustworthiness of achieved and presented results.

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2. The controller effort

Before we discuss the problem of minimizing controller's effort, let us define a few effort related terms for the continuous and discrete time domain systems.

Definition 1. *Define the normalized variability of the controller output* $v(t)$ *as:*

$$V(t) = \frac{1}{\Delta v}\left|\frac{dv(t)}{dt}\right|, \tag{1}$$

where: $\Delta v = |v_{max} - v_{min}|$ – nominal range of controller output.

Definition 2. *Define the controller's mean time effort over time interval* Δt *as an average normalized variability of the controller output*.

$$Q(\Delta t) = \frac{1}{\Delta t}\int_{t_0}^{t_1} V(t)dt = \frac{1}{\Delta t}\frac{1}{\Delta v}\int_{0}^{\mathrm{t}}\left|\frac{dv(t)}{dt}\right| dt, \tag{2}$$

where: $\Delta t = (t_1 - t_0)$. By changing integration limits in (2), we can define cumulative time effort:

Definition 3. *Define the controller's cumulative effort as an averaged over time normalized variability of the controller output*.

$$Q(t) = \frac{1}{t}\int_{0}^{\mathrm{t}} V(t)dt = \frac{1}{t}\frac{1}{\Delta v}\int_{0}^{\mathrm{t}}\left|\frac{dv(t)}{dt}\right| dt. \tag{3}$$

In the discrete time domain, the normalized variability can be expressed as:

$$V(k) = \frac{1}{\Delta v}\left|v_k - v_{(k-1)}\right|, \tag{4}$$

where: v_k – *k-th* sample of the controller output $v(t)$. By analogy to (2), the mean time effort in discrete time domain can be expressed as the averaged sum of the variability of control signal over the number of Δk samples:

$$Q_{\Delta k} = \frac{f_s}{(\Delta k - 1)}\sum_{k=k_o+1}^{k_1} V(k) = \frac{1}{\Delta \mathrm{T}}\frac{1}{\Delta v}\sum_{k=k_o+1}^{k_1}\left|v_k - v_{(k-1)}\right|. \tag{5}$$

where: $\Delta k = (k_1 - k_0)$; f_s – sampling frequency of controller output $v(t)$; $\Delta T = \frac{f_s}{(\Delta k - 1)}$ – time interval.

Remark: The introduction of sampling frequency f_s in (5) avoids deflating/inflating effects of the mean time effort for different sampling frequencies of the same control value.

Finally, by analogy to (3), the cumulative effort in the discrete time domain can be expressed as the averaged sum of the variability of control signal over the K samples:

$$Q_K = \frac{f_s}{(K-1)}\sum_{k=1}^{K-1} V(k) = \frac{f_s}{(K-1)}\frac{1}{\Delta v}\sum_{k=1}^{K-1}\left|v_k - v_{(k-1)}\right| = \frac{1}{T}\frac{1}{\Delta v}\sum_{k=1}^{K-1}\left|v_k - v_{(k-1)}\right|, \tag{6}$$

where: T – time horizon. In practice, in automation systems, the control value is usually normalized. In this case: $\Delta v = 1$, and therefore respective formulas (1) - (6) appropriately simplify.

If we further assume that the movable elements of the electro-pneumatic transducer of positioner approximately reproduce the trajectory of the control signal, then the reduction of the controller's effort leads to a diminishing of the average amplitude and the totalized travel of its moving elements. As a result, it is expected to reduce the intensity of wear of its mechanical components and thus extends MTBF. Figure 4 presents an example of two control strategies for the electro-pneumatic transducer: an aggressive marked with a red line and a conservative marked by the dark blue line. The appropriate cumulative effort values for both strategies in the time horizon of Δt=10s differ significantly, and respectively are equal to: 0.32 and 0.029. In this case, the

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eleven-fold reduction in the controller's effort allows the increase of the permissible number of work cycles due to the significant decrease of their amplitude.

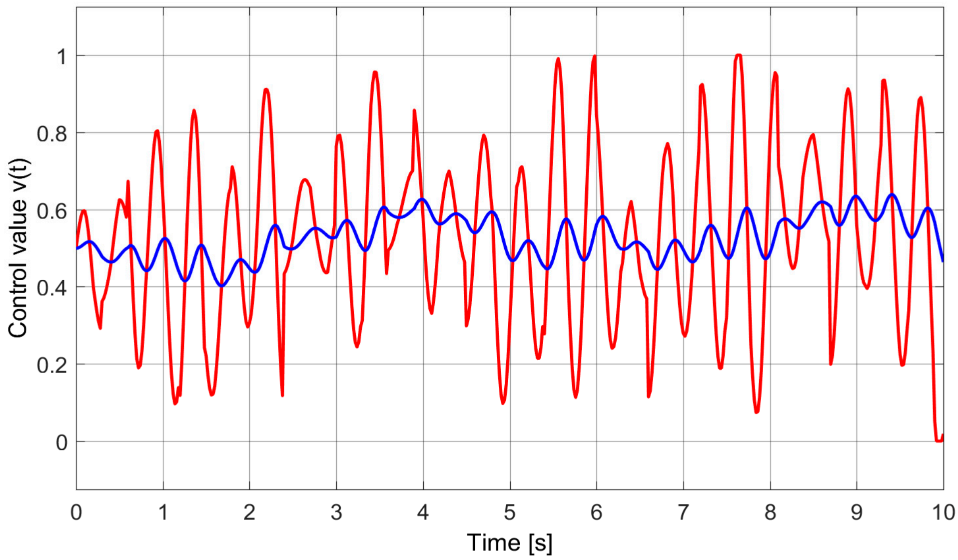

Figure 4. An example of two control strategies with a strongly differentiated effort. Value of effort for aggressive strategy Q_K=0.32 and for conservative strategy Q_K=0.029 [10].

3. Research environment

The implementation of experimental investigations in a real life scenario is usually costly and time consuming. For this reason, the choice of the structure, parameters and tests of the proposed control strategy was carried out in a simulation. For this purpose, was used a complex, phenomenological model of an electro-pneumatic final control element. This model was prepared and validated especially for assessment model based fault detection and isolation approaches [1].

The choice of this model was motivated by its availability [6] and the recognition in the international community of process safety diagnostics. Simulation tests were performed by means of the liquid level control system in which the final control element from [9] was applied. A simplified block diagram of the simulated control system is shown in Figure 5.

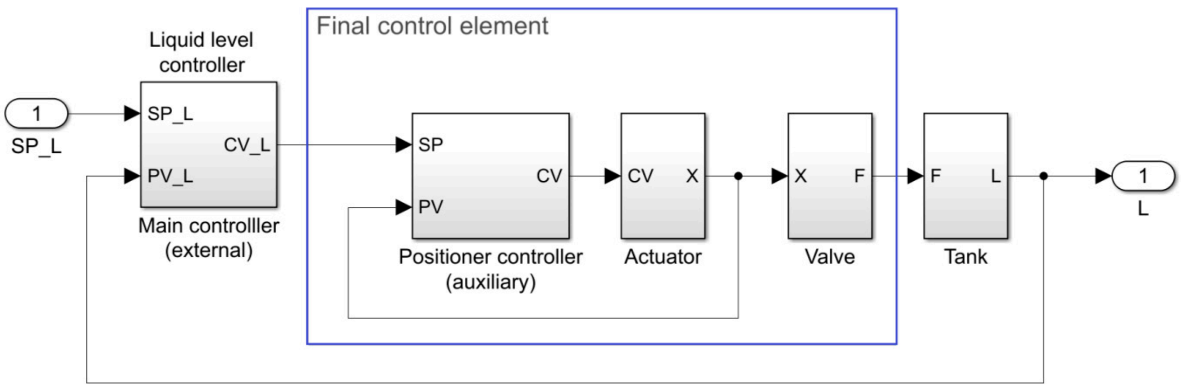

Figure 5. Simplified simulation model of the liquid level control system. Notions: SP_L - level setpoint; PV_L - measured level; CV_L - output of the main controller; SP - position setpoint of the valve stem; PV - position of the valve stem; CV - output of the internal controller; X - position of the valve stem; F - liquid flow rate; L - liquid level in the tank.

Applied final control element exhibits strong non-linearity, ambiguity and asymmetry of the static characteristics (Figure 6). In addition, asymmetry and directionality of dynamic characteristics of its components is shown in Figure 7.

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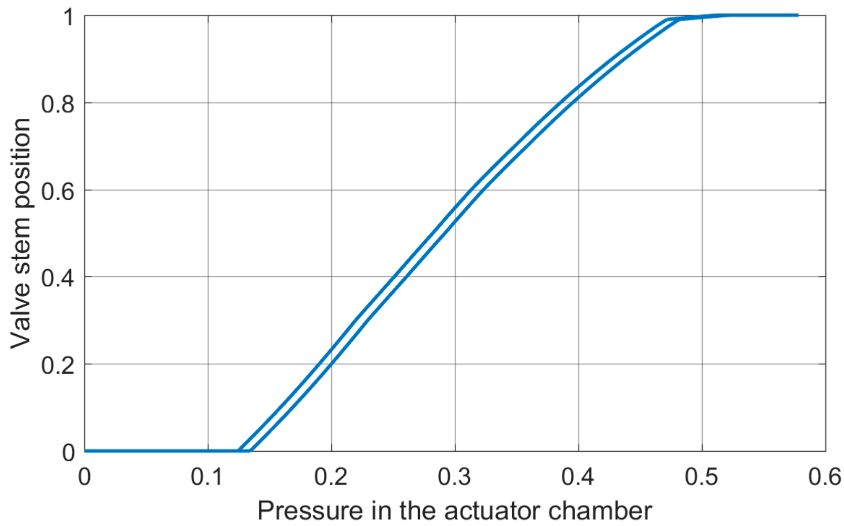

Figure 6. Normalized static characteristics of pneumatic actuator of the electro-pneumatic final control element.

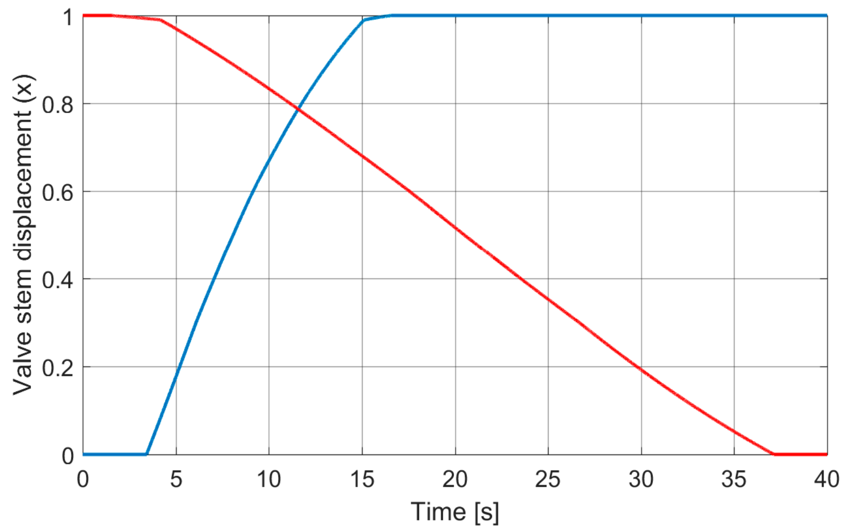

Figure 7. Positive (blue line) and negative (red line) step response of the valve stem displacement of pneumatic actuator.

It should be noted that the directionality of dynamic characteristics is a major challenge for the internal positioner's controller and has significant impact on its variability as well as on effort. Directionality is clearly discernible in the parameter values of the effective transmittance of pneumatic actuator.

$$\begin{cases} G_+(s) = \dfrac{1{,}6}{12s+1}e^{-3{,}4s} \\ G_-(s) = \dfrac{3}{115s+1}e^{-4s} \end{cases} \tag{7}$$

The dead time in the effective transmittance $G_+(s)$ results from a mechanical limitation of the positioner's rod movement and initial compression of the spring of the single-acting pneumatic actuator. In turn, the dead time in the effective transmittance $G_-(s)$ follows from a mechanical limitation of the positioner's rod movement and time required to discharge the pressure in the actuator chamber to the value at which a rod of the actuator begins the return stroke.

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4. Control quality factors

Controller effort is just one of the many control quality factors used in order to evaluate the features of automation systems [1-3]. Therefore, the minimizing of the effort of the controller cannot be separated from the analysis of the impact on other control quality factors. There will be seven control quality indicators analyzed in order to obtain a more complete view of the effects of minimizing effort of the internal controller of positioner:

- cumulative effort of the controller Q_K according to formula (6) for *T*=100s;
- normalized, average absolute tracking error e_{Kr} according to the formula (8). The value of this factor is determined in test when applying a standardized trapezoidal setpoint *SP* shape with the constant slope equal to $0.025s^{-1}$.

$$e_{Kr} = \frac{f_s}{K}\sum_{k=0}^{K}|SP(k) - X(k)|, \tag{8}$$

where: X – positioner rod displacement;

- normalized, average absolute tracking error e_{Ks} according to the formula (8). The value of this factor is determined in a test in which a rectangular setpoint with the 5% amplitude and period equal to 40s was applied.
- overshoots κ_{rise} and κ_{fall} obtained respectively for applying positive and negative 60% stepwise function. Overshoot is defined as the ratio of the amplitude of the first transitional control error e_1 to the setpoint change e_0 and expressed as a percentage.

$$\kappa = \frac{e_1}{e_0} \tag{9}$$

- settling times: T_{Rrise} and T_{Rfall} for the 60% stepwise setpoint changes appropriately in positive and negative direction Settling time is defined as the time which elapses from the moment of the setpoint change until a positioner's rod position *X* settles within $\pm 0{,}05e_0$ tolerance band around the steady state value.

5. Methodology

Without any doubt, the structure and parameters of internal positioner controller influences the controller effort factors. This paper presents briefly the results of an experimental selection of the structure and parameters of the internal controller of positioner for the control system shown in Figure 4. The four different controller structures were studied namely: classic P and PD as well as fuzzy PD and neural network one. The integral action was not considered in this case because of the necessity of a guarantee system stability and hence assurance of sufficient gain and phase margins.

For all investigated control structures there are calculated values of all quality factors presented in Section 4. It was assumed that tracking of the control value of the external controller is the primary role of the final control element. For this reason, all controllers were tuned in order to minimize value of mean absolute tracking error e_{Kr}. Some reasonable practical limitations were introduced. For example, the value of proportional gain was limited to 100.

The tests of internal positioner controller were carried out for:

- nominal values of friction and actuator's spring elasticity;
- friction varying within the range [-50% , + 50%];
- actuator's spring elasticity varying within the range [-50% , + 50%].

In order to minimize the simulation time, the tests were performed only for the extreme values of the above mentioned influencing quantities.

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6. Obtained results

The collected quality factors values obtained in the frames of performed simulation tests are presented in Table 1. The best results are highlighted in bold.

Table 1. Experimentally obtained values of control quality factors.

Experiment		Quality factor Q_K	e_{Kr}	e_{Ks}	κ_{rise} [%]	κ_{fall} [%]	T_{Rrise} [s]	T_{Rfall} [s]
P controller	Nominal parameters	0.397	4.03	9.38	8.67	0.79	8.67	29.2
	Reduced friction	0.402	3.98	9.36	2.62	0.77	8.65	29.2
	Increased friction	0.381	4.04	9.50	2.69	0.79	8.75	29.4
	Reduced elasticity	0.428	3.92	8.84	3.41	0.99	7.43	27.3
	Increased elasticity	0.344	4.34	10.2	2.12	0.64	10.1	31.0
PD controller	Nominal parameters	**0.127**	3.26	8.81	**0.06**	**0.00**	**7.10**	29.2
	Reduced friction	**0.189**	3.23	8.80	**0.06**	**0.00**	**7.10**	29.2
	Increased friction	**0.055**	4.80	9.37	**0.04**	**0.00**	**7.20**	29.6
	Reduced elasticity	**0.288**	2.93	7.85	**0.05**	**0.00**	**5.70**	27.3
	Increased elasticity	**0.103**	3.72	9.78	**0.05**	**0.00**	**8.60**	31.0
Fuzzy 1 PD controller	Nominal parameters	0.169	**2.47**	**8.71**	0.25	0.11	7.20	**29.1**
	Reduced friction	0.241	**2.68**	**8.70**	0.24	0.11	7.10	**29.1**
	Increased friction	0.103	**3.67**	**9.08**	0.00	0.00	7.20	**29.4**
	Reduced elasticity	0.423	**2.14**	**7.74**	0.15	0.15	5.70	**27.2**
	Increased elasticity	0.134	**2.92**	**9.67**	0.19	0.08	8.60	**31.0**
Neural controller	Nominal parameters	0.197	5.78	9.38	2.91	0.50	12.9	29.2
	Reduced friction	0.196	5.78	9.37	2.87	0.00	13.2	29.2
	Increased friction	0.197	5.93	9.50	2.9	0.49	13.0	29.5
	Reduced elasticity	0.234	5.62	8.79	3.78	0.77	7.80	27.3
	Increased elasticity	0.156	6.40	10.5	2.23	0.00	16.8	31.0

6.1. Discussion of results

Table 1 provides interesting data for discussion. By comparing obtained results for different types of controllers, it is possible to admit that classic proportional-and-derivative controller provides the best control quality by minimal value of controller effort. This applies equally to classic and fuzzy logic based controllers. In turn, neural network controller provides worse control quality factors with comparable drop of the value of controller effort. The worst quality control factors were obtained for proportional controller. The examples of the control outputs having lowest control quality and the highest effort are shown in Figure 8. The outputs were recorded for the 0.0125Hz trapezoidal setpoint excitation shape and the slope equal to 0.025s^{-1}. In contrast, Figure 9 depicts the best results achieved for classic proportional-and-derivative and fuzzy logic controllers.

It is clear to see from Figure 8 that lowest control quality controllers generate a significant number of high amplitude oscillations. Additionally, it negatively affects the lifetime of the electro-pneumatic transducer itself and remaining parts of final control element. On the other hand, the outputs of the PD and fuzzy logic controllers presented in Figure 9 are characterized by relatively low number of quickly damped oscillations, which should be considered as highly beneficial from the perspective of elongation of the MTBF of electro-pneumatic transducer.

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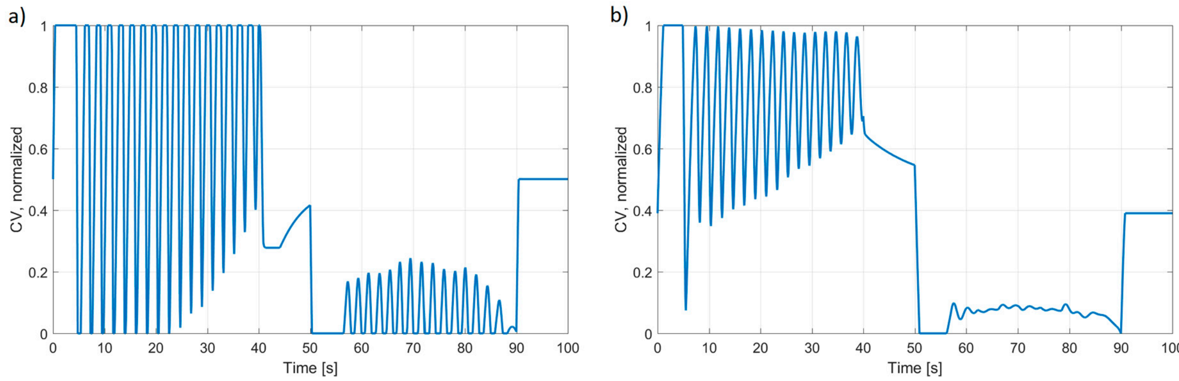

Figure 8. **a)** Output of P controller; **b)** Output of neural network controller.

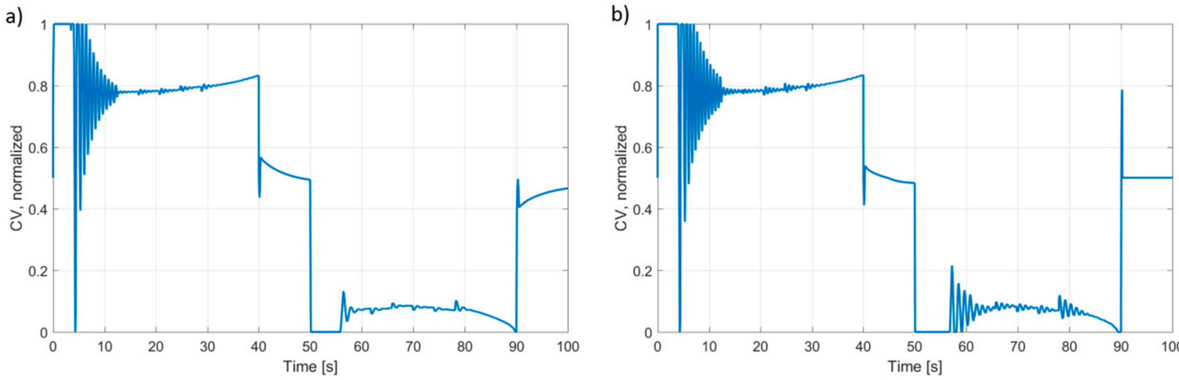

Figure 9. **a)** Output of PD controller; **b)** Output of fuzzy logic PD controller.

The most important results inferred from the research carried out are shown in Figures 10-13. The comparison of the mean time effort for all four controllers applied in the same control system and working under the same conditions is shown in Figure 10. The mean time effort was calculated here in moving time window with the width equal 10s. From this figure it comes that the principal difference between controllers depends not on the short time effort but on the value of cumulative effort over longer time. This is depicted clearly in Figure 11.

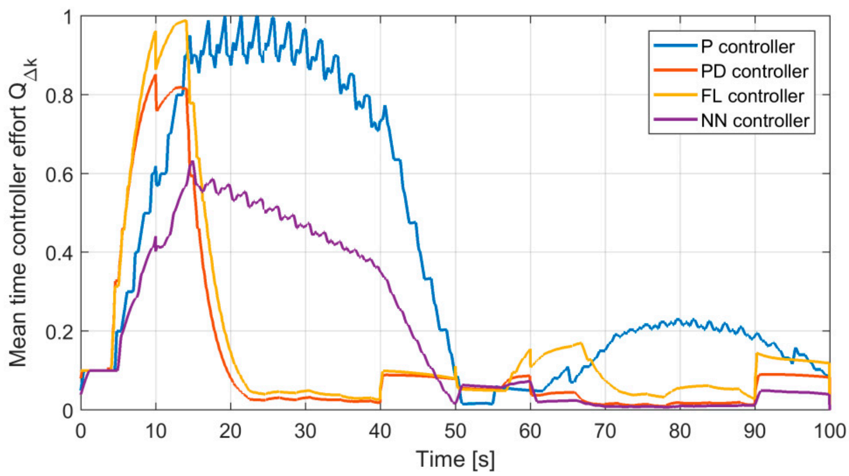

Figure 10. The comparison of the mean time effort of the four investigated controllers $(\Delta T = 10s)$.

The cumulated effort of the four investigated controllers working under the same conditions is shown in Figure 11.

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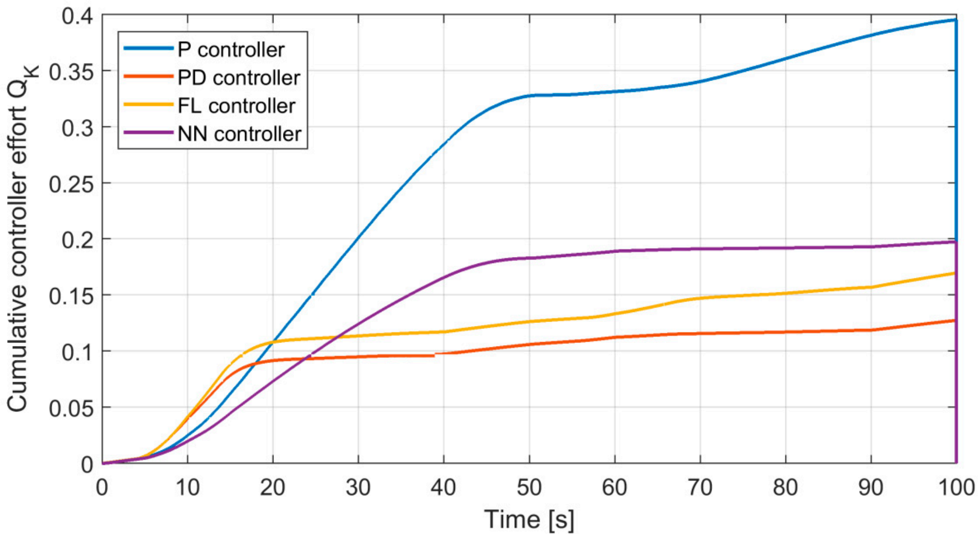

Figure 11. The cumulative effort of the four investigated controllers in time horizon *T=100s*.

The cumulated effort was calculated for time horizon *T* varying from 0 to 100s. This plot allows for the easiest and fastest evaluation of the choice of the proper structure of the internal controller in terms of minimizing the effort and energy consumed from the auxiliary air supply source (Figure 3). This graph shows that in time window (up to 25s) the cumulative effort of proportional-differentiating controllers is higher than for proportional controllers. However, from a long - term perspective, the situation evidently changes.

It is also important to determine how the choice of the control strategy affects the durability and fatigue of the electro-pneumatic transducer. The durability can be characterized indirectly by the distribution of amplitude-cycles (A-S) curve. The appropriate graph for four tested controllers is depicted in Figure 12. This graph was achieved by usage of chirp shaped setpoint. From this graph it shows that controllers with a derivative action generate large number of cycles with relatively small amplitude, and relatively low number of cycles having huge amplitudes. This observation allows further consideration about the application of an additional filter for damping small amplitude cycles. Quasi-constant A-S curve for proportional action controller gives an assumption to forecast earlier fatigue of the driven electro-pneumatic transducer. It is also clear to see from Figures 11 and 13 that in case of chirp setpoint, the cumulative effort of derivative action controllers is also significantly smaller compared to others.

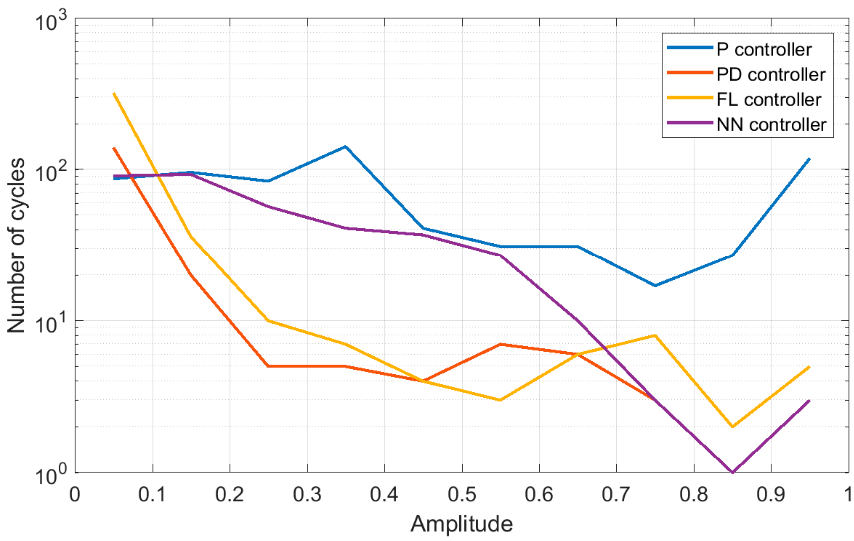

Figure 12. Amplitude-cycles curve. Conditions: setpoint – chirp signal; observation time -1000s.

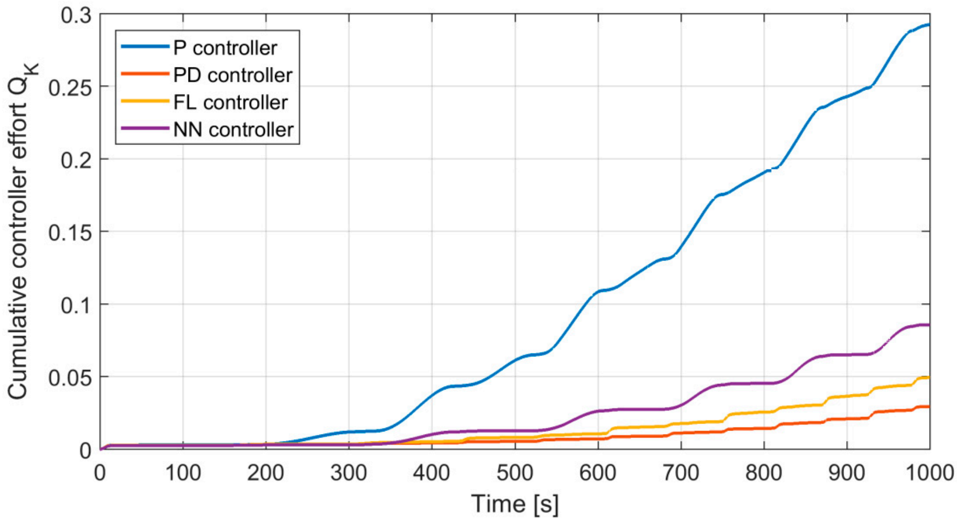

Figure 13. The cumulative effort of the four investigated controllers in 1000s time horizon and chirp setpoint.

7. Summary

The three practical measures of the control quality that have been proposed in this paper are: the variability, mean time and the cumulative effort of the controller. The simulation tests demonstrate that with the proper selection of the structure and parameters of the internal controller of the final control element, one can achieve two seemingly contradictory outcomes. On the one hand, better quality control, while on the other, simultaneous reduction of the controller effort, which in turn leads to a significant extension of the mean-time-between-failures of the electro-pneumatic transducer. This is of great practical importance because the failures of electro-pneumatic transducers are very prevalent in electro-pneumatic positioners. Additionally, it also has economic benefits because it reduces the energy consumption by the actuators.

On the example of a fairly typical liquid level control system, it was shown that the replacement of the algorithm of pneumatic actuator stem position controller from commonly used classic P to PD or fuzzy PD allows more than a three-fold reduction of effort while simultaneously obtaining much better values of quality control factors.

It is worth to mention, that frequently P controller is preferred in positioners. This comes from considerations regarding cascade systems where the external controller performs integral action and internal controller proportional action. As follows from the results of investigations presented in this paper, it does not promise neither longer lifetime nor better control quality.

It would be advisable in the future to investigate the use of additional controller output filtering to further reduce the actuator effort.

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