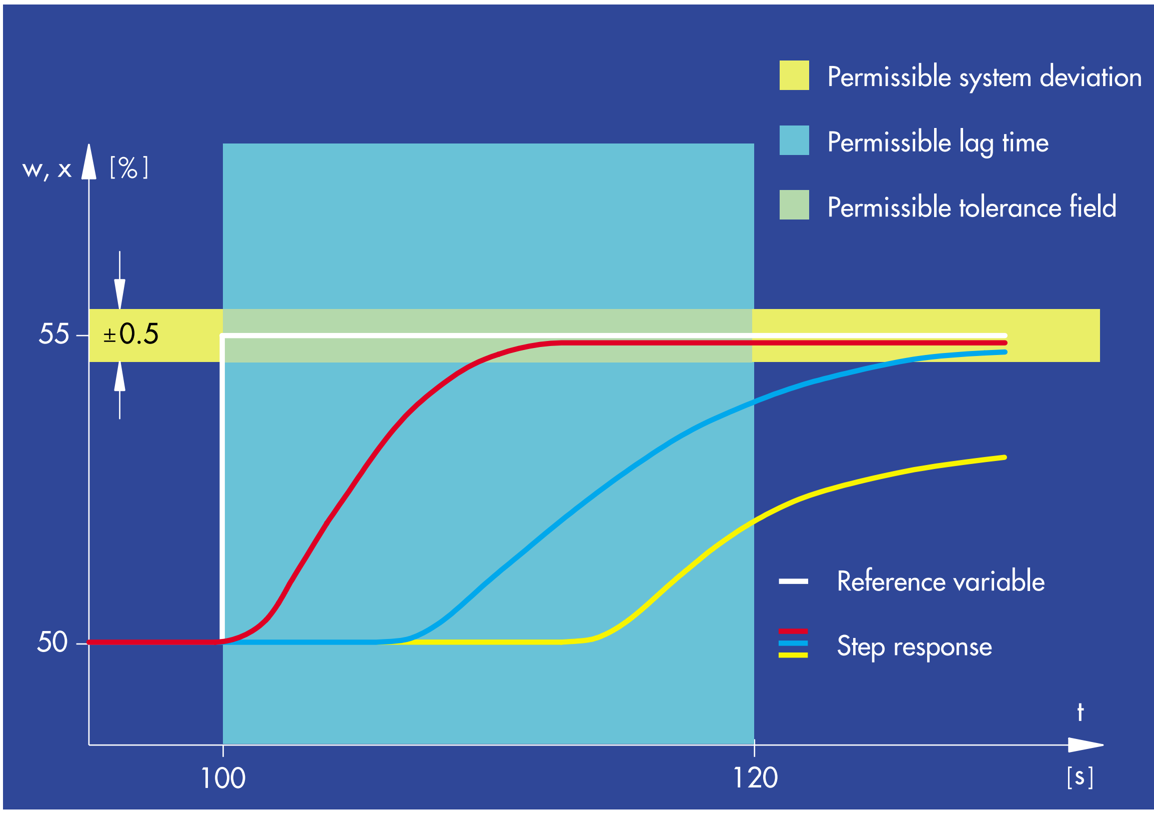
Diagnostic tools for control valves



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Digital positioners offer interesting features regarding improved process plant reliability and maintenance or servicing. This could provide the basis for using software tools for early fault diagnosis and performance visualization of control valves with extended functions. These tools can completely preserve the control valve's condition when new. It can be subjected to trend analyses as well as to preventative maintenance and servicing while in operation. This article describes these possibilities based on an example of such a new diagnostic tool.

Diagnosetools bei Stellgeräten

Digitale Stellungsregler bieten eine Reihe von interessanten Möglichkeiten im Hinblick auf die Verbesserung der Prozesszuverlässigkeit und der Wartung bzw. Instandhaltung. Auf dieser Basis können Softwaretools zur Fehlerfrüherkennung und zur Performance-Visualisierung bei Stellgeräten mit weitergehender Funktionalität eingesetzt werden. Diese unterstützen z.B. die Archivierung des Neuzustandes des Stellgerätes sowie die vorbeugende Wartung und Instandhaltung im laufenden Prozess bis hin zu Trendanalysen. Im Beitrag werden die Möglichkeiten anhand eines Beispiel-Diagnosetools aufgezeigt.

1. Introduction

Compared to conventional analog positioners, the use of digital positioners in combination with control valves provides the following advantages [1]:

- Remote control including communication capabilities (HART/ PROFIBUS-PA, FOUNDATION FIELDBUS)
- Automatic start-up plus additional configuration options without iterative adjustment of zero and span
- Self-optimization and supervision of the positioner's control loop
- Control valve monitoring

Maintenance and repair options are thus extended and the process plant reliability improves.

A study mentioned in [1] shows that 64 % of all problems in control valves are caused by positioners. Approx. 60 % of these problems are caused by false adjustment of zero, span and gain in combination with mechanical difficulties concerning the valve stem coupling (e.g. NAMUR coupling between positioner and control valve). Considering this, approx. 40 % of all causes of failure could be prevented alone by using a self-adapting digital positioner that can be integrally attached to the control valve.

Monitoring control valves without special diagnostic tools as described in this article, essentially comprises off-line initialization during first start-up or restart as well as status requests including alarm messages to the operating and monitoring software (e.g. IBIS (Hartmann & Braun), Corner Stone (ASTEC), AMS (Fisher-Rosemount), CommuWin (Endress+Hauser), Smart Vision (Hartmann & Braun), PDM (Siemens) etc.).

The positioner systems available on the market, however, do not allow errors to be monitored and analyzed in detail during process operation, although additional sensors are used. Therefore, a clear evaluation of the control valve's condition together with instructions and recommendations for maintenance and repair (which would be a requirement for scheduled preventative maintenance) is not possible.

In [1], it is described how an analysis including maintenance instructions and recommendations can be achieved alone by making use of the sensors which are required for positioning anyway, and especially by determining the dynamic behavior of the positioner's control loop. A method is introduced which uses small diagnostic test signals without mean value and with short-time small process disturbances for analysis so that all important control valve parameters can be monitored and recorded *off-line* as well as *on-line*.

In the meantime, this method has been refined and integrated in a powerful diagnostic tool whose features are described below in more detail.

2. Structure of modern diagnostic tools

Efficient valve diagnostic programs feature the following options.

Archiving control valve data (Figs. 1, 2a and 2b) in databases allows operators to quickly access comprehensive information about the control valve. In addition, they enable a more accurate and detailed diagnosis (see 3.4).

While the communication link (e.g. via HART, PROFIBUS-PA, FF) between positioner and control valve is active, possible errors, such as "Control loop error" or "Zero error", immediately appear on the screen (Fig. 3 below). In addition, currently active processes, such as "Diagnosis test active" are indicated.

If an error occurs in the positioner while the communication link is not active, the status parameter in the positioner is set to “error” in any case. When the connection is established, a message appears in the program message window (Fig. 3 on the right).

The recording of the date and time in different tests (Fig. 3 on the left) allows trends to be recognized when important valve parameters change.

A valve’s performance is determined by testing the static and the dynamic control behavior of the valve/actuator/positioner unit under off-line (process not active) or on-line (process active) conditions.

Recording the reference and the controlled variable in dependence of time without test signals also serves to indicate the behavior and the operating ranges of the control valve under standard process conditions (process supervision). The measured data is saved in the database.

Tests especially for error detection or recognition of valve parameter changes (such as packing friction) are part of diagnostic testing procedures used to create comprehensive diagnostic reports for the entire control valve. The information included in these reports should be as clear as possible so that it is not necessary to consult an expert.

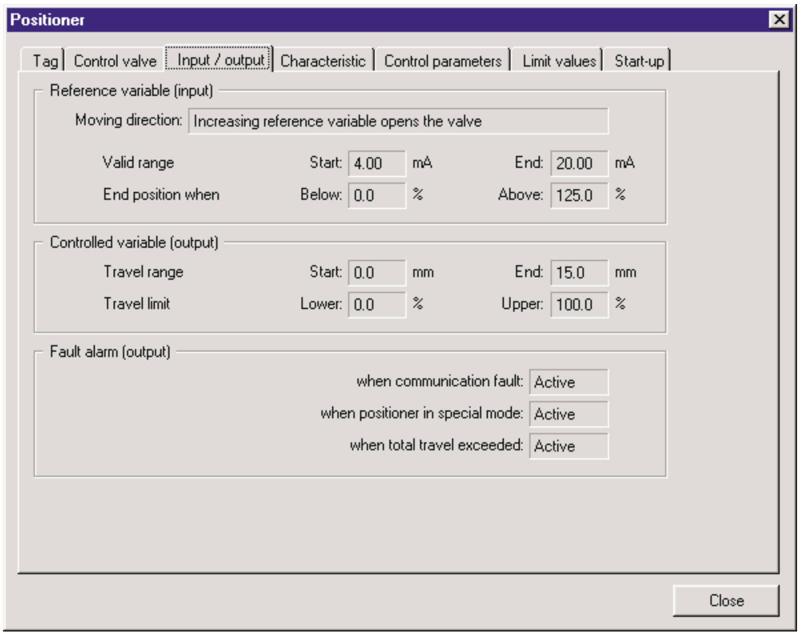


Fig. 1: Positioner data

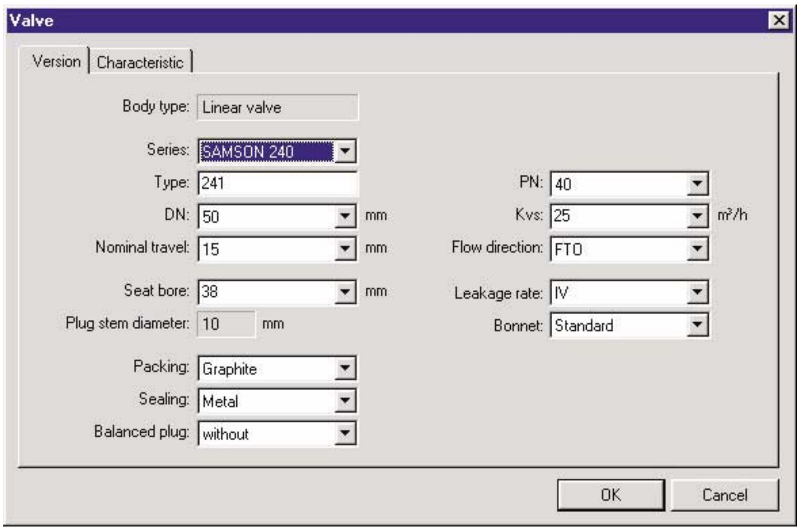
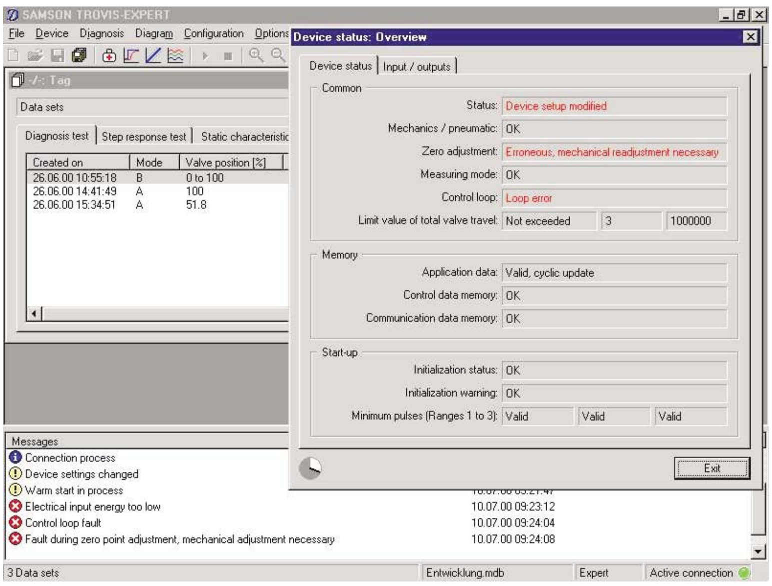


Fig. 2a: Control valve data

Fig. 3: Device status and messages, archiving according to date and time



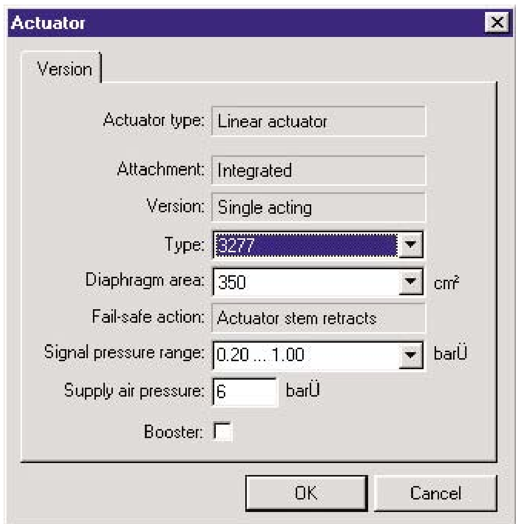


Fig. 2b: Actuator data

3. Tests in diagnostic tools

3.1. Tests for checking the static control behavior

The static control behavior of the entire control valve is strongly influenced by the friction hysteresis, the flexible reactions in the packing of the valve stem sealing and the minimum resolution of the valve stem position sensor [1].

The test is executed by introducing very small step changes of the reference variable, e.g. increments of 0.1 %. The response of the reference variable, i.e. the valve position, is not registered until steady state is reached (in addition to a given wait time). The result is represented in a diagram showing the controlled variable versus the reference variable (Fig. 4).

The program compares the evaluation parameters of the remaining minimum, average and maximum deviation from the set point value with the positioner's given dead band to determine if the control loop is acceptable or not [1].

3.2 Tests for checking the dynamic control behavior

Recording the step responses is a method well suited for the investigation of a control valve's dynamic control behavior.

The reference variable is subjected to a series of step changes in both directions, each starting from the current set point w_0 in steady state. The step changes Δw should be between 0.1 and 10 %. The entire course of the controlled variable x in dependence of time from the introduction of the step change until the new steady state is reached is recorded (Fig. 5a).

In control engineering, the transfer function h(t) is most often used to evaluate the response behavior of the controlled variable x(t) to step changes in the reference variable w from w_0 to $w_0 + \Delta w$.

$$h(t) = \frac{x(t) - w_0}{\Delta w} \text{ with } h(0) = 0 \text{ and } h(t_{100}) = 100\ \%$$

With positive step changes ($\Delta w > 0$), h(t) normally lies within a range of 0 to 100 % (or larger for overshoots). This also applies to negative step changes ($\Delta w < 0$), since $x(t) - w_0$ is < 0 (Fig. 5b).

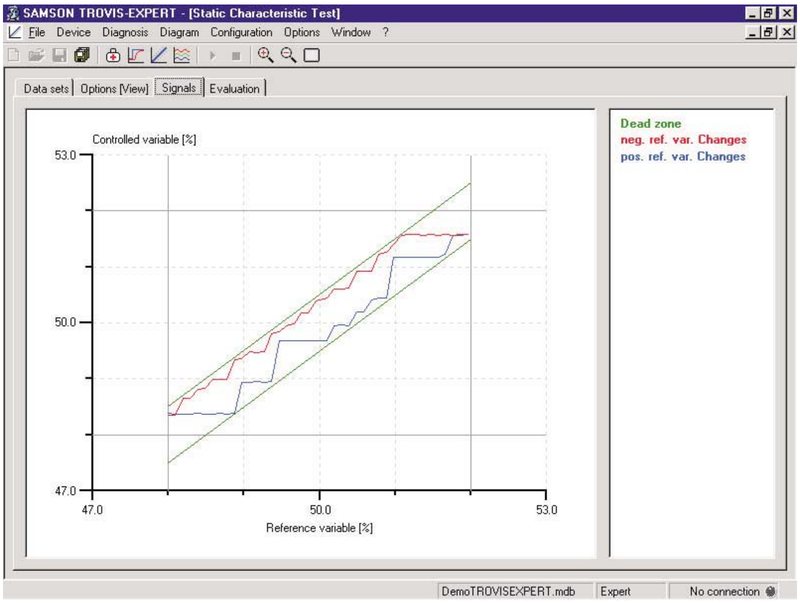


Fig. 4: Test for checking the static control behavior

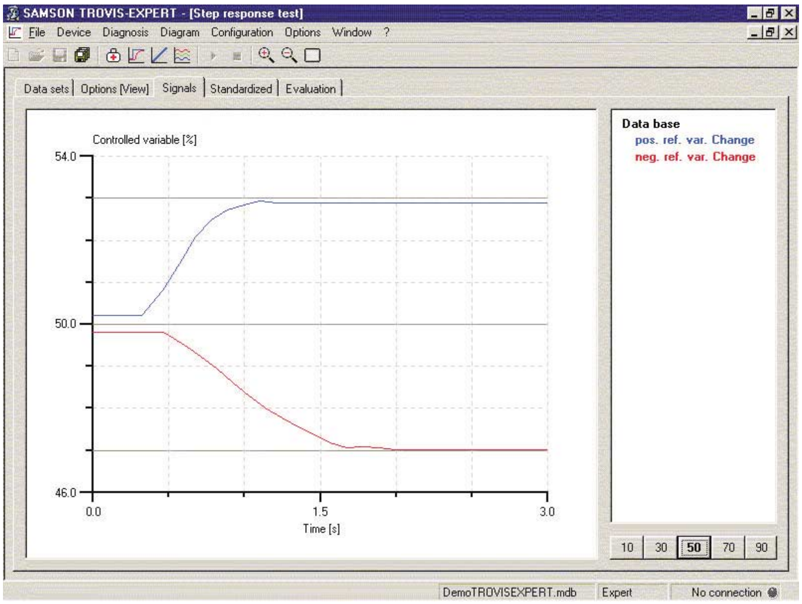


Fig. 5a: Test for checking the dynamic control behavior (step changes from 50 to 53 % and 50 to 47 %)

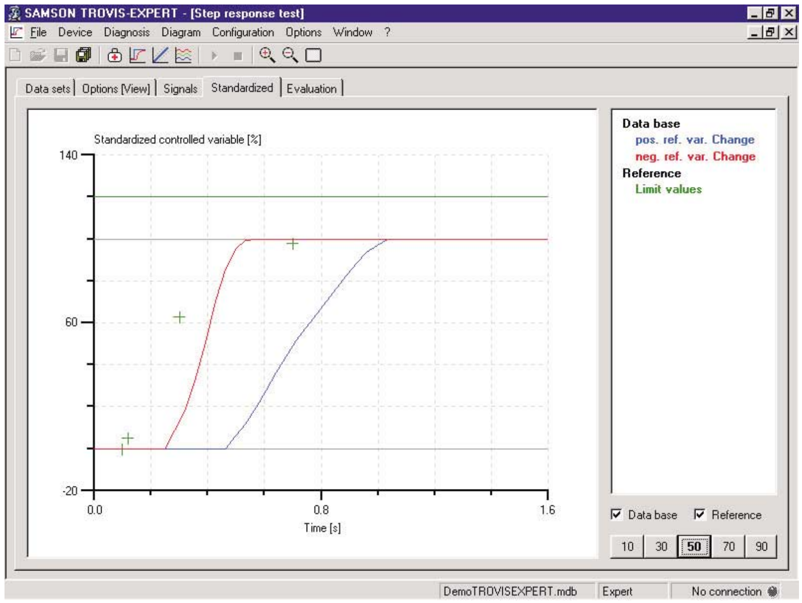


Fig. 5b: Step response evaluation (EnTech)

The following characteristics are suitable for the evaluation of the dynamic behavior (Fig. 5c):

- T_d: time span in which h = 0,
- T_{63}: $h(T_{63}) = 63$ %,
- T_{98}: $h(T_{98}) = 98$ %,
- Overshoot: $h_{max} - 100$ %, if $h_{max} > 100$ %.

Depending on the nominal size of the valve, the EnTech standard defines max. limit values for T_d, T_{63}, T_{98} and for the overshoot. Unfortunately, this definition does not consider the step change, because an optimization for step changes of 0.2 % does not necessarily result in an optimum behavior for step changes of 2%.

Diagnostic tools offer the option of additionally improving the dynamic control behavior in digital positioners. This is facilitated by comparing the effect of control loop parameter changes, such as the proportional-action gain or the dead band (digital positioners with separate pilot valves for filling and venting of the actuator), to the recorded step responses.

Users can enter their own limit values or the ones complying with the EnTech standard. However, reference values measured over the entire travel range can also be used.

3.3 Process supervision

The recording of the reference variable and the controlled variable in dependence of time without test signal provides information on the behavior of the control valve under process conditions (Fig. 6a).

These signals can now be statistically analyzed for the current measurement and for all saved measurements.

The *relative duration density* for the controlled or the reference variable [4] essentially provides information on the actual operating range of the valve. The variable to be examined is divided, for instance, into classes of 5 % and the time is counted during which the respective variable is in the individual classes. This forms the basis for the calculation of the ratio between the total time per class and the total test time for all classes. The resulting quotient divided by the class width and multiplied with 100 % results in the relative duration density (Fig. 6b).

This allows the following information to be gained:

- Operating range of the valve position is o.k.,
- Valve operates mainly in the upper or lower end positions.

If a control valve operates mainly in the lower end positions (< 20 %, closed position), the valve is either sized too large, or wear problems are to be expected in case of strong cavitation (e.g. pressure drop from 150 to 1 bar).

An additional possibility for evaluation is the *counting of spans*.

With signals subjected to time changes, a span is the distance between the maximum value and the minimum value of an oscillation. It corresponds to the double amplitude of the oscillation.

For evaluation, the controlled variable x (valve position) is divided into individual spans, e.g. 5 % , 10 %, ..., 100 %. By counting the "valleys" and "peaks", the occurrence of the individual span widths is recorded for the current test or for all measured data sets (Fig. 6c).

Counting the spans assists in evaluating the dynamic stress that a metal bellows or a packing is subjected to in a control valve. Long-term tests executed by control valve manufacturers with the nominal valve pressure resulted in information regarding the tolerable number of travel cycles for different span ranges. When the span decreases, for instance, the tolerable number of travel cycles for a metal bellows increases overproportionately.

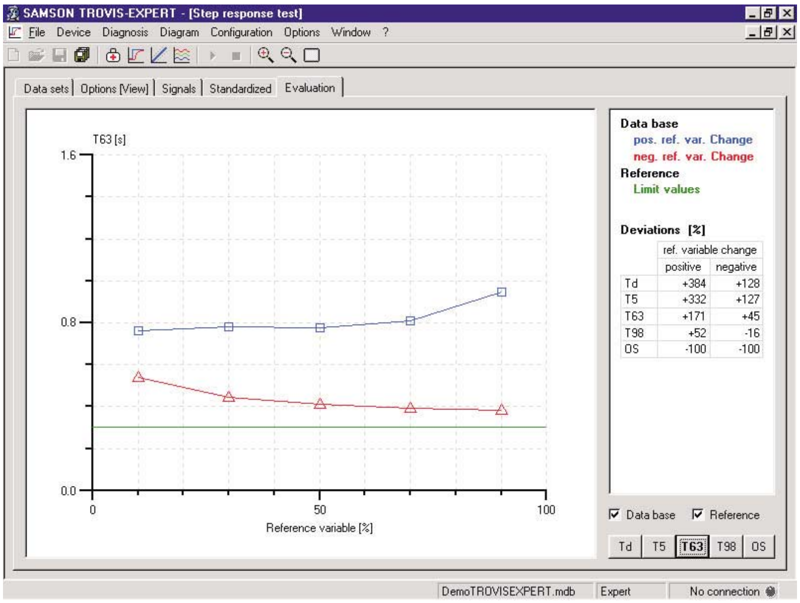


Fig. 5c: Evaluation of step responses (EnTech)

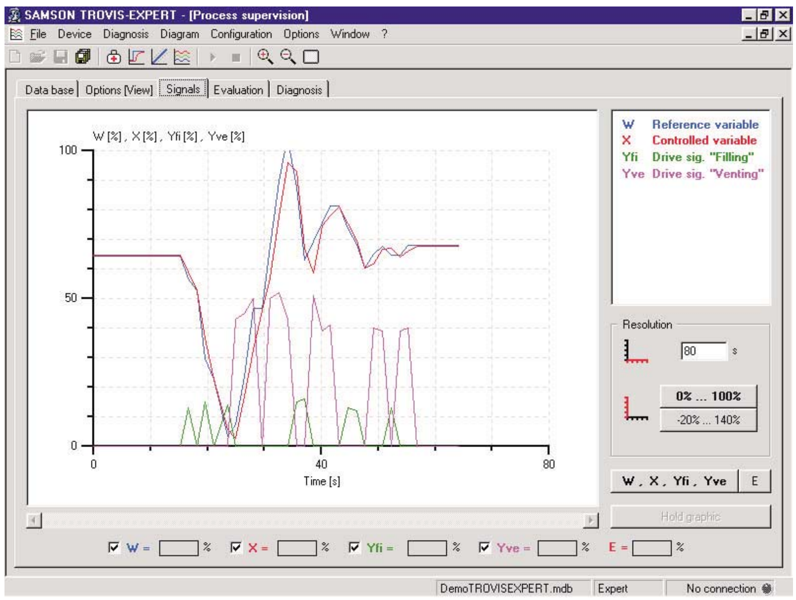


Fig. 6a: Process supervision: reference and controlled variable versus the time including the internal control signals of the pilot valves in the positioner

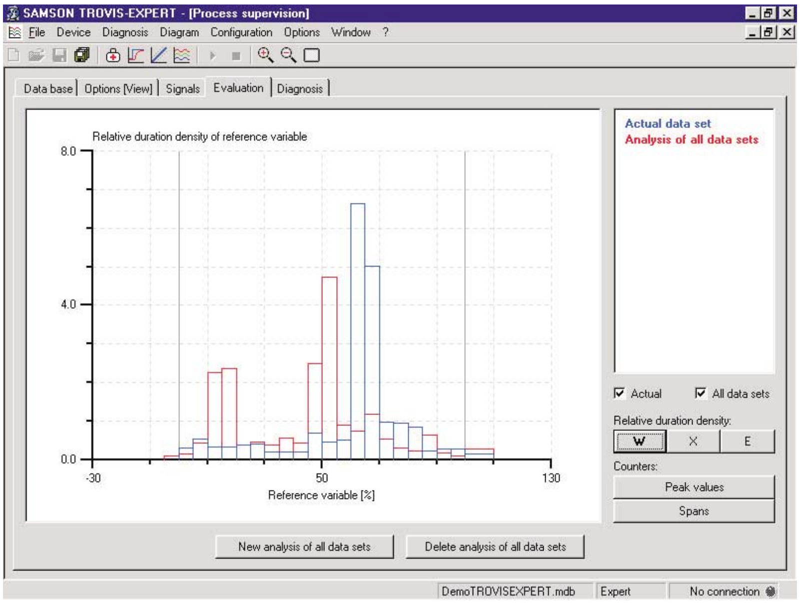


Fig. 6b: Process supervision: statistical evaluation based on the relative duration density

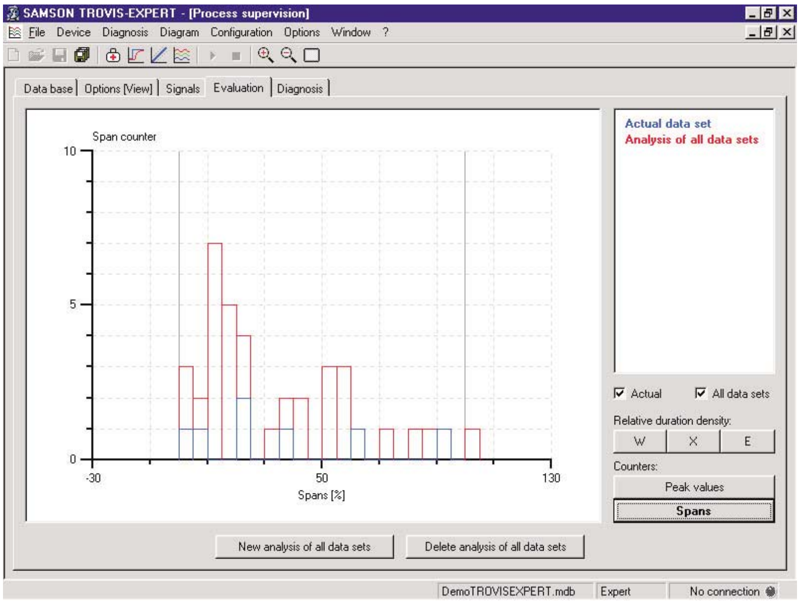


Fig. 6c: Process supervision: statistical evaluation based on the counting of spans

If the counted spans are then set in relation to the tolerable number of travel cycles for each span class (5, 10, ... 100 %), a load value can be calculated for each span class. Since the data of the tag measured and stored in the database represent only a small section of "a valve's life cycle", the counted spans must be multiplied with the quotient resulting from the stored total travel in the positioner (total valve travel) and the total travel of all values measured at the tag (database). The sum for all span classes is a measure for the total dynamic stress (Fig. 6d):

- Total dynamic stress < 0.5: low dynamic stress,
- 0.5 < = total dynamic stress < 0.8: average dynamic stress,
- Total dynamic stress > = 0.8: high dynamic stress.

3.4 Tests for early fault recognition (fault diagnosis)

The fault diagnosis is related in particular to the actuator and the control valve as well as the positioner's air supply. Most positioner brands, however, process internal routines for testing the electronic and mechanical hardware [1] themselves.

It makes sense with spring-loaded pneumatic actuators to record the signal pressure in the pressurized diaphragm chamber, mostly to gain information about the control valve.

Many positioner manufacturers implement a pressure sensor in the positioner. This serves to determine the so-called "valve signature" which plots the signal pressure in off-line operation (process not active, or valve in bypass operation) versus the valve travel. The valve signature can be used, for instance, to determine the hysteresis without positioner. On-line tests (process active), however, are usually not possible.

Any additional sensor also means higher costs and potential additional error sources. Therefore, the real advantage is the "intelligent evaluation" of the signals of existing sensors required for positioning, e.g. the measured valve position.

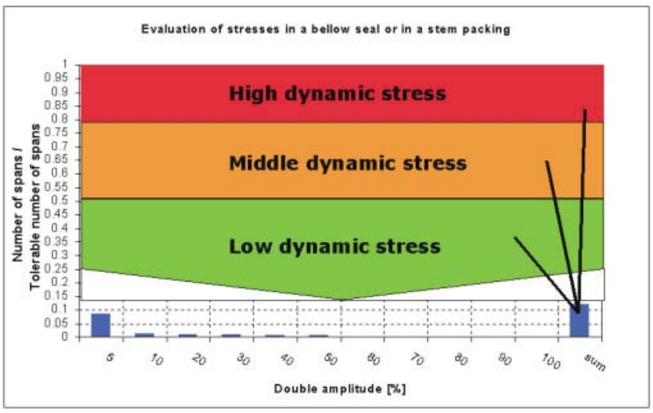


Fig. 6d: Evaluation of the dynamic stress that a metal bellows is subjected to, for instance

In positioners equipped with internal digitally controlled i/p converters, there is actually a connection between the current i and the actuator pressure for quasi-static conditions. Especially the quality of the converter is decisive in determining the height of hysteresis and the reproducibility of such a characteristic. For reasons of costs, however, low-cost equipment is used frequently whose "weaknesses" must then be compensated for in the digital control algorithm. Diagnoses based on the evaluation of the function $p = f(i)$ are therefore only difficult to realize and, up to now, unknown.

However, digital positioners with pulse-width modulated signals controlling the pilot valves and with separate actuator filling/venting function are suitable for early error recognition in off-line and on-line operation without requiring additional sensors [1, 5].

Off-line tests (process not active):

Tests can be performed over the entire valve travel range.

- Zero point test
- Leakage test
- Closing and opening time test while the positioner has its full air capacity
- Diagnosis step response tests for 5 reference valve positions (10, 30, 50, 70 and 90 %) with a small step change (max. ± 2 %).

On-line test (process active):

Tests can only be performed around the current set point at the start of the test.

- Leakage test
- Diagnosis step response test for the current valve position with a small step change (max. ± 2 %).

Table 1: Diagnosis test evaluation based on control valve changes

Parameter changes	Diagnosis step response test	Diagnosis step response test	Leakage test	Opening time test	Zero point test
New - Reference	$\Delta t_D/\Delta t_R$ **Venting**	$\Delta t_D/\Delta t_R$ **Filling**			
No change	0/0	0/0	0		
Lower friction	–/0	–/0	0		
Higher friction	+/0	+/0	0		
Changed supply pressure	0/0	+–/+–	0		
Lower supply pressure (off-line)	0/0	+–/+–	0	– springs opening	
Higher supply pressure (off-line)	0/0	+–/+–	0	+ springs opening	
Spring failure (off-line)	++/+0	+0/–	0		
Pressure difference exists (on-line)	+–/+–	+–/+–	0		
Air filter contamination	–/–	++/++	0		
Actuator leakage			+		
Zero point lower					–
Zero point higher					+

During the **zero point test,** the valve plug moves into the valve seat and the current position of the zero point is determined. Essential changes of the zero point may be, for instance, caused by wear on the closure member or seat (change < 0 or > 0) or by contamination (change > 0).

During the **leakage test,** both pilot valves are closed for a certain amount of time so that the actuator is neither filled nor vented by the positioner. Continuous valve position changes towards the negative (down) in combination with the setting "actuator springs closing" or towards the positive (up) in combination with the setting "actuator springs opening" can indicate actuator leakage (screw joints in the pneumatic section, diaphragm leakage, etc.). The leakage rate can be indicated directly as a change in the valve position [%]/time[s].

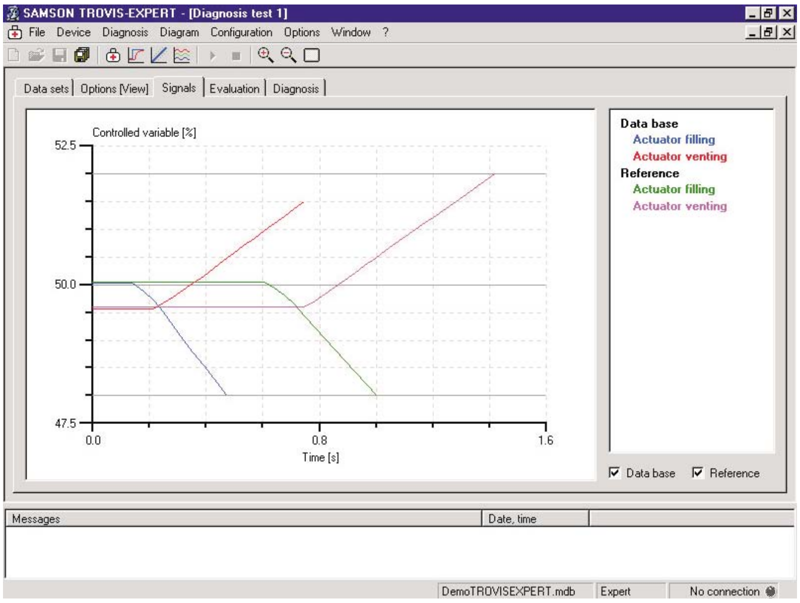


Fig. 7: Diagnosis step response test (reference test 50 %, repeat test 50 % with reduced friction)

The **closing and opening time test** at the positioner's full air capacity (pilot valves continuously open) determines four time parameters:

- Opening delay time as time between the starting of the test and the start of the valve position change (opening),
- Opening run time for valve position 0 to 100 %,
- Closing delay time as time between the starting of the test and the start of the valve position change (closing),
- Closing run time for valve position 100 to 0 %.

The **diagnosis step response test** (Fig. 7) around a certain valve position is the basis for these tests. It is characterized as follows:

- In on-line operation (active process), small step changes (max. ± 2 %) are used to introduce only *small process disturbances*
- The step changes are introduced for both directions (filling/venting of the actuator)
- Due to the continuous, but small pulse widths of the signals controlling the pilot valves and the positioner's resulting low air capacity, the valve reaches a nearly constant positioning rate which can be easily evaluated and leads to only small overshoots; the evaluation provides two delay time values Δt_D (time span without change of the valve position upon introduction of the step change) and two run time values Δt_R (time per 1 % valve position change) for filling and venting (Fig. 7); the direction is reversed while the valve is moving (52 %–>50 %–>52 % or 48 %–>50 %–>48 %) so that the delay times are essentially in proportion to the sliding friction.

The *standard evaluation* of these tests covers the following steps:

- Execution of the reference test (condition of valve when it was new) as off-line test
- Execution of on-line or off-line tests for repetition
- Comparison between the repetitive values and the reference time values from the diagnosis step responses (linear interpolation for the five reference valve positions)
- Additional options of comparison for tests repeated using the time values from the closing and opening time tests.

This standardized evaluation allows the change of important control valve parameters to be recognized as shown in Table 1.

Based on this and in combination with the values gained from experience, e.g. regarding the minimum pre-load of an adjustable packing to seal the valve stem, a recommendation or instruction can be issued for each condition.

Example 1:

Fig. 7 shows the measured step responses for the off-line reference test (3rd valve position 50 %) and the on-line reference test (50 %) with reduced pre-load of the adjustable packing. It can be seen that the delay times for filling and venting are reduced by approx. 75 %. The run times, however, are practically unchanged. The pre-load is therefore approx. 75 % smaller than it was when the valve was new.

Fig. 8 shows the comprehensive diagnosis report which evaluates the most important parameters of the actuator, the control valve and the positioner by issuing the condition and instructions. Most of the conditions can only be stated for the current test (repeated test) because the main procedure is based on the comparison between the repeat tests and the reference tests. Evaluations regarding leakage and zero can also be made for reference tests.

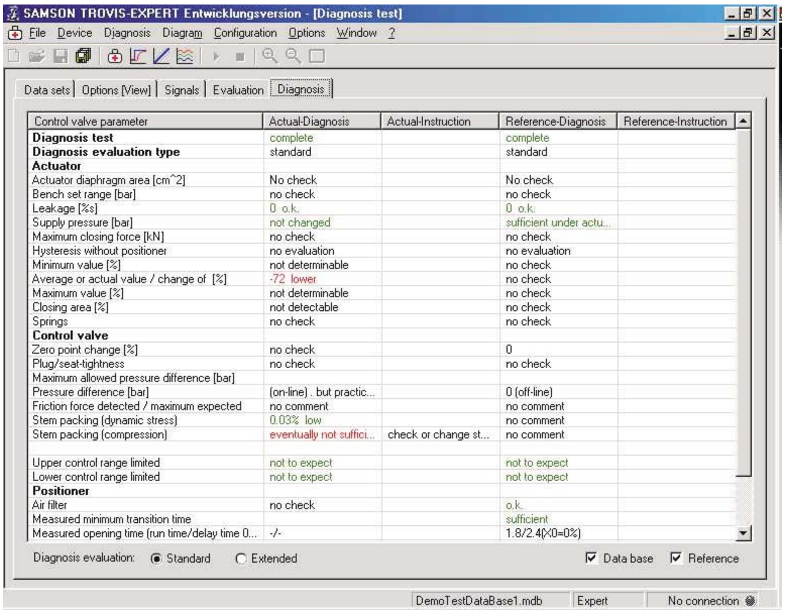
This particular report indicates that the hysteresis decreased by approx. –75 % from the actuator's "point of view" and as a result, the packing may not be sufficiently tight anymore. Consequently, the maintenance staff would be required to readjust the packing and check it for leakage.

Example 2:

Fig. 9 shows the diagnosis report after reducing the air supply pressure of the positioner. The basic diagnosis is that the supply pressure is reduced in connection with the instruction to check the pressure in the supply system (or even the pressure reducer or the control valve display). Subsequent messages for this control valve with the fail-safe action "actuator springs open valve" indicate the reduction of the closing force (contact force between plug and seat) as well as the resulting reduced maximum permissible differential pressure on the control valve.

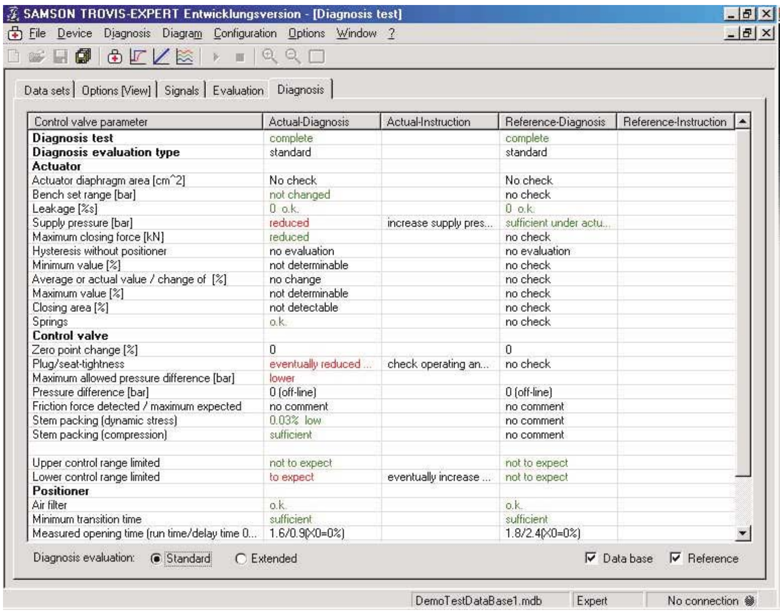
If mathematical models are available for the positioner (air capacity depending on the signal pressure, the supply pressure and the control signal), for the actuator (correlation between signal pressure and valve position) and for the control valve (frictional force, minimum required contact force, etc.), the individual parameters can also be calculated. This is much easier to do for globe valves than for rotary valves.

Fig. 10 shows the resulting extended diagnosis for the results illustrated in Fig. 9. It not only enables the off-line reference test to be extensively reviewed, especially with regard to a verification of the given actuator data (see Fig. 1c), but it also allows the current repeat test to be analyzed in more detail. For example, it does not only state "supply pressure reduced", but also indicates "reduction from 6 to 1.8 bar". It additionally states the extent of the reduction, i.e. the max. permissible differential pressure.



Control valve parameter	Actual-Diagnosis	Actual-Instruction	Reference-Diagnosis	Reference-Instruction
Diagnosis test	complete		complete	
Diagnosis evaluation type	standard		standard	
Actuator				
Actuator diaphragm area [cm^2]	No check		No check	
Bench set range [bar]	no check		no check	
Leakage [%s]	0 o.k.		0 o.k.	
Supply pressure [bar]	not changed		sufficient under actu...	
Maximum closing force [kN]	no check		no check	
Hysteresis without positioner	no evaluation		no evaluation	
Minimum value [%]	not determinable		no check	
Average or actual value / change of [%]	-72 lower		no check	
Maximum value [%]	not determinable		no check	
Closing area [%]	not detectable		no check	
Springs	no check		no check	
Control valve				
Zero point change [%]	no check		0	
Plug/seat-tightness	no check		no check	
Maximum allowed pressure difference [bar]				
Pressure difference [bar]	(on-line) . but practic...		0 (off-line)	
Friction force detected / maximum expected	no comment		no comment	
Stem packing (dynamic stress)	0.03% low		no comment	
Stem packing (compression)	eventually not suffici...	check or change st...	no comment	
Upper control range limited	not to expect		not to expect	
Lower control range limited	not to expect		not to expect	
Positioner				
Air filter	no check		o.k.	
Measured minimum transition time			sufficient	
Measured opening time (run time/delay time 0...	-/-		1.8/2.4(X0=0%)	

Fig. 8: Diagnosis report related to Fig. 7



Control valve parameter	Actual-Diagnosis	Actual-Instruction	Reference-Diagnosis	Reference-Instruction
Diagnosis test	complete		complete	
Diagnosis evaluation type	standard		standard	
Actuator				
Actuator diaphragm area [cm^2]	No check		No check	
Bench set range [bar]	not changed		no check	
Leakage [%s]	0 o.k.		0 o.k.	
Supply pressure [bar]	reduced	increase supply pres...	sufficient under actu...	
Maximum closing force [kN]	reduced		no check	
Hysteresis without positioner	no evaluation		no evaluation	
Minimum value [%]	not determinable		no check	
Average or actual value / change of [%]	no change		no check	
Maximum value [%]	not determinable		no check	
Closing area [%]	not detectable		no check	
Springs	o.k.		no check	
Control valve				
Zero point change [%]	0		0	
Plug/seat-tightness	eventually reduced ...	check operating an...	no check	
Maximum allowed pressure difference [bar]	lower			
Pressure difference [bar]	0 (off-line)		0 (off-line)	
Friction force detected / maximum expected	no comment		no comment	
Stem packing (dynamic stress)	0.03% low		no comment	
Stem packing (compression)	sufficient		no comment	
Upper control range limited	not to expect		not to expect	
Lower control range limited	to expect	eventually increase ...	not to expect	
Positioner				
Air filter	o.k.		o.k.	
Minimum transition time	sufficient		sufficient	
Measured opening time (run time/delay time 0...	1.6/0.9(X0=0%)		1.8/2.4(X0=0%)	

Fig. 9: Diagnosis report for changed supply air pressure

4. Summary

Efficient valve diagnosis programs are capable of visualizing a control valve's performance. It is essential, however, that tests be performed for early fault recognition with the objective to provide plant operators with a preventative, state-oriented maintenance.

This article describes a diagnostic tool which does not require any additional sensors in the digital positioner. At the same time, it features a variety of options for evaluation in the form of conditions and instructions being issued regarding all major control valve components, and without needing to consult an expert.

The characteristic data thus determined, however, do not always provide a clear cause of the problem, e.g. drawing a conclusion on the pre-load of a packing by looking at the friction force. Nevertheless, changes in the system are recognized which can be very helpful in achieving the above objectives.

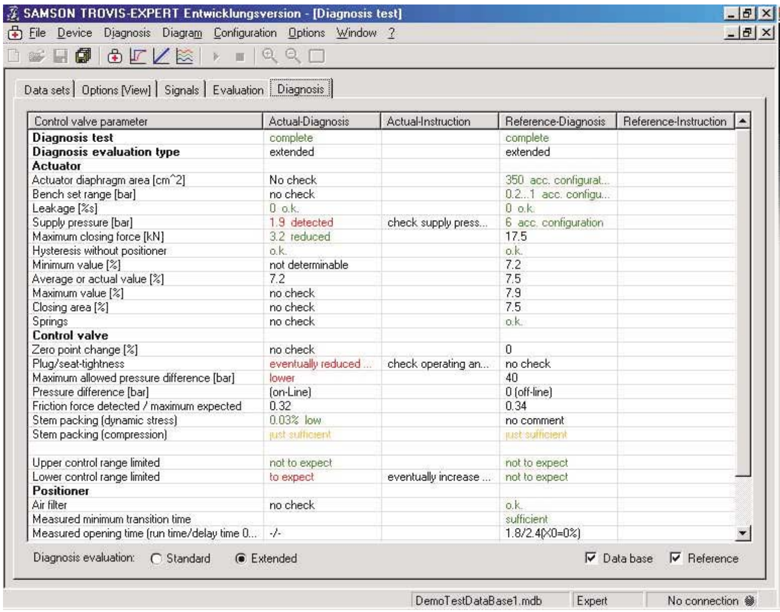


Fig. 10: Extended diagnosis report based on a mathematical model (see also Fig. 9)

Up-to-date diagnostic tools store all test results in databases according to date and time. Consequently, trends of parameter changes can certainly be recognized. However, an automatic evaluation of the control valve on this basis regarding the service life or a suggestion for the next maintenance routine in combination with a specification of the required spare parts, is still not possible at the moment.

With all due respect to the importance of a system diagnosis for preventative maintenance, it must be considered, though, that careful sizing and selection of the control valve type is still the best guarantee for keeping costs of ownership low.

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