Intelligent proportional pneumatic valves and drives for field bus applications

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ABSTRACT

The continuous trend within the factory automation and process control to use intelligent peripheral field devices increasingly leads to an extended function range of proportional pneumatic valves and drives. Typical requests in this area are:

- interfacing to a digital communication system
- line-up support
- diagnostic and service functions
- error messages / alarm
- compatibility / exchangeability

In the area of process control there is a demand to lower the installation costs and to transfer the energy and the control signal via the same wire. For this reason the presented valve is characterised by a reduced electrical power consumption. The pilot control stage operates according to the spool valve principle and reduces the pneumatic power consumption substantially, too. The maximum electrical power consumption of the entire valve including the connection of the field bus and the electrical amplifier stage amounts to less than 1 W.

KEY WORDS
continuously acting valve, piezo valve, field bus

INTRODUCTION

In today's manufacturing processes devices of the field layer are attached to the control and engineering systems via field bus systems. This serial communication opens up the possibility of making adjustments on field devices by changing parameters or using extended functionality of peripheral intelligence directly from control and engineering systems.

Everywhere electro-mechanical function units can be formed, peripheral control structures can be reasonable. This way automation systems can be built up using the Construction-Kit-Principle. By the integration of cylinder-drive, valve and controller as well as a field bus interface, newer electro-pneumatic drives represent such a function unit (figure 1).

Due to the increasing networking inside machines and production plants, communication interfaces become even more important for future components. The networking of
components with field bus systems is the basis for extended functionality such as diagnostic and service functions.

The line-up can be made by the field bus from an engineering system. Error messages as well as diagnostic information can be transmitted. For future use a preventive maintenance during operation is possible. A standardised field bus interface, that describes a common basic functionality, enables exchangeability for the valves and drives regarding the device [1, 2].

Newer developments within the area of the field bus technology permit an integrated signal and power transmission over the proper bus system. Examples of these field bus systems are ASI, Interbus loop and ProfibusPA. For a reasonable usage of this technology components with very low energy input are obligatory.

To build up an integrated low power cylinder drive with extended functionality for proportional and servo pneumatic applications, low power continuously acting direction control valves with sufficient dynamic and flow rate are required.

**DEVELOPMENT OF A PNEUMATIC VALVE WITH MINIMISED ENERGY INPUT**

Handling operations and position control have need of very dynamic control devices with natural frequencies of 80 up to 100 Hz [3].

For industrial pneumatic applications valves with a “powerless” control signal are available [4]. In this case, usually pure switching valves are concerned. Indeed these valves can be used also as proportional valves, but for this often a modification of the electrical control is necessary. By this modification the required electrical power consumption of the valve rises noticeably. The proportional valves today available at the market require an electrical power between 1.7 and 30 W (figure 2).

The valves shown in figure 2 are conventionally controlled through a voltage or a current interface. In the past few years switching valves attached to a bus system via valve clusters are state of the art, but proportional valves with integrated field bus interface are offered very rarely so far.

![Figure 1: Integrated cylinder drive (Interact courtesy of Hoerbiger)](image)

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![Figure 2: Electrical power consumption of pneumatic switching and proportional valves [5]](image)

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Continuously acting valves with flow rates higher than 400 l/min, a natural frequency above 50 Hz and a maximum power input less than 1.5 W are not available on the market by now.

The realisation of a main stage with a nominal diameter of 6 mm and the demand for the lowest possible electrical power input (\(P_{\text{Electrical}} < 1\) W) for the valve pushed the demand for a two-stage design using an electro-mechanical transducer combined with a pneumatic amplifier stage.

In the past concepts that reduce the power input of the first stage to 300 – 500 mW and ensure the continuous variability of the main stage were worked out at IFAS [6]. Operating according to the flapper-nozzle pilot principle, the pneumatic power input of these valves amounts to 173 W, however, and the high running costs of these pilot valves give rise to the additional demand for considerable reductions in their idle-state pneumatic energy input. The pilot stage was designed in two phases:

1. Selection of a suitable pilot control principle
2. Selection of a low-power actuator

**Selecting a pilot control principle**

The two physical principles described below can be applied to convert the output signal of the electro-mechanical transducer into a pneumatic signal:

- Using controllable resistors to throttle the fluid flow
- Converting the kinetic energy of the fluid flow into static energy

The fluid flowing through a spool valve is throttled by variable spool lands that represent variable flow resistors. Spool valves are currently seldom used in preliminary stages because of the substantial mass of the valve that has to be moved. On the other hand, a closed center spool valve has no pneumatic losses in the central position.

Flapper-nozzle systems comprise of a combination of two coils driving a torque motor. Variable in opposite di-
rections, the two flow resistors are formed by a flapper combined with two constant pilot nozzles. This pilot principle is most frequently applied in standard, indirectly actuated continuously-acting valves. One of its disadvantages is the high pneumatic energy loss in the central position, when both variable nozzles are open [7]. The pneumatic energy loss can only be reduced by using a second actuator that enables independent adjustment of the gaps between the two nozzles and the flapper [8].

**Selection of an electro-mechanical transducer**

Electro-mechanical transducers are required in valves to generate forces and/or travel that operate the fluidic resistors following the electrical control signals. The resistors take the form of piston ports or seat gaps according to the valve design.

Electromagnetic transducers are used almost exclusively in practice. Typical designs include the torque motor, the solenoid or proportional magnet and the plunger-coil drive. Piezo-actuators have also been used as transducers in an increasing extent in recent years.

As far as energy input is concerned, piezo-actuators have the greatest saving potential. Characterized by a very low energy requirement for static excursions, they offer a means of realizing completely new control and drive concepts. Another important advantage of these actuators is their outstanding dynamic performance. On the other hand this is offset by the high operating voltage that they require - typically in excess of 100 V - which can only be generated from 24 V with unavoidable losses.

Piezo-actuators are manufactured according to two different design concepts: stack translators or bend transducers. Stack translators have numerous fine ceramic plates that make up the electrically active part of the transducer and those are capable of generating very high forces, but have a stroke that is typically shorter than 100 μm. These actuators are already being used successfully in directly operated hydraulic valves [9-11].

If two thin transducers are bonded together to produce a double layer, opposing deformation causes a pronounced curvature of the bonded element. Bend transducers make use of this effect. Piezoelectric bend transducers are already being used in pneumatic on-off valves today [4]. More recent transducers generate up to 1 mm stroke and require 60 V operating voltage. Unlike stack translators, these actuators are only capable of generating low forces ranging between 0.5 and 1 N.

**Realised prototype**

A combination of spool valve and piezoelectric bend transducer was chosen from the pilot principles and electro-mechanical transducers described above. One of the main reasons for this were the low pneumatic losses in the central position of the pilot stage, and another was the very low energy input for the piezo-actuator for an acceptable installation size. The realised mechanical construction of this concept is shown in figure 3. The currently build prototype measures 52 x 27 x 11 mm.

![Realised Prototype](image)

All pneumatic piezo valves so far available at the market use a piezoelectric bend transducer in combination with the nozzle/impact plate principle. Within these concepts the bend transducer operates in the direction of the minimal mechanical resistance towards the nozzle. The cross section of the nozzle is adjusted over the height of an annular gap between edge of nozzle and bend transducer (figure 4 left hand).

Throughout this arrangement the bend transducer must be able to produce a force higher than the arising pressure. The low generateable force of the bend transducer working against the nozzle area limits the valve regarding the cross-sectional area or the adjustable pressure difference.

![Possible arrangements](image)

For the pilot controlled stage introduced here another arrangement was selected on purpose. The functional surfaces are laterally flowed against, so that the bend transducer does not have to take up the thrust force in its moving direction (figure 4 right hand). Thereby the stroke is independent of the actual pressure difference and the cross-section area. A valve according to the nozzle/impact plate principle, which uses this arrangement, was already mentioned by Kolvenbach in 1987 [5].

The pilot stage is designed as 5/3-way valve according to the spool valve principle. Supply pressure is supplied through the spool. The annular gap between the spool valve and the respective area seals the connections to the environment.

**Figure 5** shows a cross-sectional view of the front part of the valve with the four spool lands, the pressure supply $P_o$,
and the lines to chambers A and B to illustrate the operating principle of this concept.

Figure 5: Cross sectional view

If the slide moves upwards out of the central position shown, air flows into chamber A and out of chamber B. Slide movement in the opposite direction causes air to flow out of chamber A and into chamber B.

**Experimenter data**

In the central position, only 0.5 Nl/min leakage was measured for the pilot stage with 8 bar supply pressure and approx. 7 bar adjustable pressure difference between A and B (figure 6).

![Pressure Signal Function](image)

Figure 6: Pressure signal function

This means that the pneumatic energy loss is reduced to 6.6 W. With air flowing perpendicularly to the stroke direction, the functional surfaces of the slide valve permit outstanding dynamic performance in conjunction with the very lightweight slide. Figure 7 shows the frequency responses for ± 100 %, ± 50 % and ± 20 % and 130 Hz maximum excitation. The frequency response does not reach the -90° frequency within the measured range and the amplitude response remains stable.

After the successful testing of the prototype the enlargement of the nominal size is aimed at 0.5 mm.

Figure 7: Frequency and amplitude responses of the pilot valve

**DESIGN OF THE COMPLETE VALVE**

Beside control stage the complete valve consists of a number of further modules (figure 8). In order to build a valve with a minimal energy input, the energy balance has to be calculated for the whole system. All components have to be considered critically.

![Design of the 2-stage complete valve](image)

Figure 8: Design of the 2-stage complete valve

**Valve electronics**

The piezoelectric transducer only consumes electrical energy during its expansion process because of its electrical capacity. Any change in expansion presupposes a transfer of charge and therefore requires an electrical current. If the piezo-actuator is disconnected from the power supply, in theory it cannot discharge itself and remains in its position. The development of an amplifier stage for the piezo-actuated pilot stage was therefore aiming to find a suitable concept that makes use of this feature.

To reduce the power input the DC/DC converters are switched off during no-load operation. Short motion cycles can be executed, without the transducers being active.
condenser even compensates power peaks, which occur within a control procedure.

The quiescent current consumption of this amplifier stage is almost zero. It contains no components spending permanently energy and independently from the actuator movement. If small leakage losses are not taken into consideration the necessary performance only depends on the desired valve dynamics.

A current regulator circuit is used to restrict the maximum current input to the amplifier stage to 30 mA. This results in a maximum power input of \( P = 0.7 \text{ W} \) for the electro-mechanical transducer as a whole.

**Position sensor**

Due to the selected combination of piezo bend actuator and 5/3-way spool valve the spool position feedback of the main stage can only be realised electrically. Looking at the position sensor the following boundary conditions result from the application in an energy input reduced valve:
- Minimised energy input < 50 mW
- Range ± 1 mm
- Small building space
- Good dynamics ≥ 1 kHz

Especially newer sensor concepts using magnetic field characteristic seem to be fitting. Influences of the environment can be excluded by an optimised design of the permanent magnet with assistance of FEM [12]. Particular sensors, based on the GMR (Giant Magneto Resistance) - effect that was discovered in 1988 by Baibich and others, appear to be suitable for a robust position sensor with very low energy input. The effect is characterised in relation to conventional technologies like the Hall and the AMR (Anisotropic Magneto Resistance) - effect by higher sensitivity and effect size. Sensors with larger working range and more compact dimensions can be manufactured.

GMR and AMR sensors are built up as Wheatstone bridges. The GMR sensor tested in this project has a max. energy input of 5 mW and within a stroke of 3 mm shows a good linearity. The natural frequency of 1 MHz is according to specification of the manufacturer clearly above the required 1 kHz.

**Microcontroller**

The demands for extended functionality can only be solved by the application of microprocessors integrated into the valves. Additional to interfacing the valve to a bus system in the future more and more intelligence or higher arithmetic performance is necessary for diagnosis functions and preventive maintenance. If a processor is used anyway for these functions, it can take further functions without large expenditure. Functions, which require complex and cost-intensive additional circuits, can be shifted partially on a suitable microcontroller. Figure 9 represents the different functions of the microcontroller within the complete valve.

![Figure 9: Functions of the microcontroller](image)

**Field Bus Interface**

The pneumatic components used within a system usually have almost no influence on the used superior control or on the field bus. Typical selective criteria for the application of a bus system are:
- breakdown sensitivity
- data transmission rate
- expandability
- number of users
- availability on the market
- installation costs per node
- investment security

Open and standardised communication systems can only be accepted on the market, if a sufficient number of manufacturers offer a sufficient number of products. For this reason the specifications of different field bus systems were revealed, to enable the development of field bus components for other companies.

Solutions on the basis of international standards can fulfil the demands of operational reliability, investment protection and world-wide availability. In Europe a set of industrial communication systems were standardised by CENELEC. The world-wide standardisation takes place with IEC and ISO.

The standards described so far refer exclusively to the mechanism of data transmission and contain no information about their meaning. With the definition of so-called device profiles, which are used on the field bus systems already standardised, a definition of data contents and their importance takes place.
For the information and data, which can be exchanged with a certain type of device, the internal messages and reactions to data contents are defined exactly according to data types, default values, read and write access and if necessary units as well.

Standardised device profiles enable the development of non-proprietary diagnostic programs and uniform control surfaces. Profile-conform devices of different manufacturers can be handled with identical instruction so that the user has to be trained only on one system. This leads to a reduction of sources of error as well as to an increase of the productivity.

Bus-specific device profiles exist already e.g. for simple sensors and actuators as well as welding controls, robotic controls and electric drives.

A special device profile for fluid power technology was defined by the German Engineering Federation (VDMA). It is suitable for hydraulic as well as for pneumatic valves and drives and is implemented on the field bus systems CANopen, Interbus and ProfibusDP. The first hydraulic continuously acting valves supporting this profile for CANopen are available on the market. Opposite to hydraulic components pneumatic devices are still using proprietary device profiles.

As the first pneumatic valve this valve supports the standardised field bus profile "Fluid Power Technology". The implementation guarantees an exchange-ability of the valve regarding the control signals from the superior controller.

**SUMMARY**

The continuous acting valve of the nominal size 6 introduced here realises already most of the demands of future valves. It contains a field bus interface and supports the standardised communication profile "Fluid Power Technology". Opposite to comparable valves available on the market it consumes around 5 to 20 times less energy with extended functionality. The dynamic of the complete valve achieves the requirements for a proportional valve (2 - 10 Hz at ± 100 % [3]). In a further development step the nominal size of the pilot valve will be risen to 0.5 mm and as a result the dynamic behaviour of the complete valve will be improved as well.

The max. energy input of the complete valve is less than 1 W including the field bus interface and electronics. In static operation the electromechanical transducer and the amplifier stage take up almost no electrical energy. Contrary to other valve concepts the rest position of the main valve spool is arbitrary. Only the microcontroller and the position sensor require a continuous power input. Even the fluid amplifier stage was optimised regarding its pneumatic capacity. According to the pilot valve using the slide valve principle, the pneumatic energy dissipation is decreased significantly.

Due to its dynamic and great flow rate this valve is in opposite to other low power valves suitable to build up an integrated low power servo pneumatic cylinder drive. For extending the valve functionality to position control of a cylinder drive only an interface for a displacement sensor has to be added to the valve electronics.

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**REFERENCES**


