Sensor-Less Position Detection at Electromagnetic Actuators

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Abstract

In this presentation a new patented procedure is described which allows to detect the armature position of an actuator by means of the variance of a turn-off pulse depending on the stroke point.

In order to generate the turn-off pulse the current flow is interrupted by the coil for a short time as a result of which the magnetic coil generates a voltage pulse in dependence of the coil inductance. The voltage pulse depends on the position of the solenoid armature, so there is a clear connection between the armature position and the time sequence of the turn-off pulse. This temporal change of the voltage reduction can be detected by means of an electronic device. A big advantage of sensor-less position detection is that no electronic device or additional mechanism has to be applied directly at the actuator resp. no loss of installation space will occur. Furthermore this procedure allows the use of the actuator coil as pure sensor coil, the position detection hence may be realized also at a “force-less” armature by the use of short measurement pulses.

KEYWORDS: sensor-less, position, detection, actuator, sensor

1. Introduction

When using electromagnetic actuators there is often the requirement to know the position of the control element. By the development of suitable sensors a displacement determination is industrially established especially for high-class control tasks. Complementary to the use in complex displacement control circuits such information could be also used – in simplified form - as a signal in automatic systems in order to give, for example, functional feedback messages.

In many different surface-mounted variants actor and sensor are mechanically linked as a unit in order to record the event directly at the causing element. For this reason actor and sensor are two associated elements which form not only a mechanical but also an electrical entity. The solution developed by Magnet-Schultz uses the actuator with the related coil besides the generation of the electromagnetic force and switching movement also as sensor by measuring the inductance at the different stroke positions. This idea is not completely new and has been realized in different patents with relatively complex electronic circuits in part. In patent DE102007034768B3 /1/ a two-point current controller including frequency evaluation is used, in DE000019910497A1 /2/ the differential inductance has to be determined from the coil current flow with PWM control and in DE102005018012A1 /3/ two actuator coils are used which will be evaluated in de-energized condition only.

Compared to those examples the solution presented in this paper has got the advantages that a position detection is possible both in energized as well as in de-energized condition with a relatively low electronic effort.

2. Inductance curve at solenoids

The influences on the inductance of a solenoid have to be regarded first for the following explications can be better understood.

The inductance of a cylindrical coil is generally known under the formulas stated in (1), (2) and (3).

$$L = \frac{\mu \cdot N^2 \cdot A}{l} \tag{1}$$

$$R_m = \frac{l}{\mu \cdot A} \tag{2}$$

Therefore

$$L = \frac{N^2}{R_m} \tag{3}$$

This formula (3) states that each modification of the magnetic resistance R_m causes a modification of the inductance. The requested modification of the inductance is caused by the stroke movement of the armature in the solenoid. The less desirable effects are temperature influences and saturation effects in the magnetic circuit which can be visible e.g. in dependence of the inductance from the current flow (**Figure 1**). For a precise position detection these influences have to be taken into consideration.

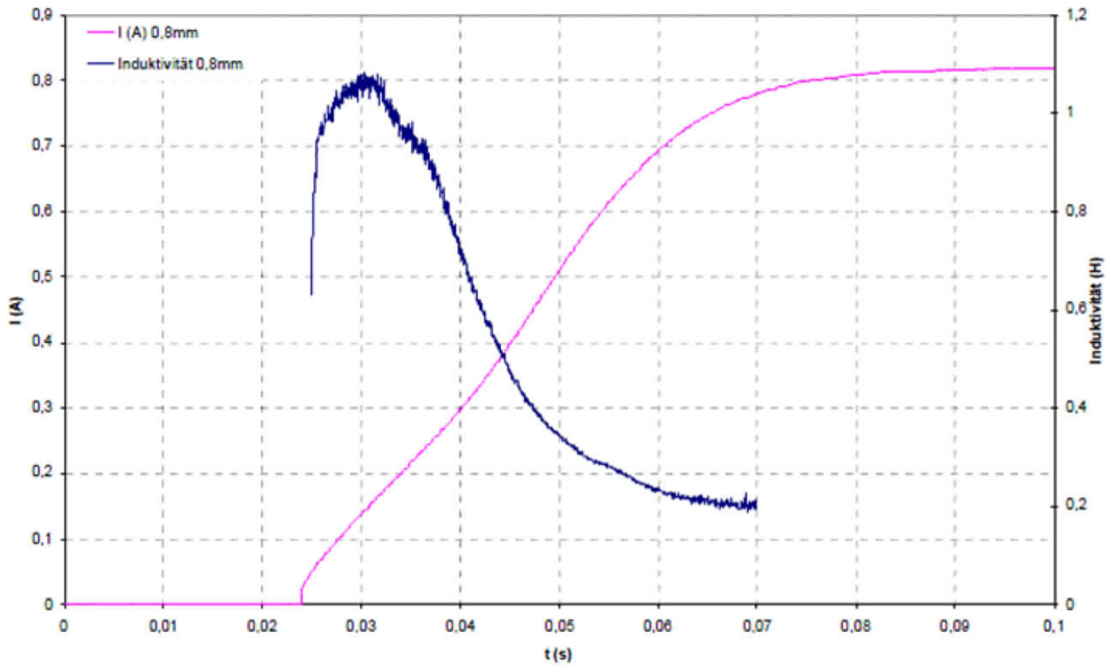

Figure 1: Inductance profile of a solenoid with current increase /4/

The current flow is a parameter which can be measured continuously and also the temperature is a measurable value which is covered to a certain extent by the current flow or which has to be measured directly.

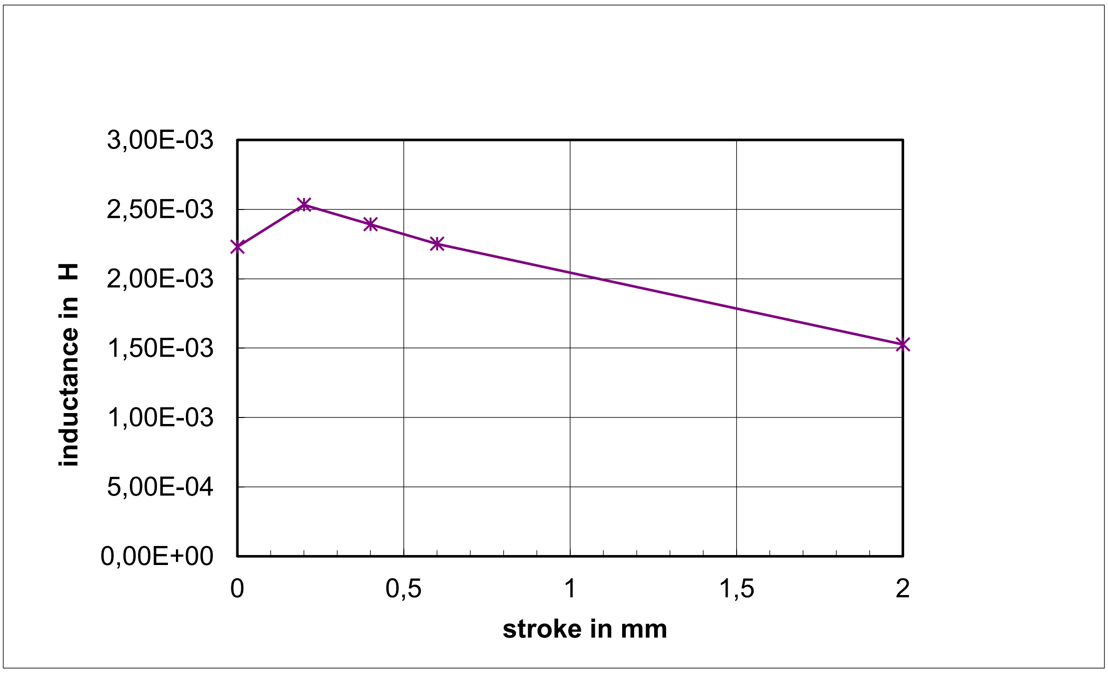

Figure 2: Inductance curve via the stroke (solenoid size 22mm)

Experience has shown that systems with flat armatures show considerably better analysis characteristics than cone armature systems. There were ambiguities frequently noted in the inductance characteristic of the cone system. **Figure 2** is underlining this as with reduction of the air gap the inductance increases first but a reduction of the inductance by saturation effects can be noted shortly before the stroke end.

3. Functional principle of the evaluation circuit

3.1. Turn-off pulse

It is well known that when turning off inductances (**Figure 3**) a voltage pulse (**Figure 4**) occurs which is generally not desirable and is damped by means of diodes or varistors. In the present case this voltage pulse serves as determination of the position because this one depends on the inductance of the coil and therefore also on the armature position. For a measuring process the coil has to be turned off for a short time and the chronological sequence of the voltage pulse is measured at a defined voltage level. MOSFETs are applied in the voltage range of 500 – 1000V in which the higher inductance peak voltages over this range are continuously cut off by a protective element (TVS diode or varistor).

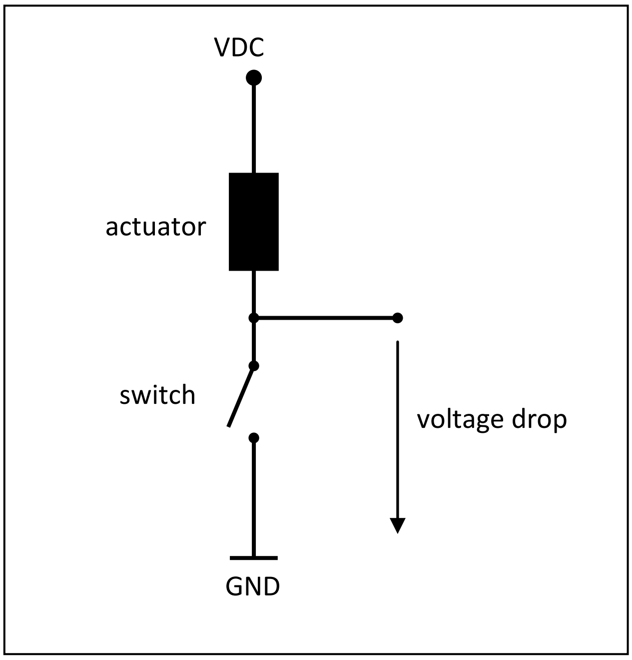

Figure 3: Simplified diagram

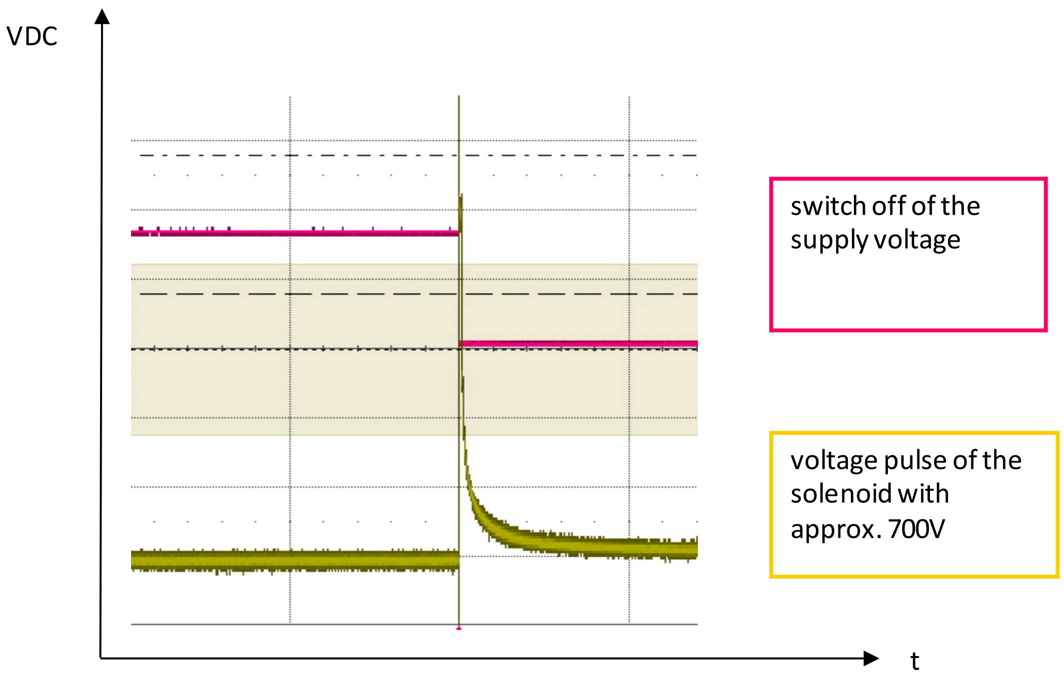

Figure 4: Turn-off pulse

Figure 5 shows the curve of the turn-off pulse at two stroke positions. For determination of the position both time periods 1 and 2 (position 1: 25µs and position 2: 50µs) have to be determined at a defined voltage threshold.

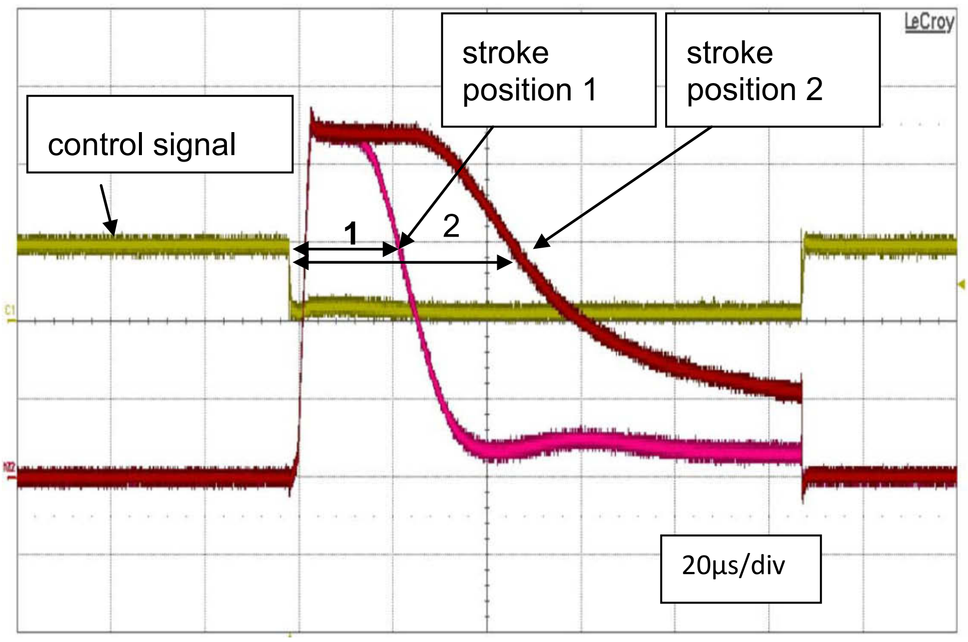

Figure 5: Turn-off pulse at two stroke positions

3.2. Measurement in energized and de-energized condition

The measurement principle described in the previous chapter shows clearly that with a suitable inductance characteristic each stroke position can be detected. Two operation conditions are to be distinguished here:

1. The solenoid is energized and operates against an external action force in a position to be registered.
2. The solenoid is de-energized and operates against an external action force in a position to be registered.

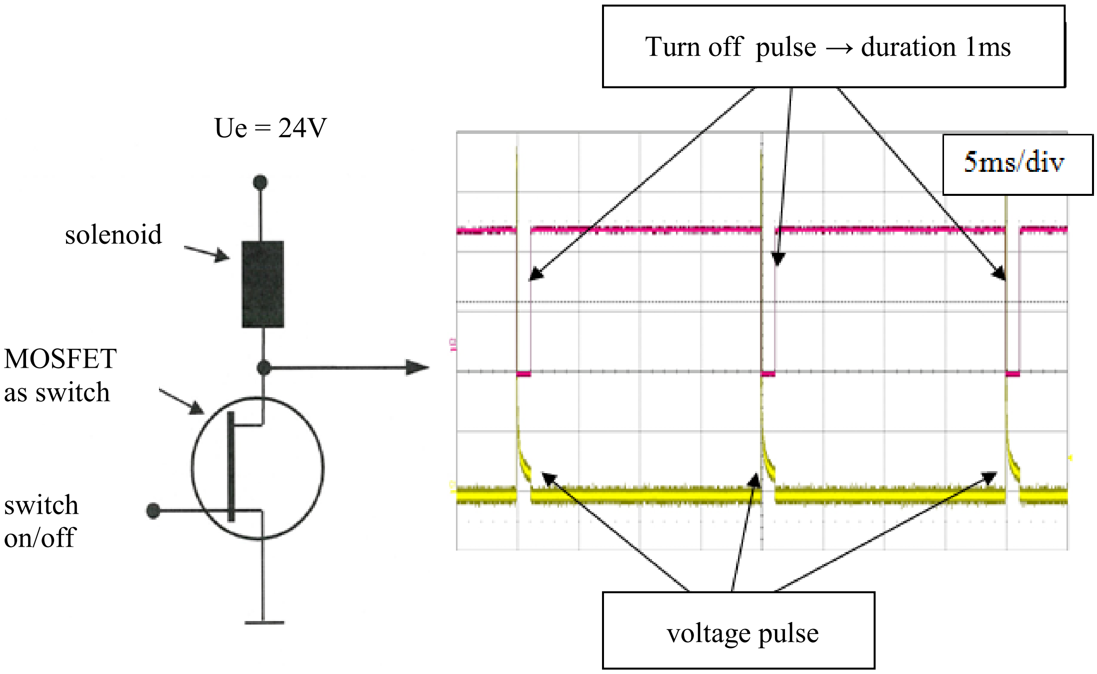

Figure 6: Turn-off pulse in energized condition

Both operation conditions require different ways of proceeding:

1. In energized condition the supply voltage is turned off for a short time (**Figure 6**) in which the solenoid shall remain in the position and may not drop.
2. In de-energized condition the supply voltage is turned on for a short time (**Figure 7**) in which the solenoid shall remain in the position and may not actuate.

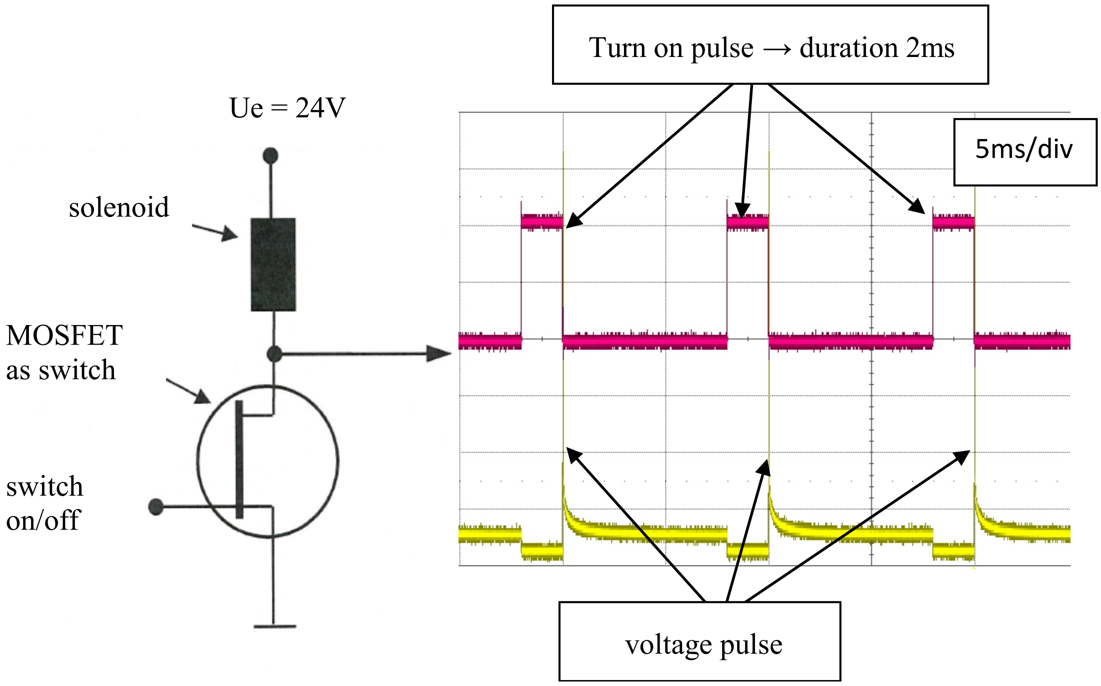

Figure 7: Turn-on pulse in de-energized position

3.3. Possibilities of sensor-less position detection

The sensor-less position detection makes use of the principle of measuring the turn-off pulse. The general suitability has been proven by means of various measurements. Restrictions have to be made in the frequency of operation because too frequent turning-on in energized condition causes a drop of the armature. This behaves similarly in de-energized condition when a too frequent turning-on makes the armature actuate.

Both of these aspects point out that measuring points set during the actuation or drop movement of the armature may lead to a change of the behaviour i.e. the actuation or drop time will be changed. As the minimum turn-off time is given by the electrical values of the solenoid this effect cannot be counteracted by a particularly short measurement time either.

For those reasons this procedure in the current state of development is primarily suitable for the position detection of both end positions of a solenoid. Intermediate positions, however, can be detected if the armature does not move.

The holding current reduction often requested for electromagnetic actuators in their energized end position can be ideally combined with the presented measuring principle. Frequency and duration of the turn-off pulse has to be adjusted to the application.

3.4. Circuit complexity

For realization of a position measurement according to the presented principle a considerably high component expense is not required. In addition to the already stated MOSFET switch a voltage divider, an operational amplifier, a shunt and a microcontroller are necessary for evaluation (see **Figure 8**). These components already exist in many control circuits so the sensor function can be implemented with relatively low hardware costs.

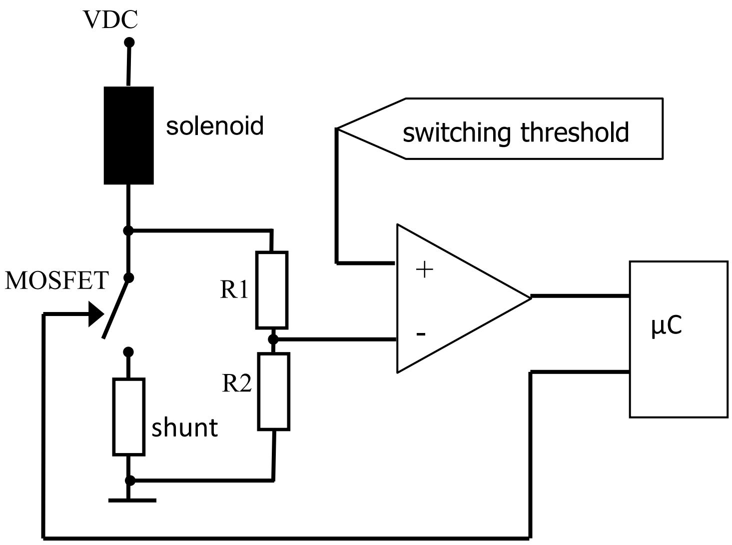

Figure 8: Circuit principle

4. Applications

The functional principle has been successfully tested at different solenoid types.

4.1. Hydraulic solenoid

Figure 9 shows the hydraulic ON/OFF solenoid size 45 with 7 mm stroke used for a measurement example. Measurement in **Figure 10** shows a time-delta of 13µs for both stroke end positions. In **Figure 11** some intermediate values from 0 to 4mm are shown.

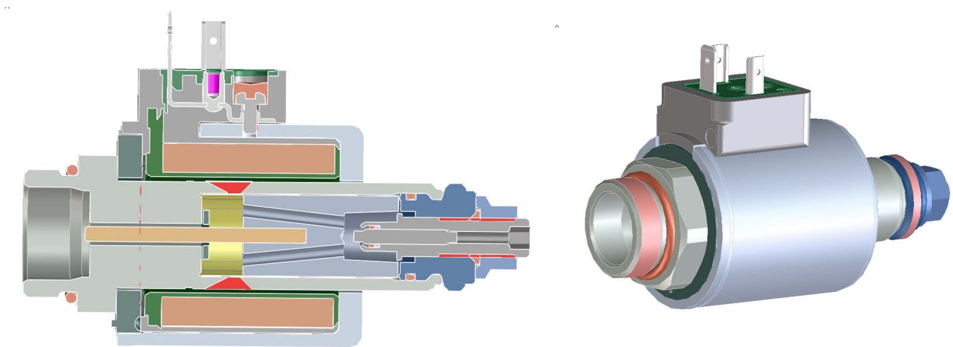

Figure 9: Hydraulic solenoid

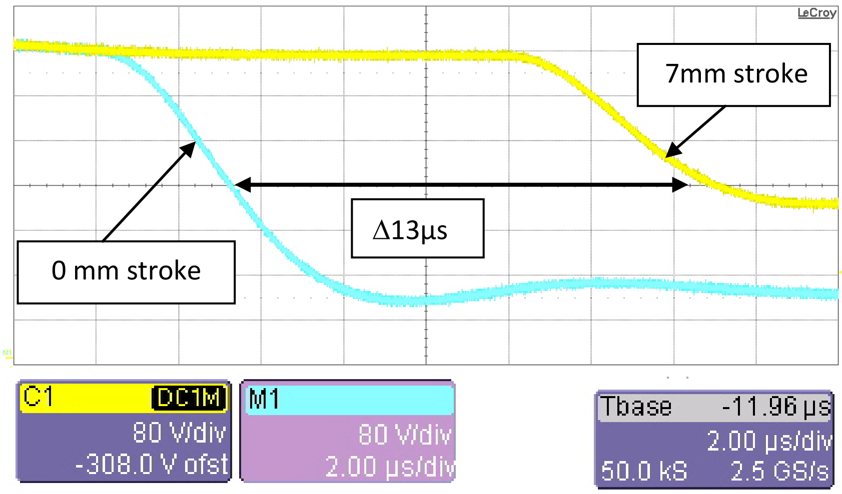

Figure 10: Voltage pulse at 0mm and 7mm stroke position

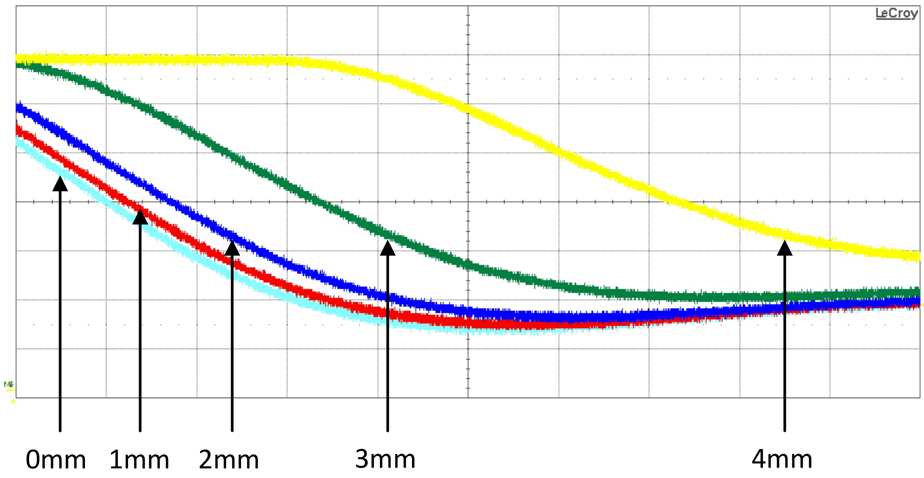

Figure 11: Intermediate values from 0mm – 4mm

3.6 Pneumatic solenoid

For a measurement example in the sector of pneumatics a solenoid size 17 mm has been used (**Figure 12).**

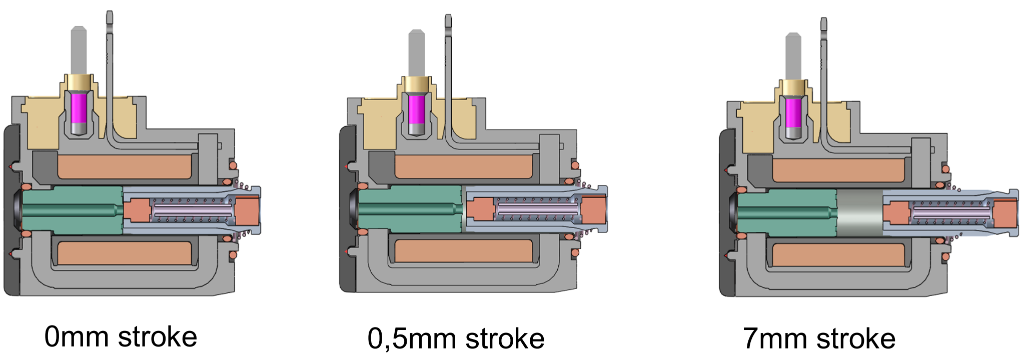

Figure 12: Pneumatic solenoid at different stroke positions

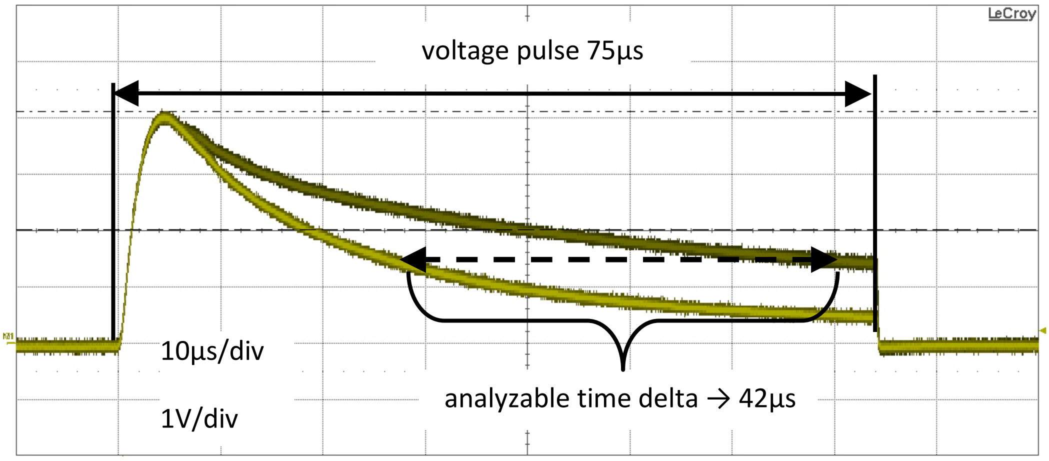

Figure 13: Voltage drop at 0mm and 6mm stroke position

Illustration **Figure 13** shows an analyzable signal of 42µs with a stroke difference of 6mm. The measurement at 0,5mm shows a similar picture with a time delta of 10µs.

If a microcontroller with a pulse frequency of 10MHz is used for evaluation, the resulting maximum resolution is 420 points with 6mm stroke and 100 points with 0,5mm stroke.

5. Summary with outlook

The procedure described in this paper uses the turn-off pulse of a solenoid in order to determine the position of the armature. Thus it makes it possible to detect both end positions of the actuator as well as constant intermediate positions without use of an extra sensor. For the generation of a measuring pulse turn-off and turn-on pulses are required which may cause an influence on the actuation and drop movement. The limitations of the method are in the dynamic field because too few measuring points can be set for an automatic control and/or each measuring pulse has a retroactive effect on the actuator position in motion. By means of two examples we were able to show that the procedure is suitable for small pneumatic solenoids (size 17) as well as for bigger hydraulic solenoids (size 45).

The steps to be taken next are to prove applicability of the procedure for further applications and to develop a control and analysis device which contains a holding current reduction as well as the position measuring procedure. Then series applications in hydraulics and pneumatics can follow.

6. References

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7. Nomenclature

L	inductance	H
μ	permeability ($\mu_0 \cdot \mu_r$)	$(V \cdot s)/(A \cdot m)$
N	number of windings	-
A	surface	m^2
l	length	m
R_m	magnetic resistance	$1/H$