Intrinsic sensor properties of solenoid actuators for fluid power

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Abstract

A systematic of the intrinsic sensor effects on electromagnetic solenoid actuators has been developed. Correlation of specific regions of a flux-current diagram $\Psi(i,x)$ with a stroke, spring preload, friction, pressure has been investigated for a number of solenoid types. Quasi-static and step response excitation coil measurement is introduced in a measurement device MagHyst® which has been used to identify the flux-current diagrams with the stroke as a parameter and to validate the results.

The main advantage of the method is that it does not need any additional sensors apart from the excitation coil of the electromagnet itself. The measurement can be carried out at real operation conditions and under load.

KEYWORDS: sensorless, condition monitoring, solenoid valve, flux current diagram

1. Introduction

To improve the functionality of the modern machines and devices, vehicles and tools, more and more electromagnetic solenoid actuators are used with constantly increasing demands on their safety and reliability. The functional reliability (operative readiness) of each electromagnet influences the reliability of a whole complex system. Such systems are found in motor vehicles, power stations, lifts and escalators, in the industrial safety systems, in white goods as well as in medical engineering, e.g. in breathing apparatus, in aerospace pilot masks and many others.

Despite all efforts during development and production of such actuators, the disturbances during operation cannot be completely eliminated. They are caused by outer and inner influencing factors leading to a deviation of technical parameters from their design values. Considering the potential damage and injury, suitable precautions should be taken for a noticeable increase of the safety and reliability. Absolute essential means for it are diagnose systems enabling the recognition of damage as early as possible. Further important step is a prediction of a potential dangerous state due to system degradation.

Using native sensor properties of the excitation coils of electromagnetic actuators it is possible to evaluate the static as well as dynamic performance in form of the static and dynamic flux linkage vs. current $\Psi(i,\delta)$ characteristic diagram. The magnetic properties of the ferromagnetic material has a very high repeatability under the same excitation conditions over the wide temperature range (-65...150°C). Moreover, they remain almost constant over the whole life-time period of an actuator. Only changes in electric and mechanic subsystems influence the magnetic behaviour. The measured characteristics comprise information about critical parameters and quality attributes of each electromagnet as switching time, friction in a system, force reserve and change of the working stroke. With it, a new quality of condition monitoring for complex safety-critical systems can be achieved. Either due to continuous monitoring or by sampling inspection the faults can be detected timely. Further statements about the expected lifetime can be derived on this basis. This functional diagnostics establishes successful in many safety-critical applications.

2. Theory

2.1 Electric and mechanic equations of an electromagnet

To use an electromagnet itself as an actuator and a sensor, we should clearly understand all processes taking place in the solenoid during its normal operation. The dynamic of a system including electric supply, electromagnet and a load can be described by a differential equation system (1) and (2). It takes into account the non-linearity (saturation) of the magnetic material of the solenoid.

$$u = iR + \frac{d\Psi(i,\delta)}{dt} = iR + \frac{\partial\Psi(i,\delta)}{\partial i}\frac{di}{dt} + \frac{\partial\Psi(i,\delta)}{\partial\delta}\frac{d\delta}{dt}$$
(1)

$$F_{mag} = m\ddot{\delta} + d\dot{\delta} + c\delta + F_{load}(t,\delta,\dot{\delta})$$
⁽²⁾

The first term of (1) is the voltage drop on the coil resistance, the second and the third terms correspond to the induction voltage due to current variation and armature movement, respectively. The last two terms describe the energy conversion process between the current supply, magnetic circuit of an electromagnet and mechanic subsystem characterised by inertia, friction, spring and fluid load forces (2). This conversion can be visualised as shown in Figure 1 and Figure 2.

Analysing equations (1) and (2) we see that magnetic as well as mechanic properties are incorporated in the transient flux curve. Some examples of the curves and their interpretation were given in /1/.



Figure 1: Magnetic on-site condition monitoring

What is not obvious and not so well-known is how different factors as pressure, temperature, vibration affect this $\Psi(i,\delta)$ curve. We try to show it with some further examples and to develop an approach how to use it in practice. But before it we need to consider some important effects.





2.2 Flux linkage estimation

From the electric equation (1) the magnetic flux linkage is calculated according to (3).

$$\Psi = \int_{0}^{t} (u - iR)dt + \Psi_0$$
(3)

The initial flux linkage Ψ_0 (integration constant) is mostly assumed to be zero. If the value of the starting flux due to magnetic remanence is of importance, though, it can be measured directly with a dedicated magnetic field sensor /2/. However, it is not always a preferred solution since it increases complexity and costs and can deteriorate the reliability of the system.

2.3 Energy conversion and force calculation

Multiplying the equation (1) with *i* dt and taking an integral over t we set up the balance of the power supply energy divided into ohmic loss and magnetic energy which can be partly converted into mechanical work.

$$\int_{0}^{t} uidt = \int_{0}^{t} i^{2}Rdt + \int_{0}^{\Psi} id\Psi = \int_{0}^{t} i^{2}Rdt + \left(\int_{0}^{t} i\frac{\partial\Psi}{\partial i}\Big|_{\delta=const} di + \int_{0}^{\delta} i\frac{\partial\Psi}{\partial\delta}\Big|_{i=const} d\delta\right)$$
(4)

Differentiating (4) by δ and simplifying it we derive an equation (5) for the magnetic force. The minus sign denotes that the positive mechanic work (actuation) is done reducing the energy stored in the magnetic field of the solenoid.

$$F = -\frac{dW_m}{d\delta} = -\frac{d}{d\delta} \bigg|_{\Psi=const} \int_0^{\Psi} id\Psi$$
(5)

Using this formalism the magnetic force can be rather good estimated from the measured flux linkage curves $\Psi(i,\delta)$ as shown in Figure 3.



Figure 3: Calculated (×) from $\Psi(i,\delta)$ vs. measured (–) force values for a proportional electromagnet

2.3 Coil resistance

For a reliable flux calculation (3) the ohmic resistance of the solenoid coil must be precisely known. Therefore it is either compensated with a bridge circuit /3/ during a quasi-static measurement or calculated as a quotient between the average coil voltage and coil current at steady-state (whilst the solenoid current and voltage remain approximately constant and can be measured with a good resolution). The resistance is subject to temperature drift, therefore a regular update is necessary. An example for the coil resistance calculation is given in /4/. An actual coil resistance value informs us about the solenoid temperature. It can be used by the protection algorithms.

2.4 Hysteresis

Magnetic effects of ferromagnetic materials are reflected in the behaviour of the solenoids. The main effects are disclosed below using some simple examples. They need to be considered by analysis of the magnetic systems. If calculated with an FEM program using an ordinary B(H) magnetisation curve, the flux linkage $\Psi(i,\delta)$ used in (1) and (2) can be thought of as a "simple" nonlinear function of two variables /5/. But in fact, the function is not single-valued due to magnetic hysteresis. The flux depends not only on the actual current and airgap but on the magnetic history, too. Different flux values exist in the iron core if the current and airgap are increased or decreased. Moreover, there is a difference for large and small signal (**Figure 4**).





Figure 5 shows the $\Psi(i,\delta)$ - curve of the excitation system without armature of the solenoid - it's a kind of open magnetic system. The lowest slope of the curve, low hysteresis and the lowest inductance of the system are the main properties of this

curve. The curves $\Psi(i, \delta_{max})$ and $\Psi(i, \delta_{min})$ show the measurement of the whole system with fixed armature at start and end positions. In both cases the magnetic circuit conducts higher flux with higher inductance and expanded hysteresis.



Figure 5: Dependence of the hysteresis on the airgap and excitation current

Higher excitation saturates the magnetic system stronger, and hysteresis losses become higher as shown right in Figure 5 (right). Preisach or Jiles-Atherton models can be used to simulate this phenomenon in details.

2.5 Eddy currents

In the real solenoids massive ferromagnetic parts are used in that eddy currents are excited during magnetic flux changing. This brings an additional ambiguity factor to the hysteresis loop. The curves of an excitation system with ferromagnetic core shown in Figure 6 were measured at different rates of reversal magnetisation.



Figure 6: Influence of the flux changing rate on the width (left) and maximal value (right) of the magnetic flux

This phenomenon is especially important for fast acting actuators as the eddy currents delay the build-up of the magnet field and force in a magnetic system.

In the previous examples some effects were shown that come from the magnetic properties of the magnetic material. These material effects make the behaviour of the whole system quite complicated, but they bring also a great advantage: The magnetic behaviour of the material or of the magnetic system has a very high repeatability under the same excitation conditions over the wide temperature range (-65...150°C) and stays constant over the whole life-time period.

Only the changes in electric and mechanic subsystems of the whole system can change the magnetic behaviour. This stability of the magnetic subsystem enables an innovative and reliable condition monitoring of magnet systems.

3. Testing in time domain vs. flux linkage-current domain

State of the art is solenoid diagnosis using a transient current at switching on/off. But the form variance (dependence) of the i(t) curve on the voltage and coil temperature inhibits using of this function under real conditions or reduces its usability. For example, to measure the curves in Figure 7 the solenoid was cooled from $T = 84^{\circ}C$ ($R = 205\Omega$) to $T = 20^{\circ}C$ ($R = 163,4\Omega$) with $\Delta R = 5 \Omega$ and a constant voltage was applied (step response). The voltage variation has similar effect on the curves. The measurement results depend on the measuring conditions and external disturbance variables which can have a greater influence onto the measurement results as the system changes due to a possible error. The simple i(t)-measurement can be useful only for a very rough validation of the switching process but any deeper analysis of the real solenoid behaviour is quite impossible.



Figure 7: Switching-on and switching-off process at a transient current curve

Therefore the valve solenoids are usually tested under some artificial conditions (i.e. constant voltage, constant current limit, constant temperature etc.)

Better results can be achieved with a little more effort if a transient magnet flux linkage vs. current diagram is invoked as shown in Figure 8. Even though the time parameters are "hidden", this representation brings a deeper insight into the solenoid function. The path of the magnetic operating point in the $\Psi(i,\delta)$ space gives information about the health condition of the solenoid.



Figure 8: Family of the dynamic (left) and quasistatic (right) magnetisation curves (8 curves) measured under the same conditions as i(t, T) from Figure 7

A very significant effect was found to detect short-circuits within the solenoids coil. This effect is evident in i(t) and $\Psi(i,\delta)$ curves as a current jump in the first moment of the current feed. It can be explained as an inductive counteracting effect of the short-circuit windings separated from the coil. The result is shown in Figure 9.



Figure 9: Curve of the normal solenoid (black) and solenoid with low (blue) and critical (red) degree of turn-to-turn short circuit

In two cases a turn-to-turn fault exists in the device under test. The lifetime of an actuator will be drastically reduced due to local heating and progressive degradation of the winding isolation at the fault place. Two of three actuators should be replaced as soon as possible.

4. Examples of sensor effects

The sensor properties of an actuator can be illustrated using a curve of a proportional solenoid shown in Figure 10.





4.1 Working cycle of switching solenoid as a $\Psi(i,\delta)$ curve

Idealized and real characteristics of a switching solenoid are shown in Figure 11.



Figure 11: Schematic representation of the working cycle (left) and working cycle (switching-in and switching-off) of a real solenoid

If the solenoid armature moves periodically between minimal and maximal airgaps, the repeatability of the dynamic $\Psi(i,\delta)$ curve is very good. It is helpful, if the magnetisation curves for the minimal and maximal airgap are known.

Curve section	Indicator	Parameter of interest	
0–1: magnetisation, response delay	gradient di/dΨ	initial airgap	
1: start of armature travel	i_1, Ψ_1	initial airgap, resultant load force F _{load} <f<sub>mag</f<sub>	
1–2: switch on, armature travel	di/dΨ average i,Ψ, oscillations	acceleration / speed of the armature movement bouncing	
2: armature stop	i ₂ ,Ψ ₂	end airgap, stroke, load force	
2–3: further magnetisation	di/dΨ	end airgap	
3: maximal magnetisation	i_3, Ψ_3	Current / force reserve, end position, temperature	
3–4: demagnetisation, release delay	di/dΨ	end airgap, hysteresis	
4: armature released	i ₄ ,Ψ ₄	$F_{mag} < F_{load}$	
4–5: armature return	di/dΨ average i,Ψ	Velocity, return spring preload	
5: first armature impact	I_5, Ψ_5	stroke	
5–0: final demagnetisation	gradient di/dΨ	airgap, armature bounce	

Table 1: Sensor effects at different sections of a flux linkage - current diagram



Figure 12: Solenoids without faults (left) and with a different end position of an armature (right)



Figure 13: Friction in the system detected via magnetic test

It is obvious that increasing friction of the system expands the $\Psi(i,\delta)$ hysteresis loop (Figure 13). The current values and the area inside the hysteresis will be used as indicators to analyse the friction behaviour of the solenoid.

Conclusion

A novel evaluation method is proposed which can be used for function test, condition monitoring and control of the electromagnetic solenoid actuators. It is based on the analysis of the transient magnetic flux vs. current diagram during switching or positioning events of the solenoid armature with an effector.

The feasibility of the proposed method is proven on some test objects. A number of solenoid actuators have been analyzed and are proved to show a clearly interpretable response on a flux-current-stroke diagram. The calculated electromagnetic forces agree very well with a force vs. displacement measurement.

The selected examples confirm the possibility of reliable non-destructive condition test on the electromagnetic solenoid actuators. Deviations in static and dynamic behaviour of such actuators can be visualised. A big advantage consists in the possibility to do measurements on actuators under load or on the actuators integrated in other functional units. As a result, changes can be easily detected on the actuators themselves as well as on the valves, electromagnetic clutches and brakes.

The measurement procedure is applicable at any stage of life of an actuator: during development to validate target performance parameter, during manufacturing (end-of-line or inline checks) as well as during operation for condition monitoring or fault isolation.

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Nomenclature

R	Resistance	Ohm
i	Current	А
т	mass	kg
с	spring stiffness	N/m
d	viscous friction coefficient	Ns/m
t	Time	S
Т	temperature	К
u	voltage	V
F _{mag}	magnet force	Ν
F load	load force	Ν
δ	airgap	m
Ψ	magnetic flux linkage	V⋅s