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Geometrical selectivity of current sensors

Streszczenie. *Analizujemy wpływ zewnętrznych prądów niezrównoważenia na bezstykowe czujniki prądowe w szczególności na matryce gradientowe czujników i układy poziomowania prądu. Najlepsze tłumienie prądów bliskich można osiągnąć poprzez użycie jarzma magnetycznego, w którym zoptymalizowano ekranowanie. Układy poziomujące zaprojektowane przez nas wykazują niski błąd przewodności i tłumią zewnętrzne prądy ponad 20 000 razy. (**Wpływ zewnętrznych prądów niezrównoważenia na bezstykowe czujniki prądowe**)*

Abstract. *We analyze the influence of external "unclamped" currents on contactless current sensors, especially the gradient sensor arrays and the current clamps. Best suppression of close currents can be achieved by using magnetic yoke with optimized shielding. DC/AC fluxgate current clamps of our design have low perming error and suppress external current by the factor of 20 000.*

Słowa kluczowe: Czujniki prądu, poziomowanie, ekranowanie, błędy pomiaru.
Keywords: Current sensors, clamping, shielding, measurement errors.

Introduction

Resistive shunt is the basic electric current sensor. Besides its simplicity it has well known disadvantages [1]:

- it has no galvanic insulation
- it dissipates energy causing elevated temperature
- the measured current should be interrupted.

However it has one important advantage: the external fields and currents have negligible effect on resistive shunt reading.

Contact-less current sensors have numerous advantages compared to resistive shunt:

- they have galvanic insulation between the measured conductor and the output
- dissipates energy can be much lower
- the sensor can be made in a form of clamps, i.e. the measured current should not be interrupted to mount the sensors.

This paper discusses geometrical selectivity of contact-less current sensors. Geometrical selectivity is a resistance to external ("unclamped") currents and magnetic fields and also to the position of the measured ("clamped") conductor. There are two ways how to achieve it:

1. using gradient magnetic field sensing or a circular sensor array of magnetic sensors such as magnetoresistors or Hall sensors. Rogowski coil is another coreless sensor with high geometrical selectivity

2. using high-permeability magnetic yoke: this technique is used in current transformers, fluxgate current sensors and in most Hall current sensors.

Gradient sensors and sensor arrays

While the suppression of the gradient sensor to homogenous field can be adjusted to high level, suppression of the close external current is principally limited. We can illustrate this fact on a simple example: if a long conductor is positioned in the middle between two magnetic sensors in a distance of 2a, the field difference will be

$$\Delta B \approx \left(\frac{1}{a}+\frac{1}{a}\right)I = \frac{2}{a}I \qquad (1)$$

while the field from the same current located in the same distance outside the sensors is

$$\Delta B \approx \left(\frac{1}{a}-\frac{1}{3a}\right)I = \frac{2}{3a}I \qquad (2)$$

For this case the external current is suppressed only 3-times. The geometrical selectivity rapidly increases with the distance of the external conductor. In a distance of 10 a, the field difference is

$$\Delta B \approx \left(\frac{1}{10a}-\frac{1}{12a}\right)I = \frac{2}{60a}I \qquad (3)$$

and thus the external current is still suppressed only by the factor of 120.

More advanced configuration with folded conductor is shown in Fig. 1: the measured conductor creates a field gradient measured by AMR sensor chip. The gradiometric base of this AMR bridge is about 1 mm long, which is only 1/10 of the distance between the two conductor arms. By analogical calculation we can find that the currrent in 10 mm distance is suppressed only 44-times, in 100 mm distance the suppression factor is 4400.

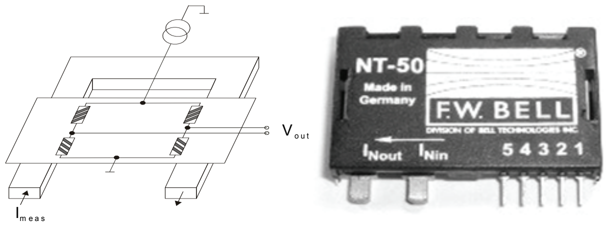

Fig. 1 AMR current sensor with gradient bridge

Circular sensor arrays with averaged output have the same geometrical selectivity against external currents as simple gradient sensors [2]. Advanced signal processing may suppress the external slightly currents more effectively [3]. Their main advantage of circular current sensor arrays is their high immunity against the position variations of the measured conductor. In [4] we have shown that increasing the number of the sensors in circular array from 4 to 8, this error can be suppressed by the factor of 40.

Yokes for current clamps

Yokes represent closed magnetic circuits around the measured conductor. The high permeability magnetic material of the yoke concentrates most of the field lines from the measured current. The magnetic flux in the core is then proportional to the measured curent regardless to the exact position of the conductor inside the core opening. The second function of the massive yoke is that it has large demagnetisation against external fields. Ideal shape of the current sensor is a ring. In the case of very high permeability the core flux is not changing with external field or field gradient. In such case the coil flux can be measured in a single point, i.e. by single turn. If the core flux is measured by the homogeneous winding, the requirements on the high permeability are much less strict. The other extreme case is coreless winding (Rogowski coil): the requirements for the winding homogeneity are very strict.

If the yoke has an air-gap (which is always the case for current clamps), the main limiting factor of finite geometrical selectivity is inhomogeneity caused by the air-gap. Air-gap presents the path for penetration of the external field into the magnetic circuit. This is serious for Hall current sensors, which require large air-gap (typically 3 mm) for the insertion of the magnetic sensor.
Another disadvantage of the yoke is that its remanence may cause perming error in case that the yoke is magnetized by over-current or large external field.

Fluxgate current clamps

In this section we show our development of fluxgate current clamps. Two closed ferromagnetic cores of our clamp sensor are excited into the deep saturation in both polarities. Resonant circuit is used for reaching high current peaks in the excitation winding. Each core is magnetized in opposite direction so that the disturbing signal injected into the measured circuit is suppressed. Detection coil is wound in the same direction around both cores so that in this winding the excitation signal is also suppressed. The measured current is passing through both magnetic cores. Even harmonics in detection winding are measured by synchronous detector. Feedback regulator (integrator) is generating the compensation current. This current is proportional to the measured current and it is sensed on precise shunt resistor.

The basic clamps are highly non-linear and their sensitivity depends on the impedance in the measured current circuit. By using feedback compensation we achieved 0.06 % relative error. Total error of our clamps is shown in the Fig. 2.

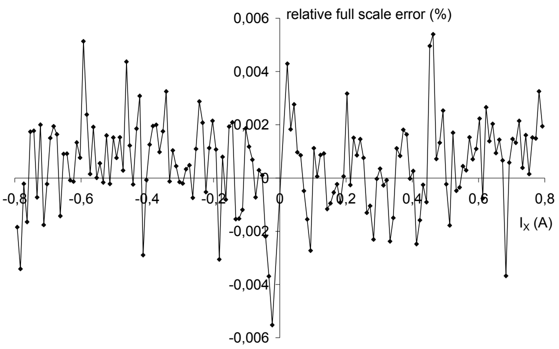

Fig. 2 Total error of dual-core clamps (closed loop).

While the perming error measured on the commercial Hall current clamps was 0.5%, the same error for our 10 A fluxgate clamps was below 0.002 % for current shocks as high as 100 A. The perming errors of these two sensors are shown in Fig. 3 as a function of the amplitude of the field shock.

The geometrical selectivity of the current clamps was compared with the commercially available Hall DC current sensor. The following table gives summary of the worst-case position of the unclamped current. Due to the minimum air-gaps our simple device has 5 to 8-times better geometrical selectivity compared to Hall current clamps.

The geometrical selectivity of the current clamps can be substantially improved by using optimized ferromagnetic shielding. Fig. 4 shows the influence of the external current for the fluxgate current clamps of earlier design [5] without shielding, with asymmetrical "CI" shielding and with symmetrical "LL" shielding.

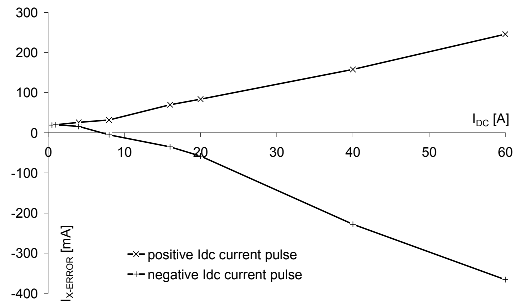

Fig. 3a Perming error of Hall probe current clamps HP1146A.

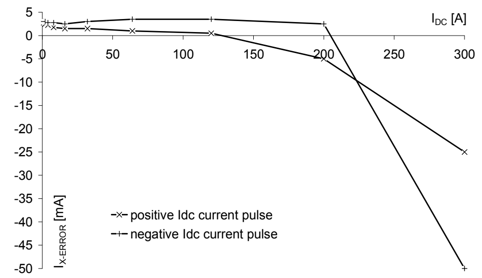

Fig. 3b Perming error of fluxgate dual-core current clamps.

Table 1: Geometrical selectivity of current clamps

near current [A]		5	10	15	20
near current error [mA]	Hall probe clamps	24	53	80	103
	dual-core fluxgate clamps	4,3	7,2	9,8	12,7

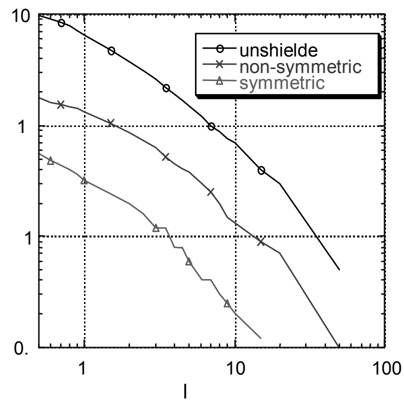

Fig. 4 Current error caused by external 40A current as a function of the conductor distance. Each measurement is made for the worst "azimuth" position - from [5]

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