Non-linear magnetic circuit analysis of fluxgate current sensor

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Abstract. The authors have made fundamental modelling of a fluxgate current sensor based on magnetic circuit. The authors have used two methods, the first one is the fourth Runge-Kutta method and the second one is the method by connecting analytic solutions. Although both numerical schemes have been derived from identical differential equations, only the results of the latter method are plausible. The authors are proposing a reliable calculation method for actual designs of fluxgate current sensors from their numerical and experimental investigations.

1 Magnetic circuit modelling

A fluxgate sensor[1] uses non-linear characteristics in magnetic permeability of ferromagnetic material saturation and hysteresis[2]. Let's start a fundamental modelling of a flux-gate current sensor[2] based on magnetic circuit in Figure 1, where V is input voltage and I is output current. The fundamental equations (1)-(3) should be solved simultaneously. The nonlinear HB-curve in Figure 2 is approximated through multiple broken lines. The equation (3) is derived from approximation to the nonlinear HB-curve by broken lines.

$$V(t) = RI(t) + NS\frac{dB(t)}{dt} \tag{1}$$

$$2\pi r H(t) = NI(t) + I_e \tag{2}$$

$$H(t) = \frac{dH(t)}{dB(t)} \cdot B(t) + H_0 \tag{3}$$

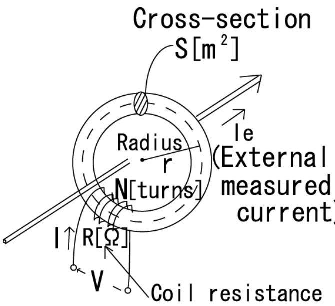


Figure 1: Fundamental magnetic circuit model for a flux-gate sensor

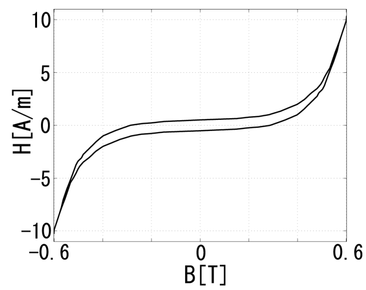


Figure 2: HB-hysteresis curve approximated by broken lines

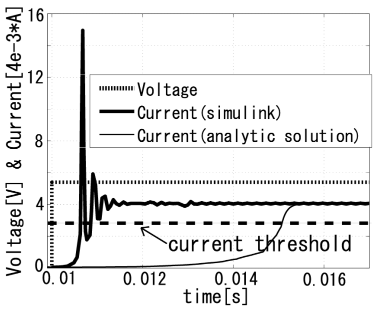


Figure 3: Step response of current

2 Simulink calculation based on Runge-Kutta method

First, we just applied the fourth order Runge-Kutta method using Simulink in Matlab. Input voltage V is rectangular wave whose amplitude is V0 (V0=5.4[V]) and has the function of switching input voltage when detecting the crossover of the threshold value of output current. Figure 3 shows the step response and the results of input voltage and output current from the simulation in I_e=0[A] are in Figure 4 (a). Figures 4 (a) and (b) show the cycle of input voltage is much shorter than the measured cycle. The calculated current responses to a voltage step input in Figure 3 shall explain the reason well. The point to switch input voltage in the Simulink calculation is much earlier than the analytic result. Consequently, the cycle of the input voltage in Simulink has become much shorter than real one. The time constant becomes drastically small in saturation area in the HB-curve. Explicit time-domain numerical methods are not reliable for an analysis of such dynamics whose time constant strongly depends on operational points.

3 The analysis by connecting approximate local analytic solutions

Second, we solved the differential equation by connecting analytic solutions. From fundamental equations (1)-(3) described above, we led the successive form connecting local analytic solution based on the transition matrix. The results of the simulations are similar to the measured ones in Figure 4 (b) and (c). Figure 5 and 6 show the results of the simulation in $I_e \neq 0$. Figure 7 shows the resultant relationship between the external current I_e and the time ratio $t1/T$, where the numerator *t1* is the duration of the positive pulse and the denominator T is the period of the square wave of the input voltage. The simulated and measured results are almost identical in Figure 7, and the good linearity between I_e and $t1/T$ has been confirmed. We can conclude that the second simulator based on the connection of the local analytic solutions gives plausible calculation.

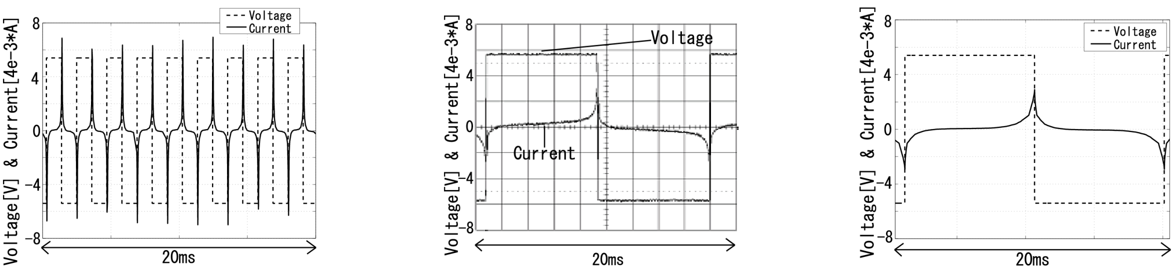
4 Conclusions

- The results of the first method, the fourth order Runge-Kutta method gave wrong results different from measurements: Explicit time-domain numerical methods are not reliable for an analysis of such dynamics whose time constant strongly depends on operational points.
- The connection of portion-wise analytic solutions of locally linearized differential equation have given plausible simulation results. The results have been in good agreement with its measurements; hence, we can conclude that the latter simulator is plausible enough to be used for actual designs of flux-gate current sensors.

References

[1] P. Ripka. Review of fluxgate sensors, *Sensors and Actuators*. A**33** (1992) 129-141

[2] LEM. *Isolated current and voltage transducer: Characteristics-Applications-Calculations* 3rd Edition



(a) Simulink (b) Measurement (c) Analytic solution

Figure 4: Input Voltage and Output Current (***I$_e$***=0[A])

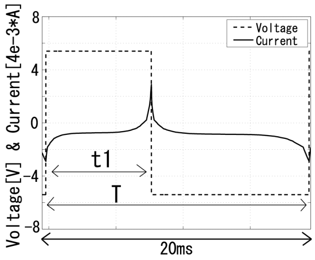


Figure 5: Input Voltage and Output Current (***I$_e$***= 1[A])

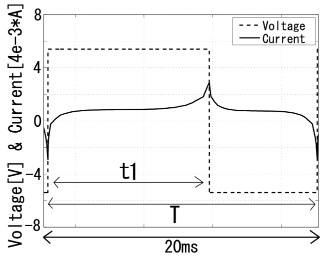


Figure 6: Input Voltage and Output Current (***I$_e$***= -1[A])

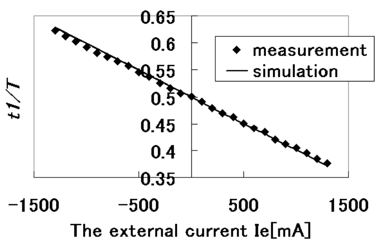


Figure 7: Relation the fraction of pulse width with the external current ***I$_e$***