INDUCTION COILS: VOLTAGE VERSUS CURRENT OUTPUT

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Abstract: The stationary air - cored induction coils are often used for the measurement of AC magnetic fields in the air [1]. The voltage induced in classical voltage output coil is proportional to the time rate of change of the magnetic flux and to the turn – cross-section product NA. Increasing of the number of turns N causes increasing of the parasitic capacitance. Parasitic capacitance with the inductance of the coil creates resonant circuit and thereby decrease the maximum measured frequency. In the case of the short-circuited coil the frequency range of the sensor is essentially expanded. Measurements performed on two types of induction coils using both modes are described in the present paper.
Keywords: Induction coil, Magnetometer

1   INTRODUCTION

Since the induced voltage is proportional to the time rate of change of magnetic field, these sensors cannot be used to measure AC fields with any DC component. The information about DC component of magnetic field would be lost. If the DC component has to be measured too, the other methods of measurement (Hall - effect sensor, magnetoresistor or fluxgate) must be used. In some cases the induction coil and the other methods can be combined [2]. Magnetic field without any DC component is assumed in this paper. We limit this study to air core coils since they are inherently linear. Performance of coils with ferromagnetic core is described elsewhere [3].

The Helmholtz coil pair with the constant of 20.3 Am^{-1}/A which is frequency independent up to 100 kHz was used as a source of testing magnetic field. The Helmholtz coils are supplied from the oscillator of the SR 770 FFT analyzer. This analyzer works in the "chirp" mode. If the supply current has constant amplitude on all the frequencies, the magnetic field with the same amplitude of the magnetic flux density is generated. The analyzer in this case displays the frequency characteristic of tested induction coils directly.

1.1   Basic parameters of used coils

Table 1.

No.	type	L_s (1 kHz) [μH]	R_s (1 kHz) [Ω]	f_c [Hz]	f_{r1} [kHz]	NA [m^2]
1	cylindrical	94 000	48	80	23	2.3
2	cylindrical	23	0.85	5 900	2 300	0.0043

where f_c is the corner frequency given by $R/2\pi L$
        f_{r1} is 1st (bottom) resonant frequency
        NA is the turn - cross section product.

2   OPEN (VOLTAGE) MODE COILS

Distributed capacitance, inductance and resistance of the coil cause several resonant frequencies. The main parasitic capacitance (parallel to the coil terminals) is responsible for the 1st (bottom) resonant frequency f_{r1}. Since f_{r1} is the basic limiting frequency, simple equivalent circuit is sufficient for the description (Fig. 1) [4,5].
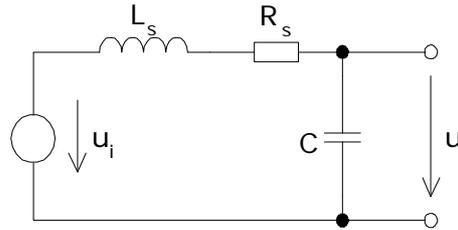
Figure 1. Simple equivalent circuit of the coil.

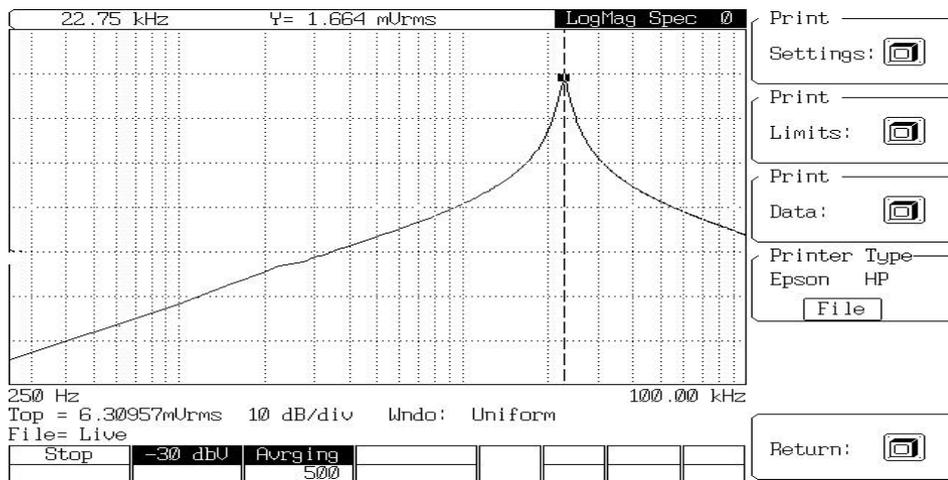Frequency responses of the coil No.1 are displayed in Fig. 2.

Figure 2. Frequency responses of the coil No. 1

This frequency response is typical for the voltage mode induction coils. The output voltage increases proportionally to frequency (20 dB/dec.) up to about 10 kHz. At higher frequencies the resonance causes gross errors. As the resonant frequency of the coil No.2 is over the frequency range of the FFT analyzer SR 770, the frequency response of this coil is not displayed.

The most typical application of voltage mode induction coils is the measurement of maximum value of magnetic flux density B_m on the frequencies much lower than fr1. The magnetic flux density in this case must be periodic, but sinusoidal waveform is not necessary. The known relation can be derived from the Faraday's law:

$$B_m = \frac{U_{AV}}{4fNA} \tag{1}$$

were B_m is the maximum value of the magnetic field density
U_{AV} is the rectified mean value of the induced voltage
f is the frequency of the basic harmonic component

The induced voltage must be measured by the voltmeter, which measures the rectified mean value. The knowledge of the signal frequency is necessary. If the information about instantaneous value of magnetic field is requested, induced voltage must be integrated by an analog integrator, or - after the sampling and ADC conversion - integrated numerically.

3   SHORT CIRCUIT (CURRENT) MODE COILS

If the induction coil equivalent circuit (Fig. 1) is connected to the current-to-voltage converter with operational amplifier (OA) (Fig. 3), the capacitance of the coil is virtually short-circuited and thus effectively eliminated [4]. The frequency range of the induction coil is essentially expanded [5].
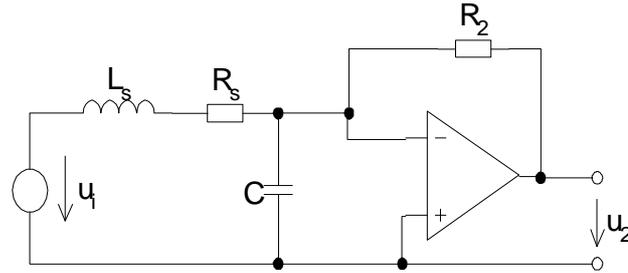
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Figure 3. The induction coil connected to the current-to-voltage converter with operational amplifier.

If we express the maximum value of the induced voltage for sinusoidal waveform using the formula $U_i = 2pfNAB_m$, the output voltage of current-to-voltage converter can be found as

$$U_2 = \frac{R_2}{\sqrt{\left(2\pi f L_s\right)^2 + R_s^2}} NA2\pi f B_m \qquad (2)$$

and at higher frequencies, where $2\pi f L_s \gg R_s$, the output voltage is independent on frequency:

$$U_2 = \frac{R_2}{L_s} NAB_m . \qquad (3)$$

Equation (3) can be rewritten in the time domain and induction coil can be used to observe the nonsinusoidal magnetic field without the integration. Since it is difficult to guarantee the stability of the current-to-voltage converter in wide frequency range, the method is usable especially for the sinusoidal and slightly distorted field waveforms in the range of 1 to 100 kHz.

Fig 4 shows the frequency dependence of the cylindrical coil No1 working in the current-output mode. The current-to-voltage converter is realized with OA LT1028.
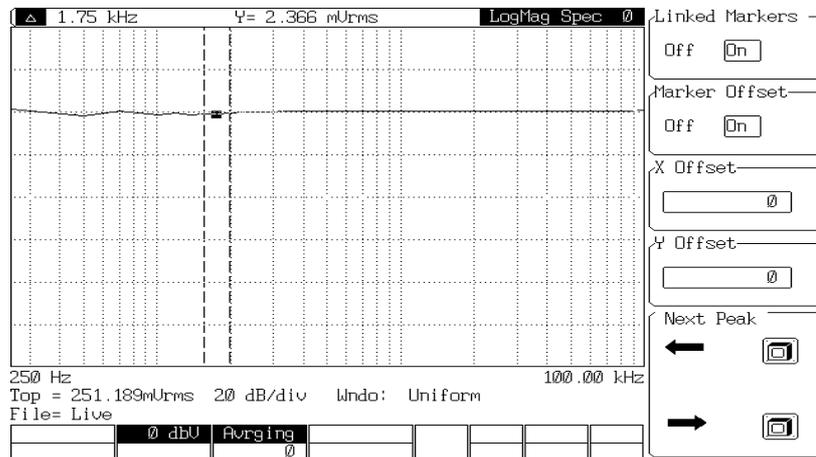

Figure 4. The frequency dependence of the coil No1 working in the current-output mode.

4   PRACTICAL APPLICATIONS OF INDUCTIONS COILS

Some problems associated with applications of previously described coils in the different conditions are shown in this chapter.

The principle of genesis of the fundamental error in the voltage mode can be observed in the Fig. 5. The coil No 1 is in this case used to measure the square wave magnetic field with frequency of 10.38 kHz and maximum value of magnetic flux density $B_m = 3\ \mu T$ (upper waveform).
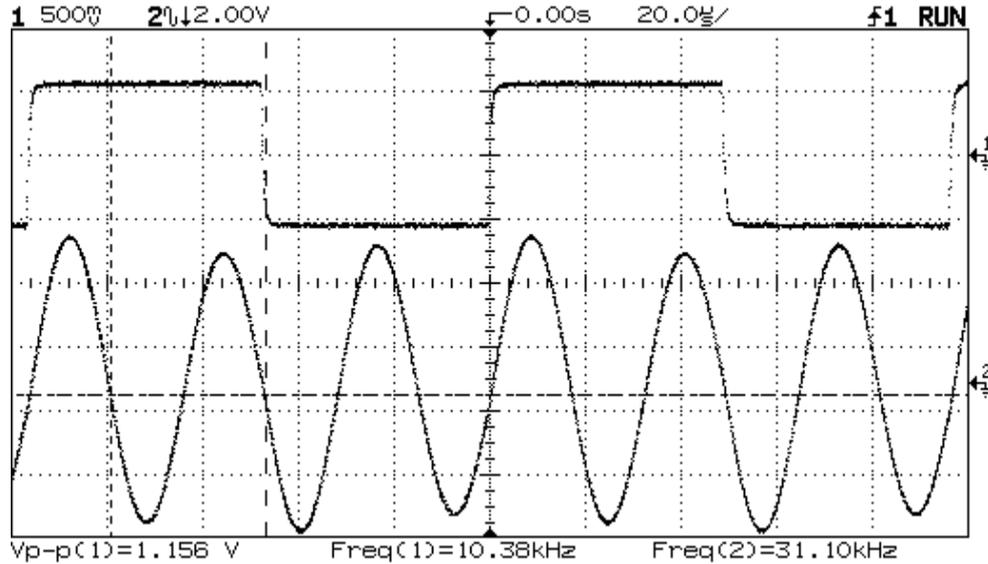
Figure 5. The measured squarewave magnetic field (upper waveform). The self-resonance excited by the third harmonic component of the measured field in the coil winding (bottom waveform)

The third harmonic component of the measured field excites in this case self-resonance in the coil winding (bottom waveform). According to equation (1) the measured field is determined as the harmonic magnetic field with frequency of 31.1 kHz and maximum value of magnetic flux density $B_m = 19.5$ µT.

Response of the short-circuited coil No1 to the same magnetic field is shown in Fig. 6. (bottom waveform).
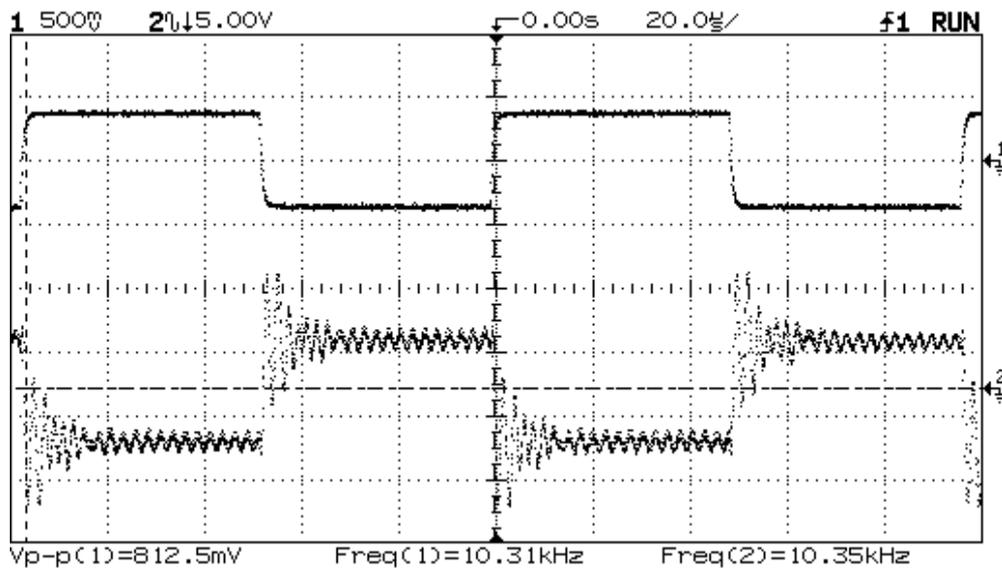

Figure 6. The measured squarewave magnetic field (upper waveform). Response of the short-circuited coil No1 to the same magnetic field (bottom waveform).

Amplitude and frequency of the output signal are correct but the shape of the waveform is distorted due to the higher resonant frequencies (about 450 kHz) caused by distributed capacitance. This capacitance cannot be eliminated by means of current / voltage converter.

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More interesting results are obtained if the coil No2 with higher self-resonance is used. In the short circuited mode this coil is well suited for the frequency up to hundreds kHz (Fig. 7) or for the short magnetic pulses (Fig. 8). The upper trace shows waveform of magnetic field and the bottom trace shows the output voltage of the current-to-voltage converter in both figures.
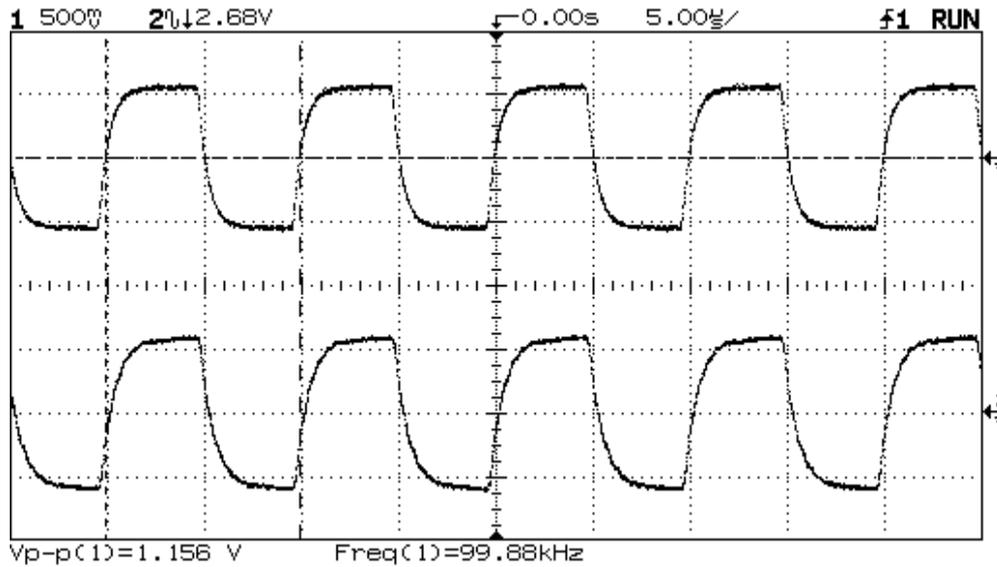

Figure 7. The measured square wave magnetic field (upper waveform). Response of the short-circuited coil No2 to the same magnetic field (bottom waveform).
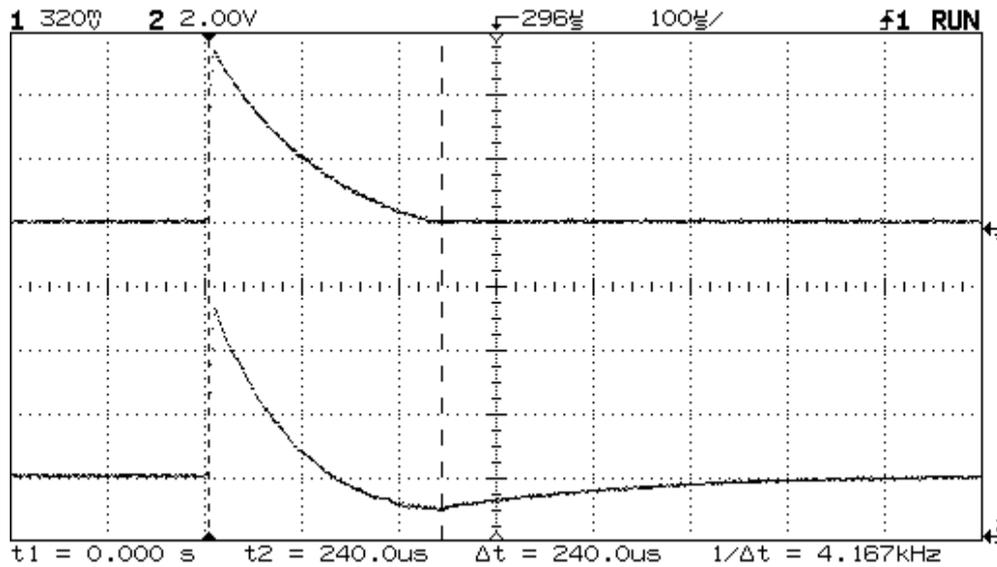

Figure 8. The measured short magnetic field pulse (upper waveform). Response of the short-circuited coil No2 (bottom waveform).

The magnetic pulse in Fig. 8 is typical waveform inconvenient for induction coils because the DC component is not zero. As the area defined by curve must be equal to zero, the shape of pulse is distorted. Amplitude of the undesirable negative parts of the coil response is determined by the time constant L_s/R_s of the coil. The same time constant causes distortion of the measured signal while measuring at low frequencies

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5   CONCLUSION

Voltage output mode of the induction coils is advantageous for determination of B_m of the sinusoidal and slightly distorted field waveforms. The whole frequency spectrum of the measured signal must be deep by under the resonant frequency of the coils in this case. Current-output mode of the induction coils eliminates the problems associated with the first resonance frequency and it requires no integrator. On the other hand, it cannot be directly used for extremely low frequencies. The possibilities of frequency compensation of current-output coils are discussed in [6].

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