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Single-coil metal detector limits

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Abstract:
The paper deals with the single-coil metal detector. It presents measurement and test results that predict practical limitations of this detection concept. The studied principle is based on the coil's inductivity change when a metal object is approached. This principle is very old and nowadays it is obsolete. Advantage of this principle is its simplicity. It can be easily implemented for several searching coils. As the result it can be constructed very cheaply device for effective and automated land screening. Six different oscillator types were tested with three different shapes of the searching coils. The sensitivity was tested on several metal objects. Maximal detection distance was tested in free air for axial distance.

INTRODUCTION

The paper presents effects that are limiting applicability of the single coil metal detector that is based on the coil's inductivity change when a metal object is approached. The searching coil is connected to the oscillator and thus the frequency of oscillation varies with the metal object presence. Typical principle for evaluation the frequency change is called *beat frequency oscillator* (*BFO*). The frequency of the searching coil is mixed with the reference signal with similar frequency which results in beats. Frequency of the beats equals to the frequencies difference. This principle is very old and nowadays it is obsolete. Advantage of this principle is its simplicity. It can be easily implemented for several searching coils and assembling the coils into matrix it can be constructed very cheaply a device for effective and automated land screening [1], [2].
Six LC oscillators based on the bipolar transistors were tested for the frequency stability. Three different shapes of the searching coils are presented and the sensitivity was tested on several metal objects. Maximal detection distance was tested in free air for axial distance.

LC OSCILLATORS

Single coil LC oscillator

There are many oscillator types. There were excluded from the test oscillators that are using several inductors or an inductive coupling (Meissner oscillator, Hartley oscillator, Lampkin oscillator). They were tested oscillators derived from the Colpitts. Their constructions differ in capacitive feedback complexity and the transistor amplifier type (common base CB or common collector CC). Figure 1 presents schemes of the tested oscillators.
Six standard LC oscillators were tested for its long term and short term frequency stability. The Colpitts oscillators, Seiler oscillators, Clapp oscillator and Vackar oscillator were designed according [3 - 6]. The biasing circuits were designed in order to be similar for all oscillators – namely the biasing current. Feedback capacitors were calculated for oscillation frequency about 80 kHz.

Frequency stability test

The oscillators differ in stability of the frequency and also in stability of the output signal when the frequency is changed. The amplitude stability is not very important for the metal detector purpose, because the frequency changes are usually very small. More important is the oscillation frequency fluctuations that are caused by the temperature changes of the transistor and by external capacitive load change. It is affecting the internal resistance and capacitance of the amplifier that it changing the resonance frequency.
Figure 2 left presents test board with the oscillators according the schemes in the Fig. 1. Each oscillator was tested separately and with the same toroit inductor. The measurement started from the room temperature and lasted 30 minutes. The components in the circuit were heated slightly namely by the bias current of the transistor that was about 5 mA. Final temperature of the transistor and the resistor was about 3 °C above the room temperature (see the thermograph in Fig. 2 right). There was significant influence of the surrounding air blow change. Thus the measurements were performed in a sealed box.

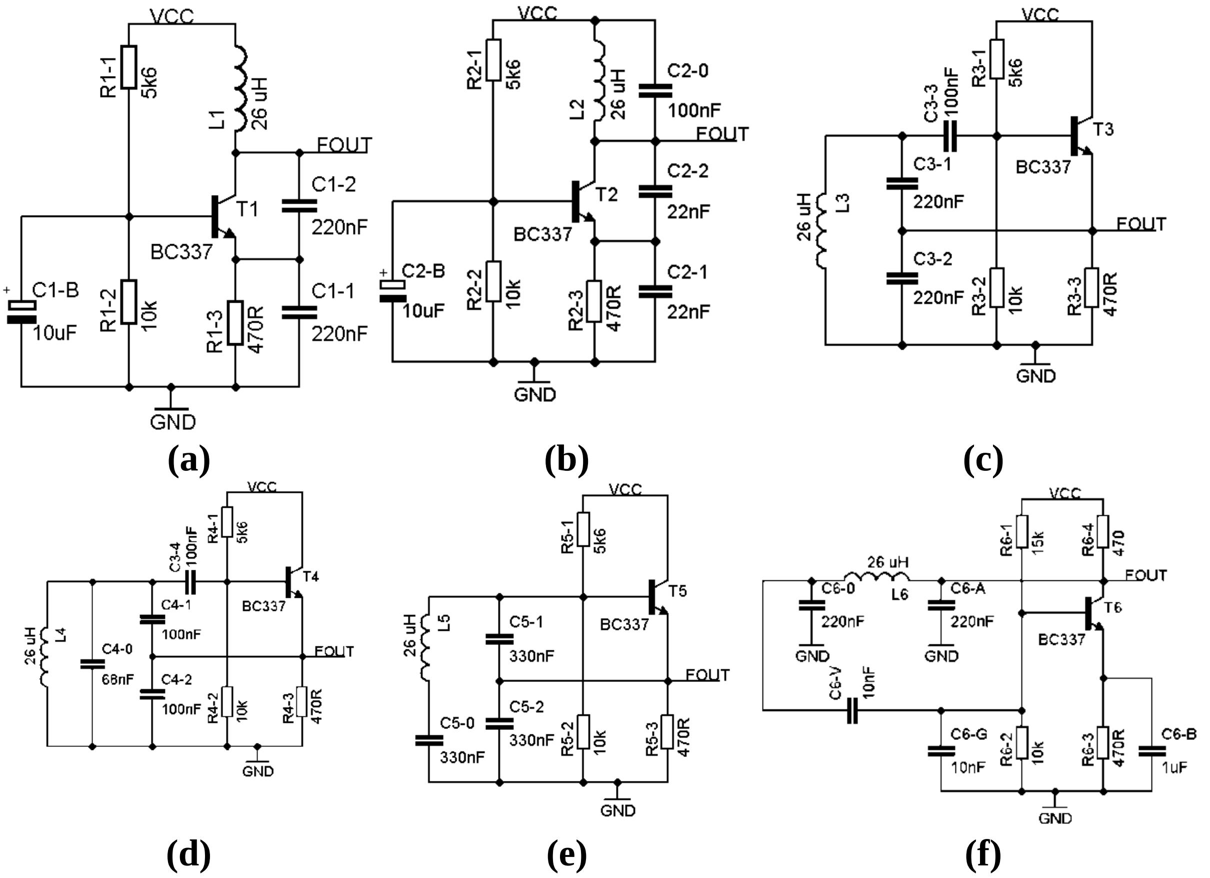

Fig. 1: Tested oscillators: Colpitts – common base (a), Seiler – common base (b), Colpitts – common collector (c), Seiler – common collector (d), Clapp – common collector (e), Vackar (f), Vcc = 5 V for all cases

Figure 2 presents the frequency change of the tested oscillators during 30 minutes of the operation. The curves in the graph are shifted to start precisely at the frequency 80 kHz to be evident the comparison of the frequency changes (real frequencies were in the range 79 kHz – 85 kHz). It is evident from the graphs that the frequency is stabilized approximately after 5 minutes. Ten the frequency drift is slow. There is also evident the short term fluctuations of the frequency – namely for the Seiler CC oscillator.

The short term stability is presented in detail in Fig. 4. The curves are calculated from the measured data that are presented in the Fig. 2. The stability is expressed for 1 second and 1 minute time intervals. This information is crucial for design of the metal detector evaluating circuits.

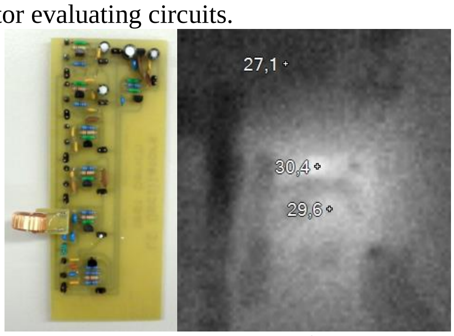

Fig. 2: Test board with the oscillators (left), Thermograph of the Clapp oscillator after 30 minutes operation –temperatures are in Centigrade units (right)

The best one-second frequency stability after 10 minutes of tempering exhibit the Colpitts CC oscillator (10^{-6}), Clapp CC oscillator ($2\cdot10^{-6}$) and Vackar oscillator ($2\cdot10^{-6}$). The stability is probably given by the minimal Miller's capacity of the amplifier (transistor is connected as a common collector amplifier with voltage transfer smaller then 1).

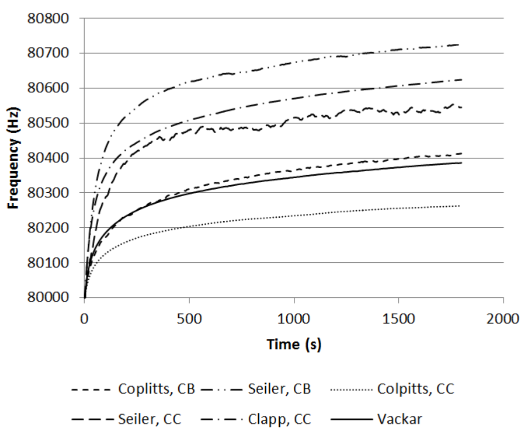

Fig. 3: Frequency change of the oscillators after stat-up

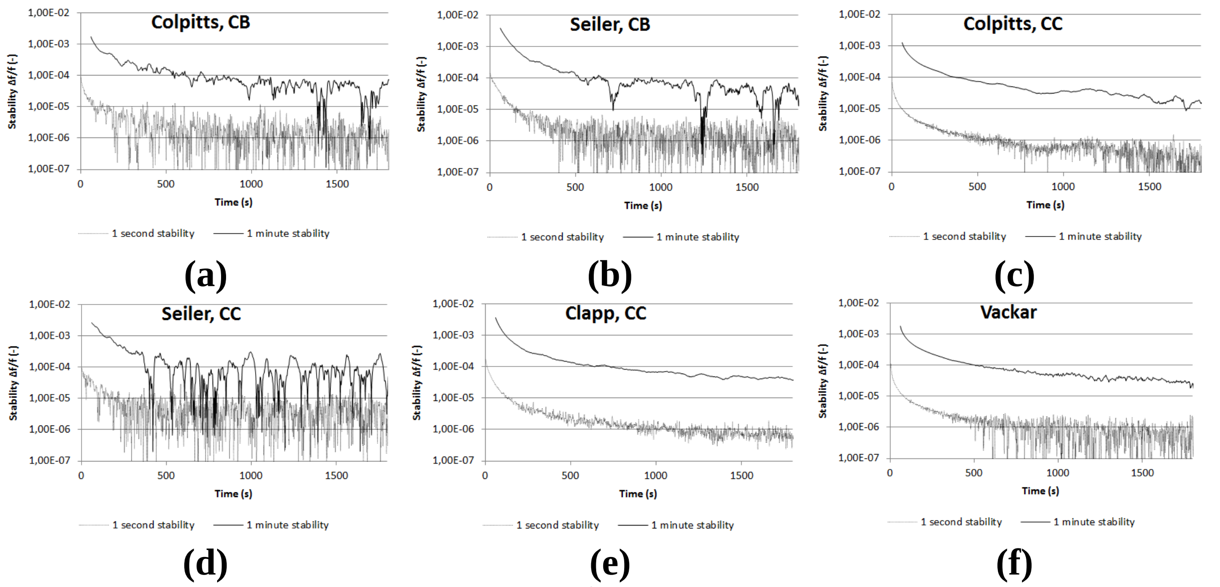

Fig. 4: Short term stability analyses according the measurement from the graphs in Fig. 2 right: Colpitts – common base (a), Seiler – common base (b), Colpitts – common collector (c), Seiler – common collector (d), Clapp – common collector (e), Vackar (f)

DETECTION DISTANCE TEST

Three different coils were tested as the metal detector (see Fig. 5). Minimal diameter of the coil was 5 cm and maximal diameter was 20 cm. The coils were formed into regular hexagonal and elongated hexagonal shapes. These shapes allow gathering the coils into matrixes to form bigger searching tool that is sensitive to small objects. The coils were connected to the Clapp CC oscillator (Fig. 1 e). This oscillator is simple, stable and it can be tuned the same frequency for all the tested coils. The oscillator stability was presumed to be better then 10^{-5} and thus the criterion for the positive detection of the metal object was 1 Hz change of the basic frequency that was about 100 kHz.

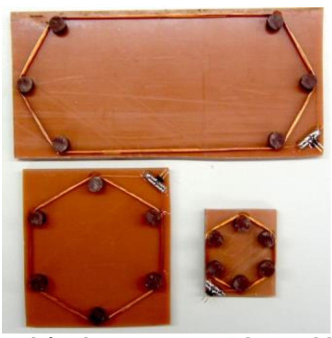

Fig. 5: Coils used for the experiments (Elongated hexagonal coil 10 × 20 cm with 20 loops, Hexagonal coil of diameter 10 cm with 10 loops, Hexagonal coil of diameter 5 cm with 10 loops)

The coils were tested with different metal and ferromagnetic objects that are presented in Fig. 6 and in the table 1. The conductive metal objects are lowering the inductivity of the coil because of the Foucault currents that are induced on the surface. The ferromagnetic objects are concentrating the magnetic field and thus the inductivity of the coil is increasing. Ferromagnetic and good conducting objects (e.g. stainless steel objects) are thus hard to be detected.

Fig. 6: Tested objects - big magnetite stone (left), smal metal objects (right). See also the table 1.

The detection distance was tested for big objects such as big copper plate and big magnetite stone. The maximal detection distance is equal to approximately two times of the coil's diameter. As the objects are getting smaller the detection distance is reduced. Tiny objects can be detected only by the small coils. Table 1 presents maximal detection distances for all the tested objects and coils.

CONCLUSIONS

The paper has presented measurement and test results that predict practical limitations of the single coil metal detector. Most important limiting factor is the frequency stability of the oscillator and dimensions of the searching coil.

The oscillator's stability is affected namely by the temperature changes in the amplifying circuit and noise fluctuations that are changing the bias point of the transistor and thus also the capacitance and resistance of the amplifier's input impedance. The circuit should be thermally isolated; the biasing current should be minimal to avoid the self-heating.

Tab. 1: Maximal detection distance in (cm) for different objects and coils with the Clapp oscillator according the Fig. 1e

Object	***Coil 10×20 cm, 20 loops***	***Coil Ø 10 cm, 10 loops***	***Coil Ø 5 cm, 10 loops***
Copper plate 20 × 20 cm	33	24	17
Big magnetite stone 350 g	16	15	11
Copper circle Ø 28 mm	13	10	6
Copper circle Ø 14 mm	6	6	4
Iron circle Ø 28 mm	13	9	6
Brass circle Ø 28 mm	13	10	7
Plummet 10 g	8	7	5
Magnetite stone 5 g	8	6	5
Magnetite stone 12 g	7	7	5
Magnetite stone 0.15 g	Not detected	Not detected	2
2 CZK coin	10	8	5

The coil must be mechanically fixed and electrically shielded from the surrounding electromagnetic noise.
When the oscillator circuit is temperature steadied the stability of the frequency can be better than 1 ppm within one second interval. Practical stability should be considered 10 ppm because of the temperature changes of the circuit caused by the external environment and mechanical deformations of the searching coil.
The frequency is stable only a short time, this is why it should be periodically updated the reference frequency and the detector should be moved fast enough above the metal object.
The metal object is detected by the coil's inductivity change. The change should be big enough to cause frequency change of the oscillator which must be bigger than its frequency stability. When the stability of the oscillator is considered to be 10 ppm, the maximal detection distance is given by the dimensions of the searching coil. Big coils are convenient for big objects detection. In this case the maximal detection distance is bigger than two times of the coil's diameter. Small objects should be detected by the small coils because the big coils are insensitive for them. To achieved maximal detection distance for the big objects and also the small objects it should be combined big and small searching coils. The coils can be gathered to a big searching head with separated evaluating circuits for each coil.

ACKNOWLEDGMENTS

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