ELECTROMAGNETIC SENSOR ARRAY FOR TRAIN WHEEL DETECTION

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ABSTRACT

This work proposes a train wheel detection system based on an electromagnetic sensor array. This sensor array is distributed in points along a section of the railway. Each sensor of the array is located next to the rail without additional electronics in this place. All the electronic signal process equipment is concentrated at a place far away the rail. To compensate the attenuation in the wires and the external noise, it is proposed to use a signal coded with Golay sequences. Combining the properties of the Golay sequences with the characteristics of the proposed sensor array, it is possible to detect the passage of the train by scattered points, and also to recognize the sense of circulation and estimate the speed of the train.

1. INTRODUCTION

Almost all commercial electronic train wheel detectors are based on RLC circuits placed next to the rail and tuned in a fixed frequency. When a train passes above the detector, the impedance changes due to the variations in the magnetic permeability and flux density produced by the wheel of the train. This causes variations in the current across the RLC circuit, which are easily measurable. Other systems propose a fail safe wheel train detector using two coils working as emitter and receiver respectively [1] [2]. The detector senses the wheels as changes in the magnetic coupling between the coils placed at either rail sides. The system described in [3] also uses a pair of coils as emitter and receiver, but it works processing a Barker code in a continuous way. The signal process is made by means of the application of the correlation function to the received signal. This process takes advantage of the Barker code correlation properties, which allows distinguishing the Barker code in spite of the external noise or the attenuation of the channel. The problem of Barker codes is their maximum length of 13 bits that limits the desired SNR of work.

The proposed system in this work uses pairs of emitter and receiver coils as track sensors. It is based on [4], but instead of two, it proposes to use an array of ***n*** sensor coils located in ***n*** detection points. With this, it is possible to detect the passage of the train by scattered points of a railway section. Moreover, we suggest detecting the direction of the circulation and estimate the speed using the same sensor array. To compensate the external noise, it uses a signal coded with Golay complementary sequences [7], and taking advantage of this, the electronic process unit is moved away of the railway. The correlation will be applied for the process of the signal. It can be implemented in reprogrammable logic systems [5], using efficient Golay correlators [6].

2. DESCRIPTION OF THE COMPLETE SYSTEM

The block diagram of the detector system is shown in fig.1. The emitted signal is coded with a pair of Golay complementary sequences of length N bits. Subsequently the signal is digitally modulated and amplified, and then is used to excite the array sensor. The sensor coils of the array are interconnected in series among them and with the circuit by means of an AC bridge. The sensor coils are placed next to the rail, in determined detection points, and are mounted in a fixed position and orientation. The study about the magnetic field and the influence of the wheel of train it was developed in [4] [9]. In the steady state (when the rail is free) the bridge is balanced and the voltage between the midpoints of the bridge is null (or nearly null). The bridge turns unbalanced when a train wheel is above any of the sensor coils. In this case a signal appears that it is treated by the process unit. This signal has the same waveform of the signal used to excite the bridge, but is attenuated and with added noise. Firstly, the signal is analogically conditioned and digitalized. Then, the signal is digitally demodulated and at the end is correlated. The output of the correlation will give the characteristics peaks of the Golay sequences, which will be validated by the peak detector. When a train passes by a detection point, the system will identify the signal by means of the peaks, even in presence of noise and interferences.

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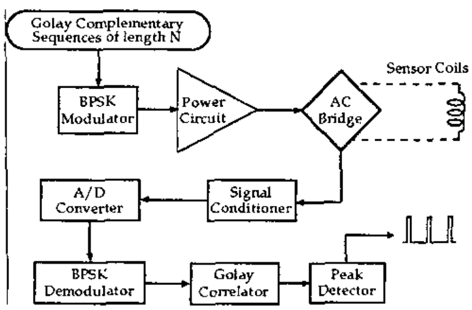

Fig. 1: Complete detector system.

3. SENSOR CIRCUIT

The sensor coils are distributed in the railway in specific detection points (fig. 2). Besides that, the sensors coils are interconnected in series with their homologous terminals connected in a different way, forming a two-wire sensor (fig. 3). The sensor circuit is based on an AC bridge, controlled by the coded signal and with the sensor coils in one of the branches. The particular AC bridge used is an implementation of the Maxwell bridge (fig. 4). When the system is in steady state (the rail is free), the bridge is balanced and the voltage between the midpoints of the two branches is null. When the wheel of the train passes by the place where there are the coils, the coefficient of coupling falls in the same ones. This causes an unbalance in the bridge, and a differential voltage appears between the two branches, with the same waveform that the coded signal from the power circuit. In order to detect the direction of the circulation, at least two points of detection are needed. We use ***n*** detection points, not only to know the direction, but also to measure the speed and the position in a certain section of the railway. The ***n*** pairs of emitter & receiver coils are connected in series (fig. 3), making an array of inductances that has a total inductance Lx. The changes in Lx, will be different according to which pair of coils is affected. The mathematical expression of Lx is:

$$L_X = \sum_{i=1}^{n} \left(L_{Ti} + L_{Ri} + 2M_i \right) \qquad (1)$$

M_i is the mutual inductance of each pair of coils, and its sign depends on the connection of the homologous points of them:

$$M_i = \pm k_i \cdot \sqrt{L_{Ti} \cdot L_{Ri}} \Rightarrow k_i \in [0;1] \qquad (2)$$

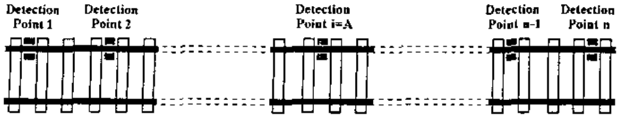

Fig. 2: Distribution of the sensor coils in the railway.

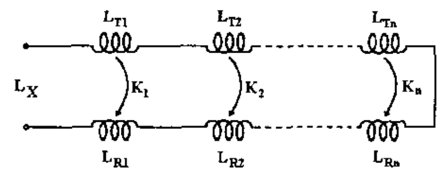

Fig. 3: Interconnection of the coils.

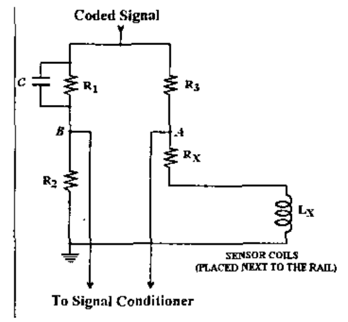

Fig. 4: AC bridge with the sensor coils.

From (2), k_i is the coefficient of coupling of each pairs of coils, and its value depends on the position, orientation and shape of the coils. Therefore, L_X will change in different ways if the wheel train is above the pair of coils 1, 2, ..., or ***n***. In order to relate the changes produced by the wheel in the magnetic field with the changes in the inductance L_X, it is necessary to analyze the mathematical expression of the magnetic flux. If the ending surfaces of the receiver coil are plane, and the flux density B is approximately constant in them, the general expression of the magnetic flux is reduced to a dot product between B and S. From this, it is possible to obtain an attenuation ratio between the two different states of the rail (free and busy) in a particular detection point (e.g. i=A):

$$r_{\Phi A} = \frac{\Phi_A^{busy}}{\Phi_A^{free}} \Rightarrow r_{\Phi A} \in [0;1] \qquad (3)$$

The coefficient of coupling (k_i) between the receiver and the emitter coil is the ratio of the flux lines produced by the emitter coil, that link the receiver coil to the total flux produced by the emitter coil. Therefore, the variations of k_i will be proportional to the variations in the magnetic flux. Supposing the inductances L_{TA} and L_{RA} are not affected for the wheel, the attenuation ratio of M_A is:

$$r_{MA} = \frac{M_A^{busy}}{M_A^{free}} = \frac{k_A^{busy} \cdot \sqrt{L_{TA} \cdot L_{RA}}}{k_A^{free} \cdot \sqrt{L_{TA} \cdot L_{RA}}} = r_{kA} = r_{\Phi A} \qquad (4)$$

The passage of a wheel by the detection point A affects only the mutual inductance of the pair of coils corresponding to that point and not over the coils placed at other detection points. So the mathematical expressions of the L_X in the cases of the free rail and the busy rail are:

$$L_X^{free} = \sum_{i=1}^{n} \left(L_{Ti} + L_{Ri} + 2M_i \right) \qquad (5)$$

$$L_X^{busy} = \sum_{\substack{i=1 \\ i \neq A}}^{n} \left(L_{Ti} + L_{Ri} + 2M_i \right) + 2M_A^{busy}$$

$$L_X^{busy} = \underbrace{\sum_{i=1}^{n} \left(L_{Ti} + L_{Ri} + 2M_i \right)}_{L_X^{free}} - 2M_A^{free} + 2M_A^{busy} \qquad (6)$$

$$L_X^{busy} = L_X^{free} - 2M_A^{free} + 2M_A^{busy} \qquad (7)$$

The values of M_A for the two cases are related by means of the expression of r_{MA} (4). Then, the attenuation of the equivalent inductance L_X is:

$$\Delta L_X = L_X^{free} - L_X^{busy} = 2\left(M_A^{busy} - M_A^{free} \right) \qquad (8)$$

$$\Delta L_X = 2\left(r_{MA} - 1 \right) \cdot M_A^{free} \qquad (9)$$

Therefore the variations in the equivalent inductance are directly proportional to the variations in the magnetic flux. Due to the magnitude of the attenuation ratio of the mutual inductance M_A is comprised between 0 and 1 (3) (4), the range of variation of ΔL_X is:

$$\Delta L_X \in \left[-2M_A ; 0 \right] \qquad (10)$$

The value of M_A can be bigger or lower than zero, this depends on the connection of the homologous points of the coils at the detection point A. It remains only to estimate the module and phase of the signal between the midpoints of the AC bridge. From the bridge of fig. 4, the expression of V_{BA} can be calculated as follows:

$$V_{BA} = \frac{Z_2 Z_3 - Z_1 Z_X}{\left(Z_1 + Z_2 \right)\left(Z_1 + Z_2 \right)} \Rightarrow Z_X = f\left(L_X \right) \qquad (11)$$

$$V_{BA} = \frac{\left(R_2 R_3 - R_1 R_X \right) + j\omega R_1 \left(L_X - C R_2 R_3 \right)}{\left(R_1 + R_2 \right)\left(R_3 + R_X \right) - \omega^2 C L_X R_1 R_2 + j\omega \left[L_X \left(R_1 + R_2 \right) + C R_1 R_2 \left(R_3 + R_X \right) \right]} \qquad (12)$$

With (12), it is possible to know the variations in the output signal related to the inductance, and therefore, related to the magnetic flux attenuation. To illustrate this, eight pairs of coils distributed in eight detection points are used (fig. 5) as example. In fig. 6 the module and phase of V_{BA} (12) are represented in a range of values of L_X comprised between 50mH and 70mH, and considering an input signal of amplitude ±1. The design values used to balance the bridge are:

- $R_1 = R_2 = 66{,}7\ \Omega$
- $R_3 = R_x = 9\ k\Omega$
- $C_1 = 0.1\ \mu F$
- Frequency of modulation = 50 kHz
- Inductance in balance point = 60 mH

The values marked in fig. 6 are resumed in Table 1. All the data it was obtained simulating the system in Simulink, with the Power System Blockset [10]. They are referred to the changes in L_X when the train is above any of the detection points (DP's, from 1 to 8). The values of ΔL_X were selected to produce approximately proportional variations in the module of V_{BA}. The values of k and r_M are equal because all the pairs of coils are physically mounted in the same way, and the effect of the passage of the wheel is similar in all the detection points. M^{free} was designed based on (9) and the sum of all the values when the rail is free is null (5).

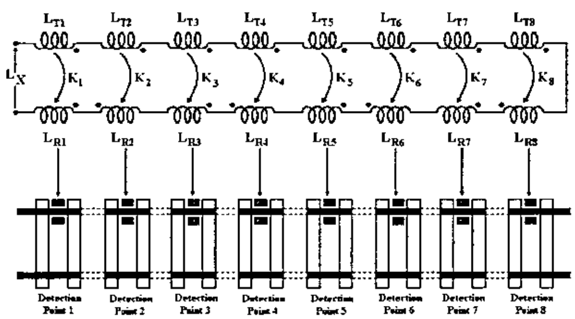

Fig. 5: Distribution of eight pairs of coils in the railway.

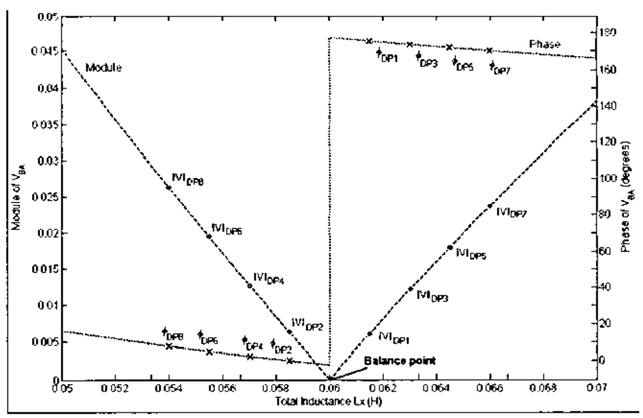

Fig. 6: Module and phase of V_{BA} related to L_X.

Table 1: Values of design parameters for the array sensor

DP	r_M	k	M^{free}(mH)	ΔL_X(mH)	L_X(mH)	ΔV_{BA}
1	0.1	0.55	+3.30	-6.0	54.0	0.026
2	0.1	0.55	+2.48	-4.5	55.5	0.020
3	0.1	0.55	+1.70	-3.0	57.0	0.013
4	0.1	0.55	+0.83	-1.5	58.5	0.007
5	0.1	0.55	-0.83	+1.5	61.5	0.007
6	0.1	0.55	-1.70	+3.0	63.0	0.013
7	0.1	0.55	-2.48	+4.5	64.5	0.018
8	0.1	0.55	-3.30	+6.0	66.0	0.024

4. PROCESS & CODIFICATION OF THE SIGNAL

4.1. Codification of the signal with Golay sequences

Given a pair of Golay complementary sequences $\{a,b\}$ of length N [7] [4] (fig. 7), the sum of the autocorrelations of both sequences is a delta of Dirac $\delta(n)$ of amplitude 2N. This is even fulfilled if the sequences are superposed [8], as long as the separation between the superposed sequences is bigger than zero. That is to say, that at least there is an element of separation between superposed sequences. In this work, it used a sequence superposition of N/2 bits:

$$A(n) = \sum_k a(n - k \cdot N/2) \ \forall k \qquad B(n) = \sum_k b(n - k \cdot N/2) \ \forall k \tag{13}$$

$$C_{Aa} + C_{Bb} = 2N \sum_k \delta(n - k \cdot N/2) + \underbrace{C_{na} + C_{nb}}_{\text{Contribution of the Gaussian noise}} \tag{14}$$

In the sum of correlations (14) it was assumed a Gaussian noise, whose contribution is 2N times lower than the amplitude of the deltas. The superposed sequences A(n) and B(n) are periodic signals with a period of N/2. Moreover N/4 of the values of A(n) and B(n) are null. The fact that N/4 of the values are null allows us to send in the time A(n) and B(n) by the same channel, with a displacement of one of them N/4 respect to the other.

In fig. 7 it can be seen a pair of Golay complementary sequences $\{a,b\}$, of length N=32 bits. In fig. 8, the same sequences $\{a,b\}$ are present but superposed N/2 bits in a continuous emission, as is mathematically expressed in (13). In this figure it can be seen how the continuous emission of both sequences produces a periodic signal, with a period of N/2 bits (in this case, 16 bits), and N/4 bits are zero.

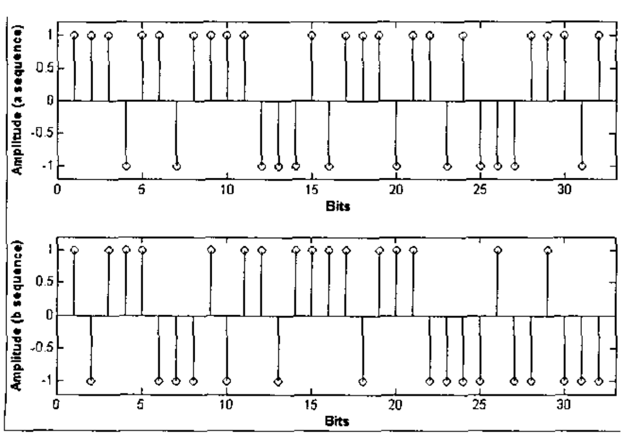

Fig. 7: Golay complementary sequences of length N=32.

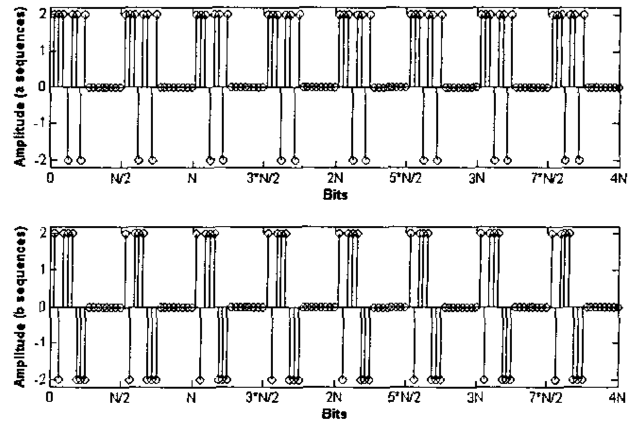

Fig. 8: Golay sequences superposed N/2 bits (with N=32).

In fig. 9, the superposed sequences, $\{a,b\}$, are multiplexed in a single emission. To make this, the a superposed sequences are displaced N/4 bits (8 bits in this example), to coincide the zeros of b superposed sequences with the values not null of a superposed sequences. Then, both sequences are emitted in a single and continuous way. In the same fig. 9 the results of the sum of correlations are shown, when the superposed sequences, $\{a,b\}$, are demultiplexed in the reception. The peaks of the correlation appear separated N/2 bits, and correspond to the beginning of each pair of sequences $\{a,b\}$.

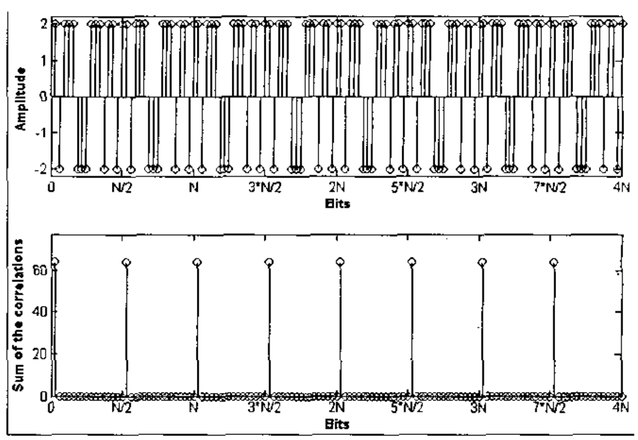

Fig. 9: Superposed Golay sequences multiplexed (upper graph) and result of the sum of correlations (lower graph).

4.2. Implementation of the system

With the generated superposed sequences, the signal sent to the emitter coil is modulated digitally by means of a BPSK modulator. So the signal adapts to the central frequency of work looked for the system, and it has a narrow bandwidth. When the wheel of the train is at a detection point (above a pair of coils), the flux in the receiver coil is approximately attenuated 10 times (r_M=0.1) [9]. Then a differential voltage appears in the bridge and is processed by the Golay correlator and the peak detector. In fig. 5 it is shown the disposition of the coils in the railway (eight in this case). In fig. 10 can be seen the results of correlation using Golay sequences of 32 bits, without noise, and supposing a train circulating through all the detection points. In fig. 11 the results of correlation with the same conditions of process and codification are displayed, but with a SNR=-9dB. All the process and codification it was realized in Matlab [10]. In this figure the effect of the passage of the wheel above the different sensors can be clearly identified by means of the different amplitudes and signs of the correlation peaks.

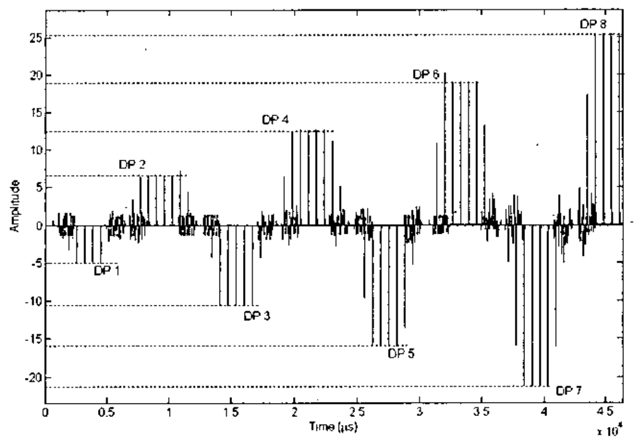

Fig. 10: Correlation peaks without external noise.

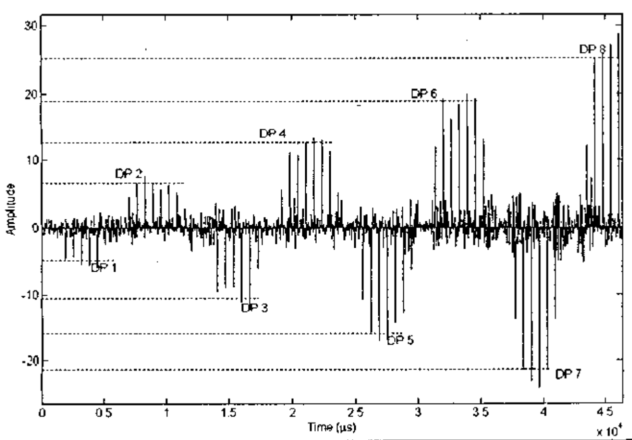

Fig. 11: Correlation peaks with SNR=-9dB.

5. CONCLUSIONS

In this work we have presented an electronic wheel detector with a sensor array capable to detect the position, sense of circulation and speed of the train at different points. This sensor array is composed of pairs of coils, which are interconnected using only two wires and are part of an AC bridge, which contribute to improve the sensibility. The detector uses a continuous emission of a coded signal to work with a low SNR. With this technique, the signal attenuation in the wires is compensated and immunity to the interferences is obtained. The signals can be detected with noise at different or the same frequency that one used in the modulation. This allows us to place the sensors in the rail without the signal process equipment in the same place. It makes easier the maintenance tasks and improves the robustness of the external equipment. The implementation of Golay sequences on FPGA, permits to work in real time and with reliability.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] K.Futsuhara and M.Mukaidono, "Realization of a fail-safe train wheel sensor using electromagnetic induction", *IEEE Trans Instrum. & measurement*, Vol.38, No.2, pp.421-426, April 1999.

[2] K.Futsuhara and M.Mukaidono, "A realization of fail-safe sensor using electromagnetic induction", *Conference on Presicion Electromagnetic Measurement 1988 (CPEM'88)*, Tsukuba, Japan. June 7-10, 1988. CPEM'88 Digest, pp. 99-100.

[3] J.Ureña, M.Mazo, J.J.García, et al., "Train axle detector based on signal codification with a Barker code", *Automotive and Transportation Technology Congress and Exhibition, ATTCE 2001*, Vol. 8, pp. 49-53. Barcelona, 2001.

[4] P.Donato, J.Ureña et al., "Use of coded signals to wheel train detection", *9th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2003)*, Vol. 2, pp. 685-691. Lisbon, 2003.

[5] A. Hernández, J. Ureña, J. P. Dérutin, et al., "Ultrasonic signal processing using configurable computing", *15th Triennial World Congress of the International Federation of Automatic Control (IFAC'02)*. Barcelona, 2002.

[6] B.M.Popovic, "Efficient Golay correlator", *IEEE Electronics letters*, Vol. 35 No. 17, 1999.

[7] M.J.E.Golay, "Complementary Series", *IRE Trans.*, IT-7, pp.82-87, 1961.

[8] C.C.Tseng and C.Liu, "Complementary Sets of Sequences", *IEEE Trans. Information Theory*, Vol. IT-18, No 5, September 1972, pp. 644-652.

[9] P.Donato, J.Ureña, M.Mazo, J.J.García A.Hernández and F.Álvarez, "Optimization of train detection in intelligent railway transportation systems", *5th IFAC Symposium on Intelligent Autonomous Vehicles IAV 2004*, Lisbon, 2004.

[10] Matlab, Simulink and Power System Blockset are a product of MathWorks. http://www.mathworks.com