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Train Wheel Detection without Electronic Equipment near the Rail Line

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Abstract- **The reliable detection of the passage of railway units by certain points of the railway line is very important for a safe circulation. Thus the system proposed in this work makes the detection with the sensor located next to the railway, without additional electronics in this place. All the electronic process equipment is concentrated in a point that can be far away the rail. Moreover, the proposed sensor is capable to detect the sense of circulation. In order to compensate the attenuation in wires and the external noise, we use a signal codified with Golay complementary sequences.**

I. INTRODUCTION

Now, the developments on security and traffic control are one of the high-priority lines of R+D in the railway scope [1]. In the automation of the railway traffic circulation is very important to have reliable detectors of passage of trains. The actual commercial electronic wheel detectors in the market are based on RLC circuits placed next to the rail and tuned in a fixed frequency of tens of kHz. In a normal condition (when the rail is free), a current of constant module and phase circulates across the RLC circuit. When the train wheel is above the detector, the inductance changes, due to the variations of magnetic permeability and flux density in its surroundings. The change in the inductance modifies the impedance of the RLC circuit, which causes variations in the current, easily measurable.

In [9] [10] is proposed the realisation of a fail safe wheel train detector using two coils working as emitter and receiver respectively. The detector senses the wheels as changes in the magnetic coupling between the coils placed at either rail sides. The coils are installed in the same plane with parallel axes and over a metal plate, and the emitter coil is excited with a harmonic current in the rank of tens of kHz.

In other systems with two pairs of coils (emitter and receiver) a code is processed in a continuous way. The system described in [2] is based on the magnetic flux codification with a 13-bit Barker code. Being interrupted by the passage of a train wheel detects its presence. The signal processing is made by means of the application of the correlation function to the received signal. This process takes advantage of the 13-bit Barker code properties, as the autocorrelation function with a very marked peak with a 13:1 ratio respect to the lateral lobes. This property allows distinguishing the Barker code making the correlation between the received signal and the transmitted one, in spite of external noise or the attenuation of the channel. The problem of Barker codes is their maximum length of 13 bits that limits the SNR.

The Spanish Railway Company, RENFE [3], imposes in its technical specifications a series of exigencies to these systems:

- The detection point will consist of two inductive detectors mounted on the rail and a process unit to provide a safe interface with the central process unit.
- The sensor coils will fulfil the norm of maximum height until a determined distance.
- The system will correctly work with trains in movement and speeds between 0 and 300 Km/h
- The equipment must be immune to external electrical interferences, such as atmospheric discharges, returns of traction of trains, as well as to the electrical or electromagnetic braking systems of the trains.
- The outer equipment will have design characteristics to exclude the inadequate operation due to mechanical vibrations or any other outer forces.

From all this, it is deduced that one of the most important aspects is that the system must be designed guaranteeing great immunity to the noise. Besides, in this work we move away the electronic process unit to the location of the control unit (normally in technical buildings). For that reason, the proposed solution is based on the emission of a coded signal generated from Golay complementary sequences. The implementation of the correlation algorithm can be made in systems of reprogrammable logic [4], by means of efficient Golay correlators [5]. With this technique, aside from compensate the signal attenuation in the wires, immunity to the external

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interferences is obtained. It means that the signals can be detected with electromagnetic noise of the same frequency that the one used in the modulation. Moreover, in this work we propose the detection of the direction of the train circulation using the same sensor system and the same Golay sequences. Following up the research, the most critical aspects will be studied: the location of the coils, the design of the sensor system, and the process of the coded signals.

II. STUDY OF THE LOCATION OF THE COILS

The study of the location of the coils is very important because we will design the sensor and signal conditioner according to it. This study it was carried out by means of Finite Element Analysis, using an special software, Quickfield 5 [6], to that end. With this software we can analyze harmonic electromagnetic fields in 2D, and calculate the density of flow, and other electromagnetic magnitudes. For this, it defines a geometric model with the shapes, sizes, and positions of the elements that compose the physic system: rail, coils and wheel train. In order to simulate the magnetic field, the beam of the rail in plane XY is drawn, the cut of the coil is drawn and the properties are assigned to him to the different zones to analyze. The most important properties to define are the permeability of the physical mediums (iron, copper, and air), the current across the coil, and the boundaty conditions. With these data, the solver calculates the value of the magnetic magnitudes in all the points of the calculation space.

After analyse and simulate several different configurations of the coils, it was choosen the location seen in fig. 1. In this configuration, the emitter coil has an inclination angle of 22.5° respect to the Y axis, and a ferrous nucleus tied to the rail. Obviously, it must fulfill the conditions of maximum height imposed by the technical norms [3]. The results of the simulation for this configuration can be seen in the fig. 2, as much for the free rail condition (a) as for the case in that it passes a wheel of the train (b). Clearly, in the second case (fig. 2b), the magnetic field lines are closing across the iron volume, which is composed for the wheel and the rail.

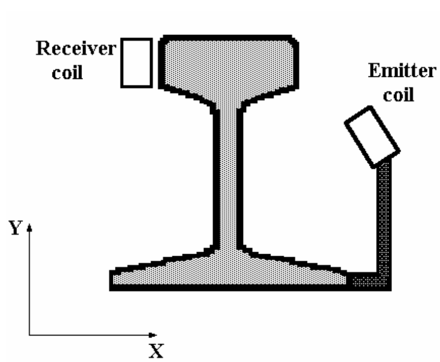

Fig. 1: Location of the emitter and receiver coils.

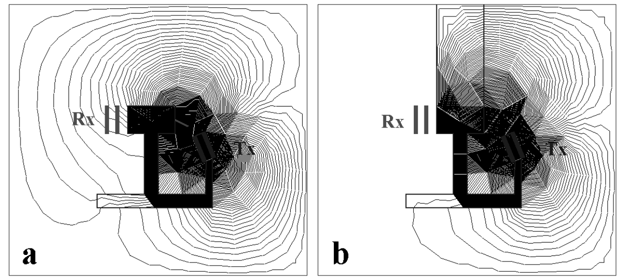

Fig. 2: Distribution of the magnetic field lines, with the rail free (a) and with a wheel (b).

III. SENSOR SYSTEM

The two pairs of emitter and receiver coils are part of an AC bridge (fig. 3), and they are connected in series, with their homologous terminals connected in a different way. The particular AC bridge used is an implementation of the Maxwell bridge. When the system is in stationary condition (the rail is free), the bridge is balanced, and the voltage between the midpoints of the two branches is null. When it pass the wheel of the train by the place where are the coils, the coupling coefficient in the same ones falls, which affects the total inductance of the branch, and causes that the bridge turns unbalanced. When being unbalanced the bridge, appears a differential voltage between the two branches which has the same waveform that the coded signal from the power circuit. Using the two pairs of coils connected like the fig. 3, the change in the total inductance (L_{total}) of the sense branch will be different according to which pair of coils is affected. The expression of L_{total} is:

$$
\begin{aligned}
L_{total} &= \sum L_{TX} + \sum L_{RX} + 2M_1 - 2M_2 \\
M_X &= k \cdot \sqrt{L_{TX} \cdot L_{RX}}
\end{aligned}
\qquad (1)
$$

Where M_x are the mutual inductances and k_x are the coupling coefficient of each pair of coils. So, L_{total} will changes of different way if the wheel train it is above the pair of coils 1 or 2. This it is useful to know the direction of circulation of the train, and we´ll use it with the signal process.

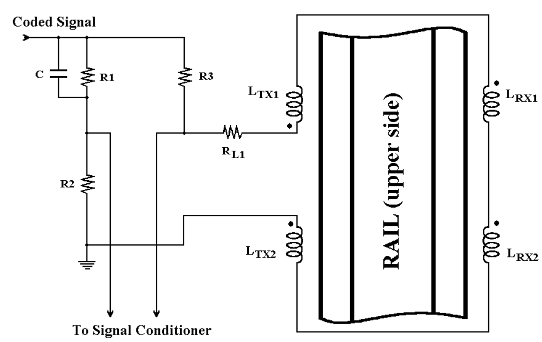

Fig. 3: AC bridge with the emitter and receiver coils placed in both sides of the rail.

IV. PROCESS AND CODIFICATION OF THE SIGNAL

A. Golay complementary sequences

Given a pair of Golay complementary sequences (*a,b*) [11], of length N, constituted by values {-1,+1} (see fig. 4), the sum of the autocorrelations of both sequences of the Golay pair is an ideal result: a delta of Dirac, δ(n), of weight 2N, that is:

$$C_{aa} + C_{bb} = 2N\delta(n) \quad (2)$$

This is even fulfilled if the sequences are superposed [8]. That is to say, if the signals are generated:

$$\begin{aligned} A(n) &= a(n-n_1) + a(n-n_2) \\ B(n) &= b(n-n_1) + b(n-n_2) \end{aligned} \quad (3)$$

Then, the sum of the autocorrelations is:

$$\begin{aligned} C_{Aa} + C_{Bb} &= A(n) * a(n) + B(n) * b(n) \\ C_{Aa} + C_{Bb} &= 2N\delta(n-n_1) + 2N\delta(n-n_2) \end{aligned} \quad (4)$$

Where * represents the cross correlation between both signals. It must be fulfilled that the separation between superposed sequences (n2-n1) > 0, that is to say, that has at least a bit of separation between superposed sequences.

B. Generation of the signal for codification

In this work, we propose to use a continuous emittion of a coded signal, and a continuous signal process by means of the cross correlation. To this, we use a particular sequence superposition of N/2 bits. The mathematical expression is:

$$\begin{aligned} A(n) &= \sum_k a(n - k \cdot N/2) \quad \forall k \\ B(n) &= \sum_k b(n - k \cdot N/2) \quad \forall k \end{aligned} \quad (5)$$

The result of the sum of correlations will be:

$$C_{Aa} + C_{Bb} = 2N \sum_k \delta(n - k \cdot N/2) + C_{na} + C_{nb} \quad (6)$$

In the previous expression it was assumed in the process a Gaussian noise (n), whose repercussion in the output comes given by $C_{na} + C_{nb}$. This contribution is, in terms of power, 2N times lower than the amplitude of the deltas.

The generated signals A(n) and B(n) with superposition N/2 have special characteristics:

- A(n) and B(n) are periodic signals of N/2 period.
- Within a period, half of the values of A(n) and B(n) are null.

Because half of the values is null, it allows us, with a simple displacement of one of them N/4 samples with respect to the other, to send in the time both by the same channel.

In the fig. 4 it can see a pair of Golay complementary sequences, *a* and *b*, of length N=32 bits. In the fig. 5 are the same sequences *a* and *b*, but superposed N/2 bits in a continuous emittion, like is mathematically expressed in (5). In this figure it can see how the continuous emittion 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. In the fig. 6, the superposed sequences, *a* and *b*, are multiplexed in a unique emittion. To this, the *a* superposed sequences are displaced N/4 bits (8 bits for 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 an unique emittion and in continuous way. Finally, in the same fig. 6 it can see the results of the sum of correlations when the superposed sequences, *a* and *b*, are demultiplexed in the reception. The peaks of the correlation appears separated N/2 bits, and corresponding with the beggining of each pair of sequences (*a* and *b*).

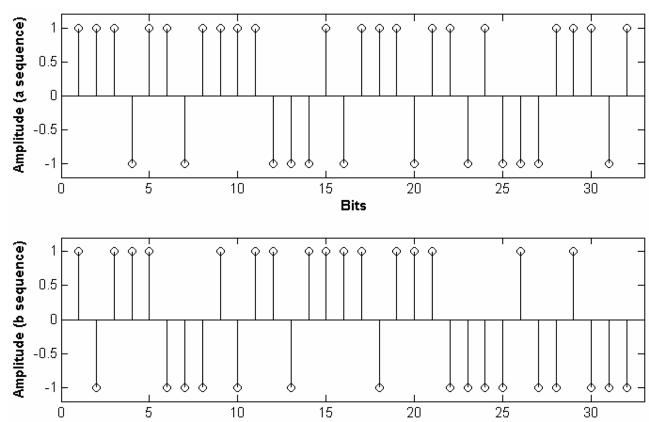

Fig. 4: Golay complementary sequences of length N=32

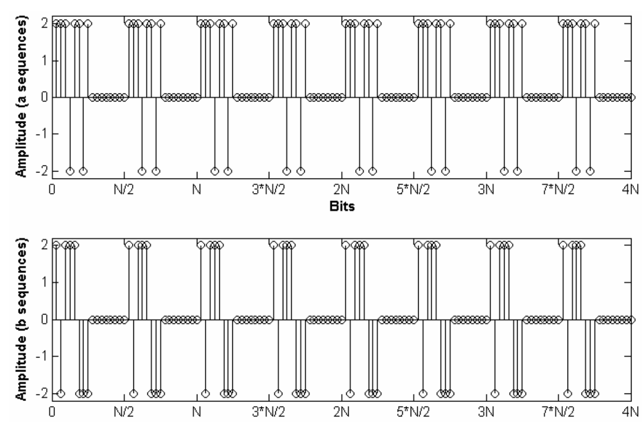

Fig. 5: Golay complementary sequences superposed N/2 bits

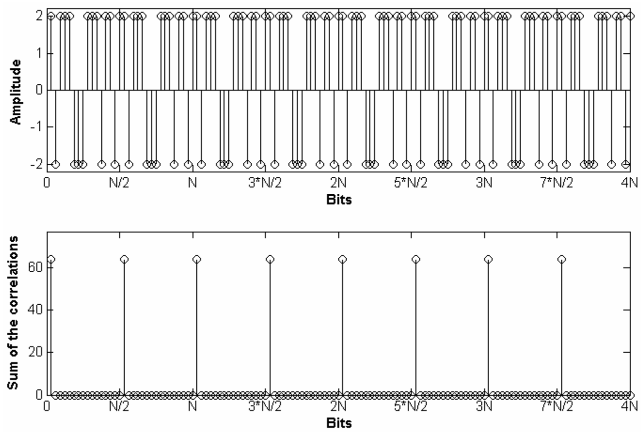

Fig. 6: Superposed Golay sequences multiplexed (upper graph) and the results of the sum of correlations of the sequences (lower graph).

C. Implementation of the system

With the multiplexed superposed sequences (upper graph in fig. 6), the signal sent to the emitter coil is modulated digitally, by means of a BPSK modulator, with a symbol constituted of two periods of an square signal of 50kHz. This way, the signal adapts to the central frequency of work wanted for the system. In adittion, we use BPSK modulation because it has a narrow bandwidth. The block diagram of the system it is on fig. 7 and it includes these blocks:

- AC bridge with the emitter and receiver coils.
- A/D Converter (sampling frequency of 1MHz).
- BPSK demodulator.
- Demultiplexer to reconstitute the order of the signals A(n) and B(n) (the first one was displaced N/4).
- Double correlator, C_{Aa} and C_{Bb}, and the sum of both outputs.
- Peak detector to recover the train of deltas.

As clock is arranged in the process equipment, as much to the emission as for the reception, the demodulation can be made synchronously. So the typical sidelobes of the asynchronous detection are avoided. When the train wheel is above of a pair of coils, the flow in the receiver coil is attenuated in an order of magnitude of approximately 100 times (about 40 dB), and the coupling coefficient falls down. This variation in the the coupling also changes the mutual inductance M (of the pair 1 or 2), and turns unbalanced the AC bridge. Then appears a differential voltage between the midpoints of the branches of the AC bridge, which it is digitalized by the ADC, demodulated by the BPSK demodulator, and processed by the double correlator and the peak detector.

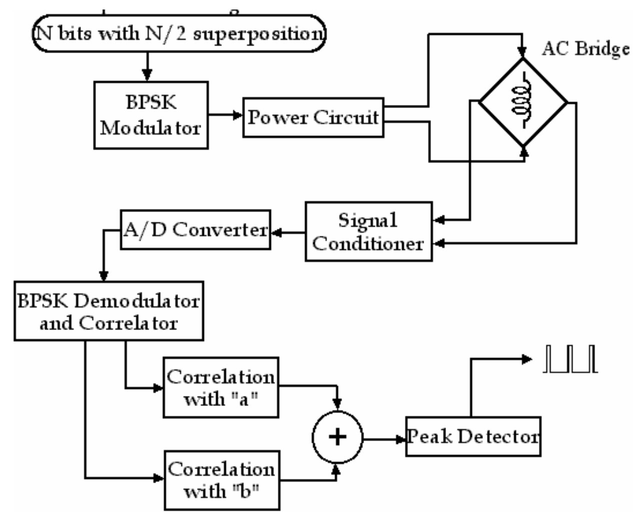

Fig. 7: Block diagram for the implementation of the complete detector system

The two pairs of emitter (Tx) and receiver (Rx) coils are placed in the rail line in points between two stations (fig. 8) or next to junctions or bifurcations. In fig. 9 and 10 it can see the results of the signal process using a codification made with Golay complementary sequences of length N=32 bits, without noise, and supposing a train circulating between "x" and "y" station (in both directions). In fig. 11 and 12 it can see the results in the same conditions of signal process, codification, and train circulation, but with a SNR=–9dB.

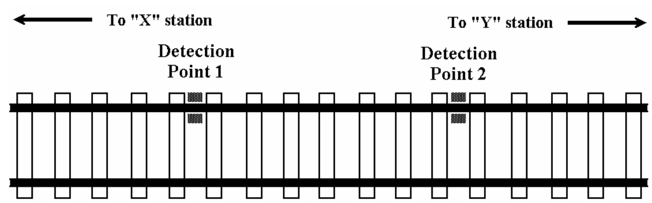

Fig. 8: Ubication of the coils in the rail line

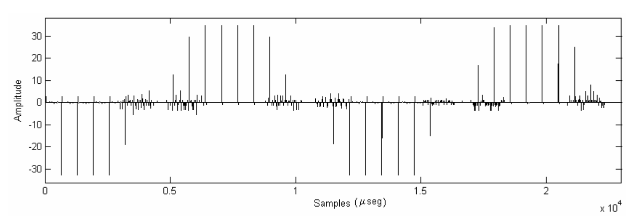

Fig. 9: Wheel train detected, circulating from "x" to "y"

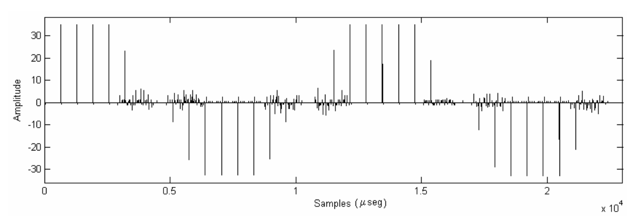

Fig. 10: Wheel train detected, circulating from "y" to "x"

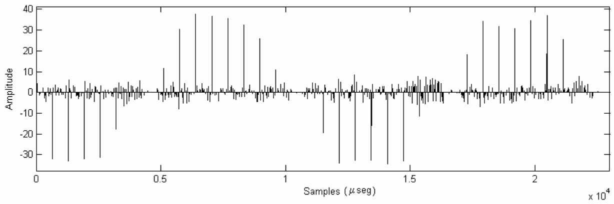

Fig. 11: Wheel train detected, circulating from "x" to "y" (SNR=-9dB)

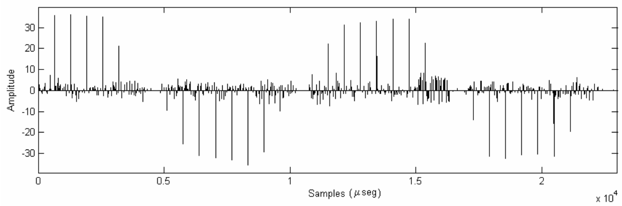

Fig. 12: Wheel train detected, circulating from "y" to "x" (SNR=-9dB)

The signal processing module is been implemented in a FPGA, taking advantage of all the operations of modulation and correlation are digital and consists of sequences of values {-1,+1}, from what all the mathematical operations are sums and subtractions [4], [5]. When practical implementation will be completed, it will begin to make real tests to determine the characteristics of the channel in the system, and his possible compensation, and other practical considerations, like the definitive distance between the sensor coils and the location of the process card and the minimum SNR of work.

V. CONCLUSION

In this work we have presented an electronic wheel detector that uses a continuous emission of coded signals to work with low SNR. This characteristic allow us the sensors can be placed next to the railway without need electronics equipment for signal processing in the same place, which make easier the maintenance and control tasks, in addition to improve the robustness of the external equipment. All the work it was made using Golay sequences of N=32 bits, but it is extensible to longer sequences of N=64 or 128 bits, with the consequential improve in the SNR of work. The use of an AC bridge configuration to connect the emitter an receiver coils allow us improve the sensibility of the sensor and the quality of the signal to be processed, moreover allow us to detect the sense of circulation of the train. The use of Golay complementary sequences combined with the implementation of the system in FPGA, allow reaching all these objectives in real time and with reliability.

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