Spread Spectrum Communication System with Particle in a Box Electronic Circuit

José Carlos Pizolato, Jr. and Luiz Gonçalves Neto

Abstract— **A spread spectrum communication system based on the electronic model of the particle in a box system is proposed. This circuit allows a robust and simple electronic emulation of the mechanical behavior of the collisions of a particle inside a box, exhibiting rich chaotic behavior. The required nonlinearity to emulate the box walls is implemented in a simple way when compared with other analog electronic chaotic circuits. In this system, binary data stream information is transformed in the frequency modulated signal by the binary frequency shift keying (BFSK) modulator. The chaotic signal of the particle in a box electronic circuit is used to generate a broadband signal in the voltage controlled oscillator (VCO) of the transmitter. The frequency hopping signal send to receiver is generated by mixing the binary frequency shift keying and the broadband signal. The demodulation process is done when the VCOs of transmitter and receiver are synchronized by a phase lock loop (PLL) circuit. The performance of the demodulation process is verified through the eye pattern technique applied on the recovered bit stream. A binary data stream information was sent through a transmission channel with the following lengths: 1000 meters and 5000 meters. The experimental results demonstrated that the particle in a box electronic circuit can be used in a spread spectrum communication system.**

***Index Terms*—Spread Spectrum, Frequency Hopping, Chaotic Circuit, Particle in a Box Electronic Circuit.**

I. INTRODUCTION

IN conventional spread spectrum communication systems pseudorandom signals are used for broadening the spectrum by modulating the phase (in direct-sequence), or the frequency (in frequency hopping (FH)) of the carrier signal, which provides a better antijam performance, low power spectral density, and implies the reduction of multipath effects [1]. At the receiver a corresponding dispreading technique is used to reconstruct the baseband signal. Despreading techniques usually require synchronization between the transmitter and the receiver.

There has been significant interest in exploiting chaotic dynamics in communications [2-8]. Chaotic systems provide a rich mechanism for pseudo-random signal generation, with potential applications to spread spectrum communication systems [4,9-13]. Analog chaotic oscillators provide a natural way of generating smoothly varying frequency modulation (FM) [14]. In the literature there are several electronic circuits which can be used to generate chaotic signals for applications in frequency modulation. Some examples are the Chua's circuit [4, 15, 16], the Lorenz-based chaotic circuit [9], the chaotic Rössler circuits [17] and the particle in a box electronic circuit [18].

Usually chaos synchronization is very susceptible to channel noise, distortions, and interference. To minimize the performance degradation associated with these factors, communication systems based on chaotic pulse position modulation and chaotic frequency modulation (CFM) have recently attracted much interest [1,14]. The CFM communication scheme is a modification of the frequency hopping scheme, in which a chaotic signal is used to spread the spectrum instead of a pseudo-noise sequence. A spread spectrum communication system which uses CFM for spreading the spectrum and BFSK modulation for the information signal was proposed in reference [1]. In that work the Rössler system was used as the chaotic oscillator. However, the analog implementation of the chaotic circuit requires several operational amplifiers and components. Reference [18] presents the particle in a box electronic circuit. In that article the nonlinearity is implemented in a simple way and with fewer analog devices when compared with other analog electronic chaotic circuits.

This paper proposes the application of the particle in a box electronic circuit to implement a communication system which uses the CFM for spreading the spectrum and BFSK to modulate the information signal. In the electronic implementation of this system, the transmitter has the particle in a box electronic circuit which controls the voltage control oscillator (VCO) to generate a broadband signal. On the receiver there is a phase lock loop (PLL) circuit to do the synchronism between the VCOs of the transmitter and receiver. The binary data stream is recovered by a frequency shift keying (FSK) demodulator that uses the resulting signal generated by the product between the VCO and the received signal. The performance of the proposed system is verified through the eye pattern technique [19] applied on the binary

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data stream recovered at the receiver. In the demodulation process, the robustness of the spread spectrum system was evaluated with the box electronic circuit. The transmission channel was simulated using the model "T" transmission line. The eye patterns were constructed for transmission lines with 1000 metes and 5000 meters.

This paper is organized as follows. In section II, it is discussed the electronic circuit implementation of the particle in the box electronic circuit system. This circuit will be used in the implementation of the analog chaotic oscillator. In section III, the particle in the box electronic circuit is applied in a alternative spread spectrum frequency hopping system. In section IV, the performance of the alternative frequency hopping system is evaluated through the eye pattern technique. Any conclusions about the experimental tests are done in the section V.

II. The Analogic Chaotic Oscillator

The particle in a box electronic circuit described in Fig. 1 was used in a secure communication system [18]. This circuit simulates the mechanical behavior of the collisions of a particle inside a box. It is based on the "electronic bouncing ball circuit", proposed by Zimmerman, Selasch and Neto [20], which is used to study the regular, chaotic and random behavior of a bouncing ball on a vibrating surface. The key devices of the particle in a box electronic circuit are the anti-parallel diodes D_1 and D_2 and the resistor R_L. They electronic implement the nonlinearity this circuit in a simple way when compared with other circuits [9, 15, 16]. The association of these devices simulates the collision of the particle in walls in the x direction, resulting in the term $I_D(V_2)$ shown in Fig. 2.

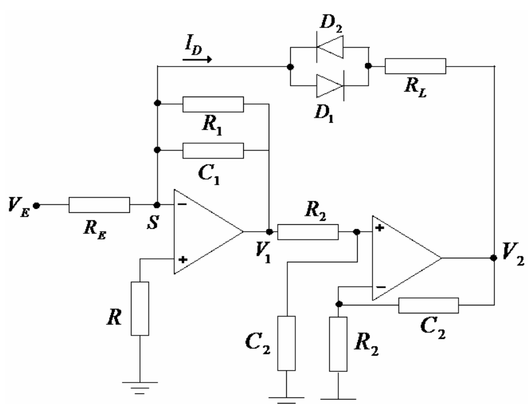


Fig. 1: The particle in a box electronic circuit described by equation (1). The component values are: resistors (kΩ): R_1=47; R=R_E=R_2=10; R_L=0.51; capacitors (nF): C_1=C_2=12; diodes D_1 e D_2: 2N4148; Operational Amplifiers: 741 or equivalents. This circuit simulates the mechanical behavior of the collisions of a particle inside a box.

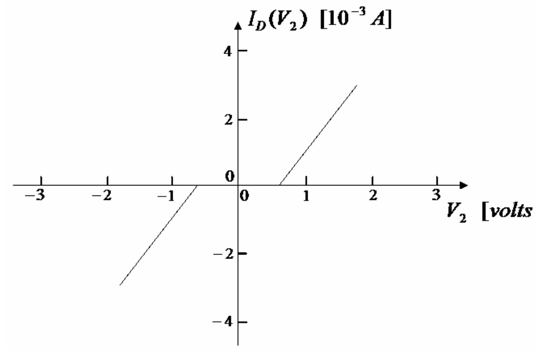


Fig. 2. Curve of current $I_D(V_2)$ versus voltage V_2 of the anti-parallel diodes (D_1 and D_2) in series with the resistor R_L of the particle in a box electronic circuit.

The particle in a box electronic circuit has as input a sinusoidal signal $V_E = V_{\max}\sin(wt)$, and the contribution of the currents in the point S, shown in Fig.1, results in the differential equation:

$$R_2 C_1 C_2 \frac{d^2 V_2}{dt^2} + \frac{R_2 C_2}{R_1}\frac{dV_2}{dt} + I_D(V_2) = -\frac{V_E}{R_E} \qquad (1)$$

In the equation (1), the signal V_2 corresponds to the position x of the system described in Fig. 1, and the signal dV_2/dt corresponds to the velocity dx/dt. The component values are Resistor (kΩ): $R_1 = 47$; $R = R_E = R_2 = 10$; $R_L = 0.51$; capacitors (nF): $C_1 = C_2 = 12$; Diodes D_1 and D_2: 2N4148; Operational Amplifiers: CI 741 or equivalents. The components of the operational amplifiers can be seen in the reference [21]. All resistors and capacitors used in this work have an error of +/-10% in their nominal values.

The periodic or chaotic behavior can be obtained by the variation of the parameter of bifurcation of the circuit in Fig. 1, which controls the dynamic of the system. The variation of the parameters w or $V_{\max}$ of the input sinusoidal signal $V_E = V_{\max}\sin(wt)$ can be used as the bifurcation parameters. As a first example to show the dynamic of the chaotic behavior of the particle in a box system, the amplitude $V_{\max}$ has been chosen as parameter of bifurcation. The initial conditions of this circuit were $(V_2 = 0 \ \ and \ \ dV_2/dt = 0)$. The variation of $V_{\max}$ can causes a periodic oscillation with period T, passing by a period doubling bifurcation, respectively with period $2T$ and $4T$, until a non-periodic chaotic oscillation. In the electronic simulation of this system, the period doubling bifurcation is limited to $4T$ due to the noisy level present in the circuit [20]. This period doubling behavior followed by the chaotic oscillations is shown in the phase diagrams of Fig. 3.

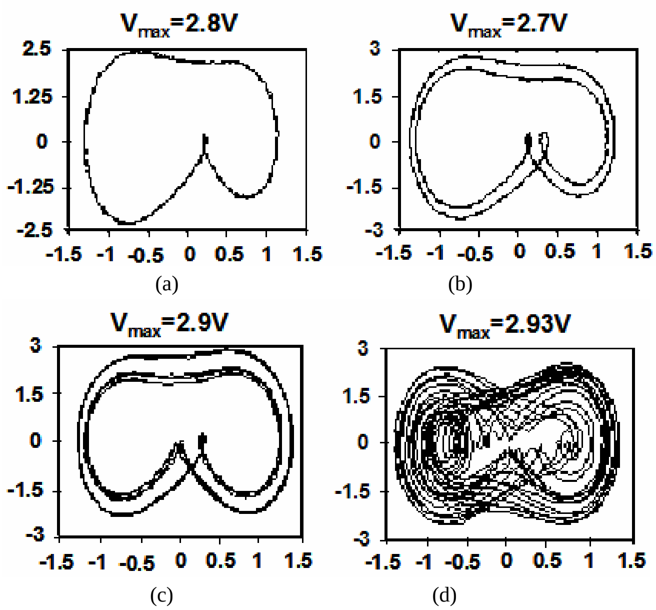


Fig. 3. Phase diagrams of the particle in a box electronic circuit for the fixed oscillating frequency *w*=12208 rad/s with the initial conditions $(V_2 = 0 \;\; and \;\; dV_2/dt = 0)$: (a) Period 1. (b) Period 2. (c) Period 4. (d) Chaos.

The particle in the box electronic circuit has been used in the communication system [18]. This circuit is implemented in a simple way and with fewer analog devices when compared with other analog electronic chaotic circuits. In this work it is proposed the application this circuit as the analog chaotic oscillator in an alternative spread spectrum frequency hopping (FH) system.

III. Application of the Particle in the Box Electronic Circuit in a Spread Spectrum System

A conventional spread spectrum system by frequency hopping is illustrated in Fig. 4. A frequency generator generates a carrier with a random frequency using a pseudo random sequence. The recovery process of the information is obtained when the receiver synchronizes with the transmitter. The carrier signal has a frequency in each instant and it has a wideband in frequency domain. An alternative way to generate the carrier with random frequency applies an analog chaotic oscillator. The block-diagram of this system is shown in Fig. 5.

The spreading of information in the transmitter is done by the particle in the box electronic circuit of Fig. 1. The input sinusoidal signal $V_E = V_{\max}\sin(wt)$ is chosen to get a phase diagram of Fig. 3(d) with $V_{\max} = 2.93V$ and $w = 12208 \;\; rad/s$ to the initial conditions $(V_2 = 0 \;\; and \;\; dV_2/dt = 0)$. The chaotic signal $V_2(t)$ in the output of the second operational amplifier of this circuit is

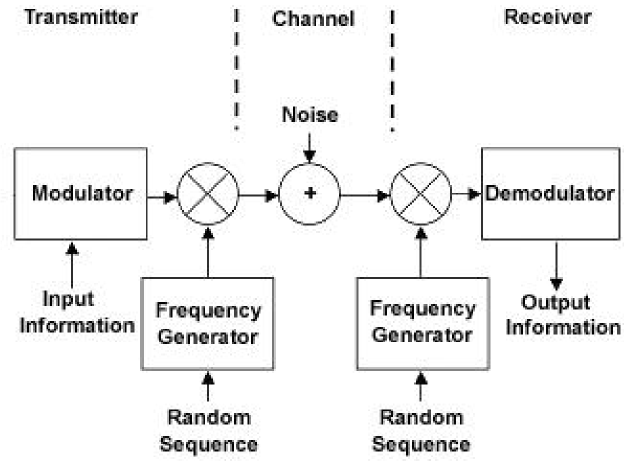


Fig. 4. Scheme of a spread spectrum system by frequency hopping

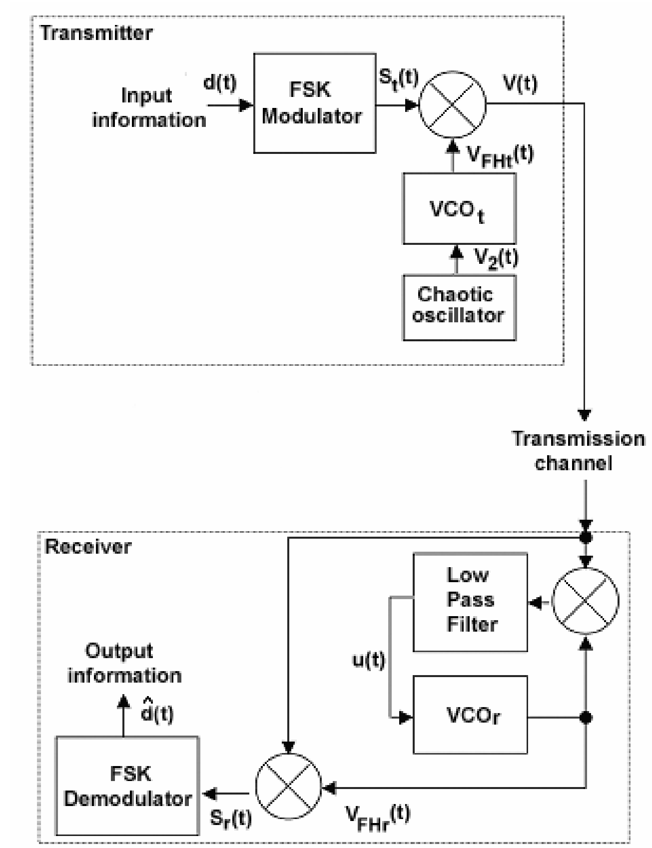


Fig. 5. Block diagram of the alternative *spread spectrum* using an analog chaotic oscillator (the particle in the box electronic circuit).

illustrated in Fig. 6. In this case $V_2(t)$ is a wideband signal with a chaotic behavior and it is applied in the input of the voltage controlled oscillator of the transmitter (VCO_t) to generates a sinusoidal carrier $V_{FHr}(t)$ with chaotic variable frequency. The VCOs blocks were electronic implemented with CI ICL8038. The frequency of VCO_t, modulated by the chaotic signal $V_2(t)$, is described by equation 2.

$$\dot{\varphi}_t \equiv w_t = w_o(1 + m_1 V_2) \tag{2}$$

in which w_o is the 'natural' frequency of VCO_t, m_1 is the modulation gain coefficient (m_1=0.11) and $V_2(t)$ is the chaotic signal.

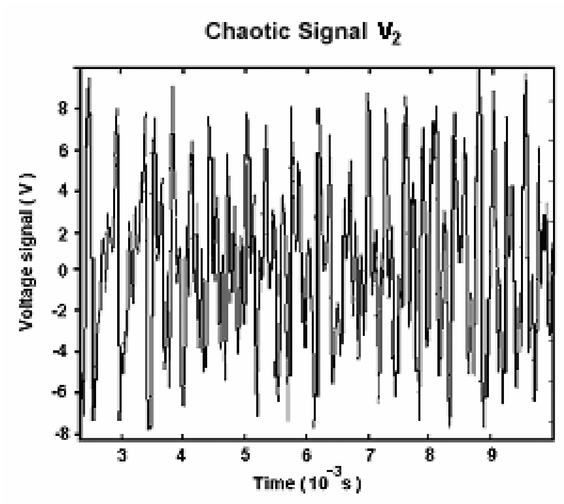


Fig. 6. Chaotic signal V_2 of the particle in the box electronic circuit with the initial conditions $(V_2 = 0 \;\; and \;\; dV_2 / dt = 0)$.

The input information $d(t)$ (a binary data stream) is applied in the FSK modulator generating the BFSK signal $S_t(t)$ of Fig. 7(a) with the power spectrum shown in Fig. 7(b).

The FSK modulator block was electronic implemented with CI ICL8038. The BFSK signal and the chaotic sinusoidal carrier are multiplied by the phase discriminator block (⊗) resulting in the spread spectrum signal of Fig. 8. The block (⊗) was electronic implemented with CI MM74C932. The signal $V(t)$ of Fig. 8 has a wideband from 20 kHz to 60 kHz and it is described by equation (3).

$$V(t) = P_s \cos(w_i t + \Omega t d(t) + \theta) \qquad (3)$$

in which P_S is the amplitude of the signal S_t, w_i is carrier frequency, $d(t)$ is the binary data stream information, Ω is a parameter of the FSK modulator and θ is a phase factor.

The local VCO_r, the phase discriminator (⊗) and the low pass filter (LPF) form a phase locked loop (PLL). The LPF has the transfer function done by equation (4).

$$K(s) = 1/(1 + T_f s) \qquad (4)$$

in which T_f is the time constant of the filter.

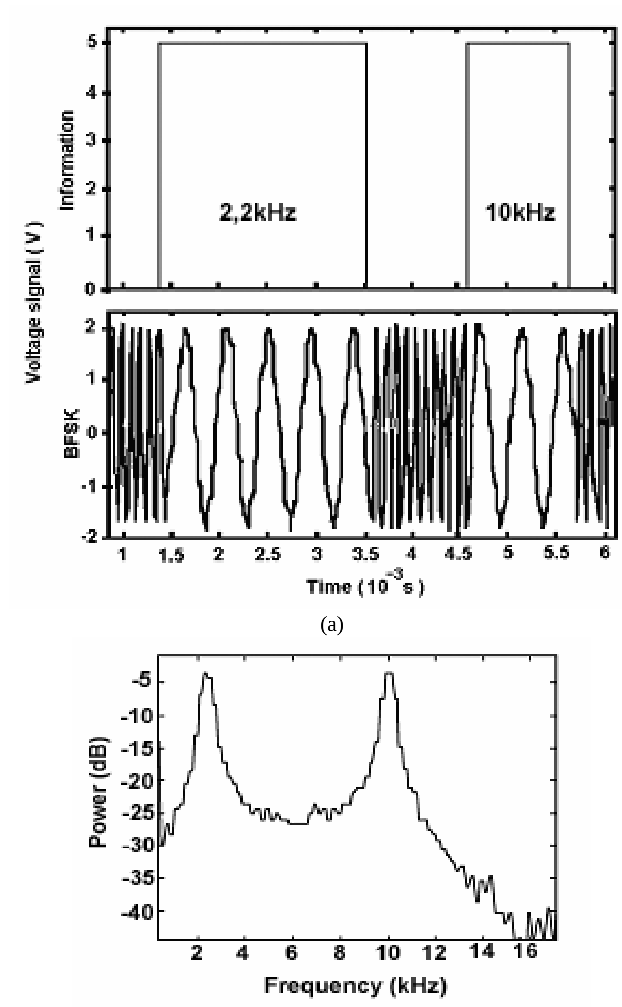
The frequency detection is performed using the PLL that synchronizes transmitter and receiver. In this case the frequency of VCO_r is described by equation (5).

$$\dot{\varphi}_r \equiv w_r = w_o(1 + m_2 u(t))$$

(5)

in which m_2 is the modulation gain coefficient (m_2=0.12) and $u(t)$ is the output signal of the LPF.

If the PLL is able to compensate the frequency deviations and keep the VCOs synchronized, the sinusoidal carrier with chaotic variable frequency $w_r \cong w_t$ can be recovered in the receiver. After, the BFSK signal $S_r(t)$ is recovered using the phase discriminator block (⊗) and a FSK demodulator is used to recovery the binary data stream $\hat{d}(t)$ from $S_r(t)$ signal. The block FSK demodulator was electronic implemented with CI LM565.



(a)

(b)

Fig. 7. BFSK modulation. (a) BFSK signal. (b) Power spectrum of the BFSK signal

IV. COMMUNICATION USING THE ALTERNATIVE SPREAD SPECTRUM FREQUENCY HOPPING

A spread spectrum system of Fig. 5 was electronic implemented as described in the section 3. A random binary data stream of 256 bits is used like input information signal $d(t)$. The transmission channel was implemented by a transmission line model T with 0 meters, 1000 meters and 5000 meters of length. At the receiver the input information signal $\hat{d}(t)$ is recovered of spread spectrum signal $V(t)$.

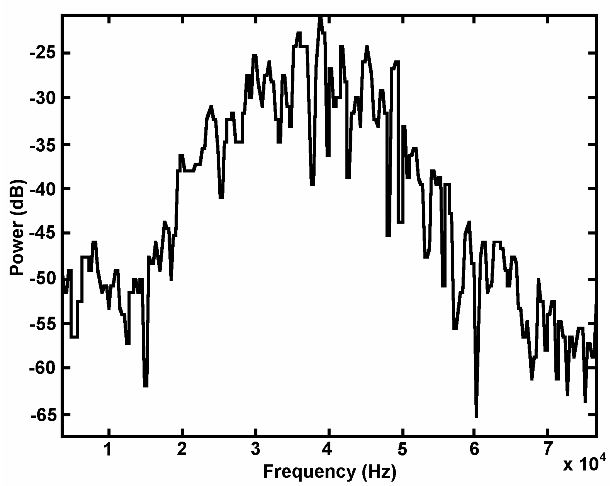
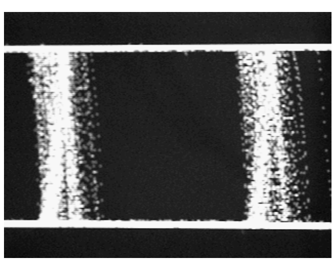
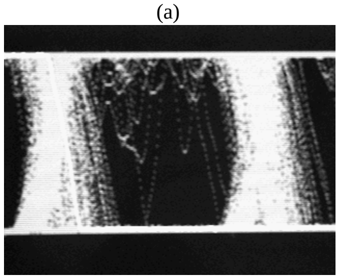


Fig. 8. Power spectrum of the spread spectrum signal V(t)

The eye pattern technique [19] is used to verify the performance of the recovery process of the binary data stream. A recovery process without bit error should have a pattern like an opened eye. Fig. 9(a) illustrates the recovery process with transmission line like a short line circuit. The pattern is an opened eye because the communication process does not present high level of bit error. Fig. 9(b) illustrates other recovery process with transmission line of 1000 meters. In this figure the eye is closer than the last case because of the bit errors introduced by the length of the transmission line. Fig. 9(c) illustrates the recovery process with transmission line of 5000 meters. In this case, the eye pattern is closer than the case with transmission line of 1000 meters. The recovery process presents problems such as high amplitude distortion, temporization errors and phase distortion (timing jitter). These eyes pattern show the influence of the length of transmission line in the quality of detection.



(a)



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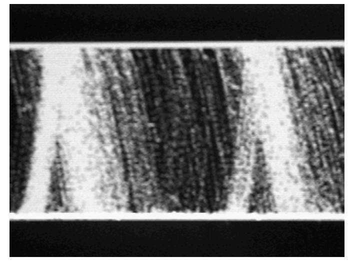

(c)

Fig. 9. Eye pattern of the binary data stream recovered. (a) Transmission line is a short circuit. (b) Transmission line of the 1000 meters. (c) Transmission line of the 5000 meters

V. Conclusion

A possible approach to spread spectrum communication system was demonstrated. In this paper it was implemented a spread spectrum communication system frequency hopping that uses an analog chaotic circuit. The particle in a box electronic circuit was used like the analog chaotic circuit. The rich chaotic behavior of this circuit was used in to generate a sinusoidal carrier with random variable frequency. This circuit was chosen because it is implemented in a simple way and with fewer analog devices when compared with other analog electronic chaotic circuits. The performance of the systems was verified through the eye pattern of the recovered binary data stream. The recovery process presented problems such as high amplitude distortion, temporization errors and phase distortion (timing jitter). The eyes pattern showed the influence of the length of transmission line in the quality of detection. The experimental results in this paper show that the particle in a box electronic circuit is an interesting alternative to implement a spread spectrum communication system.

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