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COMPARISON OF LONGITUDINAL VELOCITY ESTIMATION METHODS IN A PIEZOCERAMIC MATERIAL: PULSE-ECHO VERSUS THROUGH-TRANSMISSION

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Resumen
Los métodos no destructivos permiten la caracterización de diferentes materiales y determinar los posibles defectos internos presentes en diferentes estructuras. En este estudio, caracterizamos la velocidad longitudinal de diferentes muestras de un material piezocerámicos utilizando dos técnicas: pulso-eco, y transmisión-recepción. Para ello, se utilizan diferentes señales como la burst, chirp MLS y TSP (Time Streched Pulse) y MLS (Maximum Length Sequence). Se utilizan además dos algoritmos para obtener el tiempo de llegada; para pulso-eco, los cruces por cero de diferentes ecos dentro del material y para transmisión recepción, se utiliza el método de la correlación cruzada. Este estudio tiene como objetivo presentar las ventajas e inconvenientes de cada sistema así como qué señales pueden ser más útiles para la caracterización de la velocidad longitudinal en el sistema de transmisión-recepción.

Palabras clave: NDT; velocidad longitudinal; ultrasonidos; caracterización materiales; algoritmos de detección.

Abstract

Non-Destructive-Testing methods allow the characterization of different materials and determine the state of possible internal defects in several structures. In this study, we characterize the longitudinal velocity of several samples of a piezoceramic material using two techniques: pulse-echo, and through-transmission. For this purpose, different signals are used, such as burst, chirp, TSP (Time Streched Pulse) and MLS (Maximum Length Sequence). Two different algorithms were used to obtain the time of flight: for pulse-echo, zero crossing of the different echoes within the material, and for the transmission-reception method, the cross-correlation method. This study aims to present the advantages and disadvantages of each of the two systems as well as the signals that can be more useful for characterizing the longitudinal velocity in the through-transmission system.

Keywords: NDT; longitudinal velocity; ultrasounds; material characterization; detection algorithms.

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1 Introduction

In aquaculture, systems such as echo sounders play an important role in optimisation and performance processes [1]. Other systems such as satellite buoys allow remote monitoring over long periods of time of the biomass in tanks, as well as a rapid response to disturbances caused by feeding deviations or other factors [2]. All these systems are based on active monitoring using ultrasound and therefore a crucial part of this system are the ultrasonic transducers. Characterisation of these transducers is essential for the correct functioning of the systems [3-4]. This characterization includes their sensitivity in transmission and reception, as well as their directivity patterns at different powers. However, it is also convenient to characterise not only the performance and behaviour of the transducer, but also some properties of the materials that make it up, including the active element, which are usually piezoceramics.

For the characterisation of these piezoceramics, non-destructive testing methods are used to determine certain properties of the materials without damaging them [5]. These include ultrasonic inspection to determine the longitudinal velocity of the material [6-7] and attenuation [8-9]. In this article, a material widely used for the manufacture of transducers is used and evaluated in two systems: pulse-echo and transmit-receive. The aim is to compare which method gives better results, comparing the measured speed with the speed given by the manufacturer. In addition, in the transmission-reception system, different signals are used, in order to know with which of them we obtain a value closer to the theoretical one.

The article consists of a brief theoretical background of the signals used, as well as a description of the set-ups and algorithms used for indirect longitudinal velocity measurement. Subsequently, the results are introduced and concluded with the comparison characteristics between systems, as well as the signals used for the transmit-receive system.

2 Theoretical background

There are several types of signals used to determine the time of flight in materials inspection. Commonly used signals and broadband signals robust to background noise have been chosen for this study.

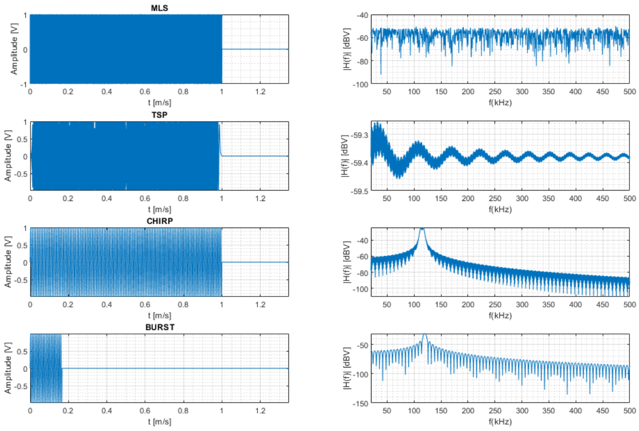


Figure 1 – Used signals (left) and their spectrum (right).

2.1 Signal theory

2.1.1 Burst signal

These signals are used in non-destructive testing because they allow the calculation of several parameters such as the velocity from the time of flight and the attenuation of the material to be studied [9]. Their theoretical expression in the time domain is:

$$s_{tx}(t) = A_{tx} cos\ (2\pi f_0 t)\ rect\left(\frac{t-\frac{NT_0}{2}}{NT_0}\right) \tag{1}$$

Where A_{tx} is the amplitude of the signal, f_0 is the frequency, T_0 is the period, N is the number of cycles, and $rect()$ is the rectangular function. By applying the Fourier transform to the above expression, we obtain:

$$S_{tx}(f) = \frac{A_{tx} N T_0}{2} sin\ c\left((f - f_0) N T_0\right) e^{-j2\pi(f-f_0)NT_0} \tag{2}$$

2.1.2 Chirp signal

A chirp signal is defined according to Eq. 3, and has a high peak in the cross-correlation. In addition, another remarkable feature is that it is uncorrelated with another chirp defined in another frequency range or inverted.

$$x(t) = sin\ \left(\phi_0 + 2\pi\left(\frac{f_1 - f_0}{2T} t^2 + f_0 t\right)\right) \tag{3}$$

Where ϕ_0 is the initial phase, f_0 is the final frequency, f_1 is the final frequency, and T is the signal duration.

2.1.3 MLS signal

MLS (Maximum Length Sequence) signals are pseudo-random signals with a binary amplitude. The amplitude can have two values [10].

2.1.4 TSP signal

On the other hand, TSP (Time Stretched Pulse) [11] are signals used in room acoustics to obtain the impulse response. The definition of the TSP signal is given by Eq. 4. It is a signal defined in frequency and the inverse Fourier transform is used to obtain the time signal.

$$H(k) = \begin{cases} e^{jpk^2}, 0 \leq k < \frac{N}{2} \\ 1, k = \frac{N}{2} \\ H * (N-k), \frac{N}{2} < k < N \end{cases} \tag{4}$$

2.2 Inspected material properties.

The material inspected is an 11.6 mm thick Ferroperm™ Piezoelectric ceramics disc [12]. The applications where it is used are in the construction of broadband transducers in NDT, medical, immersion and Doppler fluid flow meters. According to the manufacturer, its key characteristics are a high thickness coupling coefficient and high permittivity. However, its most interesting feature for us is that the longitudinal velocity is known (3200 m/s) and we can use it as a reference material to compare measurements.

Figure 2 – Example of sample for Pz37.

3 Methodology

For this experiment, two different set-ups have been designed for the emission and reception of ultrasonic signals in order to obtain the propagation velocity of piezoelectric ceramics. The first set-up is based on the pulser-receiver technique, which is widely used for non-destructive testing applications. The second system is based on the through transmission technique.

3.1 Pulse-echo

In this system, a computer is used as the transmitter and receiver controller. The computer is connected to a function generator (Rigol GG5071) in charge of generating a 1 MHz Burst signal of 1 cycle with the maximum output voltage of the generator (20 Vp). In turn, the PC is connected to an oscilloscope (Tektronix TD2200) where the echoes received from the emission are recorded. A Parametrics 1 MHz transducer has been used, connected to both the generator and the oscilloscope. A schematic of the system can be seen in Figure 3.

This system has been used as a control system as there is a lot of literature confirming its validity [13] for this type of measurements. The measurements were taken by placing the ceramic to be studied on a smooth surface and attaching the transducer to the top of it using Vaseline. Six repetitions were taken with this system. Each time a measurement was repeated, the transducer was uncoupled and reattached.

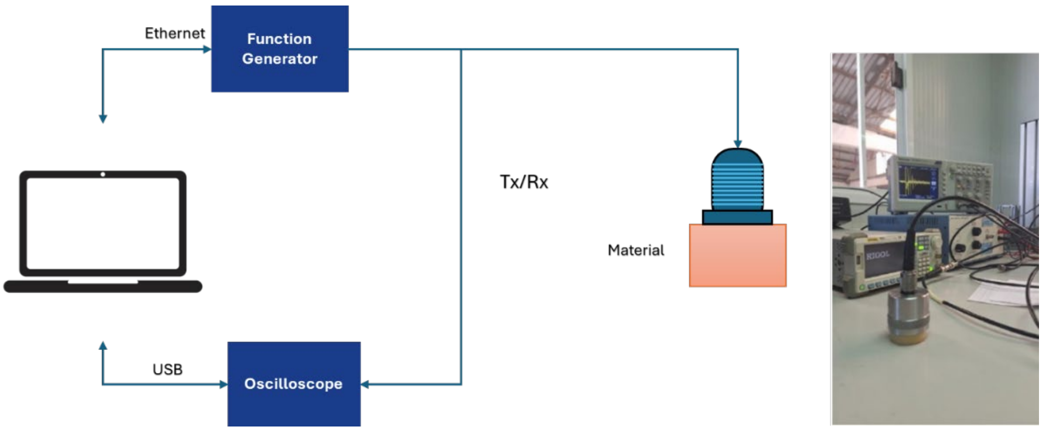


Figure 3 – (Left) Schematic of the pulse-echo system. (Right) Photograph of the assembly.

3.2 Through transmission.

In this set-up, a computer was also used as the transmitter and receiver controller. For the reception part, an RTM3002 oscilloscope has been used, whose configuration parameters are controlled from the control computer, and a receiver transducer connected to channel 2 of the oscilloscope. On the other hand, the emission part is made up of a Red-Pitaya in charge of signal generation, a Piezo Systems. Inc. Model EPA-104, and an emitter transducer. The two transducers used for both emission and reception are AIRMAR P7 95-155A kHz.

From the computer, the desired signal type has been selected for broadcasting from the Pitaya-Network. This broadcast signal is defined with a duration of 1 ms and a frequency between broadcasts of 100 ms. The total number of emissions has been set to 128. The signal has an amplitude of 3.184 V at the output of the Pitaya-Network. This output is connected via a T-type connection to channel 1 of the oscilloscope and to the input of the linear amplifier. A gain of 3 dB is applied to the signal from the amplifier and connected to the transmitting transducer. The receiving part has been configured with the averaging option with a total of 128 signals and 100000 samples per signal in a 2000 µs window.

To fix the ceramics and attach the transducers to them, the following assembly is available (see Figure 4) which allows the transducers to always be pressed with the same pressure, thanks to the use of a torque spanner, used on the upper pressure nut adjusted to always exert the same pressure.

In addition, the electronic delay introduced by the system from signal emission to reception was obtained. In order to obtain this delay, the two transducers have been placed in front of each other and the time between emission and reception has been measured. This delay must be taken into account when calculating the time of flight.

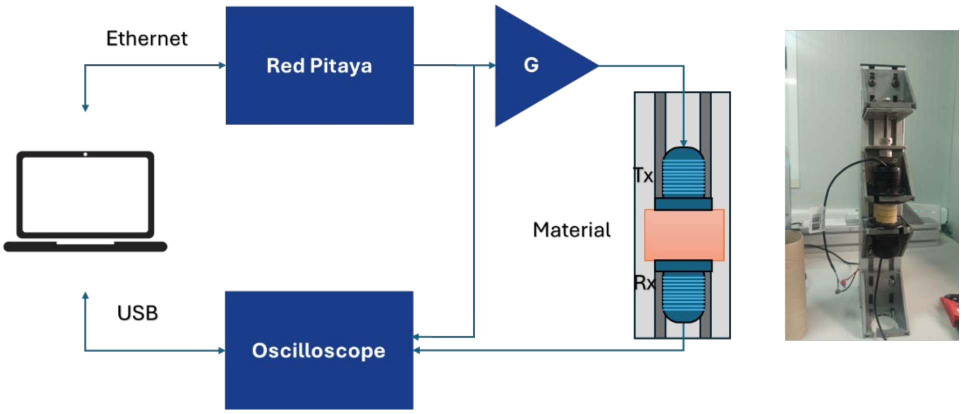


Figure 4 – (Left) Simplified schematic of the assembly for the through transmission system. (Right) Picture of the completed assembly.

3.3 Time of flight detection algorithms.

3.3.1 Zero-crossing intervals.

The zero-crossing algorithm is based on identifying the first maximum corresponding to the first echo of the transmitted signal (see Figure 5). Subsequently, the nearest zero crossing is searched for. Then, the next maximum corresponding to the next echo is searched for. In this case, for each measurement, three intervals have been taken into account, which are then averaged.

With this time, as the wave travels twice the distance in each echo, the longitudinal velocity is calculated as:

$$v = \frac{2d}{t}, \tag{5}$$

where d is the measured distance and t is the mean flight time of all intervals.

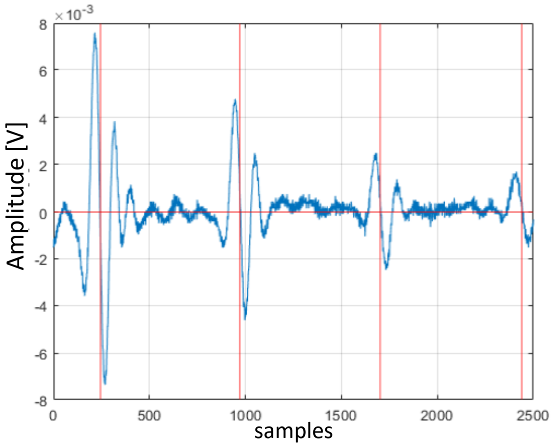
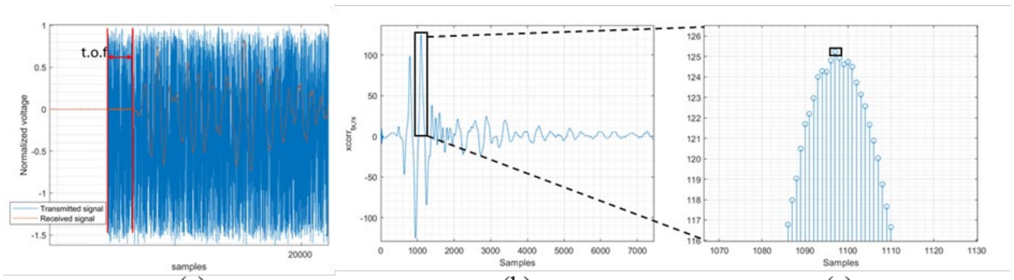


Figure 5 – Example of multiple echoes and the three intervals detected by the algorithm, indicated by the red lines.

3.3.2 Normalized cross-correlation.

Another method to obtain the time-of-flight (Figure 6a) is to obtain the position of the maximum of the cross-correlation of two signals (Figure 6b and 6c). The sample where the maximum correlation peak is located is directly related to the received signal offset with respect to the emitted signal. This offset is equivalent to the time of flight in samples. The T.O.F. value can be obtained by dividing the value of the offset by the sampling frequency [14].



(a) (b) (c)

Figure 6 – (a) Time of flight represented between the normalized transmit and receive signals.(b) Maximum of the correlation between the transmitted and the received signal, also shown in black. (c) Zoom of the peak corresponding to the maximum, also shown in black.

4 Results

In this section we will summarise the results obtained. The longitudinal velocity of the material will be expressed as the average of the six ceramic velocities ($\bar{v}$). In addition, the error in the indirect measurement will be considered as the standard deviation (σ). The relative error as well as the dispersion between samples will also be presented.

$$v_{estimated} = \bar{v} \pm \sigma \, , \tag{6}$$

By means of the theory of differentials, the uncertainty or error comited σ in the measurement can be determined:

$$\sigma_{tx-rx} = \left(\frac{d}{t^2}\,\sigma_t + \frac{1}{t}\sigma_d\right) \tag{7}$$

$$\sigma_{pusle-echo} = 2 \cdot \left(\frac{d}{t^2}\,\sigma_t + \frac{1}{t}\sigma_d\right), \tag{8}$$

where σ_{tx-rx} and $\sigma_{pusle-eco}$ are the errors committed in the transmit-receive and pulse-echo systems, respectively. σ_t and σ_d are the error of time and distance. In addition, the dispersion (D) and relative error (ϵ_r) are calculated:

$$D(\%) = \frac{|v_{max} - v_{min}|}{\bar{v}} \cdot 100 \tag{9}$$

$$\epsilon_r(\%) = \frac{|v_{theorical} - \bar{v}\,|}{v_{theorical}} \cdot 100 \tag{10}$$

4.1 Pulse-echo system.

In the results obtained with the control system, the distribution of the histogram can be seen, as well as the whisker diagram represented in the violins (see Figure 7).

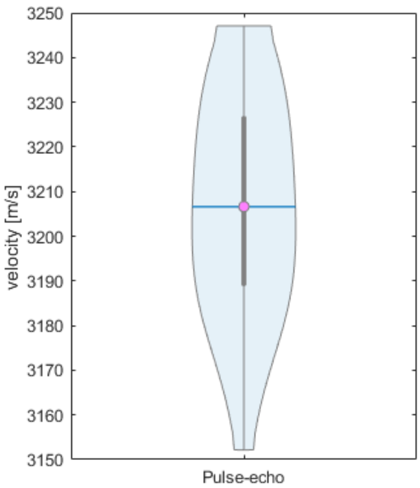


Figure 7 – Violin plot representing the values of the velocity measurements for the pulse-echo system. The blue line represents the mean and the magenta dot the median.

In Table 1, we observe the result of the measured longitudinal velocity, with the average of the six individual velocities, as well as their standard deviation. Furthermore, it has a low dispersion of 3% and also a very low relative error (a difference of only 10 m/s, or 0.3%). Therefore, this system is very close to the theoretical longitudinal speed value set by the manufacturer.

Table 1 – Results of velocity for pulse-echo system.

	Pulse-echo (1MH)
Velocity(m/s)	3210 ± 24
D (%)	3
ϵ_r(%)	0.3

4.2 Transmission-reception system.

Figure 8 shows the longitudinal velocity distribution for the transmit-receive system. It can be seen that the results obtained for the MLS and TSP signals are similar to each other. The mean value of the velocities differs by 50 m/s. Even so, the velocities are far from the theoretical velocity.

On the other hand, the results obtained for the chirp signal have a low velocity value compared to the results for the MLS and TSP signals. In addition, compared to the theoretical velocity value.

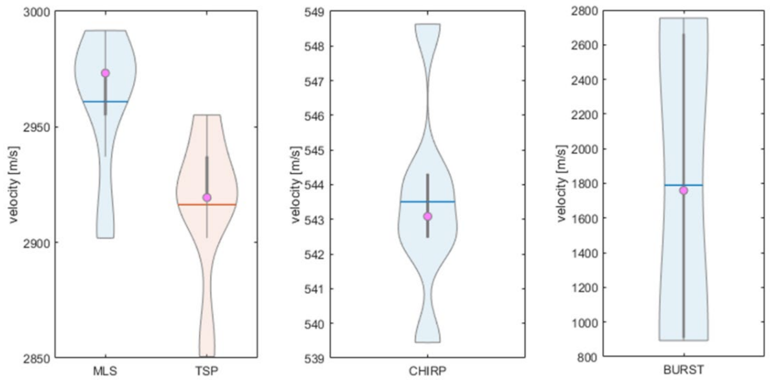


Figure 8 – Distribution of the data presented for the through transmission for the following excitation signals: (a) MLS and TSP; (b) chirp; (c) burst.

Finally, the burst signal has higher velocity values than the chirp signal but lower than the MLS and TSP signals. The results obtained with this type of signal have shown the greatest dispersion between samples of the four signals used (see Table 2).

Table 2 – Results of measured speeds for the through transmission system and their excitation signals

	MLS	TSP	Chirp	Burst
Velocity (m/s)	2960 ± 30	2920 ± 30	544 ± 3	2000 ± 1000
D (%)	3	3	1	104
ϵ_r(%)	7.5	8.5	83	44

4.3 Pulse-echo vs through transmission systems.

If we compare the measurements made in both systems, considering the best velocity results obtained with the MLS excitation signal, we can conclude that the system with the best velocity estimation is the one obtained with the MLS excitation signal. Representing together the violins of the two systems (see Figure 9), together with the summary of the velocity results obtained, it can be concluded that the system with the best velocity estimation in terms of proximity to the theoretical value of the material velocity (3200 m/s) is the pulse/echo system.

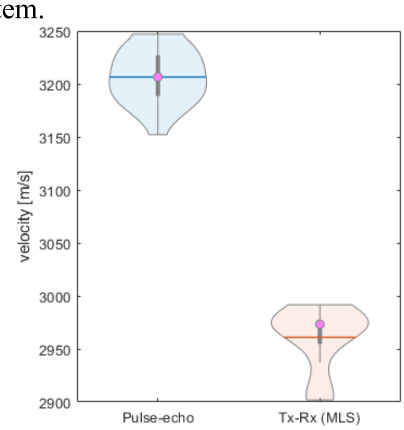


Figure 9 – Data distribution between the pulse echo system and the through transmission system (Tx - Rx) for the MLS excitation signal.

On the other hand, both systems present a similar measurement error, as well as the same dispersion between samples (see Table 3).

Table 3 – Comparison of measured results between studied Pulse echo and transmission-reception system for MLS excitation signal.

	Pulse-echo (1MH)	Tx – Rx (120 kHz)
Velocity (m/s)	3210 ± 24	2960 ± 30
D (%)	3	3
ϵ_r(%)	0.3	7.5

As a way to improve the estimation of longitudinal velocity and generate more measurements from those of the samples under study, a method previously performed by this group for the characterisation of fish velocity is used [15]. This method consists of grouping samples, measuring the thickness and arrival time for different groupings of the material and calculating the linear regression by the least squares method (see Figure 10). The independent variable (x) is time and the dependent variable (y) is distance. In this way, the slope of the straight line is used to obtain the longitudinal velocity of the material.

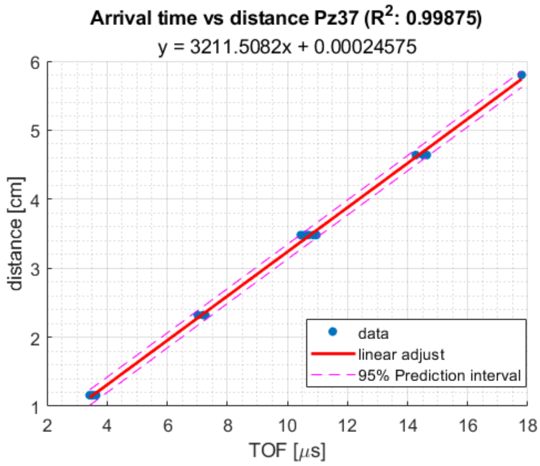


Figure 10 – Linear regression model based on the measures of different piezoceramic groups (five).

The estimated velocity following the procedure of [15], calculated by the least squares linear regression fit, is 3210 ± 30 m/s. This gives a velocity estimate equal to that of the pulse echo system.

5 Conclusions

As mentioned above, material characterisation is an important part to take into account in the design, manufacture and control process of any transducer, whatever its purpose, since its behaviour depends not only on the electronics, but also on a good choice of material and its mechanical properties, including speed.

From the results obtained with the control system (Pulse-Echo), it was possible to confirm the value of the longitudinal speed of the ceramic with a relative error of 0.3 % of the theoretical value. As for the transmission-reception system, the results do not resemble the theoretical velocity. It has been concluded by means of the correlation method that the signals that give the best results are the broadband MLS and TSP signals with a relative error of 7.5% and 8.5% respectively, of which the MLS is the one that comes closest to the theoretical speed. The burst and chirp signals do not perform well with errors of 44% and 83%.

However, by using the method of grouping different piezoceramics, we were able to match the results of velocity estimation between systems.

From the dispersion between samples of the two systems we have been able to establish that both methods are valid and that external factors such as coupling do not affect the measurements to a great extent, except for the burst signal where the dispersion is high. Repeatability in data acquisition is confirmed.

The main advantage of the pulse/echo system is that it is faster to run and can be run on individual ceramics, which allows a control system in the production line of ultrasonic systems.

As future lines, a transmit-receive system with transducers of a higher frequency range is being established. The purpose of this is to avoid the grouping of the various ceramics in order to be able to evaluate each one individually and to be able to carry out quality control.

6 Acknowledgements

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