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Shape optimisation of the SEAREV wave energy converter.

A. Babarit, A.H. Clément.*

Laboratoire de Mécanique des Fluides CNRS UMR6598

Ecole Centrale de Nantes

1, rue de la noë

44300 NANTES

Abstract

The aim of the SEAREV project is to design a wave energy converter which will be economically viable for a moderate wave climate of about 20 kW/m. The energy production must be maximised while the costs must be minimised, which is a multi-objective optimisation problem. The mean annual energy production depends on the given deployment site, and also the shape of the device, because of the wave-structure interactions. The optimisation problem is a shape optimisation problem, with two objectives and several constraints. In our optimisation, there is a two layer process ; one layer using genetic algorithms and the second using a gradient based method. Results of energy production with respect to displacement of the device are presented for different shapes. The main interest of this approach is that it highlights the important device parameters. From the wide range of generated shapes and corresponding results, it can be seen also that optimisation is necessary.

Introduction.

The SEAREV device belongs to the second wave energy converter generation. It is a floating device, completely enclosed, with an onboard moving mass : an off-center cylinder which is free to rotate about its axis, see figure (1). Under the action of the waves, the floating hull and the internal mass start to move, each with its own motion. The relative motion between the hull and the moving mass is used to drive a generator via an hydraulic pump.

In this study, the considered site is located near Yeu island, on the Atlantic coast of France. Numerical simulators of the device, which have been presented in previous work [1], are used to compute the response of the device ; wave-body interactions being described using the classical linear potential theory approach. From the response of the device, we are able to derive the energy production over a full year at the given site and this constitutes the core of the optimisation. Each considered shape, described using a parametric approach, is evaluated using this method.

To deal with a multi-objective shape optimisation problem in numerical fluid mechanics, genetic algorithms are the best state of the art method. They are widely used by many researchers to deal with shape optimisation of wings [5], [6], military vessels and sailing boats [4], ... However, we are not aware of any application of this optimisation method to a wave energy converter. This paper is such an application to the SEAREV wave energy converter.

1 Methods.

1.1 Computation of the energy production.

1.1.1 Equations.

The floating body is assumed to have two vertical planes of symmetry. We assume that the axis of the internal cylinder, around which it rotates, is perpendicular to the main symmetry plane of the hull. We assume that the direction of propagation of the waves is parallel to this plane.

Under these assumptions, in a 2D incident wave train, the floating body only moves in surge, heave and pitch mode. For the device, the motion takes place in the (xOz) plane.

Let x_G and z_G be the surge and heave motion of the centre of gravity G of the floating body, θ the pitch motion and α the relative motion between the floating body and the inner pendulum. The power take off (PTO) system utilises this relative motion α . Let m_b be the hull mass and I_b its inertia, m_p the inner pendulum mass and I_y its inertia. Let $l = AP$ be the distance between the center of rotation A of the inner pendulum and its own center of gravity P , and $d = \overline{GA}$ be the distance between the center of gravity of the floating body and the center of rotation of the pendulum.

We assume the amplitude of the waves and the resulting motion of the body to be sufficiently small to validate the classical linear theory approach.

Let $\mathbf{Z} = (x_G \ z_G \ \theta \ \alpha)^t$ be the position vector. In linearized theory and in the frequency domain, one can write the equation of motion as :

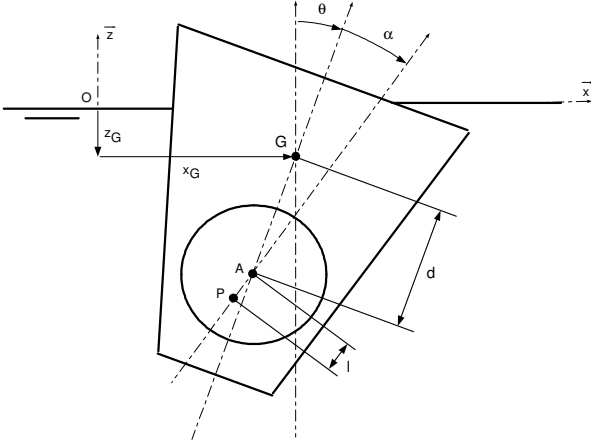


Figure 1: The SEAREV wave energy converter : principle.

$$\begin{pmatrix} -(\mathbf{M} + \mathbf{C}_M(\omega))\omega^2 \\ +i(\mathbf{B} + \mathbf{C}_A(\omega))\omega \\ +(\mathbf{K} + \mathbf{K}_H) \end{pmatrix} \mathbf{Z} = \mathbf{F}_{ex}(\omega) \quad (1)$$

where :

- \mathbf{F}_{ex} represents the hydrodynamic excitation force due to the incoming and diffracted wave.
- \mathbf{C}_M is the added mass matrix and \mathbf{C}_A is the hydrodynamic damping matrix related to the radiation of waves by the body. They are computed, as is the excitation force \mathbf{F}_{ex} , using AQUAPLUS [2].
- \mathbf{M} and \mathbf{K} are matrices representing the mass and stiffness of the device respectively. These matrices contain coupling terms between the pendulum and the floating body. They are given by :

$$\mathbf{M} = \begin{pmatrix} m_b + m_p & 0 & & & & \\ 0 & m_b + m_p & & & & \\ m_p(d-l) & 0 & & & & \\ -m_p l & 0 & & & & \\ & m_p(d-l) & & -m_p l & & \\ & 0 & & 0 & & \\ I_b + I_y + m_p(d-l)^2 & & & I_y + m_p l^2 - m_p d l & & \\ I_y + m_p l^2 - m_p d l & & & I_y + m_p l^2 & & \end{pmatrix} \quad (2)$$

$$\mathbf{K} = \begin{pmatrix} k_x & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -m_p g(d-l) & m_p g l & 0 \\ 0 & 0 & m_p g l & m_p g l & 0 \end{pmatrix} \quad (3)$$

- \mathbf{B} is the matrix which represents the energy absorption system. In this study, the power take off is modelled by a simple linear damping torque applied to the centre of rotation of the cylinder. It is given by

$-B_{PTO}\dot{\alpha}$. So the external damping matrix \mathbf{B} reads :

$$\mathbf{B} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & B_{PTO} \end{pmatrix} \quad (4)$$

In the frequency domain, the mean power absorbed by the device is given by :

$$\hat{p}(\omega) = \frac{1}{2} B_{PTO} |\omega \alpha(\omega)|^2 \quad (5)$$

where $\alpha(\omega)$ is derived from equation (1).

From this last equation, one can see that the absorbed power is a function of :

- the device's mechanical characteristics :
 - masses m_b, m_p .
 - lengths l, d .
 - inertia I_b, I_y .
- the shape of the floating body through the hydrodynamics coefficients $\mathbf{C}_M, \mathbf{C}_A, \mathbf{F}_{ex}, \mathbf{K}_H$.
- the power take off, B_{PTO} .

1.1.2 Mean annual extracted power.

In our study, we considered Yeu island, on the West Coast of France, as a test case site. Two years of sea state statistics were available for this site, see figure (2). On this site, the mean annual wave power flux is about 23 kW/m , which is around the low limit commonly considered for wave energy exploitation. The energy spectrum model used here is the ITTC spectrum, given by [8] :

$$S(f) = \frac{A}{f^5} e^{-\frac{B}{f^4}} \quad (6)$$

with $A = \frac{5}{16} \frac{H_{1/3}^2}{T_1^4}$ and $B = \frac{5}{4} \frac{1}{T_1^4}$.

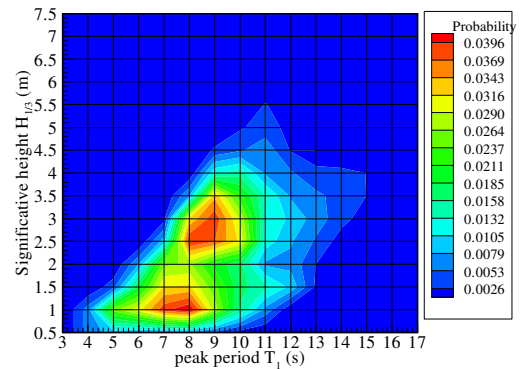


Figure 2: The ressource at the island of Yeu

After sampling with frequency intervals of Δf , the amplitude of each component of each frequency component is given by $a(f) = \sqrt{2S(f)\Delta f}$. In linear theory, the mean absorbed power for a given sea state is :

$$\hat{P} = \sum_{j=1}^{N_\omega} \hat{p}(\omega_j) \left(a\left(\frac{\omega_j}{2\pi}\right) \right)^2 \quad (7)$$

where the amplitudes a only depend on the sea state and $\hat{p}(\omega_j)$ is given by equation (5). To calculate the total absorbed energy E over a full year, we must sum the power absorbed for all possible sea states weighted by their probability of occurrence (in hours per year). This gives :

$$E = \sum_{H_{1/3}} \sum_{T_1} C(H_{1/3}, T_1) \times \sum_{j=1}^{N\omega} \hat{p}(\omega_j) \left(a\left(\frac{\omega_j}{2\pi}, H_{1/3}, T_1\right) \right)^2 \quad (8)$$

From this, we can see that the annual energy production will depend on the site and on the mean absorbed power function. In order to maximise the energy production, the task of the designer is to fit the power function to the given site. As we have already said, this function depends on the shape of the floating body and the mechanical characteristics of the device and the PTO. The mechanical characteristics of the device and the PTO are numerical values that can be used as parameters for the optimisation process in a straightforward manner. However to deal with the shape of the floating body, we had to choose a way to link numerical parameters to the hull shape.

1.2 Mesh generation.

Shape optimisation in fluid mechanics necessarily implies a re-meshing of the problem as a function of a new set of parameters. The choice of method is very important because it has to be such that :

- the generated meshes stay in the domain of validity for the fluid model.
- the generated meshes are the most varied
- the number of parameters is low.

In this study, we chose a parametric approach. This means that the general shape of the body is given and that the parameters are characteristic lengths of the shape. For example, we considered first a parallelepipedic shape, whose parameters were length, beam, draught and the vertical position of the center of gravity, see figure (3).

The advantage of this method is that the parameters are physical variables that help the understanding of the results. Obviously, the disadvantage is that the generated meshes are not very varied as they are all from the same family. This can be compensated by running several computations with different general family shapes. Moreover, comparisons between the results from these shape gives us an understanding of the main characteristics of an optimal device.

1.3 Optimisation methods.

The goals of the optimisation are :

- to maximise the absorbed power.
- to minimise the displacement, which is presumed to be proportional to the cost. Indeed, at such an early stage of the design, a detailed cost function has not

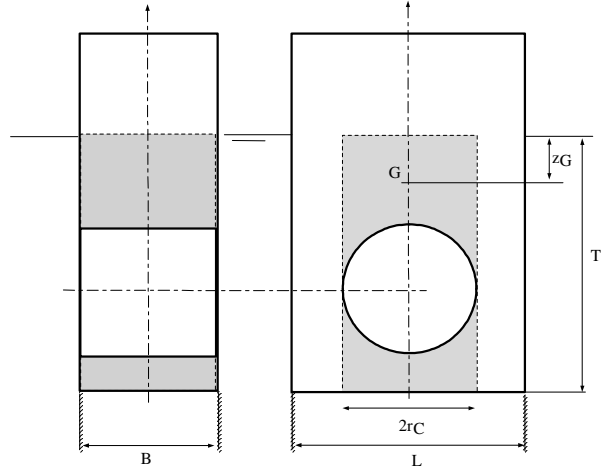


Figure 3: Parametric description of a parallelepipedic hull.

been yet established. We decided to minimize the total displacement, because we expect that the lighter a device is, the cheaper it will be to build and manage.

The optimisation problem is multi objective. There are several constraints that must be observed. For example, the static stability of the device must be positive in pitch and roll. Furthermore, the inner pendulum must have a realistic density (we have chosen here the density of concrete) and the draught of the floating body must be kept reasonable (fifteen meters max), etc...

For such a global optimisation problem, the best choice is to use genetic algorithms as these are known to be very efficient in these circumstances [3]. Genetic algorithms are non deterministic optimisation algorithms. They attempt to reproduce the Darwinian process of species evolution that can be found in the living world. For our problem, the genome of each *individual* is a set of parameters used to define a particular shape of the hull, the mechanical characteristics of the inner pendulum and PTO . From a set of initial individuals, which form a *population*, genetic algorithms first make a call to numerical codes that compute the transfer functions - equation (1) - and the absorbed energy - equation (8) - of each individual, see figure (4). Then they select the best ones and *cross* them to create a new *generation*, which is potentially better than the first one (Darwin's hypothesis). Finally, iterating the process leads to better designs. Moreover, to mimic the evolution of life forms, genetic algorithms also introduce mutations in the population from time to time, in order to enhance the potential and to enlarge the field of possibilities. For shape optimisation problems, genetic algorithms constitute the very best choice, but they are known to converge rather slowly.

In our optimization, each evaluation (computation of the annual absorbed energy at the reference site) of an individual is quite CPU time consuming (about 5 min/individual on a pentium 4, 2 GHz PC). The computation of the hydrodynamic coefficients was identified as the most time consuming part of the computation. Once it was performed, the

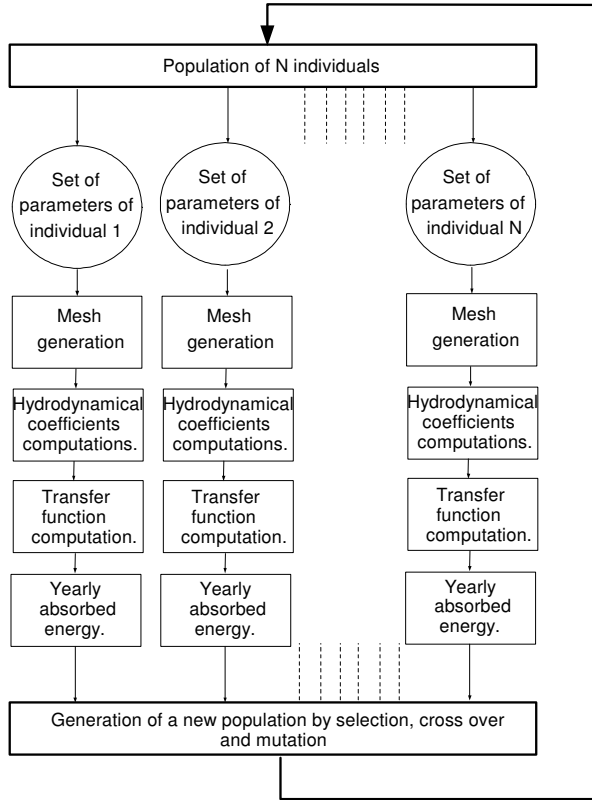


Figure 4: Genetic algorithms for SEAREV's shape optimization.

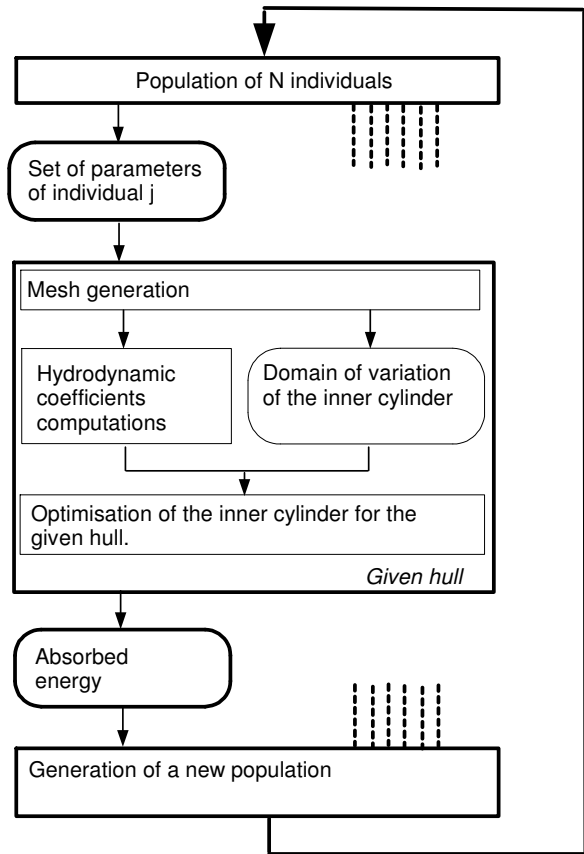


Figure 5: The two layer optimisation process

calculation of the absorbed energy afterwards was practically instantaneous. So the optimisation process was split in two sub-processes, to accelerate the global computation.

The idea is first to compute the hydrodynamic coefficients for a given hull shape. If the shape is given, the displacement can be found. To maximize the absorbed energy, we need to find the optimal pendulum for this hull. The best way to do this is to use a gradient method [3]. This consists of computing the direction in which the energy growth rate is the highest, and moving a step in this direction. Iterating the process leads to the local maximum closest to the initial point. The algorithm used is the Fletcher-Reeves algorithm [7]. Globally, we reduced by 4 the number of optimization parameters in the genetic algorithm optimization loop by using this method.

There is an inner optimization loop to compute the optimal pendulum for a given shape of hull. Hull shape optimization, in the outer loop, is performed by genetic algorithms, using the high performance commercial code ModeFrontier [9]. The whole process is summarised in figure (5).

2 Results.

We considered first a very simple shape : a parallelepipedic hull whose 4 parameters were the length, the beam,

the draught and the vertical position of the gravity center, figure (3). In figure (6), we plotted the result of the evolution of a population of 30 individuals over 60 generations, which represents about 10 days of computation on a pentium 4, 2GHz PC. The horizontal axis of the figure corresponds to the total displacement in tons and the vertical axis to the mean yearly absorbed power (kW), at the Yeu island site (a 23kW/m wave resource level site).

In the present approach, the best individuals are those that deliver the most energy with the least displacement ; they would be located in the left upper part of the plots in figure (6). Naturally, this corner of the plot is empty, but one can clearly identify a frontier on which optimal individuals accumulate , and above which there are no dots. This is the well known Pareto front, which is the locus of the optimal individuals.

We can also see that many of the devices are not optimal, which shows that energy production is strongly related to the shape of the device. This shows how this optimisation work is important for the viability of the project. Moreover, although the number of parameters for the shape is only 4, a rough exploration of the design space would have taken about 20^4 evaluations of individuals : about three years of computation. Using genetic algorithms, the exploration was more accurate and the mapping of the Pareto front took

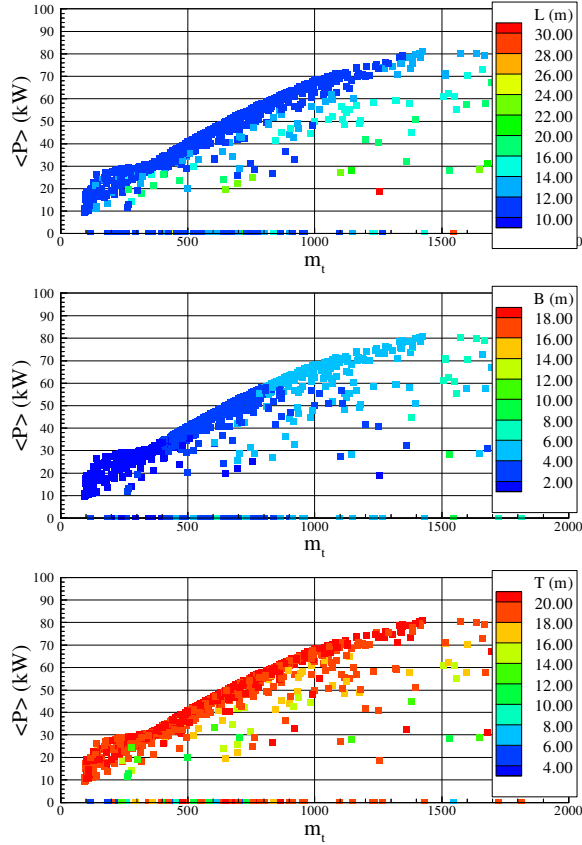


Figure 6: Results of the shape optimisation of a parallelepipedic hull.

only 1800 individuals and ten days of CPU time.

On the Pareto front, the absorbed power growth rate is about 0.1 kW/t for the smaller devices. It decreases with the increase of displacement to reach about 0.05 kW/t for the 2000 ton devices. This gives an idea of the power absorption ability of the device per ton of displacement. On the Pareto front, the length and the draught of the devices do not change with the displacement and are equal to ten and twenty meters respectively. This shows that the optimal designs are the one with the largest draught instead of the largest length, which was not previously obvious.

In the optimisation of the SEAREV device, we considered many different families of shapes. From the results using the initially simple shapes, we improved our understanding of the device and we refined our meshes. In figure (7) we plotted the Pareto front corresponding to different shapes that we optimised.

After the parallelepipedic shape, we considered a cylindrical shape, figure (8). Shape optimisation was performed and the Pareto front associated with its optimisation is shown by the red squares in figure (7). We can see that the energy production is half of that for the parallelepipedic shape for a given displacement.

A possible reason for this was it was impossible for the device to have an high draught with a small displacement.

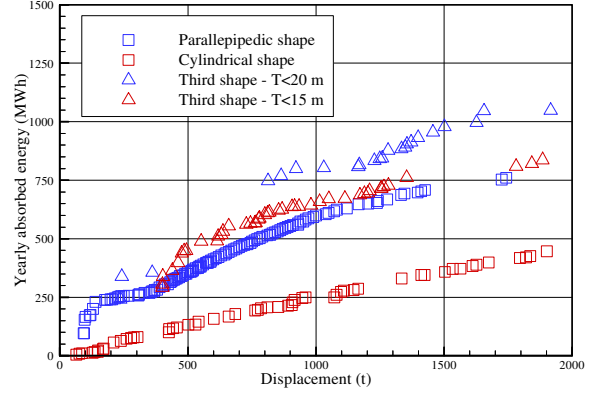


Figure 7: Comparison of the Pareto front of the optimised shapes.

Bearing this in mind, we tried a third geometry composed of a semi-cylindrical hull with a keel to house the cylinder. A first computation used a draught constrained to twenty meters. Results are shown in figure (9) by the blue triangles. Of all the geometries that we tried, this one was the most efficient at absorbing the waves. Another optimisation was conducted with the same geometry but with a draught constrained to fifteen meters. It appears that the efficiency is reduced by a factor proportional to the reduction of the draught.

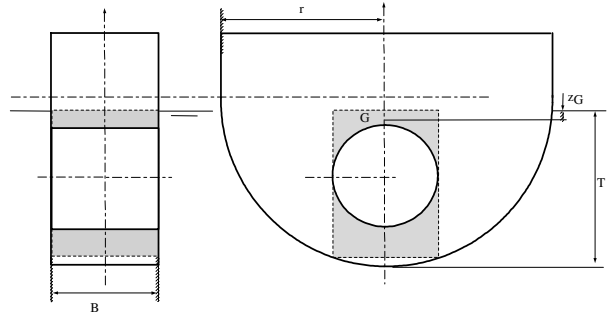


Figure 8: Description of the cylindrical shape.

One can see that for a given displacement, the energy production on the Pareto front designs can vary by a factor of three depending on the geometry of the shape. For the SEAREV device, it can be seen that there is a high correlation between the energy production and the draught of the system.

Conclusion.

A numerical optimisation using genetic algorithms was performed in order to compute the optimal design for the SEAREV device. Several geometries, depending on only a few parameters were considered. It was shown that for

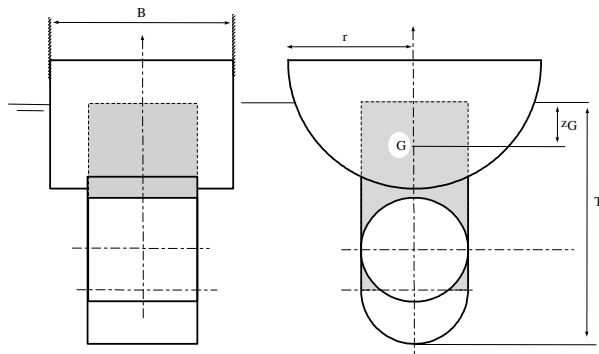


Figure 9: Description of the third optimised geometry.

a given family of geometric shapes, the values of the characteristic lengths were important for achieving an optimal design. It was shown that the efficiency also depended on the family of shapes.

In this optimisation work, about 8000 individuals were generated and evaluated automatically. The parametric approach we used for the mesh generation limited the variety of the shapes, but it helped to highlight the main characteristics of the device. We showed that numerical optimisation is a powerful tool which could certainly be applied to other wave energy converters.

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