Seismic behaviour of reactor cores
Application of homogenization techniques

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ABSTRACT

The SYMPHONY experimental program, performed at the CEA Saclay, pointed out the importance of Fluid Structure Interaction on the seismic behaviour of LMFBR reactor cores, composed of hundreds of assemblies immersed in sodium (or in water for the experimental tests). A physical model is presented here, using the results of previous researches on the dynamic behaviour of tube bundles in liquid. This model takes into account the inertial effects of the fluid, with the coupling terms between the assemblies, and consequences on the relative displacements. It, also, takes into account the damping due to the fluid. This damping mainly limits, in this case, the relative displacements of the assemblies. This model gives a qualitative explanation to the low values of the displacements obtained for the Fuel Assemblies in some hexagonal configuration tests. Simpler models, that do not take into account the fluid structure interaction, are not able to explain these phenomena. One of the conclusions in that the one row models, used to describe the seismic behaviour of the reactor cores, overestimate, in many cases, the displacements of the assemblies.

NOMENCLATURE

V_L : Liquid velocity

P : Pressure

$x, x_a, andX$: Displacements

M : Mass Matrix

K : Stifness Matrix

g : Gap between the assemblies

D : Diameter of the assemblies

Greek letters

ω : Pulsation

ρ : Mass Density

β : reduced damping

ABREVIATIONS

D.O.F. : Degree Of Freedom

LMFBR : Fast Breeded Reactors

F.A. Fuel Assemblies

N.S. : Neutronic Shields

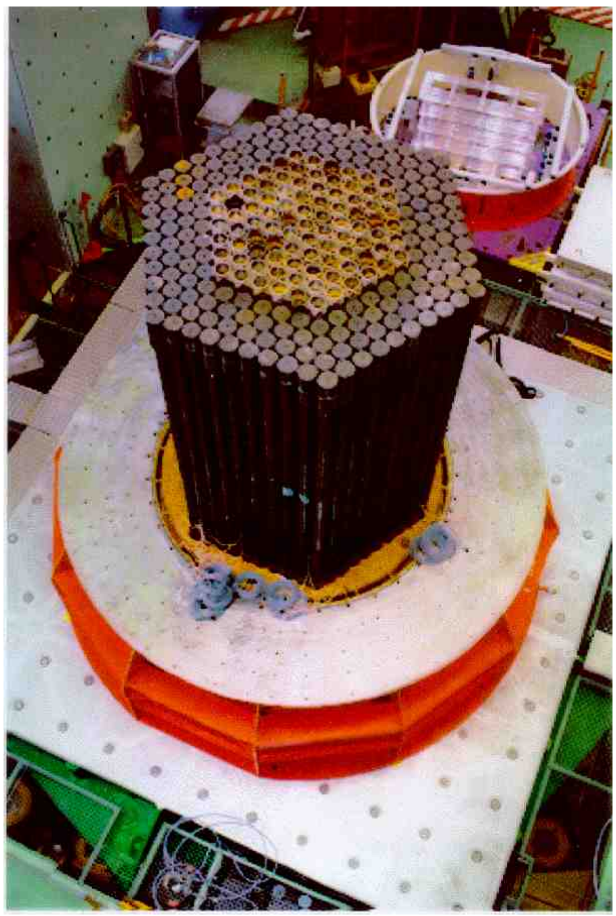
F.S.I. : Fluid Structure Interaction

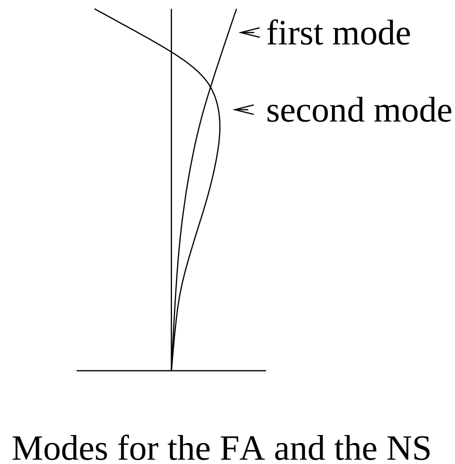
1 INTRODUCTION : SYMPHONY

1.1 The SYMPHONY Program

The SYMPHONY program is carried out from 1993 up to 2000, with the scope to study the seismic response of LMFBR reactor cores (/1/ et /2/). LMFBR reactor cores are composed of Fuel Assemblies (FA) at the center and Neutronic Shields (NS) at the periphery, immersed in a vessel full of sodium. The experimental part includes single assembly tests of the FA and the NS, one or three row tests, and hexagonal configuration tests. All tests are performed in air and in water (water characteristics are close to those of sodium).

The interpretation of the tests is based on beam models for the assemblies, taking into account the impacts between assemblies, and the fluid structure interaction. Figure 1 shows the assemblies of the hexagonal tests (FA, NS, without the vessel), and some dynamic characteristics of the assemblies. The general shape is similar for the first and second modes of the FA and the NS. The transfert fonction, obtained with withe noise tests for one NS tests, shows high damping, especially for little displacements, and in water.





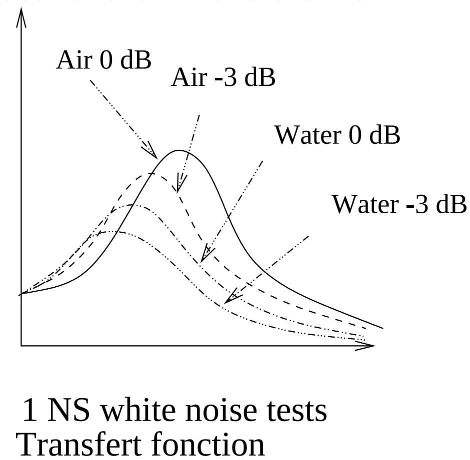


Figure 1: SYMPHONY experiment: hexagonal tests (FA at the center and NS at the periphery, and characteristics of the assemblies (general shapes of the modes, and high damping for the NS)

1.2 Fluid Structure Interaction

In the first interpretations of the tests in water, Fluid Structure Interaction is taken into account in a simplified way. For the one assembly tests, the added mass notion leads to lower frequencies in water than in air, as for a one D.O.F. system. For the row tests, or the hexagonal tests, a global added mass is considered, corresponding to a global uniform movement of the assemblies. The bundle is there considered as a single D.O.F. system. The added mass matrix is diagonal. This global FSI method does not take into account all the complexity of the physical phenomena, as the non uniform movements of the bundle.

1.3 Main Results

Theoritical results are in a quite good agreement with the experimental ones, for the single assembly tests, the row tests and the hexagonal tests in air. Fuel assemblies displacements and impacts forces can be quite well predicted by the models. For the hexagonal tests in water, very strong coupling between the assemblies by the fluid leads to much lower displacements than for the tests in air. Table 1 presents the results of white noise tests on the hexagonal structure, with different levels (0 dB, -3 dB, and -6 dB). Tests have been performed with FA only. Displacements in air or in water are close (about 45 mm for the 0 dB test). The tests in a complete core configuration (FA and NS) present interesting results. For the tests in air, the displacements of the NS are low (about 20 mm for the 0 DB test), but the displacements for the FA are about 40 mm (close to the tests with only FA). The tests in water show very low displacements for both FA and NS (13 mm for the 0 dB test). Theoritical interpretations, based on the global added mass notion, are not able to explain these results. Therefore, we propose, in the third section, a model for the dynamic behaviour of the LMFBR reactor cores. This model is based on the results of previous researches on the dynamic behaviour of tube bundles in fluid.

		0 dB	-3 dB	-6 dB
FA only	Air	46	24	13
	Water	45	29	16
Complete Core Air	FA	40	23	–
	NS	20	15	–
Complete Core Water	FA	13	8	4
	NS	13	8	–

Table 1: SYMPHONY hexagonal tests, White noise results: displacements (in milimeter), for the FA and the NS.

2 FLUID STRUCTURE INTERACTION FOR TUBE BUNDLES

We present here some elements on the dynamic behaviour of tube bundles immersed in a fluid. The fluid structure interaction considered take into account the inertial effects and the damping effects due to the fluid.

Inertial effects

The common equation used, in seismic studies, to describe the inertial effects is the equation of a perfect, incompressible fluid (/13/). $\rho \frac{\partial V_F}{\partial t} = -\vec{\nabla} P$ and $div V_F = 0$ (Laplace equation), where V_F is the fluid velocity, t the time, ρ the mass density of the liquid, and P the pressure. The force, applied by the fluid on the sructure, is: $F = M_w \ \ddot{x}_a - M_a(\ddot{x} - \ddot{x}_a)$ where F is the applied force, M_w the mass of water displaced by the solid, x the displacement of the solid, x_a the displacement of the vessel. M_a is the added mass. $-M_a\ddot{x}$ is the applied force for an acceleration of $\ddot{x}$ for the solid, and no movement for the vessel. Masses, forces, displacements and accelerations are scalar values for one degree of freedom systems, and matrix or vectors for multi degrees of freedom. Using the relative displacement of the assemblies $X = x - x_a$, the movement equation for the assemblies is: $(M_s + M_a)\ddot{X} + K \ X = -(M_s - M_w)\ddot{x}_a$ where K is the stiffness of the system, and M_s the mass matrix of the solid. The Laplace equation is simple, and well suited to Finite Element techniques. It is possible to determine the F.S.I. matrix.

Nevertheless, in the case of reactor cores, the calculations are hardly limited by the size of the numerical problem to solve, It is difficult to obtain the FSI matrix, or to perform calculations on the whole system. Two complementary research directions can be identified:.

- Theoritical analysis are developed. They give a general description of the dynamic behaviour, for exemple on the maximum and minimum values of the natural frequencies of the system, and on the general shape of the modes (Figure 2). They give theoritical bases to interprete the results of the calculations (PLANCHARD 1994 /7/, ALLAIRE 1998 /5/).

- Homogenized methods are developed, that replace the physical heterogeneous medium (fluid ans tubes) by an homogeneous equivalent medium. They use asymptotics methods (HAMMAMI 1990 /3/, SANCHEZ-PALENCIA 1992 /8/), or structuration methods (SHINOHARA 1981 /6/, CHEVAL 2000 /4/).

In fact, up to now, most of the work done on the dynamic behaviour of the LMFBR reactor core focused on the theoritical developments. So, only few calculations have been perfomed on the behaviour of a global core, in realistic conditions (PREUMONT 1990 /9/).

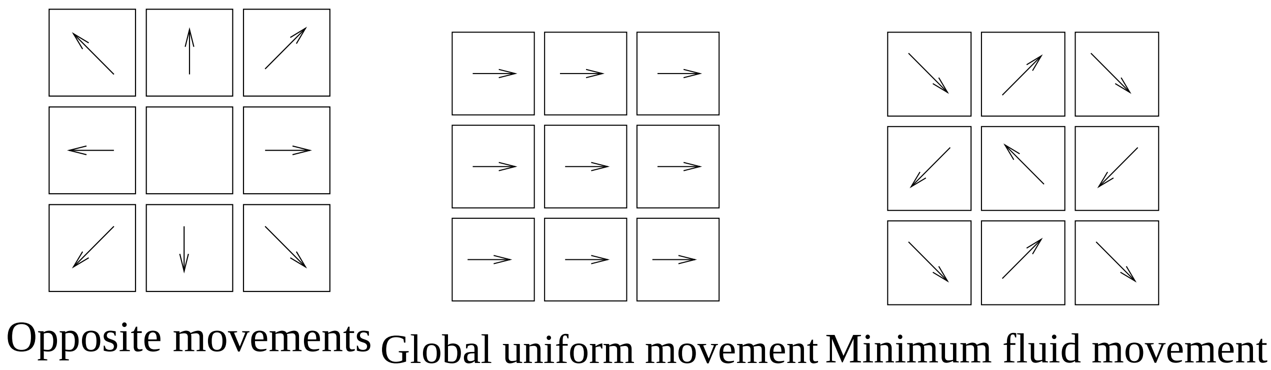


Figure 2: Different vibration modes

Figure 2 presents the most relevant vibration modes of a tube bundle (ALLAIRE /5/). The first mode is not a seismic mode. With opposite movements, it maximizes the fluid movements in the gaps between the assemblies, and has the lowest frequency. The second mode is a seismic mode, with global uniform movement. The third mode is not a seismic mode. It minimizes the fluid movement, not only in the gaps, but in the space betwwen the assemblies and the vessel, too. Its frequency is high, and close to the in air one.

A coupled system: the "Multiple Tuned Mass Dampers"

The "multiple tuned mass dampers" problem is an exemple of coupled, multi D.O.F. system. The objective of such structures is to provide a reduction of the displacemnt of the main oscillator, by addition of sub oscillators. The objectives and the behaviours of the MTMD and of the LMFBR reactor cores are differents. The MTMD studies may help to understand the complexity of the reactor core problem, and why it is difficult to obtain validated results. In the MTMD case, the global equation is easy to write completely, and quite easy to analyse. Many results have been obtained, in the evaluation of the added damping, depending on the number and on the natural frequencies of the suboscillators (FUJINO 1994 /10/). LMFBR cores are an other exemple of multi degree of freedom system, but, in this case, the global equation, with the FSI matrix, is not so easy to write. So, the second step, that is the analyse the design of the cores, is to be done (Figure 3).

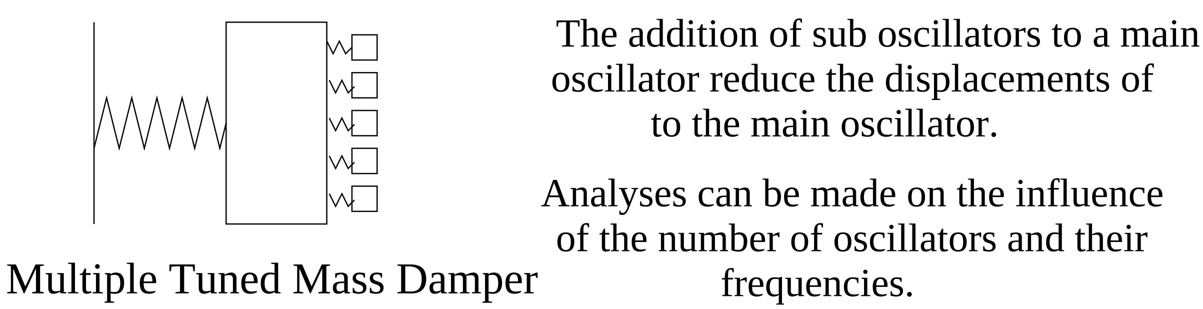


Figure 3: the Multiple Tuned Mass Damper Model

Damping effects

Damping effects due to the presence of the fluid are important in the vibration of the tubes. The values of the damping can not be explained by a Poiseuille flow for the fluid. PREUMONT performed tests, showing high damping in water (/9/). This damping could be due to dissipative effects in the fluid flow. In our case, the confinement is high : if "g" is the gap between the assemblies, and D the diameter of the assemblies, D/g = 40. So, in some configurations, displacements for the fluid may be 40 times the displacement of the assemblies. To displacements of 30 mm for the assemblies correspond displacements of 1.2 m for the fluid (about 10 times the diameter of the assembly). To velocities of 1 m/s for the assemblies correspond velocities of 40 m/s for the fluid. The hypothesis of small displacements, that is made in the study of the fluid inertial effects and the added mass notion, is no more verified (/13/). With high values of the Reynolds number for the flow in the gaps, we may have an approximation of the damping, using formula for flow in tubes or between two plates. We may, also, consider energy dissipation at the crossing of three gaps. Both methods give similary results, and a damping value about 50 %. This damping concerns mainly the relative displacements of the assemblies, with movements in opposite directions, that generate important fluid flow in the gaps. For a global uniform movement of the assemblies, fluid circulations are important mainly in the wide space betwwen the assemblies and the vessel, and are low in the gaps: damping effects are lower.

3. MODEL

Presentation of the model

The model takes into account the inertial effects of the fluid, the damping effect for the relative displacements, and, for each assemby, the damping, the mass and the stiffness. The objective of the model is to interprete the hexagonal tests of SYMPHONY, with FA at the center, and NS at the periphery. We use a simple 2D model, of 7 x 7 = 49 assmblies (Figure 4). Each assembly is a two directional elementary oscillator (x and y). The 9 central assemblies represent the FA. A numerical resolution of the flow equations is performed. Homogenized methods are not used, but it is possible, only with this simple model, to point out some interesting features. The main results on the dynamic characteristics of the model are compared to the theoritical results presented in the second section. The fluid structure interaction matrix is determinated by 2 x 49 = 98 elementary calculations.

This model take into account the damping for each assembly, called elementary damping, with a term : $2c\dot{X}$. It tries also to describe the damping due to the dissipation of energy in the fluid motion. We only give a brief description of this point, that is still under developpement. The damping forces are assumed to depend mainly on the relative motion of the fluid near the assemblies: $F_D = \beta_D(V_S - V_F)$, where F_D are the forces, V_S et V_F are the local velocities of the solid and the fluid and β_D called the ralative damping factor. The $(V_S - V_F)$ term is obtained from the FSI matrix. This matrix contains informations on the relations between the fluid and the solid accelerations. This relation is also valid for the velocities Using the FSI matrix, we built a matrix M_D, with $V_S - V_F = M_D\dot{X}$, where X is the relative displacement of the assemblies in the vessel (second section). The M_D matrix is then modified, in order to have no damping for a global uniform movement of the assemblies. The relatvie damping can be taken into account in the equation with the term : $F_D = \beta_D M_D \dot{X}$, This method is only an approximation, because two main reasons. First, the damping due to the dissipative effects is not linear. Secondly, the velocity of the fluid (V_F) is deduced from the FSI matrix, calculated with the assumption of no damping.

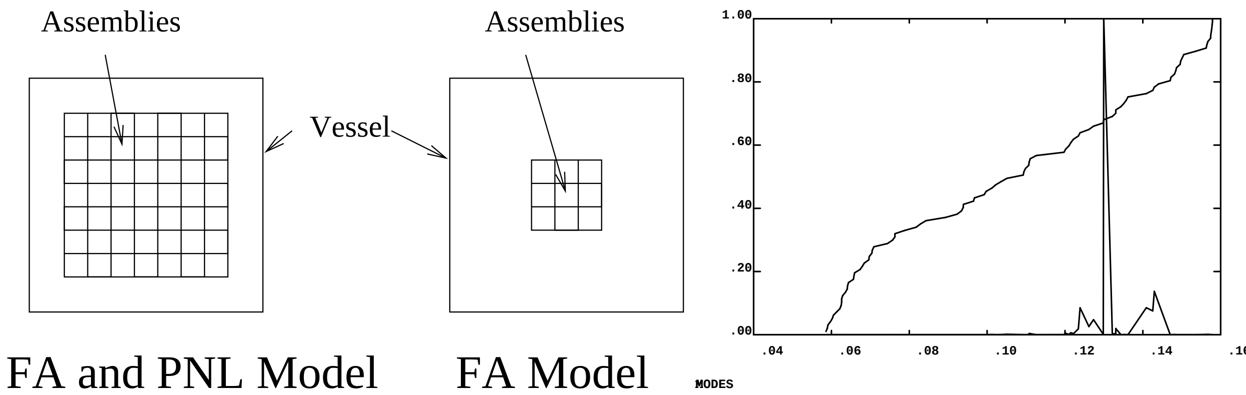


Figure 4 : Model, and characteristics of the modes : Frequencies are from 0.06 Hz to 0.16 Hz (about the in air frequency) participation factors are high for frequencies about 0.13 Hz

The natural frequencies of the model, presented in the Figure 4, are from 0.06 Hz to 0.16 Hz (for a frequency in air of 0.16 ($\omega = 1$). This result corresponds to the theoritical analysis. 0.06 Hz is the frequency of opposite movement modes. 0.16 Hz is the in air mode (solid movement minimizing the fluid movement, even between the vessel and the assemblies, and low participation factor). The highest participation factors are obtained for 0.14 Hz, corresponding to global uniform movements. Fluid movements are, for this frequency, important only in the space between the vessel and the assemblies.

Results of the model, named "complete model", are compared with the results of the "global model", where the fluid strucutre interaction is reduced to an added mass for each assembly, without coupling. A white noise excitation is used, as in the SYMPHONY tests presented in Table 1.

Results of the model

The most relevant results of the model are summarized in Table 2. For identical characteristic of the asemblies (frequency in air of 0.16, $\omega = 1$). displacements are, for the complete model, higher than for the global model (for $\beta = 0$, 0.24 m for the global model, and 0.30 m for the complete model). This result is obtained if the relative displacement damping is not taken into account, and for low values of the low elementary damping values. For the higher values of the elementary damping, displacements are close for both models. Taking into account the relative displacement damping, displacements of the assemblies are close for both global and complete model.

		$\omega^2 = 1$ Hz FA + NS				$\omega^2 = 1$ FA only	$\omega^2 = 1$ et 2		$\omega^2 = 1$ $\beta = 0.1$ et 0.3
		$\beta = 0$	$\beta = 0.02$	$\beta = 0.04$	$\beta = 0.1$	FA $\beta = 0$	$\beta = 0$	$\beta = 0.1$	
Air		0.19	0.13	0.099	0.057	0.19			
Water : Global FA		0.24	0.14	0.098	0.060	0.19	0.24	0.060	0.060
Water : Global NS		0.24	0.14	0.098	0.060	0.19	0.13	0.038	0.032
Water Complete	FA	0.23	0.12	0.089	0.060	0.22	0.18	0.049	0.047
	NS	0.30	0.16	0.11	0.066		0.19	0.050	0.041
Water Damping	FA	0.14	0.10	0.082	0.058	0.22			0.046
	NS	0.19	0.13	0.098	0.066				0.040

Table 2 : Results of the Model : The FA pulsation is 1. The NS puslsation is 1 or $\sqrt{2}$.

Results are presented for different characteristics of the FA and the NS. If the NS are stiffer ($\Omega = 2$), or with an higher damping ($\beta = 0.3$), the displacements are, in air, or in the global model, lower than for the FA. For the complete model, displacements are low, not only for the NS, but also for the FA. The fluid "transmit" the damping of the NS to the FA. PREUMONT (/9/) observed identical calculation results, with, for the NS, higher frequencies than for the FA. In water, the NS limits the displacements of the FA.

4. APPLICATION TO SYMPNONY

In the SYMPHONY hexagonal tests, natural frequencies of the FA and the NS are close. Nevertheless, damping is much higher for NS (Figure 1, in the first section). The low values of the FA displacement, observed in the test, correspond to the average phenomena. It is not necessary to use the relative displacement damping.

Relative displacement damping may occur in the test with only FA. In those tests, experimental displacements are close for air and global displacments. We can do the hypothesis that relative displacement damping stabilize the system.

The importance of the damping was pointed out in previous studies. S. KITAMURA (Internal CEA report) got good test computer correlations for displacement versus time curves, considering the FA as an elementary one D.O.F. oscillator, without coupling, and a damping value of 30 %. This damping value correspond to the NS damping.

The results are obtained with a simple model, with only 49 assemblies. This model can not be considered as a complete explanation of the SYMPHONY experiments, or of the seismic behaviour of the LMFBR reactor cores. But it gives a possible qualitative explanation. The inertial effects of the fluid lead to close displacements of the FA and the NS. If the elementary displacements (without coupling) of the NS is lower than that of the FA, the coupling by the inertial effects will reduce the displacements of the FA. This results, obtained by PREUMONT for frequency differencies of the FA and the NS, is obtained, here, for differencies in the elementary damping of the assemblies. Relative displacement damping is not necessary to explain the close FA and NS displacements. But it could explain the uniformity of the displacements in the tests with only FA.

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5. VALIDATION OF THE MODEL, AND LIMITS

The modal characteristics of the model correspond to the theoritical results for such a problem: no seismic modes for low frequencies and for frequencies close to the frequency in air, seismic modes for global movement of the assemblies (ALLAIRE /5/). The model provides results close to the the model of PREUMONT (/9/). NS may limit the FA displacements, when frequencies or damping are different.

It could be interesting, in order to validate the model, to perform studies, as in the MTMD case, and to deduce the global behaviour of the system by an analytical way, using the main modal characteristics of the bundle. The results of the numerical simulations could be easier to understand, and to validate. The large heterogneity in the displacements of the FA, with higher values than in air, is obtain only in simulations, and need more validation. The damping for the relative displacements is, up to now, only an hypothesis.

6. CONCLUSION

The model presented here give a realistic qualitative explaination of the SYMPHONY experiment. This model can not, obviously, be used now in LMFBR reactor cores studies, for two main reasons. First, this model need to be fully validated, mainly the possible influence of the dissipative effects dues to the fluid. Secondly, many other physical phenomena are not taken into account in this model, as the impacts betwwen the assemblies.

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