



## **Numerical simulation and experimental validation of gap supported tube subjected to fluid-elastic coupling forces for hybrid characterization tests**

W.Benmalek<sup>1&2</sup>, M.Collet<sup>1</sup>, E.Foltete<sup>1</sup>, M.Ouisse<sup>1</sup>, M.Corus<sup>2</sup> and I.Negreanu<sup>2</sup>

<sup>1</sup>FEMTO-ST Institute, Applied Mechanics Department, 24 rue de l'épitahe,  
25000 Besançon, France

Email: [wissam.benmalek@femto-st.fr](mailto:wissam.benmalek@femto-st.fr), [manuel.collet@univ-fcomte.fr](mailto:manuel.collet@univ-fcomte.fr)  
[emmanuel.foltete@univ-fcomte.fr](mailto:emmanuel.foltete@univ-fcomte.fr), [morvan.ouisse@univ-fcomte.fr](mailto:morvan.ouisse@univ-fcomte.fr)

<sup>2</sup> Electricité de France R&D, 1 Avenue du Général de Gaulle,  
92141 Clamart Cedex, France

Email: [mathieu.corus@edf.fr](mailto:mathieu.corus@edf.fr), [ionut.negreanu@edf.fr](mailto:ionut.negreanu@edf.fr)

### **ABSTRACT**

*In steam generators, the primary loop tubes are subjected to fluid coupling forces and impacts. Understanding the behavior of these tubes is crucial when designing steam generators. In fact, it can afford an optimization of produced energy and a long average life of the structure.*

*Up to now, the effect of the coupling forces on structural behavior was identified on reduced scale structures. Thus, the aim of our research is to give a better understanding of stabilizing effects of shock and coupling with fluid elastic forces. In order to validate numerical investigations, since fluid elastic forces are difficult simulate and expensive to reproduce experimentally, the fluid coupling forces will be assumed to be represented using velocity dependant (fluid and structure) damping and stiffness matrices, and experimentally reproduced using active vibration control into hybrid experimental tests to simplify big structure characterization.*

*In this paper, a method for modeling the structure behavior in order to estimate the effects of the coupling between the fluid elastic forces and impacts is presented. This strategy implies lower costs and avoids difficulties associated to the case of fluid in the experiments. This model will be implemented in the active control loop in the next step of the study.*

## 1 INTRODUCTION

Steam generators are heat exchangers used to convert water into steam from heat produced in a nuclear reactor core. They are used in pressurized water reactors between the primary and secondary coolant loops.

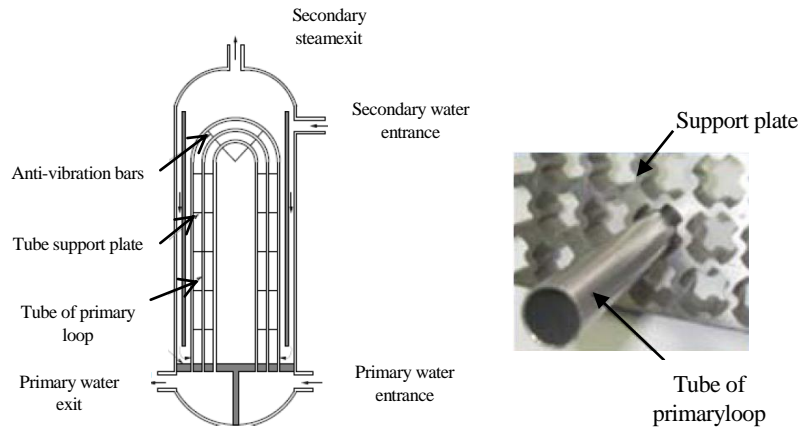


Figure 1. Steam generator

When the steam generator is working, the phase of water in the secondary loop changes partially from liquid to steam. This fluid, when rising up with high velocity and pressure, interacts with the tubes of the primary loop (inversed U shaped), thus the tube is subjected to flow excitation. This excitation can be split into two kind of forces: Turbulence forces which are independent of the movement of the tube and the so-called fluid-elastic coupling forces, depending on acceleration, velocity, displacement and fluid velocity [1], [2]. The total flow excitation can be finally expressed as:

$$F_t + F_f(\ddot{x}, \dot{x}, x, Vr) = F_t - M_f \cdot \ddot{x} - C_f(Vr) \cdot \dot{x} - K_f(Vr) \cdot x \quad (1)$$

$$V_r = V / (f * D)$$

With

$F_t$ : Fluid turbulence force

$F_f$ : Fluid-elastic coupling force

$V_r$ : Fluid reduced velocity

$V$ : Fluid velocity

$f$ : frequency of vibration

$C_f$ : Fluid-elastic damping coupling matrix, depending on  $Vr$

$M_f$ : Fluid added mass Matrix

$K_f$ : Fluid-elastic stiffness coupling matrix, depending on  $Vr$

$D$ : tube diameter

Under some specific conditions of steam pressure and velocity,  $C_f$  is enough negative to render the structure instable, this phenomenon is called fluid-elastic instability, which can damage the structure. However, the primary tubes as presented in figure 1, are supported by a plate which guide them and limit their amplitude of vibration. In fact, the impacts between tubes and the plate tend to stabilise the system. Thus, we can finally represent the whole problem as below:

$$M \cdot \ddot{x} + C \cdot \dot{x} + K \cdot x = F_t + F_f(\ddot{x}, \dot{x}, x, Vr) + F_c \quad (2)$$

With

$F_c$ : Impact force

$C$ : Structural damping matrix

$M$ : Structural mass matrix

$K$ : Structural stiffness matrix

Because these mechanisms are complex and difficult to realize into experimental set up, the main aim of my study is to develop hybrid control loop for simulating this coupling effect into experimental characterization test bench.

## 2 SYSTEM DESCRIPTION

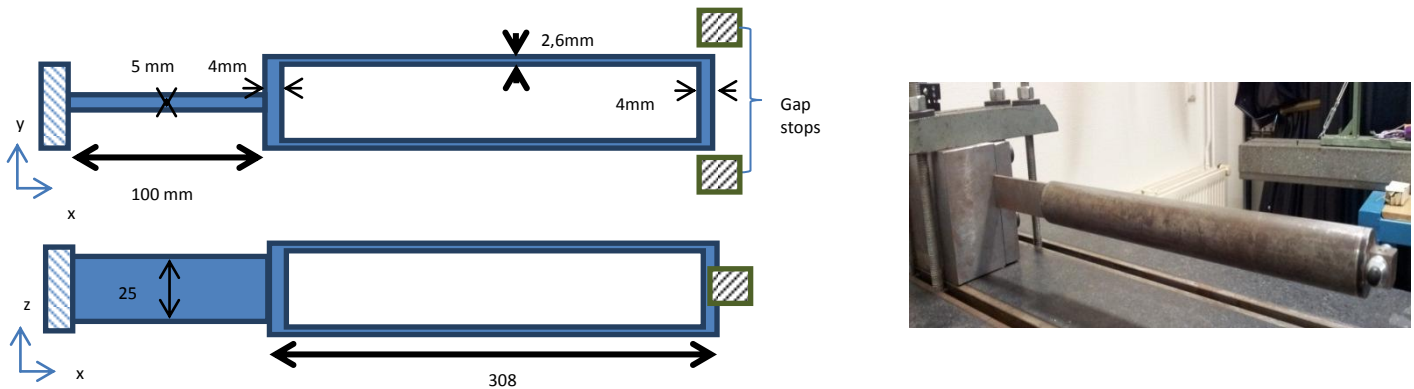


Figure 2. Gap supported tube

The studied structure (figure 2) is composed by a tube attached to a flat plate clamped in rigid block. On the free side, two gap stops are located to create punctual impacts depending on vibration amplitude.

A finite element shell model has been developed to generate mass matrix, damping matrix and stiffness matrix. This model was updated in order to match the numerical behavior with experimental one. Two criterions were used to compare the numerical and experimental model: modal analysis criterion (MAC) and frequency error criterion. The fig.3 summarizes the results for the 6 first modes.

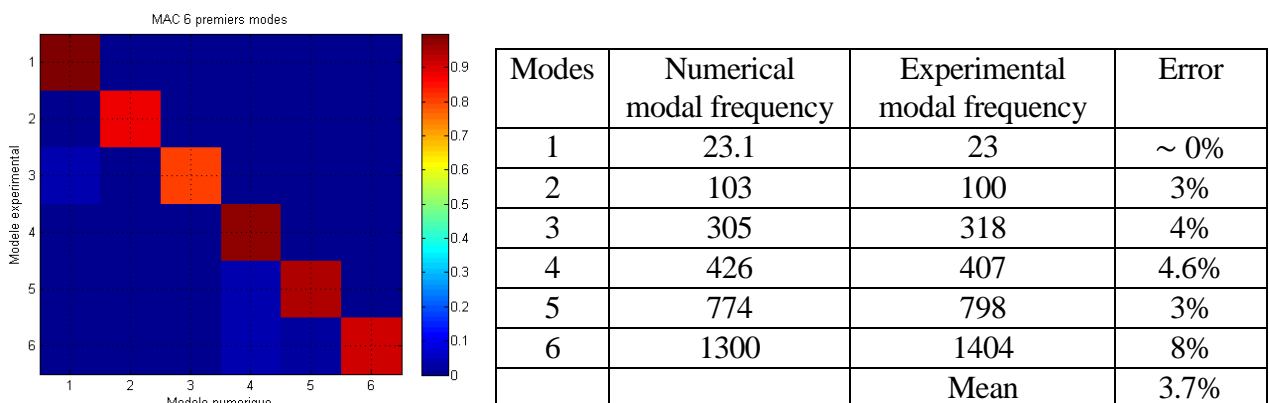


Figure 3. Modal updating

## 3 NUMERICAL SIMULATION

To simulate the temporal response of the tube, the fluid-elastic coupling forces are projected on the first mode which is predominant in the tube response and the effects of higher modes are almost negligible as explained in the CEA experiments[3]. Concerning the impact forces, they are computed in an explicit manner:

$$\begin{cases} F_c(t) = K_c \cdot (x_c(t) - j) & \text{if } |x_c(t)| > j \\ F_c(t) = 0 & \text{if } |x_c(t)| \leq j \end{cases} \quad (3)$$

With

$F_c$ : Impact force

$j$ : Gap distance

$x_c$ : Displacement of tube

$K_c$ : Impact stiffness

The impact stiffness  $K_c$  has been identified experimentally by measuring impact duration. This method will be detailed in the presentation.

Figure 3 shows the time response of the free end when the tube is subjected to fluid-elastic and impact force. Newmark time integration method with mean acceleration combined with Newton-Raphson algorithm was used. Exceptionally the supported gap was located in the middle of the tube in order to compare numerical results with CEA experimental ones [3].

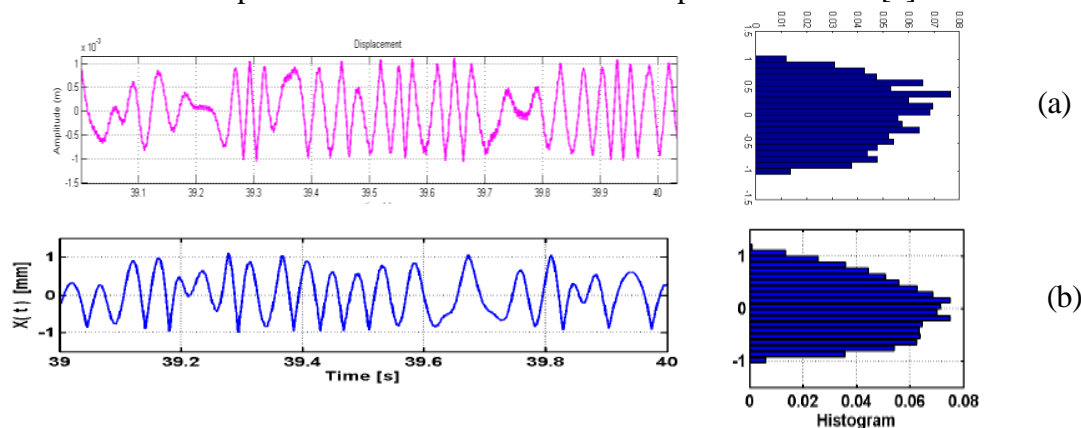


Figure 3. (a) Computed response at fluid velocity 2.5m/s with support gap 0.5mm  
(b) Experimental response at fluid velocity 2.5m/s with support gap 0.5mm

As we can see in figure 3, the numerical estimation is close to the experimental one. Furthermore, the difference we notice between the computed and the experimental response is due to turbulence excitation which is a random force and also the uncertainty related to numerical model.

#### 4 CONCLUSION

Actually a numerical model of the structure was gotten; this model was updated by experimental modal analysis. The Newmark integration method gave estimation about the response of the tube subjected to fluid excitation forces and impacts. The next step that we are working on is, to find a controller to reproduce experimentally the fluid effect on the real structure.

#### REFERENCES

- [1] S. T. H. Tanaka, « Fluid elastic vibration of tube array in cross flow », *Journal of Sound and Vibration*, n° 1, p. 19-37.
- [2] H. J. Connors, « Fluidelastic vibration of tube arrays excited by cross-flow », *ASEMA*, p. 42-46, 1970.
- [3] P. Piteau, X. Delaune, J. Antunes, et L. Borsoi, « Vibro-Impact Experiments and Computations of a Gap-Supported Tube Subjected to Single-Phase Fluid-Elastic Coupling Forces », 2010, p. 395-407.