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► To cite this version:

Wissam Benmalek, Manuel Collet, Emmanuel Foltête, Morvan Ouisse, Mathieu Corus, et al.. Numerical simulation and experimental validation of gap supported tube subjected to fluid-elastic coupling forces for hybrid characterization tests. 1st Euro-Mediterranean Conference on Structural Dynamics and Vibroacoustics (MEDYNA 2013), Jan 2013, France. pp.1 - 4. hal-00993420

HAL Id: hal-00993420

<https://hal.science/hal-00993420>

Submitted on 20 May 2014

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

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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 to 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.

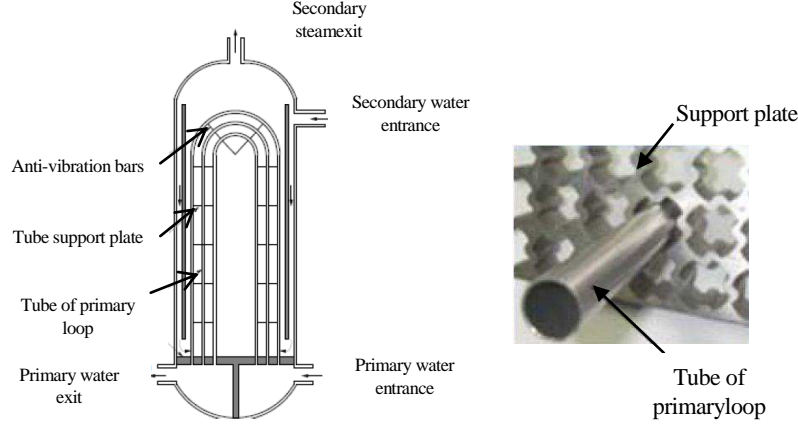


Figure 1. Steam generator

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 (inverted 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

V_r : Fluid reduced velocity

f : frequency of vibration

M_f : Fluid added mass Matrix

D : tube diameter

F_f : Fluid-elastic coupling force

V : Fluid velocity

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

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

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

M : Structural mass matrix

C : Structural damping 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

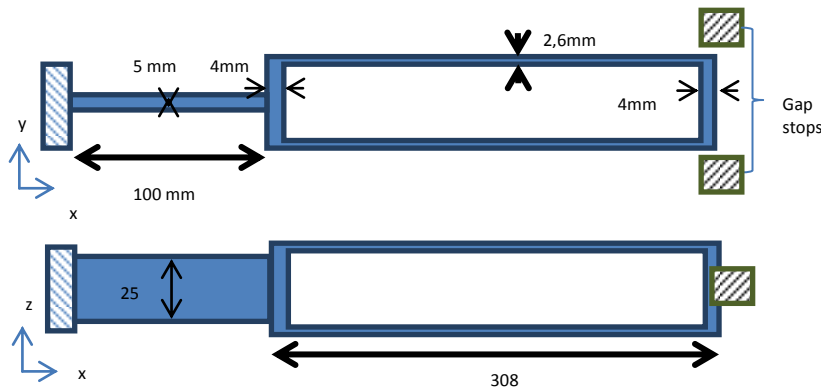


Figure 2. Gap supported tube

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.

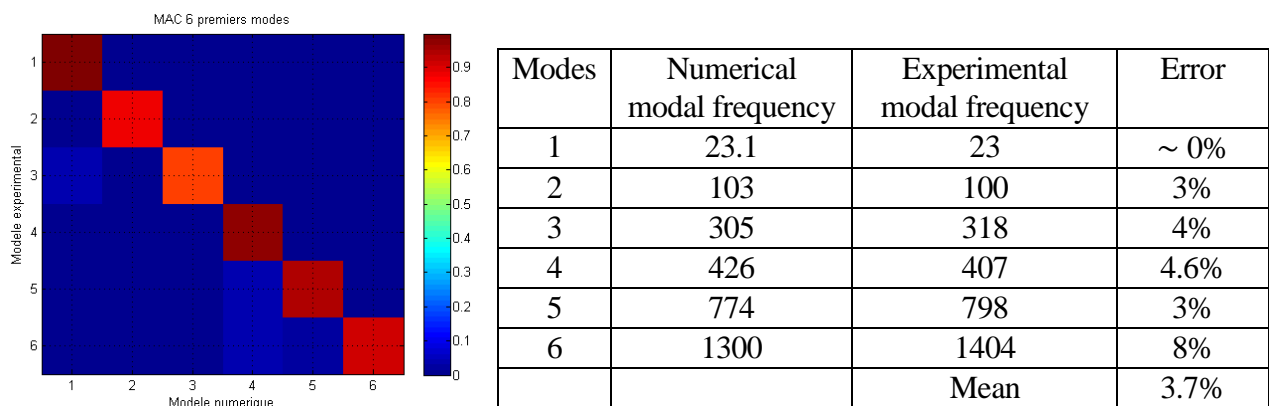


Figure 3. Modal updating

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].

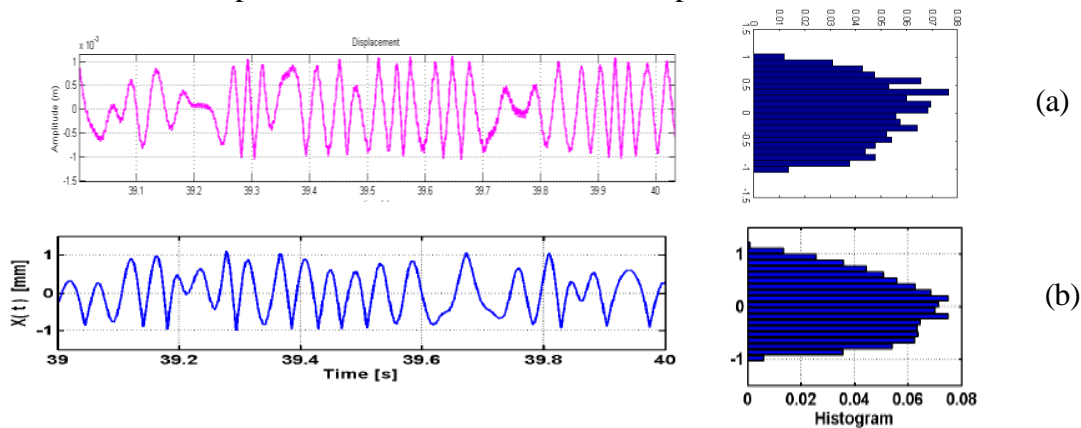


Figure 3. (a) Computed response at fluid velocity 2.5m/s with support gap 0.5mm
(b) Experimental response at fluid velocity 2.5m/s with support gap 0.5mm

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.

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