

## AB INITIO SIMULATION OF CORIOLIS MASS FLOWMETER

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*Abstract: Fluid Structure Interaction (FSI) is the basis of the working principle of Coriolis Mass Flowmeter (CMF). Up to now the description of this coupling has been done using some crude simplifications. Within this weak coupling approximation, the action of the fluid on the structure, the so-called Coriolis force, is easily derived from the structure movement. Clearly the fluid properties effects are out of the reach of this simple model. Nevertheless, CMF are very competitive and are used in many fluid (liquid and gas) flow metering applications. Therefore an "a priori" understanding of their behaviour is needed.*

*This study presents the results achieved with ADINA, a multipurpose FE code with a special strength in FSI. The vibration characteristics of a clamped-clamped straight pipe conveying various fluids are calculated. The model consists of a pipe described as a shell and a real fluid. It is a computation starting from "first principles". The results compare quite well with the experimental and the theoretical values. In a Finite Element (FE) procedure the geometry and/or the material properties and/or the loads are readily changed. Therefore a tool is available for simulating and comparing different CMF designs.*

*Keywords: Coriolis Mass Flowmeter Simulation, Fluid Structure Interaction.*

### 1 INTRODUCTION

Depending upon the output of the flowmeter it is classified as a volumetric flowmeter or a mass flowmeter. Mass flow metering is the ultimate goal of any flow measurement. It can be done by combining volume flow and density measurements. However, high accuracy is achieved only with the direct mass flowmeter. Among this brand of flowmeters, the Coriolis Mass Flowmeter is the best candidate for the nomination „ true mass flowmeter“. Indeed, with a single fluid calibration (water) CMF are successfully handling applications in single phase (liquid or gas) and multiphase (liquid-gas, liquid-liquid, liquid-solid) flow measurement. Unfortunately, one has to confess the lack of a full understanding of the influence of the fluid properties in some applications.

### 2 SIMPLE DESCRIPTIONS OF CMF

The physical phenomenon underlying a CMF is the fluid structure interaction. The vibration behaviour of a pipe conveying a fluid is affected by the flow. Due to the vibration of the pipe the fluid particles experience a change of momentum. This change of momentum is related to a force (2<sup>nd</sup> Newton's law), the action of the pipe on the fluid. The 3<sup>rd</sup> Newton's law tells that the fluid reacts on the pipe. This (reaction) force is called a Coriolis force because it is resulting from a local rotation of the pipe and a linear velocity of the fluid in this rotating frame.

## 2.1 The Analytical Approach

The above description can be cast into a tractable analytical equation if the following hypotheses are done:

- (i) the pipe geometry (aspect ratio and thickness) allows a beam approximation of its vibration behaviour,
- (ii) the fluid is incompressible and non viscous,
- (iii) the flow is well developed,
- (iv) the vibration amplitude is small,
- (v) the coupling is in one way, namely the pipe vibration has no effect on the fluid flow,
- (vi) the structural damping is neglected.

More details can be found in the references [1,2]. The actual theoretical understanding of CMF is limited to this simple model. Only very few attempts, e.g. in [3], have been done to relax one of the above hypotheses. This analytical model is of a very limited help during the design process of a new instrument.

## 2.2 The Empirical approach sustained by CAE tools

For design purpose, the engineers have developed conjectures based on a large amount of experience. The validity of these conjectures is sustained by the very high level of reliability of the new generation of CMF (e.g. uncertainty  $\approx 0.1\%$  of reading). To give a few, the design of a CMF uses "empirical rules" and "guidelines" such as:

- (i) equilibrated drive mode ( frequency  $\omega_1$  and shape  $\Sigma_1$ ),
- (ii) clean vibration spectrum:  $\forall n,m \quad \frac{W_n}{W_m} \notin N$ ,
- (iii) none of the mechanical resonance frequency is an integral multiple of the electrical main frequency (50 Hz and 60 Hz),
- (iv) low pressure drop,
- (v) mechanical integrity (max. allowable process temperature, pressure, etc.).

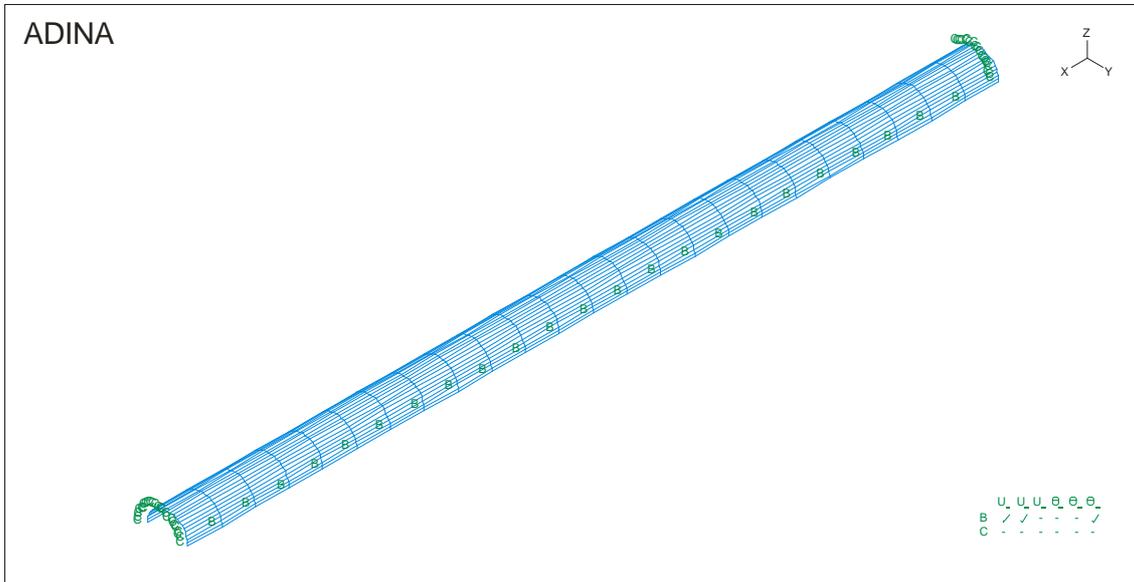
The above design criteria can be addressed in an objective function to optimise using classical FEM and CFD codes. However physical prototypes are needed to study the behaviour of the instrument in a rig. This is a real frustration in the today's trend toward virtual prototyping and testing.

## 3 DESCRIPTION OF CMF AS A FSI PROBLEM

In the analytical and empirical approaches, the lack of a real fluid description is due to the mathematical difficulty inherent to Computational Fluid Dynamics (CFD) and coupled fields problems. CFD is recognised as one of the most difficult application of the numerical methods. Coupled fields problems are also tricky. During a long period of time CAE tools were specialised, i.e. confined to a closed physics fields (structural analysis, fluid dynamic analysis, electromagnetic analysis, etc.). Fortunately, since few years some commercial Computer Aided Engineering (CAE) software are offering a multiphysic package. Furthermore some vendors are claiming to be able to solve FSI problems. They justify this statement by the coexistence of a structural code and a fluid dynamic code. Of course this coexistence facilitates the data exchange between the two codes, but it does not guaranty the ability to solve FSI problems. Indeed, when the interaction is weak and/or is an one-way coupling, the simple data exchange scheme might be appropriate. But, when the coupling is strong/tight, the problem is non-linear. The FSI has to be considered explicitly. At the author knowledge the only available commercial code with a build-in (strong) FSI capability is ADINA. It will be used in this study.

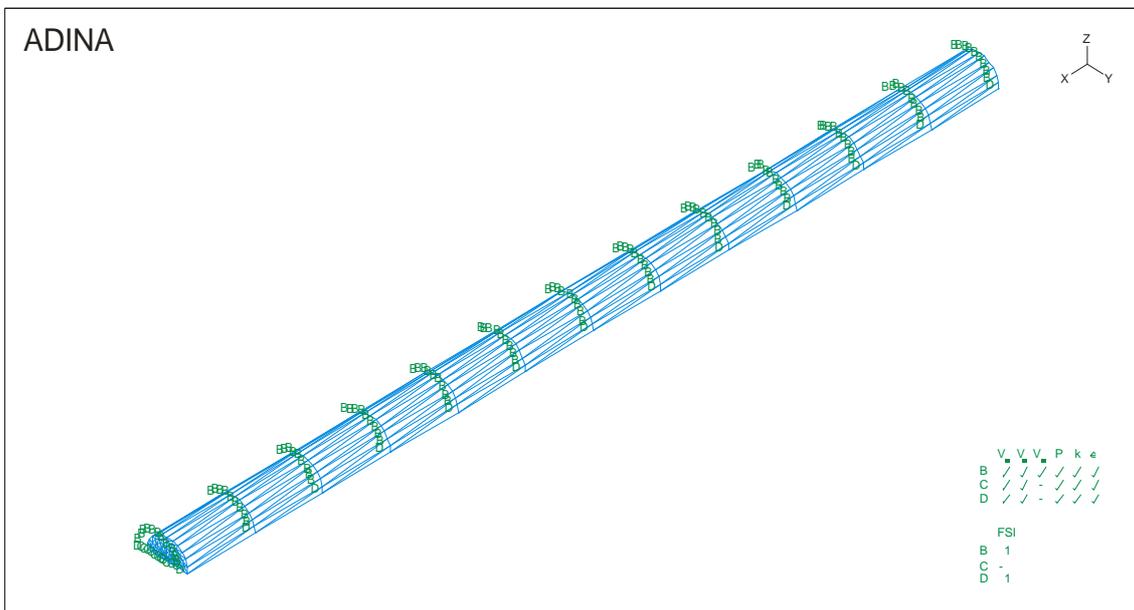
### 3.1 The Solid and Fluid Models in ADINA

For a sake of simplicity the twin parallel straight tubes will be considered. This simple, however real, geometry has many advantages. First of all, the time consuming model generation in 3d is reduced to a minimum. The mechanical structure is defined by a hollow cylinder (length, radius and thickness). This surface is meshed with shell elements (fig. 1a).



**Figure 1a.** Solid model.

The fluid occupies the interior of the cylinder. This volume is meshed with CFD elements (fig. 1b).



**Figure 1b.** Fluid model.

As it is seen in the fig. 1 the fluid mesh and the structure mesh need not to be identical at the FSI interface.

The straight tube design has another advantage. A quasi equivalent 2d model, possessing the main features of the 3d model, can be build. This simplification can save a large amount of computation time, at least for the first investigations. Nevertheless, the results presented in this paper are all obtained using the 3d-model, therefore the 2d-model will not be discussed further.

### 3.2 The Boundary Conditions and Loads

In the twin tubes design, the coupling masses joining the tube ends correspond to vibration nodes (property of a tuning fork). Therefore, instead of using the symmetry property it is equivalent to impose a clamped-clamped or pinned-pinned boundary condition. For the CFD part of the simulation the inlet velocity and the outlet pressure are assumed. The no-slip boundary condition is prescribed at the interface fluid-structure.

### 3.3 The Analysis and Postprocessing Procedures

To get the resonance frequency the structure is submitted to a variable force (e.g. a shock) then let to vibrate freely. The Fourier transformation of the free vibration amplitude gives the fundamental frequency. The steps of the procedure are illustrated in the fig. 2a & b.

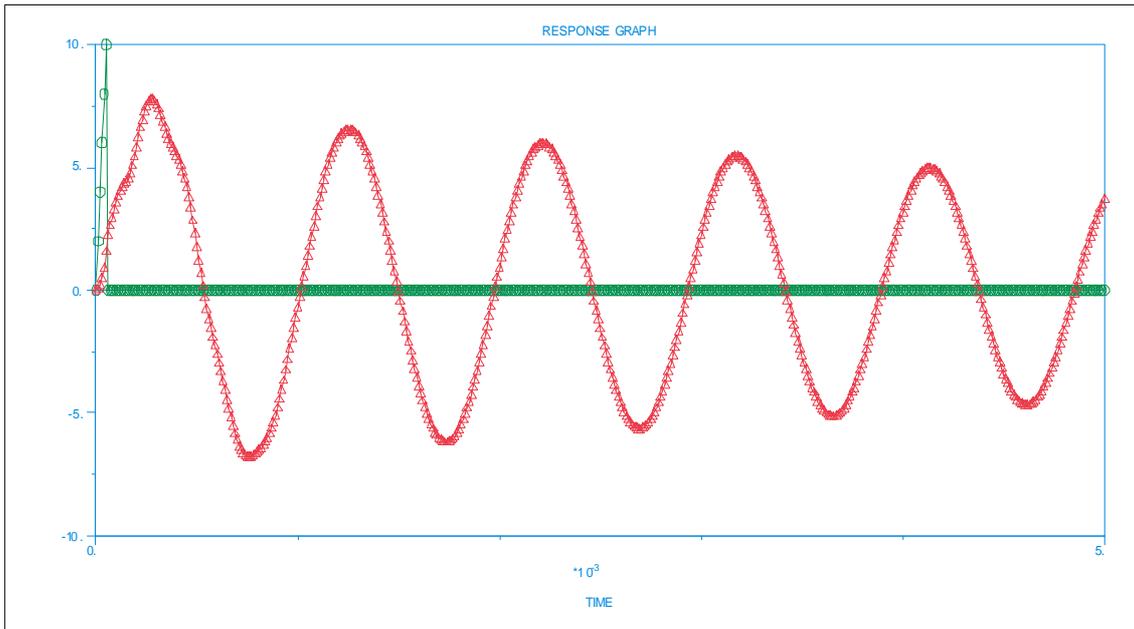


Figure 2a. System response to a variable force.

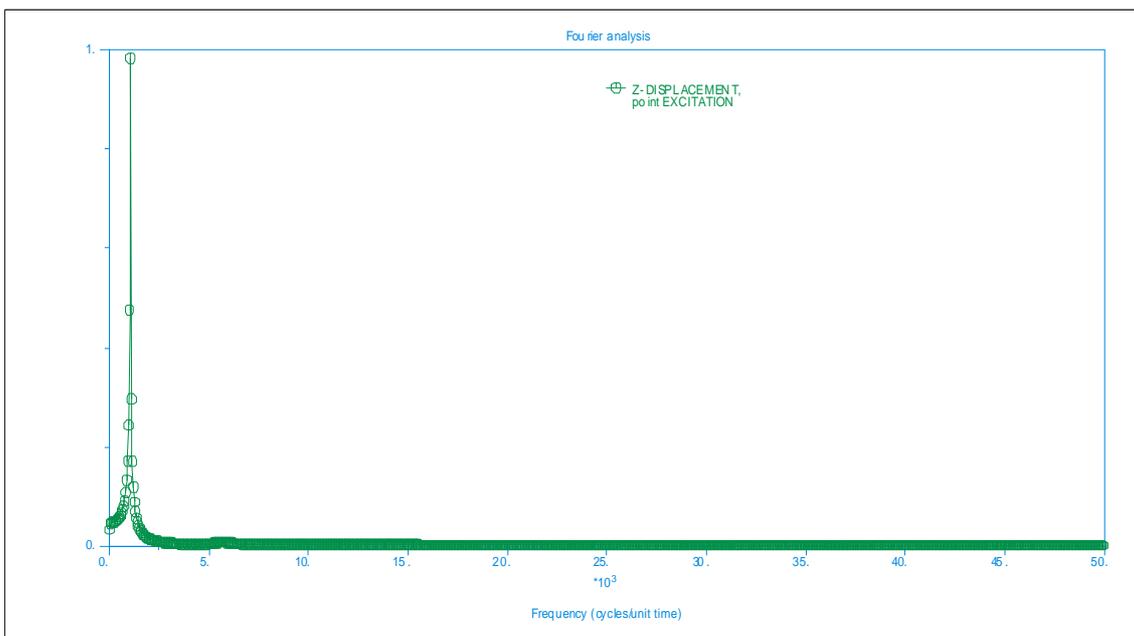


Figure 2b. Fourier transform of the vibration amplitude in the free regime.

When the resonance frequency is known, the next task is to calculate the flow sensitivity of the meter. The determination of this meter factor mimics the way the instrument runs in the reality. In a full transient dynamic analysis, the tube is driven in the fundamental mode (determined previously), while the fluid flowing through it. A full transient analysis is a very involved analysis requiring a large computer resource. The choice of the integration time step (ITS) is crucial and belongs to the analyst responsibility in ADINA-FSI. The analyst has to conciliate two contradictory requirements. The phase shift calculation demands accuracy, therefore a small ITS. But the runtime will be prohibitive if the ITS is too small. For the sake of simplicity, instead of experimenting numerically, it is advisable to use an ITS smaller or equal to 1/20th of the structure period (inverse of the resonance frequency) [ref. 4]. The drive force and the system response, as function of time, are depicted in the fig. 3a & b.

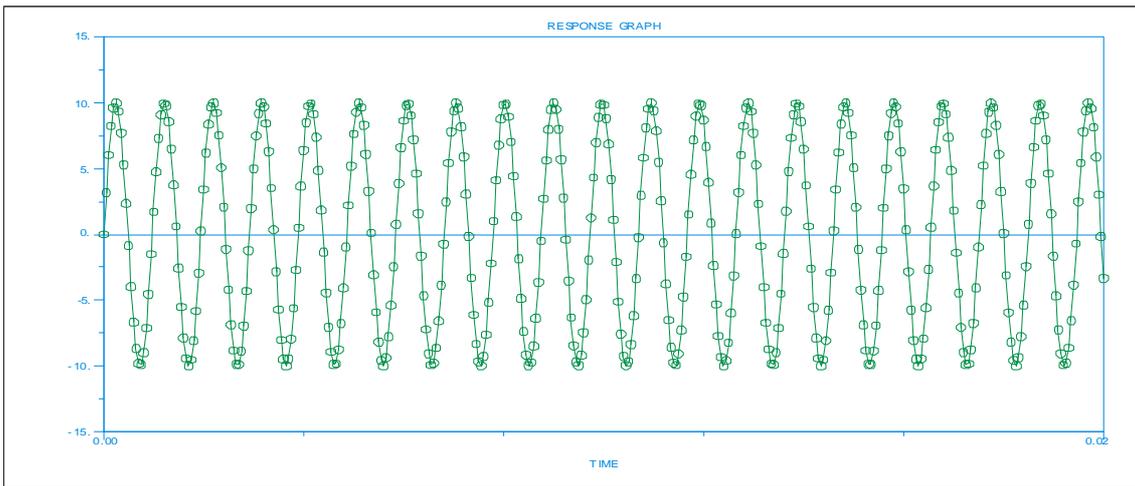


Figure 3a. Sinusoidal driving force.

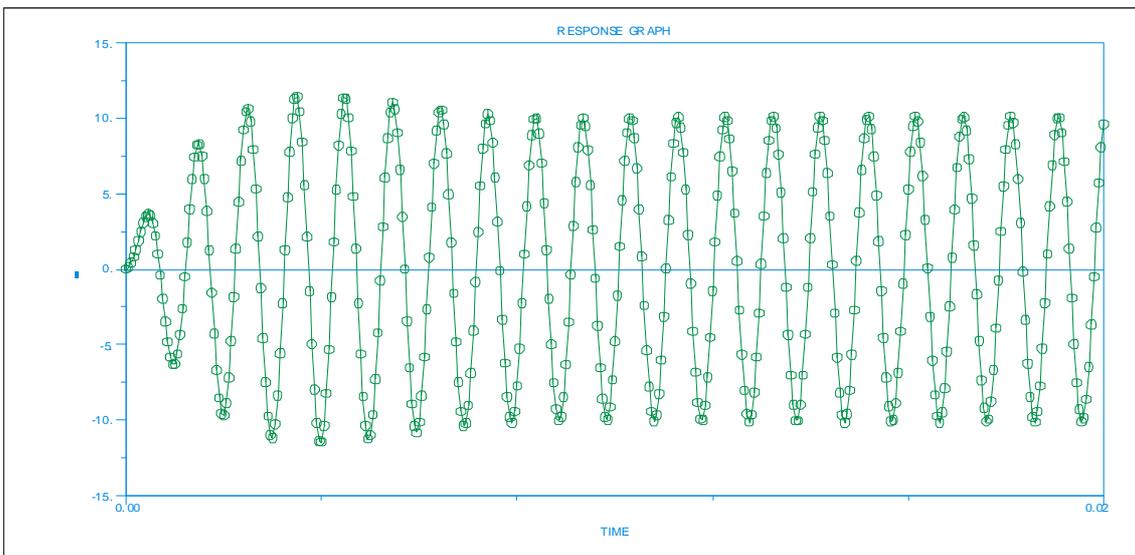


Figure 3b. Transient response of the system to a sinusoidal force.

The vibration amplitudes at the locations of the pickup sensors are the data needed for the determination of the phase shift. It exists two methods for the phase shift computation. One is local and the other integral. In the local method, the computation of the phase shift is reduced to the reading of the zero-crossing times of the sensor amplitude. In the fig 4a is shown the two pickup signals over many periods, while in the fig. 4b the signals are zoomed around a zero-crossing zone.

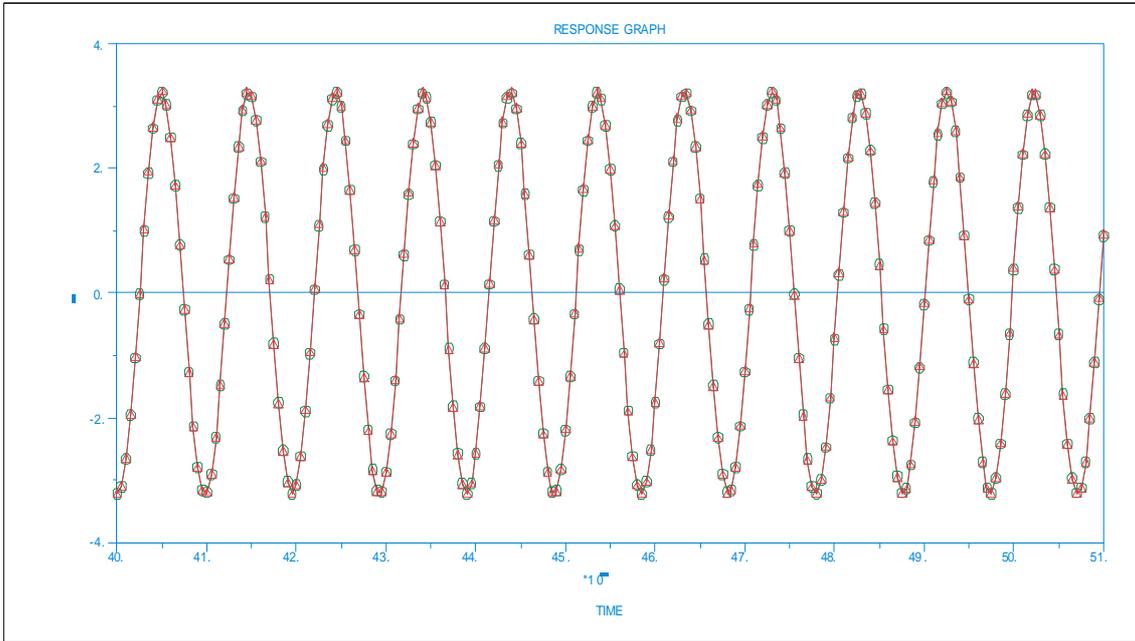


Figure 4a. Zero-crossing method (unzoom)

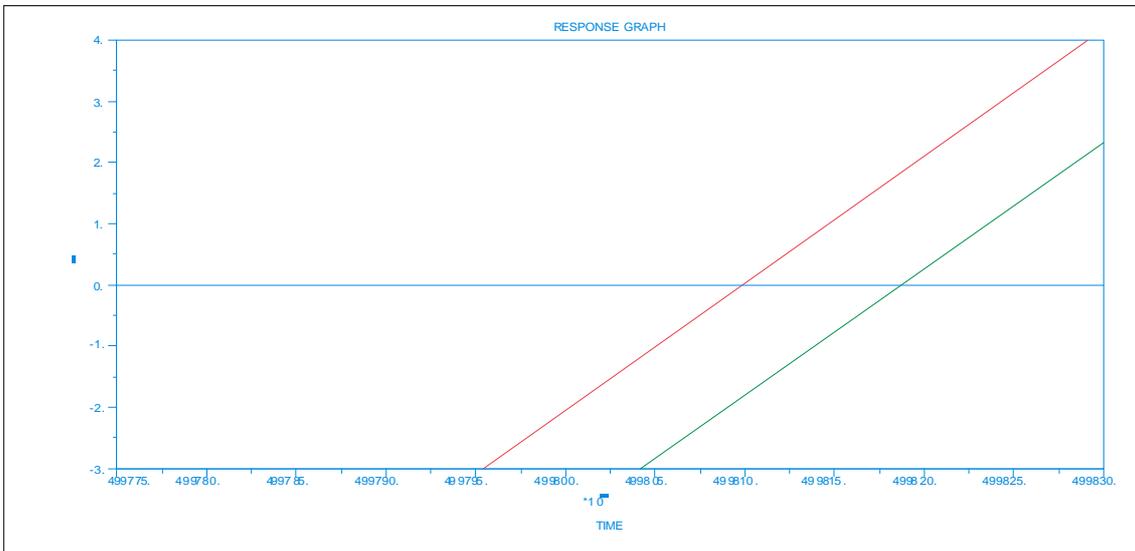


Figure 4b. Zero-crossing method (zoom)

The local method has a drawback. As stressed above, again the choice of the integration time step is critical. Any inaccuracy on the data near the particular chosen zero-crossing can have a huge effect on the calculated phase shift. The alternative method, the integral one, relies on a mathematical algorithm. It is elegant and can easily be implemented in a Digital Signal Processing System. Because the phase shift is small, it is given by the ratio of the amplitude of two signals: the difference of the amplitudes of the pickup signals (hereafter called "difference signal") divided by their common value. The relationship can be transferred in the frequency domain. The fig. 5a & b show the Fourier transform of the mentioned signals.

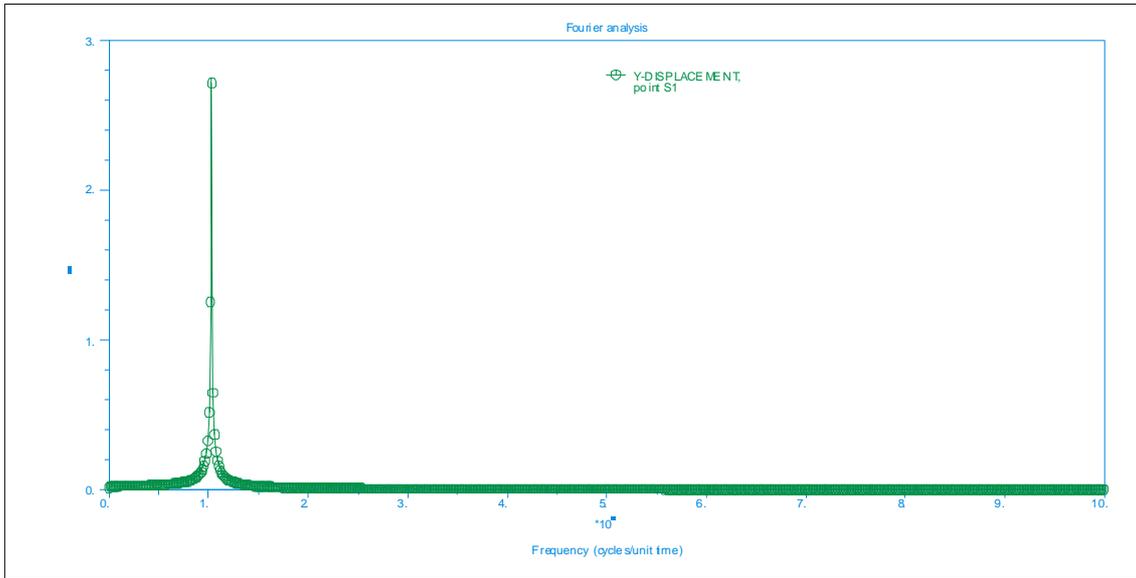


Figure 5a. Fourier analysis of the pickup signal

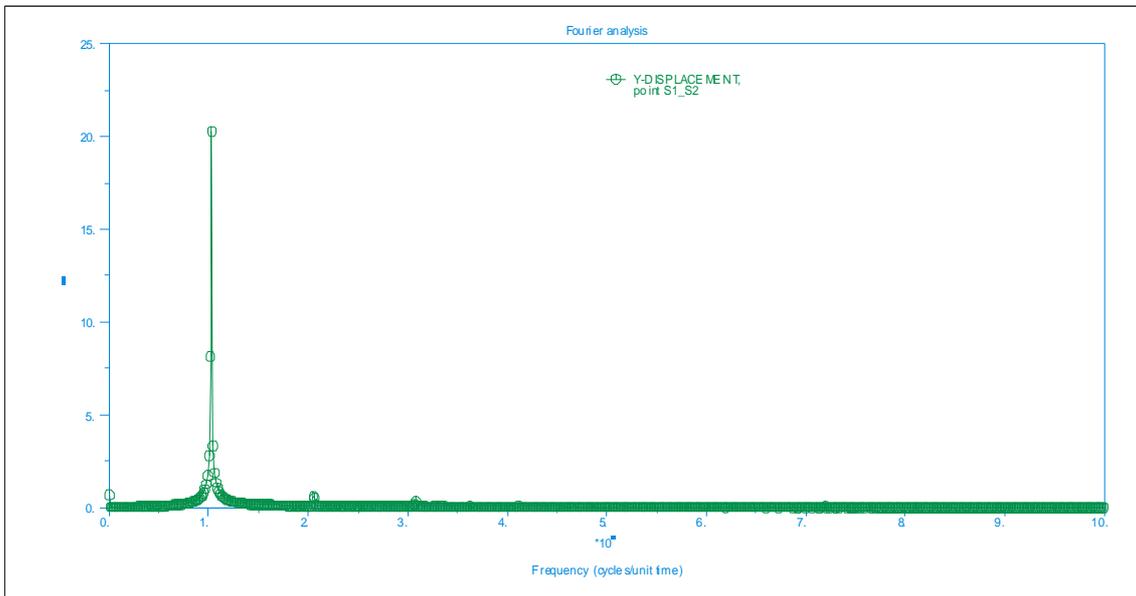


Figure 5b. Fourier analysis of the "difference signal"

## 4 EXAMPLES

To illustrate the above described procedures consider a clamped-clamped tube:

Outer diameter      0.01270 m  
 Inner diameter      0.01138 m  
 Length              0.23800 m

The tube is made of Titanium the ubiquitous material used for the straight pipe design.

Young's modulus    110 GPa  
 Density              4500 kg m<sup>-3</sup>

The characteristics of the vibrating tube conveying water or air at low pressure are of interest.

### 4.1 The Resonance frequency variation as used in the fluid density measurement

The classical theoretical way for handling the frequency change with the fluid density is the added mass method. In the CMF analytical model it is assumed that the added mass is exactly the one enclosed by the measuring tube(s). The assumption is legitimate for a straight tube vibrating in a pure lateral mode and conveying an incompressible fluid. Because the fluid does not affect the stiffness of the structure, the frequency is readily calculated. This approximation is easy to implement in any FEM code. Another pure FE method for solving the problem is to use the so-called acoustic fluid element offered by most of the structural mechanic code (see ref. [3]). In this acoustical fluid-structure interaction model the fluid is defined by its density and compressibility (sound velocity). The above two models are pretty good for the density calibration description of CMF. Nevertheless, it deserves to be noticed that in none of them the viscosity and the flow rate of the fluid are playing a role. Once again, in the full FSI description of a CMF all the properties of the fluid are taken into account by the model. Together with the effect of the fluid on the system frequency, its influence on the modal damping is described too. However, for the frequency computation this feature is not essential. Therefore all the hypothetical fluids used in the computation are supposed to have the same viscosity, low, namely 10<sup>-4</sup> Pa·s, to fulfil one of the theoretical hypotheses. In the table 1 are reported the resonance frequency as function of the fluid density using ADINA-FSI. The data are compared to the analytical solution using the simple beam and the added mass approximation.

Table 1. Variation of the resonance frequency with the fluid density.

| Fluid density<br>[kg m <sup>-3</sup> ] | Frequency using ADINA-FSI<br>[Hz] | Analytical Frequency<br>[Hz] |
|--|-----------------------------------|------------------------------|
| 0                                      | 1300                              | 1325                         |
| 700                                    | 1021                              | 1036                         |
| 1000                                   | 939                               | 959                          |
| 1300                                   | 878                               | 898                          |

The agreement is better than what is considered as the engineering accuracy (±5%). In fact the discrepancy contains a large systematic part that can be explained by at least two reasons. The discretization of the FE model (mesh size and time step) has been kept within limits to maintain the Coriolis effect simulation runtime reasonable (phase shift computation). Furthermore it exists some differences between the shell model and the beam model of a pipe.

### 4.2 The Meter sensitivity in flow measurement – Water Calibration

Normally CMF are calibrated with water and this meter factor used for all the flow measurement purposes. The property data used to define water are a density of 1000 kg m<sup>-3</sup> and a dynamical viscosity of 10<sup>-3</sup> Pa·s. In the figure 6 is shown the calculated calibration curve.

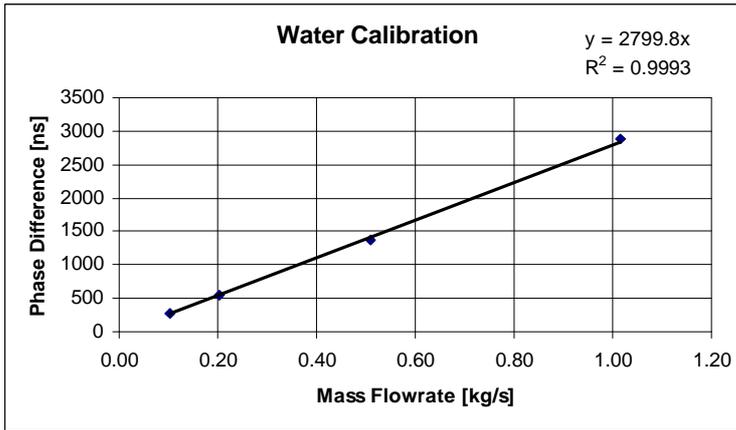


Figure 6. Flowmeter calibration curve

As it is well documented CMF are very linear. The linear fit is practically perfect with a correlation factor of 0.9993. The meter sensitivity, for the actual sensor positions (1/3 & 2/3), is 2799 ns/(kg/s). The analytical value is 2394 ns/(kg/s). For the comparison of these two results the arguments outlined before are still valid. Above that a new and important factor is coming into play. The FSI model is a two-way coupling while the analytical model is similar to an one-way coupling. In fact it seems that the analytical solution lies in between the two-way coupling and the one-way coupling. However more data are needed to ascertain this observation.

### 4.3 The Gas Measurement

CMF are used for gas measurement, but the specifications have to be conservative. In this application the meter is practically restricted to work in its low flow range. This limitation is due to the high noise level induced by the turbulent flow of a compressible medium (gas). In the figures 7a & 7b are shown the vibration spectrum with air if the structural damping is neglected and the drive weak. The boundary conditions are defined by the inlet velocity (150 m/s) and the outlet pressure (0 Pa). When compared to the fig. 5a&b, the fig. 7a&b show clearly that the evaluation of the phase shift is becoming clumsy. The so-called "Coriolis signal" located at the drive frequency is no more dominant in the spectrum of the "difference signal".

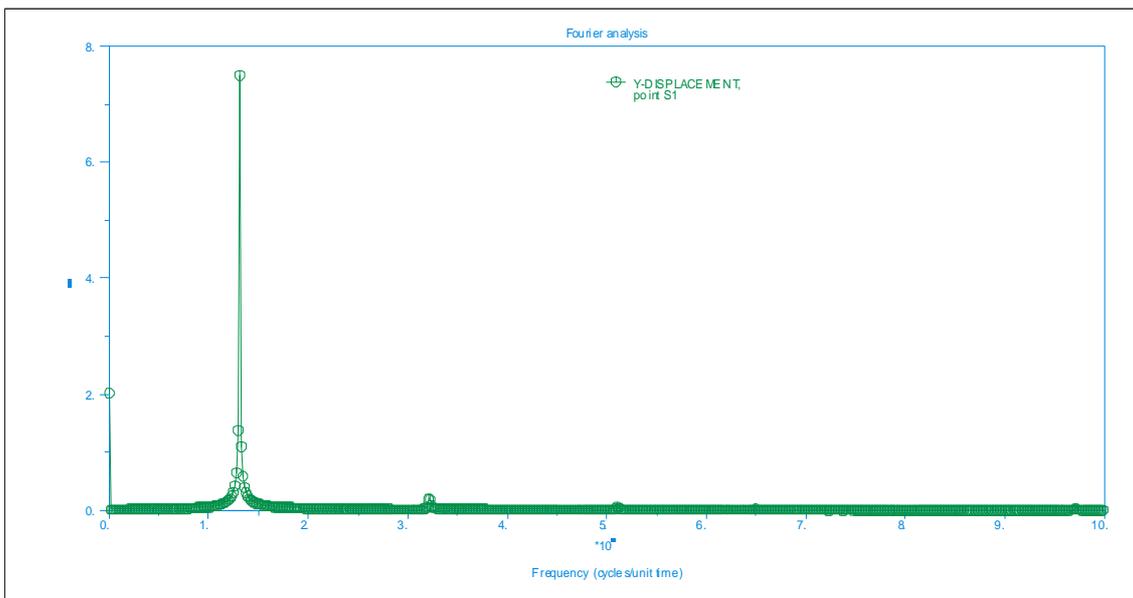


Figure 7a. Fourier transform of the pickup signal

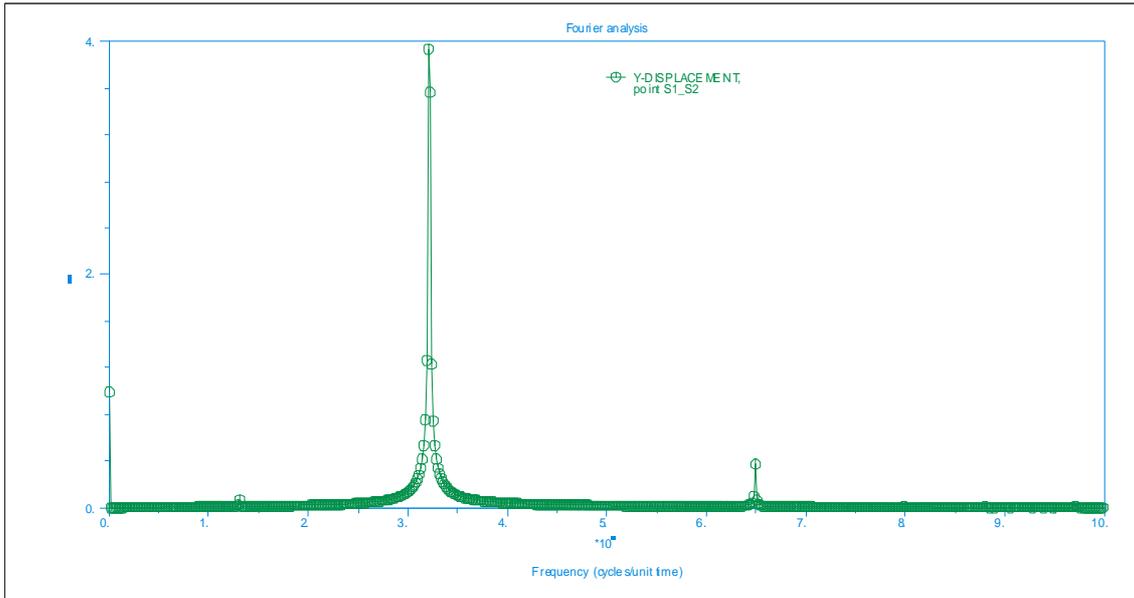


Figure 7b. Fourier transform of the "difference signal"

## 5 CONCLUSION

In the actual drive for better design, CAE simulation tools have an unique strength. Their business benefits are acknowledged in many industrial branches. In the R&D departments „virtual Prototyping and testing“ is replacing the „established“ methods. This trend has reached the design of flowmeters. Today it is common to simulate a Vortex Flowmeter or a Magnetic Flowmeter. Unfortunately, due to the lack of FSI code, the simulation of a CMF, the most innovative technology in flow measurement, was beyond the designer capability.

The main objective of the present work was to ascertain if the ADINA package, the leading FSI code, was suitable for the "ab initio" simulation of CMF. The appropriate procedures have been found. Describing a CMF as a Full Transient FSI problem is feasible, but the technique requires a huge number crunching capability. In this publication the emphasis is put on some simple illustrations of the procedures that are utilised. The technical question regarding the convergence problem and their issues have not been discussed. It deserve to notice that as for any non linear problem some skill is needed to bring ADINA to convergence in a reasonable time. Nevertheless, FSI is at the forefront of the research in FE method. FSI simulation is not a routine, but also it is no more an emerging procedure. The codes are evolving very rapidly together with the hardware. With the availability of FSI codes like ADINA, the design of CMF can be revisited and put on a less empirical basis.

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