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FLUID STRUCTURE INTERACTION APPLIED TO THE COUETTE-CIRCULAR PROBLEM

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Abstract. *In the present work we show a brief description of the Fourier pseudospectral method (FPM) to solve the problems of coupled motion of a rigid body and a viscous incompressible fluid. The propose problem consist about a transient motion between two rotating coaxial cylinders mounted on elastic spring. This can represent any other problems with a similar structure, for example, the drilling movement. The numerical results are presented which show the influence of the Taylor number of high excitation associated dynamic response of the cylinder.*

Keywords: *VIV, Fourier Pseudospectral Method , Circular Couette*

1. INTRODUCTION

The computational engineering, in particular computational fluid dynamics (CFD), is a fundamental tool to study the matter involving the flow, heat transfer, interaction fluid-structure. This in turn motivates considerable research efforts in complex phenomena modelling, to increase the field of investigation of computational applications. The computational code is a tool to solve CFD problems. Any researchers use the notion in fluid-structure interaction studies is that of added mass of mechanical systems vibrating in a liquid (Coma *et al.*, 1997; Tae-Wan *et al.*, 2003; Kim *et al.*, 1988)

This paper pertains to the study of tube damping in liquid, that is interaction fluid-structure. The interaction fluid-structure (FSI) occurs when a structure vibrates in contact with fluid, the fluid shall be displaced to accommodate the motion. Then fluid pressures are generated as a result, this present work discusses about the Circular Couette, where inside cylinder is mounted on elastic spring.

This problem was inspired in practice by Kim *et al.* (1988), which do any experimental works about the motion of a tube inside the other tube support involves simultaneous lateral and rocking-type motions. Most of the time the movement starts from a position that is eccentric to the center of the tube support.

In the present paper were used Fourier Pseudospectral Method (FPM), for fluid modeling and geometry is modeling by Immersed Boundary Method. The computational code are two-dimensional, (Mariano, 2011) . This problem has numerous applications of this idea may be found in the problems of vibration of heat exchanger tube bundle, fuel assemblies of nuclear reactors (T.T and Chen, 1978), space engineering (see Morand and Ohayon Çengel and Cimbala (2012)).

2. GENERAL FORMULATION OF THE PROBLEM

The flow between concentric cylinders, Fig. 1, in the laminar regime has a velocity field form given by the following equation, Mariano (2011), and $U_0 = W_0 = 0$

$$V_0 = Ar + \frac{B}{r^2} \tag{1}$$

The velocity field is, respectively, and corresponds to the exact solution of the Couette flow, for the case of rotating

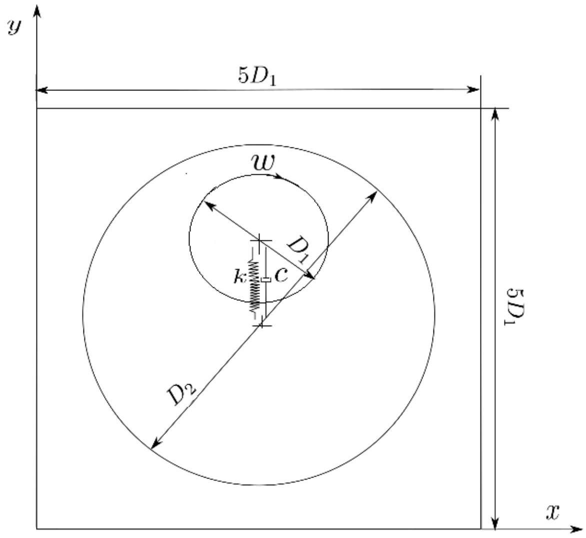

Figure 1: Illustrative diagram of the Cicular couette flow problem mounted on elastic spring in axis y.

inner cylinder with the outer cylinder being fixed, the constants A and B can be expressed in the Eq.(2).

$$A = \frac{w_2 R_2^2 - w_1 R_1^2}{R_2^2 - R_1^2}; \qquad B = \frac{(w_1 - w_2)(R_1^2 R_2^2)}{(R_2^2 - R_1^2)} \tag{2}$$

3. NUMERICAL METHOD

3.1 Fourier Pseudospectral Method - FPM

FPM is based at solution at integration the term of Fourier series (DFT) along all discrete domain. This procedure is of "infinite order ", in the sense that it may be shown to converge faster, although it is, to require only periodic boundary condition. The spectral methods applied to problems with smooth solutions attain high order of spatial convergency rates, because it use all collocation points to calculate a derivative in one point, (Canuto *et al.*, 1988, 2006; Mohd-Yusof, 1997; Briggs and Henson, 1995). The Eq.(3) at spectral domain is given by Eq.(4).

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = \frac{-1}{\rho}\frac{\partial P}{\partial x_i} + \nu \frac{\partial}{\partial x_j}\Big(\frac{\partial u_i}{\partial x_j}\Big) \tag{3}$$

$$\frac{\partial \widehat{u_i}}{\partial t} + \iota k_j (\widehat{u_i * u_j}) = -\iota k_i \hat{P} - \nu k^2 \widehat{u_i} \tag{4}$$

where k is wave number, and $k^2 = k_j k_j$, $\widehat{u_i}$, is the vector velocity transformated to Fourier space using the DFT, and ι is the complex number $\sqrt{-1}$, and $NLT = \iota k_j (\widehat{u_i * u_j})$ is the convolution product, It is solved by using Fourier pseudospectral method, Canuto *et al.* (1988); Briggs and Henson (1995).

Using the projection method, Canuto *et al.* (2006), the pressure field becomes post processing condition. The Eq.(6) is Navier-Stokes, discretizated at time and projected on the plane π, where $\wp(\widehat{TNL^t_m})$ is non-linear term projected term.

$$\frac{\widehat{u_i}^t - \widehat{u_i}^0}{\Delta t} + \wp(\widehat{TNL^t_m}) = -\nu k^2 \widehat{u_i}^t \tag{5}$$

3.2 Immersed Boundary - IBM

The term IBM, is used in present paper to model structure characteristics, this method uses two domains Peskin (1972), lagrangian and euleran domain. Among many different kind of IBM, this work was used by Direct-Forcing method (DFM), It is used to calculate the Lagrangian field. The DFM developed by Mohd-Yusof (1997), extracts the forcing directly from the numerical solution, which is determined by difference between the interpolated velocities in the boundary points and the desired at the physical boundary velocities.

The Figure (2) represents the domain used to calculate the immersed boundary, where $\vec{x}$ represents position any point at the field Eulerian (Ω) and $\vec{X}$ position any point at the field Lagrangian (Γ_1 and Γ_2), (Peskin, 1972).

The interaction fluid-structure using the IBM consist to put the force from fluid solution at lagrangian domain. This is possible using the source term f_i, which represents the force origin by IBM. Then to the Eulerian domain, the Eq.(6) is applied:

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = \frac{-1}{\rho}\frac{\partial P}{\partial x_i} + \nu \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}\right) + f_i \tag{6}$$

The Direct-Forcing method (DFM) is used to calculate the Lagrangian field (Mittal and Iaccarino, 2005). The DFM developed by Mohd-Yusof (1997) extracts the forcing directly from the numerical solution, which is determined by difference between the interpolated velocities in the boundary points and the desired at the physical boundary velocities. In the present work was chosen direct-forcing, due the good results obtained by Mariano (2007, 2011); Moreira (2011) together with the Fourier pseudospectral method. In This methodology, both domains (Lagrangian and Eulerian) change informations using the Eq.(7).

$$f_x = \begin{cases} F_x(\overrightarrow{X}, t) & if \quad \overrightarrow{x} = \overrightarrow{X} \\ 0 & if \quad \overrightarrow{x} \neq \overrightarrow{X} \end{cases} \tag{7}$$

For the purpose of discussion of the general concepts, let us write the time-discretized at horizontal velocity component, Eq.(8), in the following form:

$$\frac{u^{t+\Delta t} - u^* + u^* - u^t}{\Delta t} + rhs + f_x = 0 \tag{8}$$

where *rhs* regroups the convective and viscous terms at some intermediate time level between *t* and *t*+Δt. The Eulerian force term which yields the temporal parameter u*. Then the Eq. (6) is solved in two steps, given by Eqs. (9) and (10) for both directions.

$$\frac{u^* - u^t}{\Delta t} + rhs = 0 \tag{9}$$

The lagrangian source term is given by Eq.(10) for X$_l$.

$$F_x = \frac{U^{t+\Delta t} - U^*}{\Delta t} \qquad \forall X_l \tag{10}$$

where U$^{t+\Delta t}$ is the boundary condition and U* is the temporal parameter interpolated. Lastly, the update by the eulerian velocity is given by Eq.(11) where f_x is calculated by Eq.(6):

$$u^{t+\Delta t} = u^* + f_x \Delta t \tag{11}$$

It is possible if the Eulerian and Lagragian mesh are coincident, case the geometry is non coincident the force origined the immersed boundary have to be distributed. Peskin (1972) propose a function distribuition is given by Eq.(13):

$$f_i(\vec{x}) = \sum_{\Gamma} D_h(\vec{x} - \vec{X}) F_i(\vec{X}) \Delta s^2 \tag{12}$$

$$D_h(\vec{x} - \vec{X}) = \frac{1}{h^2} W_g(r_x) W_g(r_y) \tag{13}$$

where D_h is the distribuition function, $r_x = \frac{x-X}{\Delta x}$, $r_y = \frac{y-Y}{\Delta y}$, Δs is distance of lagrangian points and W_g is the weight function.

$$W_{gc}(r) = \begin{cases} 1 - \frac{1}{2}|r| - |r|^2 + \frac{1}{2}|r|^3 & if \quad 0 \leq |r| < 1; \\ 1 + \frac{11}{6}|r| + |r|^2 - \frac{1}{6}|r|^3 & if \quad 1 \leq |r| < 2; \\ 0 & if \quad 2 \leq |r|; \end{cases} \tag{14}$$

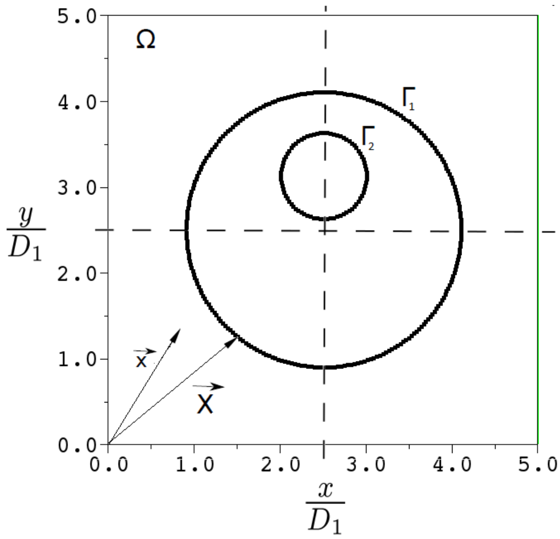

Figure 2: Scheme of eulerian and lagrangian mesh.

3.3 Simulation Parameter

The geometry of the problem and the boundary conditions employed in the simulation are displayed in Fig. 2. The spring is linear with the stiffness and damping coefficient $\xi = 1.23710^{-3}$. The mass ratio and the diameter of the cylinder are given as $m^* = 148.16$, Eq. (15), and $D_1 = 0.16$ cm, respectively. The fluid under consideration is water with $\nu = 1.010^{-5} m^2 s^{-1}$. Two Different field fluid velocities $u_\infty = 1.0$ m/s are considered, such that the Taylor number, Eq. (16), are 30 and 50.

$$m^* = \frac{m_s}{\pi \rho_f D_1^2 L}, \tag{15}$$

onde m_s is the structure mass, and ρ_f is the specific mass of fluid.

$$T_a = \frac{\omega_1 D_1 (D_2 - D_1)}{2\nu} \tag{16}$$

The simulation were realized by 256x256 colocations points and admensional time, $t^* = 300$.

4. RESULTS

Figure 3 and Figure 4 show horizontal and vertical velocity fields respectively, at time $t^* = 18,6$. Note rotation effect Fig. 5, from inner cylinder does not generate instability in the flow. Its occurs due to inner cylinder is simetric and balanced in the axes, Fig. 5, and Fig. 6.

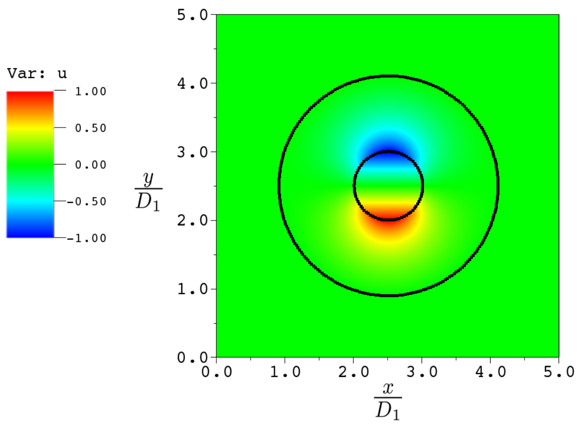

Figure 3: Horizontal velocity field at Ta=30

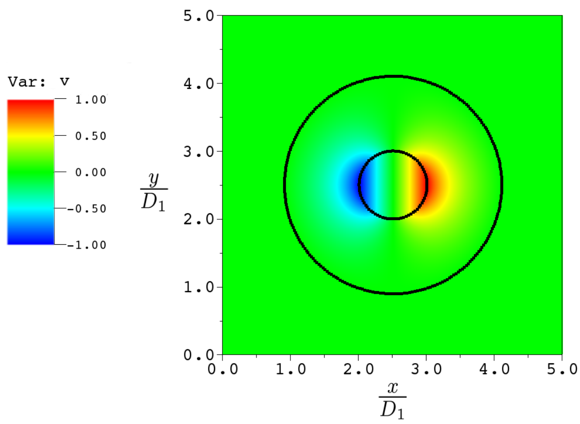

Figure 4: Vertical velocity field at Ta=30.

The Figure 7 and Figure 8 show the barycentre position relative of inner duct, for values different Taylor numbers, Ta= 30 and Ta=50, respectively. The structure position describe, harmonic and damped motions. For Ta = 30, shows amplitude

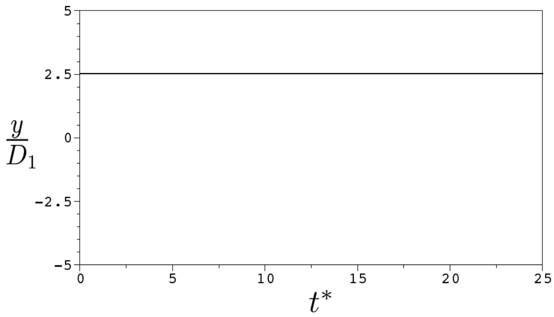

Figure 5: position at inside cylinder, to Ta=30.

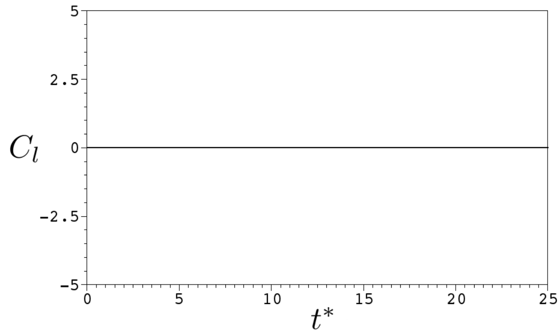

Figure 6: Lift coefficient, to Ta=50.

is reducing due to fluid dynamics rotation. This occurs by reducing the displacement amplitude of the structure, and time reduction to attain the equilibrium position.

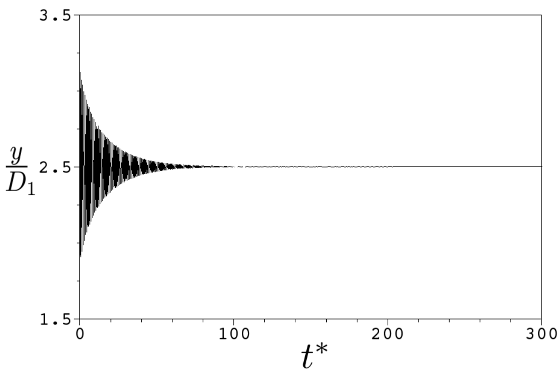

Figure 7: Time evolution of the center of the internal duct, Ta = 30.

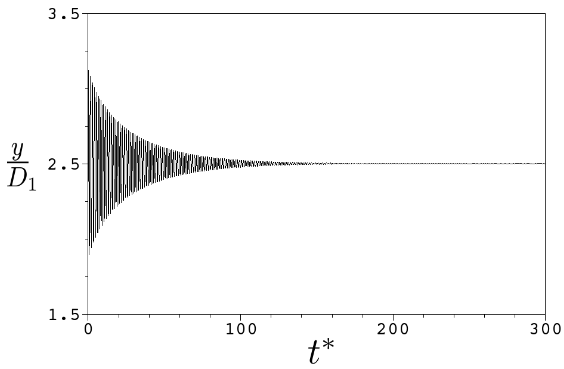

Figure 8: Time evolution of the center of the internal duct, Ta = 50.

The Figure 9 and Figure 10 shows the vorticity due to inner cylinder moves to the lower part, forming a recirculation downstream of the structure, at time t^* =12.5 and moment that cylinder return to the top at time t^* =25. In these figure note the symmetric vortex around the inner cylinder during its move, down and up. It is possible because is only spring modeling vertical direction and the fluid is homogeneous.

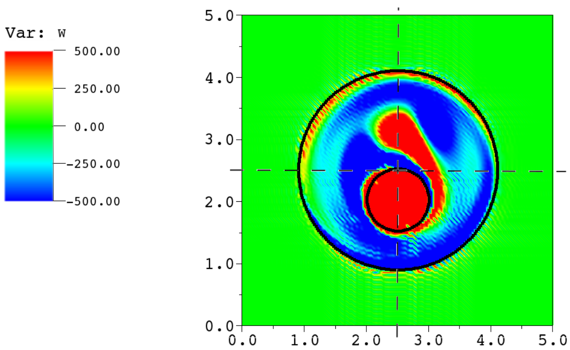

Figure 9: Field vorticity at Ta=50, t^* =12,5 .

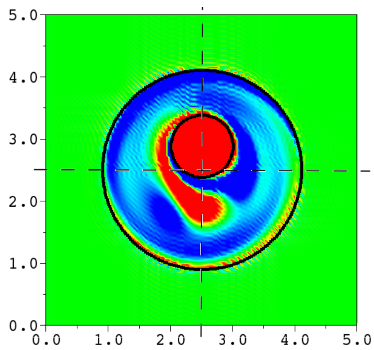

Figure 10: Field vorticity at Ta=50, t^*=25 .

5. CONCLUSION

In this paper a computational strategy for $fluid - rigid$ body interaction has been presented, couple Fourier Pseudospectral Method and Immersed Boundary.

The FPM method is employed for the spatial discretization of the Navier-Stokes equations, coupled the IBM, which is used for modeling structure moving, show results based in physics problem. The characteristics of the present method is illustrated in two numerical examples.

The methodology seems very well suited for situations where the rigid body is mounted on a soft flexible support and undergoes large displacements.

6. ACKNOWLEDGEMENTS

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