NUMERICAL SIMULATION OF SMALL AMPLITUDE OSCILLATORY CYLINDER UNDER INCOMPRESSIBLE LAMINAR 2D FLUID FLOW USING A NON-INERTIAL REFERENTIAL GRID

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Abstract. *This work purpose to provide a numerical estimate of fluid-elastic forces of a mobile tube under* 2D *transverse fluid flow. At first, we carried out a numerical validation on vortex wake characteristic behind a tube isolated rigid* 2D *with* $Re = 200$*: Strouhal number* Sh *and coefficients of lift* C_L *and drag* C_D*. These values will be useful for following simulations. Finally, a harmonic movement perpendicular to flow is imposed on the tube, having a frequency ratio* f_o/f_k *and a reduced amplitude* S_o/D*. We compare this results to Meneghini (1993) comparing to the temporal force signals by report to displacement, and drag and lift forces by report to frequency ratio. The test parameters of vibrating tube with* $Re = 200$ *are the frequency ratios* $f_o/f_k \in [0.85 - 1.20]$ *and the reduced amplitudes of* $S_o/D = 0.015$.

Keywords: *fluid-elastic interaction, CFD, forced movement, 2D fluid flow.*

1. INTRODUCTION

Many industrial components are made of a variety of tubes which vibrate under flow fluid. The analysis of fluid-elastic forces under small amplitudes of vibration is an research field which interest the thermonuclear area. Unfortunately, this kind of problem is rarely analyzed by literature. For example, ALE method is example of numerical formulation to describe fluid-structure problems. The ALE method describe dynamic meshes around structures to treat vibratory problems under fluid flow. However, the ALE performance for determining fluid-elastic forces to small vibrations amplitudes is still ignored.

An alternative method is consider a indeformable mesh attached to a mobile structure. This approach is known as **A**ccelerate **R**eference **F**rame (ARF), Figure 1. The ARF method is applied to study structures vibrations of indeformable and isolates bodies under open fluid flow (Blackburn and Karniadakis, 1993; Blackburn and Henderson, 1996; Blackburn et al., 2001). Li et al. (2002) improve this this technique adding a rotation movement to the translations degree of freedom. And, with coordinator mapping, Newman and Karniadakis (1997) generalise to the case of structure displacement varies tridimensionally.

A circular cylinder at forced movement under uniforme fluid flow is cinematic equivalent to a fix cylinder under a oscillatory transversal flow superposed to a uniforme flow (Meneghini, 1993). This different fluid flow different dynamically in raison of the Froude-Krylov force that result an inertia force. And, by report to the movement of non-inertial frame reference, the calculate forces may be corrected to 'prendre en compte' inertial effects.

In this paper, we present a numerical example of this non-inertial referential. This work purpose to provide a numerical estimate of fluid-elastic forces of a mobile tube under 2D transverse fluid flow. We carried out a imposed harmonic movement on the tube perpendicular to flow, having a frequency ratio $f_o/f_k \in [0.85 - 1.20]$ and a reduced amplitude $S_o/D = 0.05$. We compare ARF to Meneghini's thesis (Meneghini, 1993) comparing to the temporal force signals by report to displacement, and drag and lift forces by report to frequency ratio. The test parameters of vibrating tube with $Re = 200$ are the frequency ratios $f_o/f_k \in [0.80 - 1.20]$ and the reduced amplitudes of $S_o/D = 0.015$.

Simulations were compared with Meneguini's experimental results (Meneghini, 1993). This methods are implemented in CAST3Ma numerical platform of French Nuclear Agency CEA/Saclay.

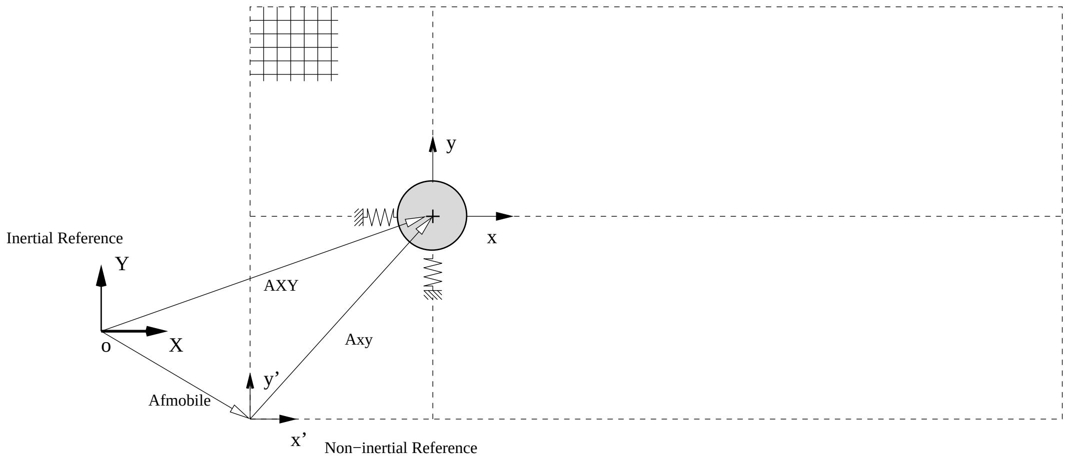


Figure 1. Scheme show the principal of the ARFmethod. The fluid flow is resolved by report to a non-inertial frame $x'y'$ fixed to structure. The mesh is indeformable and displace with cylinder. And, the mesh displacement is coupled to movement-dependent forces by report to global frame XY where fluid flow U_∞ is described.

2. ARF METHOD APPLIED TO FLUID-STRUCTURE PROBLEMS

A slender 2D structure is characterized by a linear mass M_s, a natural frequency $f_s[Hz]$ and a reduced damping ξ_s. Into a inertial coordinate system, the structure mouvement's response due to a distributed fluid force $\mathcal{F}_f$ is described as,

$$\ddot{\mathbf{s}} + 2\xi_s\omega_s\,\dot{\mathbf{s}} + \omega_s^2\,\mathbf{s} = \mathcal{F}_f/M_s \tag{1}$$

The correspondent Navier-Stokes equations in a related reference attached to cylinder,

$$\begin{cases} \nabla\cdot\mathbf{u} = 0 \\ \dfrac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\dfrac{1}{\rho}\nabla p + \mathbf{b} + \nu\Delta\mathbf{u} - \ddot{\mathbf{s}} \end{cases} \tag{2}$$

Then, the Dirichlet-Newmann coupling process make use of the variables acceleration $\ddot{\mathbf{s}}$ and fluid force $\mathcal{F}_f$ into Equations (2) and (1) respectively,

$$\mathcal{F}_\xi = \int_{\Gamma(t)} (-p\,\mathbf{n} + \nu[\nabla\mathbf{u} + \nabla^T\mathbf{u}]\cdot\mathbf{n})\,\mathbf{d}\Gamma \tag{3}$$

The transversal flow over vibrating cylinder in forced movement is cinematic equivalent to a fluid flow around a fixed cylinder superposed to a transversal oscillatory flow, Figure 2. Both configuration are dynamically different en raison of Froude-Krylov force resultant of inertial effects due to control volume acceleration Fox and McDonald (1985); Meneghini (1993).

Then, by report to oscillatory direction, it's necessary to make a correction of the fluid-elastic force obtained by,

$$\mathcal{F}_f = \mathcal{F}_\xi + (\rho\pi D^2/4)\cdot\ddot{\mathbf{s}}_{cyl} \tag{4}$$

where, $\mathcal{F}_f$ is the fluid-elastic force applied around to cylinder relatif to inertial frame; $\mathcal{F}_\xi$ correspond to the fluid-elastic force relatif to a reference frame fixed to the cylinder, and $\ddot{\mathbf{s}}_{cyl}$ is the cylinder acceleration. Consequently, the force coefficient in oscillatory direction $\mathbf{e}_y$ (Lift coefficient) is written as,

$$C_L = C_{L,\xi} + (\pi D/2U^2)\cdot\ddot{\mathbf{s}}_{cyl} \tag{5}$$

where, $C_{L,\xi}$ is the lift coefficient relatif to a reference frame fixed to the cylinder, and C_L is the inertial lift coefficient.

3. NUMERICAL EXAMPLE

To validate this application of ARFmethod, we simulate a mobile cylinder under uniforme fluid flow. This cylinder have a forced vibration around Strouhal ($Sh \sim 0.2$). Meneghini (1993) analyze this case. This case has Reynolds number $Re = 200$ and dimensional amplitude $S_o/D = 0.015$ with a unitary cylinder diameter D. To simulate this case, the fluid domain are $L_x \times L_y = 35D \times 10D$ with $25D$ downstream.

This simulations use quadratic finite elements Q2+BUBLE, and mesh size and time-step determination is done by numerical criteria (de Morais, 2008).

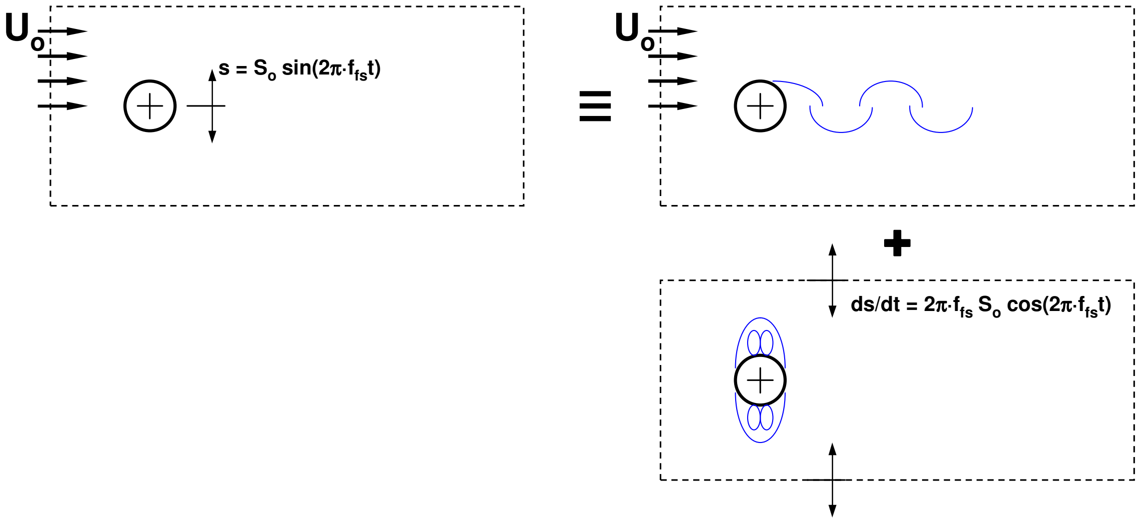


Figure 2. Cinematic equivalence of a oscillatory cylinder under permanent flow.

Spatial and temporal criteria The spatial criteria adopted establish $N_\delta = 160$ elements around cylinder. If we consider a square elements, this spatial criteria correspond to two elements into boundary layer, $N_\delta \geq \mathcal{C} \cdot 2\pi\, \sqrt{Re}$. The correspond mesh have 17600 elements and 71040 nodes, Figure 3.

CFL criteria determine the time step $\Delta t = 0.0023$, 15 times smaller than $\Delta t \geq \Delta x / U_\infty = 0.035$ (de Morais, 2008).

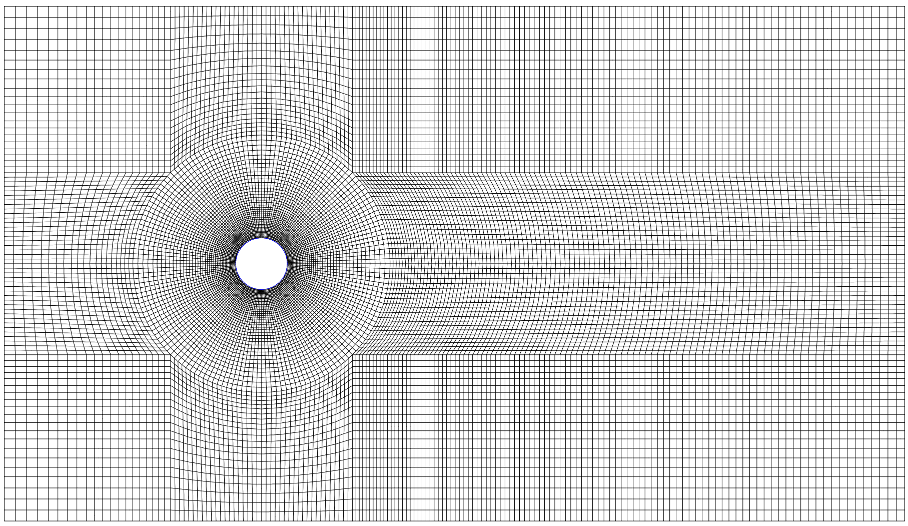


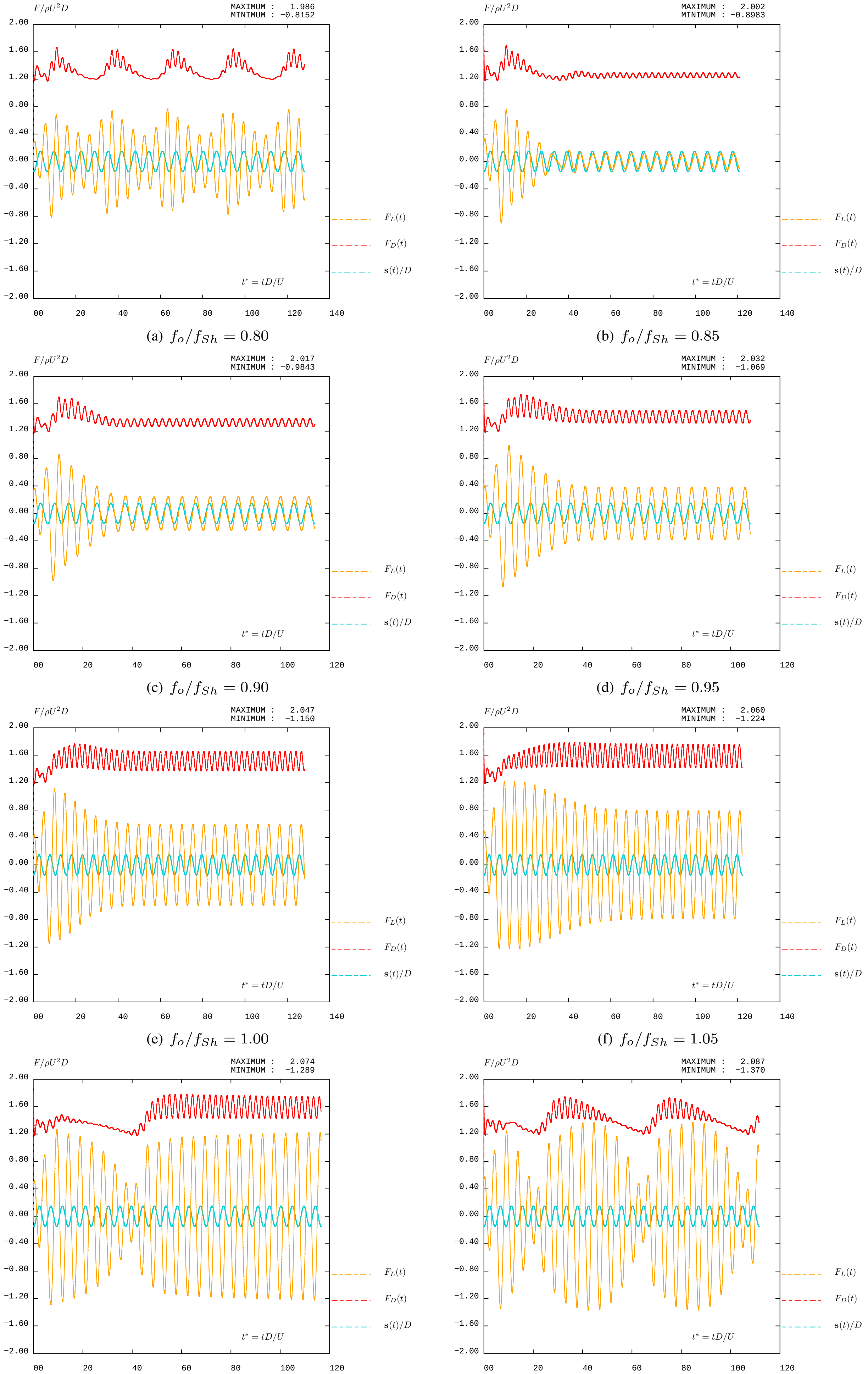
Figure 3. Fluid mesh around mobile cylinder.

Numerical forces time history Figure 4 present the fluid forces evolution for different frequencies ratio f_o/f_{Sh}. We observe the *lock-in* phenomena on the range $f_o/f_k \in [0.85 - 1.10]$. This moment correspond to the limits of zone 2S with detachment of isolated vortex at maximal velocity. At this level of reduced amplitude $S_o/D = 0.15$, Meneghini (Williamson and Govardhan, 2004; Meneghini, 1993) establish the synchronization limit between $f_o/f_k \in [0.950 - 1.17]$ approximately. The numerical data are very close to experimental results, $f_o/f_k \in [0.95 - 1.10]$ (Williamson and Govardhan, 2004). It's necessary step reduced frequency more precise to have a fine description of the *lock-in* transition at zone 2S.

Figure 5 present the phase between displacement **s** and lift coefficient $2\mathcal{F}_{f,L}(t)/\rho D U^2$ around Kármán vortex street obtained by inter-spectre $S_{\mathcal{F}_{f,L}\,\mathbf{s}}$. We compare numerical results using diagonal mass (EFM1) and consistent mass(EF) with Meneghini's data.

Mean drag coefficient $2\overline{\mathcal{F}_{f,D}}/\rho D U^2$ and fluctuant lift coefficient $2\mathcal{F}'_{f,L}/\rho D U^2$ as function of frequencies ratio f_o/f_k are show in Figures 6(a) and 6(b). We observe a good accord with numerical results and literature.

The numerical phase results in diagonalize mass EFM1 and consistence mass EF matrix don't present great differences. To obtain precise numerical simulation using CAST3M, we advise the use of consistence mass matrix. The mean drag and fluctuant lift can represent precisely the "lock-in" phenomena.



(a) $f_o/f_{Sh} = 0.80$
(b) $f_o/f_{Sh} = 0.85$
(c) $f_o/f_{Sh} = 0.90$
(d) $f_o/f_{Sh} = 0.95$
(e) $f_o/f_{Sh} = 1.00$
(f) $f_o/f_{Sh} = 1.05$
(g) $f_o/f_{Sh} = 1.10$
(h) $f_o/f_{Sh} = 1.15$

Figure 4. Temporal displacement evolution $\mathbf{s}(t)/D$, and drag $2\mathcal{F}_{f,D}(t)/\rho DU^2$ and lift fluid forces $2\mathcal{F}_{f,L}(t)/\rho DU^2$.

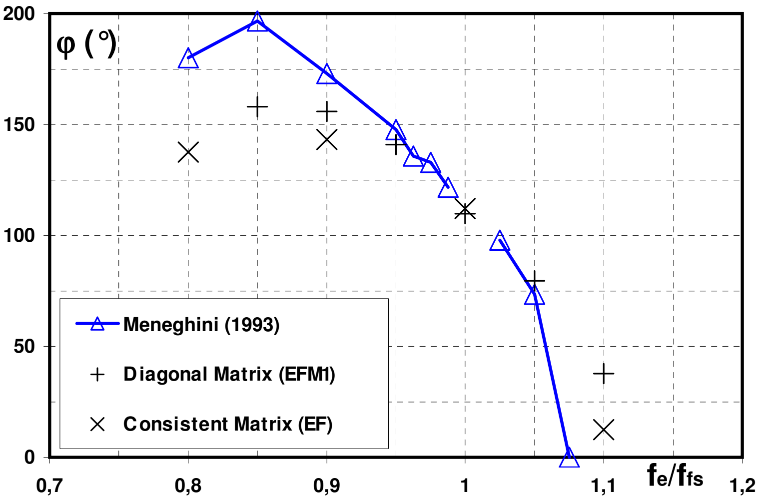
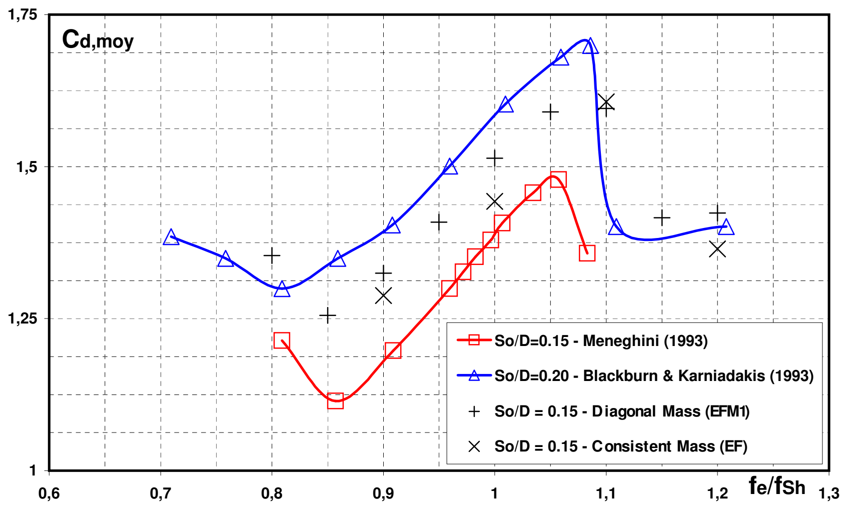
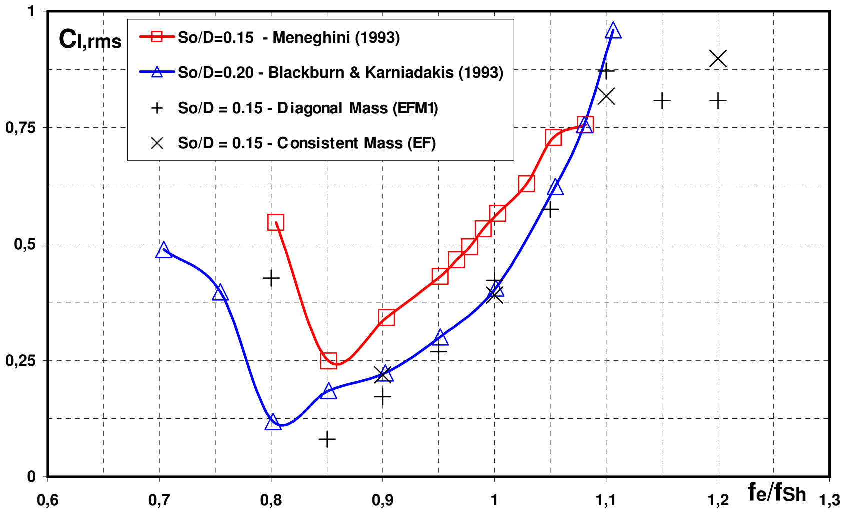


Figure 5. Displacement-lift phase *versus* f_o/f_k to $S_o/D = 0.15$.



(a) $2\overline{\mathcal{F}}_{f,D}/\rho DU^2$



(b) $2\mathcal{F}'_{f,L}/\rho DU^2$

Figure 6. $2\overline{\mathcal{F}}_{f,D}/\rho DU^2$ et $2\mathcal{F}'_{f,L}/\rho DU^2$ *versus* f_o/f_k pour $S_o/D = 0.15$.

4. CONCLUSIONS

We present a numerical example of using non-inertial referential technical ARF to provide a estimation of fluid-elastic forces of a mobile cylinder under 2D transverse fluid flow. We carried out a imposed harmonic movement on the tube perpendicular to flow, having a frequency ratio $f_o/f_k \in [0.85 - 1.20]$ and a reduced amplitude $S_o/D = 0.15$.

This numerical example is necessary to validate this implementation and to compare fluid-elastic results with others methods, like ALE and TRANSPIRATION.

5. ACKNOWLEDGEMENTS

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