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Publication date
2020

Document Version
Final published version

Published in
Proceedings of the 6th European Conference on Computational Mechanics

Citation (APA)
Dolfen, H., Bertocchi, F., Rohde, M., Vierendeels, J., & Degroote, J. (2020). Investigation of the gap vortex street in densely packed tube arrays in axial flow using CFD and experiments. In R. Owen, R. de Borst, J. Reese, & C. Pearce (Eds.), *Proceedings of the 6th European Conference on Computational Mechanics: Solids, Structures and Coupled Problems, ECCM 2018 and 7th European Conference on Computational Fluid Dynamics, ECFD 2018* (pp. 1009-1020). (Proceedings of the 6th European Conference on Computational Mechanics: Solids, Structures and Coupled Problems, ECCM 2018 and 7th European Conference on Computational Fluid Dynamics, ECFD 2018). International Centre for Numerical Methods in Engineering, CIMNE.

6th European Conference on Computational Mechanics (ECCM 6)
7th European Conference on Computational Fluid Dynamics (ECFD 7)
1115 June 2018, Glasgow, UK

INVESTIGATION OF THE GAP VORTEX STREET IN DENSELY PACKED TUBE ARRAYS IN AXIAL FLOW USING CFD AND EXPERIMENTS

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Key words: Gap instability, Vortex street, Vortex-induced vibrations

Abstract. Axial flow in tube bundles with small pitch-to-diameter ratio, a geometry encountered in nuclear reactor cores and heat exchangers, often displays periodic fluctuations. A significant velocity discrepancy between the inter-cylinder gap and subchannel center originates from the difference in through-flow area, feeding an instability. As it is associated with velocity-shear, it is similar to the Kelvin–Helmholtz type and the term 'gap instability' is adopted. A vortex street arises and structural vibration of the cylinders might develop due to the fluctuating pressure. Numerical simulations of this phenomenon were performed.

The computational domain was constructed to match the most important geometrical features of an experimental setup. The bundle consists of 7 steel tubes in triangular array, placed in a hexagonal conduit. A flexible segment made of silicone is embedded in the central tube, with both extremes clamped to the steel parts of the cylinder. In the experiment, data of the fluctuating velocity was gathered using laser Doppler anemometry measurements.

As first step, a completely rigid structure was considered. Unsteady Reynolds-averaged Navier–Stokes (URANS) simulations were used to test if this particular geometry also triggers the gap vortex street, which was the case. The phenomenon clearly appears as oscillations of the velocity components. Subsequently, fluid-structure interaction (FSI) simulations, taking into account the flexible part, allowed to assess the effect of the fluctuating flow field on the structure. A comparison between one-way and two-way coupled simulations was made.

1 INTRODUCTION

The focus of this research is the vibration of rod bundle geometries induced by axial flow. These geometries are common in nuclear reactor cores and heat exchangers. Different kinds of fluid-structure interactions can contribute to the load imposed by the fluid on the structure. The characterization of this load is important to assess safety and performance, and a lot of research has been dedicated to it in the past.

A first mechanism is turbulence-induced vibration. A fluctuating pressure field associated with the turbulence acts on the structure and excites vibrations. These were characterized by Curling and Païdoussis [1, 2] with experimental measurements. An analytical model for the response of a cluster of cylinders to the incident pressure field was derived earlier by Païdoussis and Curling [3]. The interest in this phenomenon has not ceased up to today, an example of recent work being the numerical research of De Ridder [4], in which vibration of a cylinder in turbulent annular flow was investigated using large eddy simulations (LES).

Another phenomenon is vortex-induced vibration. The best known example is the vibration of a cylinder in cross-flow resulting from the fluctuating forces associated with a von Kármán vortex street. Vortex shedding can however also occur in other flow situations. It is known that densely packed rod bundles are able to trigger a flow instability similar to the Kelvin–Helmholtz instability. This instability originates from the velocity shear between the inter-cylinder gap and subchannel and is the driving force for the vortex shedding. Meyer and Rehme [5] have investigated this shedding of large coherent structures with their experiments on compound rectangular channels and attempted to characterize the structure of the vortex street. The large-scale, quasi-periodic coherent structures appeared as a street of alternating, counter-rotating vortices. Other experimental work include that of Guellouz and Tavoularis [6, 7], who investigated a single cylinder near a wall. Building on this work, Chang and Tavoularis [8] performed numerical simulations on the same geometry using URANS simulations. The formation of large-scale, quasi-periodic coherent structures was again confirmed. A multi-rod geometry was experimentally investigated by Baratto [9]. This work identified the interaction of the different vortex streets, showing the possibility that the vortex street at one location is influenced by the one in an adjacent, or even remote location. This result expresses the need for further research, as was addressed by Chang and Tavoularis [10] by investigating a similar multi-rod geometry numerically. Again an interaction between the different streets coherent structures was found, forming a network. In an attempt to unify the nomenclature, Tavoularis [11] termed the instability as ‘gap instability’ and the resulting vortex street as ‘gap vortex street’, forming a ‘rod bundle vortex network’.

A more elaborate overview on the subject of gap vortex streets up to 2010 can be found in the paper of Meyer [12]. Examples of recent research are Choueiri and Tavoularis [13, 14], De Ridder [15] and De Moerloose [16]. This investigation mainly builds on the work of De Ridder [15].

Besides turbulence-induced and vortex-induced vibration, also fluid-elastic instabilities can arise. In that case, a strongly coupled interaction between the flow and structure

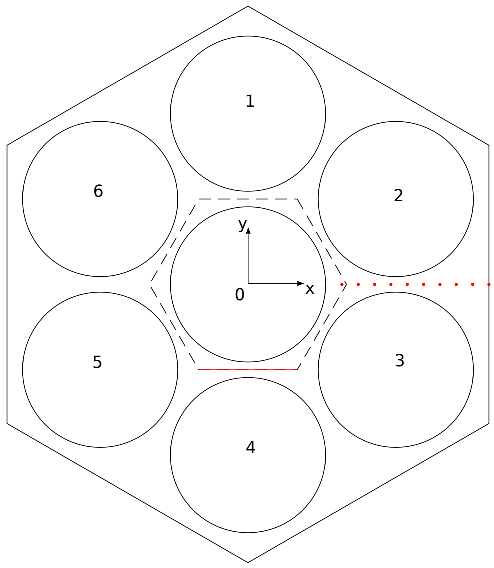


Figure 1: Cross-section of the geometry of the 7-rod bundle with indication of the measurement locations.

causes large amplitude motion. This can cause impacting between adjacent rods and short-term failure. This situation is usually avoided by design. However, also the small-amplitude vibration caused by turbulence or vortex-shedding can cause damage, due to fatigue and/or fretting.

For this study, the gap vortex street is investigated using Computational Fluid Dynamics (CFD). Subsequently, fluid-structure interaction simulations are performed, for a configuration free of fluid-elastic instabilities. The resonance frequency of the structure is in this case close to the expected excitation frequency of the fluctuating flow. In an attempt to assess the influence of the feedback of the structure on the flow, a comparison is made between one-way coupled simulations and two-way coupled simulations. The results could facilitate future research. Using the data, a comparison will be made with an experimental setup located at Delft University of Technology, in a later stage of the research. In this experimental setup, data on the velocity is collected using laser Doppler anemometry measurements.

2 METHODOLOGY

A schematic of the geometry under investigation is given in Figure 1. Seven steel rods are placed in a hexagonal duct. The central rod has a flexible part made of silicone, clamped at both ends to the steel parts of the rod. The clearance between the cylinder and duct matches the inter-cylinder gap. The geometrical data can be found in Table 1. It is a densely packed rod bundle and the pitch-over-diameter of 1.1 is in the range of P/D-ratios for which the gap vortex streets occur.

A structured, hexahedral grid is used, with 538 axial divisions, 120 divisions in circumferential directions and 5 divisions between the cylinder wall and the middle of the gap.

Table 1: Geometrical data of the rod bundle.

Parameter	Value
Diameter D	0.025 m
Pitch P	0.0275 m
Length L	0.7 m
Flexible length L_f	0.07 m

The structural mesh contains 1850 elements.

The commercial CFD-package ANSYS Fluent, applying the finite volume method (FVM), is used. The k-ω SST model is applied for turbulence modeling. At the walls, no-slip boundary conditions are imposed. Streamwise periodic boundaries with a pressure gradient of 4905 Pa/m drive the water flow. This streamwise periodic boundary condition was also used by Chang and Tavoularis [8], the main benefit being the reduced domain length and therefore mesh size, as the flow is inherently developed. All quantities were discretized using second order schemes.

The finite element method (FEM) is used for the structural side, implemented in the Computational Solid Mechanics (CSM) software package Abaqus.

For the coupling between fluid and structure during the FSI calculations, an in-house code is used. A partitioned approached is followed, utilizing the IQN-ILS algorithm [17].

During the FSI-calculations, the loads on the fluid-structure interface are repeatedly reported by the CFD model to the CSM model. The CSM model calculates the deformations and reports these back. For the one-way case, the loads on an undeformed cylinder are reported by Fluent, but interpreted by Abaqus as acting on its deformed geometry. This mismatch between the fluid and structure side is always present in one-way simulations and an important consideration when doing them, but the difference is here considered negligible because the deformations are small.

The length of the domain (0.7 m) is deemed to be large enough compared to the flexible part (0.07 m), so that the downstream influence of the structural motion has decayed when reaching the flexible part again, after re-entering the domain.

Before the FSI was switched on, 8.89 s of flow time were simulated with the structure rigid, to allow the flow to settle, using time steps of 0.289 ms. In this phase non-iterative time advancement (NITA) was used. After that the coupling (either one-way or two-way) was switched on and the PISO-algorithm was used to compute 1200 more time steps.

3 RESULTS

In this section the results are discussed, involving a discussion about the flow structure and a comparison between one-way coupling and two-way coupling.

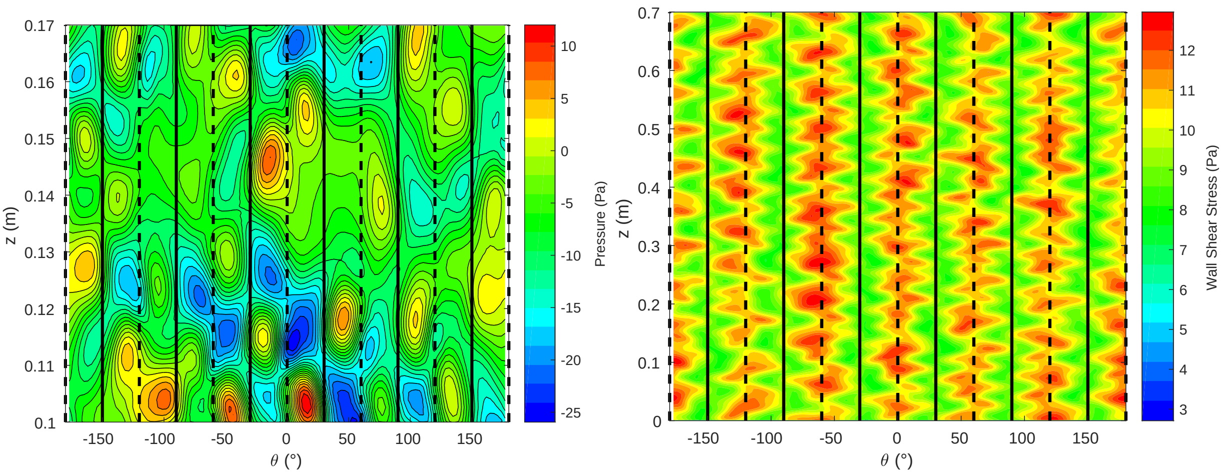


Figure 2: (a) Pressure on the flexible cylinder wall and (b) shear stress on the complete cylinder wall. The dashed lines indicate subchannels, while the solid line indicate gaps.

3.1 Coherent structures and incident pressure field

For the first part, it is checked whether the vortex streets appear for this particular geometry and flow conditions, and if they are captured by the URANS-simulations. This was the case, as expected, and a more detailed discussion follows below. The figures that are used in this paragraph are extracted from the results of the two-way coupled simulations, but the discussion on this level is equally valid for the one-way case.

Figure 2a displays the incident pressure field on the wall of the flexible cylinder. Figure 2b shows the shear stress on the central cylinder (indicated by '0' on Figure 1) along the entire length (note the different range of the z-axis). The circumferential positions corresponding to a subchannel are indicated by a dashed line, while those corresponding to gaps are indicated by solid lines. The pressure field gives a good impression of the structure of the flow. Regions of low and high pressure can be observed in between the gaps and subchannels.

Figure 3 facilitates examining the flow structure in more detail. It shows only four pressure cells in a plane in between cylinders, indicated in Figure 1 as the bottom edge of the dashed hexagon (solid red line). The in-plane components of the velocity vectors are plotted in overlay, but are given constant length for clarity purposes. These velocity vectors are calculated relative to the bulk velocity, estimated as the mass flow rate divided by the density and throughflow area. For clarity, the figure has been stretched in horizontal direction. This figure indicates a clear link between the pressure and velocity field and reveals the vortical nature of the flow structure. Low pressure regions are indeed associated with a vortex because they provide the centripetal force to curve the flow towards the vortex center. The high pressure regions are located at the convex side of the streamlines, which is to be expected as they provide the force to curve the flow away. The vertical centerline of the figure corresponds with a gap. The vortices can thus be seen to appear in counter-rotating pairs, at alternating sides of the gap. This the flow structure that

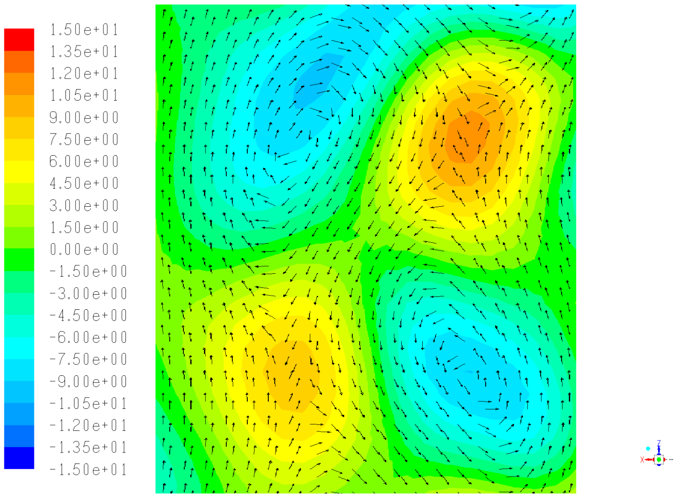


Figure 3: Plot of the pressure contours on a plane in between cylinders, indicated as a solid red line in Figure 1, with an overlay of velocity vectors relative to the bulk velocity and given constant length.

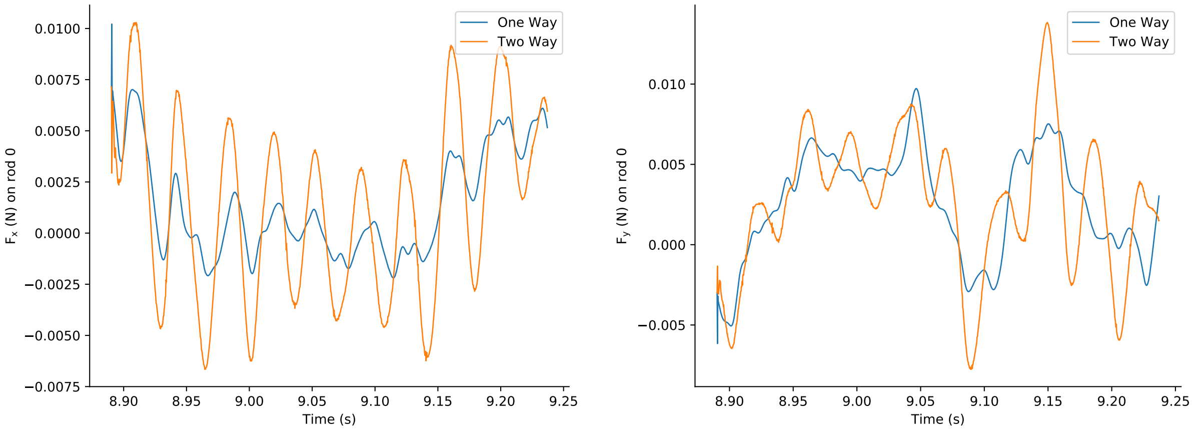
has also been proposed by Meyer and Rehme [5], among others. In the gap region, in between the low and high pressure zones, the flow follows an oscillatory trajectory, with the low pressure cells at the concave sides. This flow path can also be observed in Figure 2b, as the wall shear displays the same oscillatory behavior, transporting high velocity fluid from the subchannels towards the gaps and vice versa. Increased mixing rates have indeed been observed for this kind of geometries in past investigations, which have been summarized by Meyer [12].

Going back to Figure 2a, the alternating vortex streets from adjacent gaps form a kind of rhombic network, connecting the low pressure regions. Similarly, a connection of the high pressure regions forms a similar rhombic mesh, but shifted spatially. This structure is however disrupted at some locations. This is likely due to the chaotic nature of the quasi-periodic flow pulsations, as Baratto [9] states it: ‘The coherent structures are not perfectly periodic in time and possibly interact among themselves so that the signals would occasionally contain phase shifts and even missing periods.’

3.2 One-way coupling to two-way coupling comparison

In this section the comparison between one-way coupling and two-way coupling is made by examining the forces acting on the rods.

Figure 4a and 4b show the x- and y-components of the total force acting on the flexible cylinder as a function of time, for both the one-way and two-way case. A remarkable difference is to be seen, as the force components for the two-way case display a higher amplitude than those for the one-way simulation. This indicates that the feedback from structure to the fluid has an important influence. This can possibly be due to a lock-in mechanism. As the difference in results for one-way simulations and two-way simulations is not negligible, relying solely on one-way coupling is believed to be insufficient for this



(a) (b)

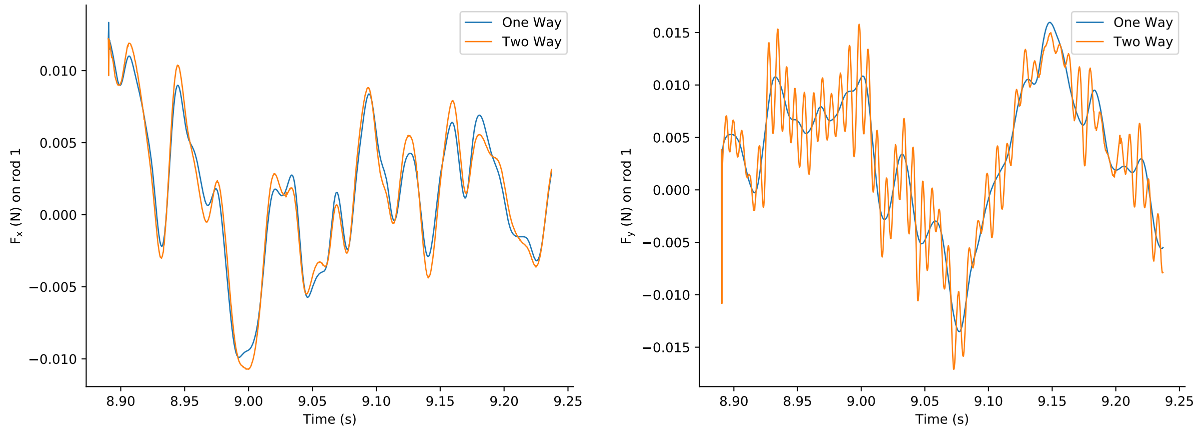
Figure 4: Force in (a) x-direction and (b) y-direction on the flexible segment of rod 0.

case.

For the axial component (not shown), no difference is seen between the two force components. This is because the traction force is small, compared to the tranversal components associated with the pressure field, thus inducing small displacement. Moreover, the deformation induced by traction does not significantly change the geometry from the point of view of the flow.

Figure 5a and 5b show the force components on a part of rod 1 with the same axial location as the flexible part. Upon investigation of the force in x-direction on rod 1 also a higher amplitude is found for the two-way coupled case, although the difference is less pronounced than on rod 0 because rod 1 is rigid. This result is obscured for the y-component, due to a high frequency component that seems to be superposed on it. It is hypothesized that it originates from a kind of radial mode, as will be explained in the following paragraph.

The use of periodic boundary conditions in an incompressible solver implies that using a pressure reference is necessary, to avoid a floating pressure. In ANSYS Fluent, this is achieved by making a certain point of the domain the pressure reference location. The pressure value at this location is subtracted from the entire pressure field every iteration. The pressure in this point is thus constant. In this case, the entire pressure field has a fluctuating nature due to the convection of the coherent structures. This causes a constantly changing global pressure level because the local fluctuations in the pressure reference point are applied as an offset to the entire field, and consequently a changing compressive force acts on the flexible cylinder. This excites a breathing mode, a vibration of the cylinder radius. This vibration cannot be found in the forces acting on the central cylinder, as the global pressure level cancels out over the circumference. The associated displacement however has an influence. Via its feedback on the fluid domain it creates extra forces acting on the peripheral rods. This extra force is expected to be only found in a component radiating away from the center, and not in a direction perpendicular to



(a) (b)

Figure 5: Force in (a) x-direction and (b) y-direction on rod 1.

it. Indeed, as can be seen from Figure 5a and 5b, the high frequency content is only found in the y-component, this direction is coincident with a line connecting the centers of rod 0 and rod 1. The x-force, which is perpendicular to this line, does indeed not show a high frequency component. The same observations were found by expressing the forces on every peripheral rod in components along a radial and circumferential direction, reinforcing the conclusion.

3.3 Displacements

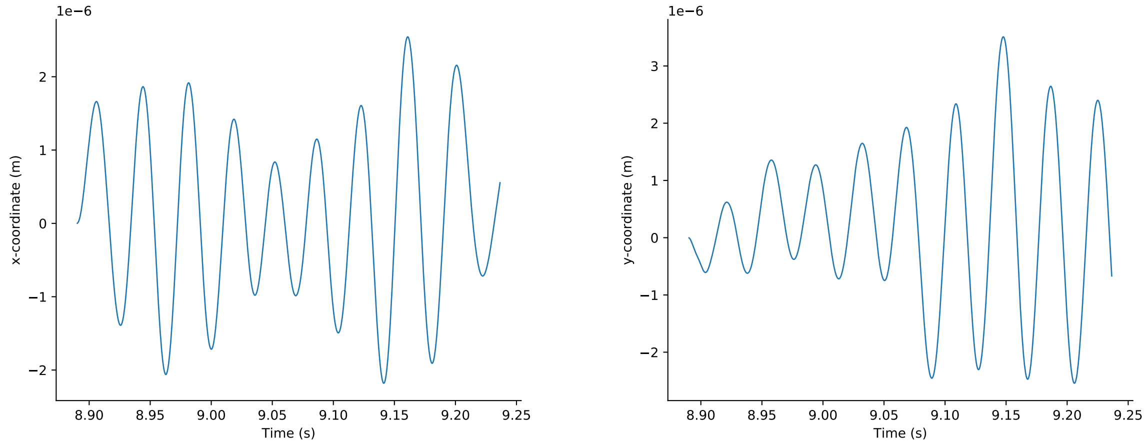
Further evidence of a breathing mode causing high frequency force components is found when looking at displacements of the two-way coupled case.

Figure 6a and 6b show the centerline displacement for an axial coordinate of 0.0135 m, i.e. the center of the flexible cylinder, as a function of time. This gives an indication of the transversal vibration of the rod. It can be seen to be a low frequency motion, more or less in correspondence with the forces (see Figure 4a and 4b).

In order to assess the radial mode, the average radius of a cross-section, again at an axial coordinate of 0.135 m, is calculated. The result is depicted in Figure 7. It can be seen that the breathing mode amplitude is an order of magnitude smaller than the beam mode amplitude. Its frequency is higher, and resembles that of the extra force component observed in Figure 5b, as expected.

The simulation time window of 0.346222 seconds of flow time is too short to perform a rigorous frequency analysis (e.g. by using FFT). The signals cannot be considered stationary yet (see for example the forces on rod 1, Figure 5a and 5b), but a rudimentary analysis is attempted by estimating the number of periods.

The forces on the central rod and the consequential lateral motion have about 9 to 10 periods, indicating a frequency of 26 to 29 Hz. Information on the velocity components (not shown here) was collected in some points of the domain, indicated in Figure 1 by red dots. 10 to 11 periods were present, indicating a frequency of 29 to 32 Hz. A frequency



(a) (b)

Figure 6: Centerline displacement in (a) x-direction and (b) y-direction of the flexible rod at z=0.135 m.

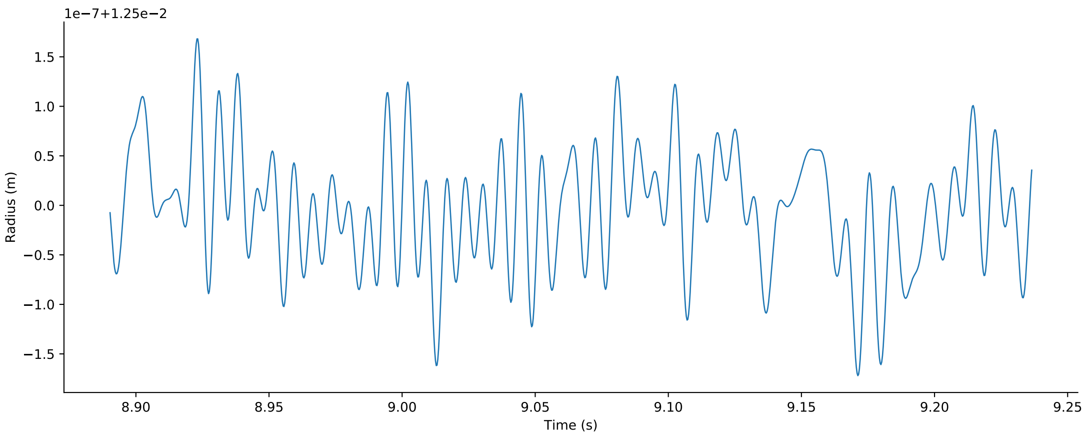


Figure 7: Average radius at z=0.135 m.

of 31 Hz was reported earlier by De Ridder [15]. As these frequencies are close, the beam mode vibration is clearly associated with the vortex shedding.

In Figure 5b, about 46 oscillations can be found, which corresponds to a frequency of about 133 Hz. The signal displayed in Figure 7 is a bit chaotic, but 42 to 46 periods can be found. As this signal contains more periods compared to the time window, an attempt to do a frequency analysis can be made. The fist local maximum of the autocorrelation of the signal is found at a shift of 25 to 26 timesteps. This would correspond to a frequency of 133 to 138 Hz.

It is clear that two distinct phenomena are found here: at a low frequency the beam mode vibration associated with the vortex shedding, and at a high frequency the breathing mode vibration excited by a changing global pressure level. While not being unphysical, the breathing mode is associated with the numerical setup rather than with the physics involved in the actual case of interest. A possible solution to this is changing the pressure reference: instead of keeping one single point of the domain fixed at a constant pressure, the entire volume average can be kept constant. This is expected to average out fluctuations and consequently diminish or even eliminate oscillations of the global pressure level. This will be attempted in the continuation of the research, confirming or debunking the claim that a breathing mode is caused by the pressure reference point.

4 CONCLUSIONS

Numerical simulations of a 7-rod bundle similar to an experimental setup has been performed. The appearance of a rod bundle vortex network has been confirmed and its structure has been examined. After that, a comparison between one-way and two-way coupled simulations has been made. This revealed that the forces, especially those on the flexible structure, displayed a higher amplitude, which could indicate a kind of lock-in phenomenon coming into play. It at least discourages the use of one-way coupled simulations for this particular case in future research.

A high frequency component was also found in the force components radiating away from the central cylinder, acting on the peripheral cylinders. It was hypothesized that they originate from a breathing mode of the central cylinder, triggered by a changing global pressure level. This oscillating global pressure level is believed to be caused by the numerical setup, namely the use of a pressure reference point.

Future research will include further investigation into this breathing mode and the elimination of it, and comparing quantitatively data with the experimental setup. This will be the frequency content of the velocity components as well as the displacement of the central cylinder.

5 ACKNOWLEDGEMENTS

This work was performed in the framework of the H2020 SESAME Project. It has received funding from the Euratom research and training program 2014-2018 under grant agreement No 654935 (SESAME). The computational resources (Stevin Supercomputer Infrastructure) and services used in this work were provided by the VSC (Flemish Supercomputer Center), funded by Ghent University, FWO and the Flemish Government department EWI.

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