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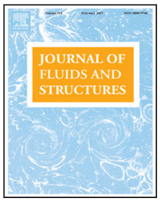

Numerical investigation of large-scale vortices in an array of cylinders in axial flow

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ABSTRACT

Axial flow around an array of cylinders is commonly encountered in nuclear reactors and heat exchangers. This geometry is subject to important flow instabilities. The chaotic flow fluctuations due to turbulence are not the only source of vortex structures: large-scale vortices have also been observed, both experimentally and numerically. The periodic pressure fluctuations caused by the coherent vortex structures are possibly a source of fretting and fatigue in the aforementioned applications. In order to comprehend this phenomenon, Large-Eddy Simulations are performed on a numerical domain containing a single rigid cylinder with periodic boundary conditions, representative for a cylinder in an infinite square array. The research in this paper mainly focuses on the influence of the cylinder spacing, which is analysed by calculating the Cross Spectral Density (CSD) function of the cylinder wall pressure for different cylinder spacings. The spectral analysis shows that the amplitude of the pressure fluctuations increases up to a well-determined intercylinder gap, after which it decreases exponentially for incrementing gap size. With the weakening of the instability, the location on the cylinder circumference where the maximum pressure amplitude occurs, changes as well. Finally, it is shown that the coherent vortices are transported as a whole at a convection speed which is dependent on the cylinder spacing. An updated model for this convection speed is proposed.

1. Introduction

An array of cylinders subjected to axial flow is encountered in numerous applications. Of special interest are heat exchanger geometries in general (Kakaç et al., 2012) and nuclear reactor core arrays specifically (Païdoussis, 1982). The problem of fluid–elastic instabilities in both cross-flow (Pettigrew and Taylor, 2003) and axial flow (Au-Yang, 2001; Païdoussis, 1998) has been investigated analytically, experimentally and numerically. Most analyses focus on the buckling behaviour of a single cylinder (Modarres-Sadeghi et al., 2007) or of an array of cylinders. Chaotic dynamics, due to turbulence-induced vibrations, are also analysed extensively (Curling and Païdoussis, 1992; Païdoussis and Botez, 1993). However, the tube bundle geometry gives rise to non-chaotic flow phenomena as well. The earliest recollection of the existence of coherent vortices dates back to Nikuradse (1930). The secondary flow described in that report finds its origin in nonuniform turbulent mixing in a non-circular duct, but is relatively weak compared to the vortex street which dominates

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Nomenclature

CFD	Computational Fluid Dynamics
CSD	Cross-Spectral Density
DFT	Discrete Fourier Transform
A_{flow}	through-flow area [m^2]
A_{wall}	wall surface area [m^2]
C_S	Smagorinsky model parameter [–]
f_{LM}, f_{MM}	Smagorinsky model quantities
D	cylinder diameter [m]
D_h	hydraulic diameter [m]
f_{min}	dimensional frequency [Hz]
G	tophat filtering function
h	cell width [m]
k	discrete frequency variable [–]
L	domain length [m]
n	discrete time variable [–]
N	number of divisions [–]
p	(wall) pressure [Pa]
P	cylinder pitch [m]
$P(\theta, z, St)$	Fourier variable of the pressure [Pa]
Re	Reynolds number [–]
(r, θ, z)	cylindrical coordinate system [$(m, ^\circ, m)$]
LES	Large-Eddy Simulation
PSD	Power Spectral Density
URANS	Unsteady Reynolds-Averaged Navier–Stokes
S_{ij}	shear stress tensor [1/s]
St	Strouhal number [–]
t	time [s]
T	number of considered time steps [–]
u	instantaneous velocity [m/s]
U	mean velocity [m/s]
U_c	convection velocity [m/s]
(x, y, z)	cartesian coordinate system [(m, m, m)]
x_i	general spatial coordinate [m]
γ	coherence function [–]
Δ	LES filter width [m]
μ	dynamic viscosity [Pa s]
ν	kinematic viscosity [m^2/s]
ν_t	turbulent kinematic viscosity [m^2/s]
ρ	fluid density [kg/m^3]
τ_{ij}	residual stress tensor [m^2/s^2]
τ_w	wall shear stress [m^2/s^2]

the velocity field. A schematic representation is shown in Fig. 1, which indicates that the flow instability is related to a cross-flow mechanism across the gap between two adjacent cylinders, creating coherent vortices on either side of the gap. The vortex street is not stationary, but is transported through the flow. The symbol U_c denotes the convection speed of the coherent structures. An example of the transverse velocity component across a cylinder gap region – obtained through the Large-Eddy Simulations described in this paper – is shown in Fig. 1. Both the axial flow speed difference and the cross-flow fluctuations cause pressure oscillations on the cylinder wall. As a result, the cylinder wall pressure distribution is greatly dependent on the large-scale vortices. This provides the opportunity to analyse the vortex street by considering the cylinder wall pressure, which is the subject of this paper.

The large-scale vortices are related to the close spacing of the cylinders. Consider the schematic top view of a square cylinder array in Fig. 2. The drawn array is assumed to be infinitely wide and long, i.e. boundary and entrance effects are not taken into account. Two flow regions are distinguished: the gap region (g), located in between two adjacent cylinders, and the subchannel region (s), positioned in the middle of four cylinders. Due to the smaller flow area, the influence of the cylinder wall friction on the flow is stronger in the gap region than in the subchannel region. Consequently, the axial flow velocity in the subchannel region is higher than in the gap region. The flow velocity difference between a gap region and a neighbouring subchannel region leads to the existence of a Kelvin–Helmholtz instability.