Wind-structure interaction simulations of ovalling vibrations in silo groups

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Abstract

During a storm in October 2002, wind-induced ovalling vibrations were observed on several empty silos of a closely spaced group of silos in the port of Antwerp (Belgium). In this paper, three-dimensional numerical simulations are used to investigate this complex case of wind-structure interaction. The computed amplitude of the ovalling vibrations of the silos is similar to that in the observations, indicating that the adopted modelling approach can be suitable for the analysis of new silo groups.

Both one-way and two-way simulations are presented, for a single silo and for the silo group. In the one-way simulations, the wind pressure is applied on the structure, disregarding the structural displacements in the wind flow simulation. By contrast, the two-way simulations also take into account the effect of the structural motion on the wind flow. For a single silo, the one-way and two-way simulations yield similar results. Conversely, for a silo in the group, the ovalling vibrations are significantly larger in the two-way simulations than in the one-way simulations. Consequently, aeroelastic effects and/or interactions between the wake-induced excitation and the vibration are present in the silo group for the investigated case.

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Furthermore, it is shown that the aerodynamic loading and vibration amplitudes are considerably larger for silos in the group than for a single isolated silo.

Keywords: wind-structure interaction, aeroelastic instability, wind-induced vibration, ovalling, silo

1. Introduction

Given the tendency to build ever taller, more slender and hence increasingly flexible structures, many present-day constructions are susceptible to wind-induced vibrations. Although mostly very small, these vibrations can become excessive and there are many examples of catastrophic structural failure due to wind-induced vibrations (Païdoussis et al., 2011; Belloli et al., 2011; Sheldard, 1967; Billah and Scanlan, 1991). For the design of flexible structures, it is therefore increasingly important to understand the mechanisms that are causing these vibrations and to provide engineers with proper methodologies and tools to investigate these phenomena.

In the present paper, the case of a group of 40 silos in the port of Antwerp (Belgium) is studied (figure 1). During a storm in 2002 wind-induced ovalling vibrations with an amplitude of approximately 0.1 m have been observed on several empty silos at the windward side of the group. This vibration is significant compared to the gaps of 0.3 m between the silos. As is typical for ovalling deformations, the cross section of the axisymmetrical structure deforms as a shell, without bending deformation with respect to the longitudinal axis of symmetry (Païdoussis and Wong, 1982).

The ovalling vibrations of the silo group show some similarity with the collapse of 3 cooling towers from a group of 8 at Ferrybridge (UK) during a gale in 1965 (Pope, 1994). However, these collapsed cooling towers were located at the leeward side of the group while the ovalling vibrations in the silo group occurred on the windward side. A major difference between the silo group and the cooling towers is the size of the gaps between the individual objects, respectively 5%

Figure 1: Southwest corner of the silo group in the port of Antwerp (Belgium) where ovaling vibrations were observed in October 2002.

25 of the diameter compared to approximately one diameter. This entails that the
 26 flow blockage effect for the silo group is much higher than for the cooling towers.
 27 Furthermore, the cooling towers are made of reinforced concrete as opposed to
 28 aluminium for the silo group, resulting in lower damping for the latter. The
 29 investigation of this incident with the cooling towers identified a tensile merid-
 30 ional failure within the shell fabric as dominant initial mode of failure. For the
 31 particular wind direction during the gale, the mean meridional force increased
 32 by 30% and the resonance force doubled, whereas the quasi-static fluctuating
 33 force remained more or less the same compared to an isolated tower (Pope,
 34 1994).

35 Because of the complexity of this wind-structure interaction (WSI) problem,
 36 a simplified phenomenological model or experimental methods are not suitable
 37 to investigate the ovaling vibrations. Other aeroelastic applications, e.g. flutter
 38 of bridge decks or galloping of cables can be modelled with a two degrees of
 39 freedom system in a wind tunnel (Païdoussis et al., 2011). However, a scale
 40 model of a silo structure that has the appropriate flexibility is not easily con-
 41 structed. Furthermore, in situ measurements of the structural response under
 42 normal wind loading by Dooms et al. (2006) could not decisively pinpoint what
 43 mechanism is causing the ovaling vibrations.

44 By contrast, the versatility of numerical techniques to simultaneously incor-
 45 porate complex wind flow details and structural flexibility, even for problems
 46 with complex geometries, is a great advantage. Procedures are available to
 47 couple a numerical model for the wind flow, i.e. computational fluid dynamics
 48 (CFD), and the structure, e.g. finite element (FE) models. Hence, this WSI
 49 problem can be studied numerically. Numerical studies on the flutter of bridges
 50 have been performed by Mannini et al. (2011a) and Šarkić et al. (2012), for
 51 example. Furthermore, the motion of light-weight membrane structures under
 52 wind load is analyzed numerically by Hojjat et al. (2010) and Michalski et al.
 53 (2011). In addition, the deflection of wind turbine blades during operation is
 54 calculated by Bazilevs et al. (2011). However, the behaviour of silos and other
 55 cylinders under wind loading is still often investigated without taking the struc-
 56 tural displacement into account in the flow calculation (Uernatsu et al., 2015;
 57 Gorski et al., 2015; Zhao et al., 2013, 2014).

58 In this paper, WSI simulations are performed to investigate the wind-induced
 59 overvibrations of individual silos mounted in a group arrangement. Com-
 60 pared to our previous work related to this silo group (Hillewaere et al., 2012),
 61 a significantly different methodology is proposed. Our previous work only con-
 62 tained CFD simulations, with rigid structures. In this work, flexible structures
 63 are considered, with and without including the influence of their motion on the
 64 wind flow. The model of the silo group was 2D in our previous work and has
 65 been extended to 3D in this paper, which among other things entails including
 66 the atmospheric boundary layer. Consequently, only frequencies and circumfer-
 67 ential mode shapes could be calculated in our previous work, without changes
 68 along the axis of the silo, and no magnitudes of the vibrations. In addition, the
 69 turbulence modelling has been improved to resolve a fraction of the turbulent
 70 fluctuations. Finally, the results in our previous work overestimated the excita-
 71 tion by the flow in the wake of the silo group because the simulations were 2D
 72 which preserves large vortices and prevents their break up.

73 The goal of this paper is threefold. First, the necessity of taking into account
 74 the structural displacement in the flow calculations for this aeroelastic problem

is analyzed. The differences between the results with and without including displacement in the flow will shed light on the mechanisms possibly causing the vibrations. Second, the effect of the group arrangement on the magnitude of the vibrations is determined by comparing by WSI simulations for a single silo with those for the entire closely spaced silo group. As mentioned above, the cooling towers at Ferrybridge experienced higher loading but they are more widely spaced so it is unclear whether that finding also applies to the silo group. Third, it is assessed whether the adopted modelling approach is suitable as an engineering tool for the analysis of new silo groups and possibly of similar structures to avoid the ovalling vibrations.

The paper is organized as follows. In section 2, details of the ovalling phenomenon are given and the present state of knowledge on wind-induced ovalling vibrations is briefly sketched. In section 3, the methodology for performing WSI simulations is explained in detail. The numerical models and techniques used for modelling both the wind flow and the silo structures are subsequently explained in section 4. In section 5, the results of the WSI simulations are described. Finally, the main conclusions of the study are given in section 6.

2. Observation and physical interpretation of ovalling vibrations

Wind-induced ovalling vibrations have been observed on several empty silos at the windward side of a group consisting of 40 silos in the port of Antwerp (Belgium) during a storm on 27 October 2002. Based on observations and an in-depth analysis of available low resolution video footage of the ovalling event, the amplitudes of the ovalling shell oscillations were estimated in the order of 0.1 m. Displacements of this order of magnitude are reasonably large compared to the silo diameter $D = 5.5$ m and the limited space of 0.3 m between adjacent silos. The largest vibrations were observed at the windward corner of the silo group (silo 1 in figure 2). Other silos at the windward side also showed ovalling but with smaller amplitude.

As shown in figure 3, the group of 8 by 5 thin-walled aluminium silos is

104 mounted at 16.66 m above ground level. Only the upper cylindrical part of the
 105 silos is exposed to the incoming wind flow. The lower conical parts are embedded
 106 in a rectangular building that is 49 m long and 31.6 m wide. Each silo is 25 m
 107 high and is composed of aluminium sheets with a varying thickness decreasing
 108 with height from 10.5 mm to 6 mm. Because the simulation of highly turbulent
 109 wind flows around complex geometries is a challenging task, simplifications in
 110 the computational model are required. Therefore pipes, cables, walking plat-
 111 forms on top of the silos as well as the staircase next to the group will not be
 112 considered in this analysis.

Figure 2: Plan view of the silo group with numbering of the individual silos. Normative dimensions are given as well as the definition of the angle of incidence α .

113 No measurements are available of the wind field near the silo group at the
 114 time the ovalling instabilities were observed. However, at a permanent meteo-
 115 rological station in Deurne, about 7 kilometers east of the silo group, the hourly
 116 average wind speed was monitored and ranged from 61 to 68 km/h with peaks up

Figure 3: Lateral view of the silo group.

117 to 113 km/h. As indicated in figure 4, the silo group is located in flat surround-
 118 ings near the river Scheldt and the main wind direction was west-southwest at
 119 the time of ovalling (figure 4 and $\alpha \approx 30^\circ$ in figure 2). With this information,
 120 a loading condition can be created which is expected to be similar to the one
 121 causing the observed ovalling in 2002 and sufficiently accurate to identify the
 122 underlying physical mechanisms that caused the vibrations.

123 A distinction is generally made between three different excitation mecha-
 124 nisms for flow-induced vibrations or more specifically wind-induced vibrations
 125 (Blevins, 1990; Païdoussis et al., 2011; Weaver et al., 1993; Žukauskas et al.,
 126 1988; Price et al., 1987): turbulence-induced vibrations, wake-induced vibra-
 127 tions and fluidelastic instability (FEI). In the case of wind, the latter is also
 128 called aeroelastic instability (AEI). Turbulence-induced excitation (or buffet-
 129 ing) originates from fluctuations in the wind flow around the structure, e.g. from
 130 natural turbulence in the wind flow attacking the structure. Wake-induced ex-
 131 citation is due to periodic vortex shedding in the wake of the structure, possibly
 132 with interaction (e.g. lock-in) between this wake and the structural motion. By
 133 contrast, aeroelastic phenomena are self-excited and the fluctuating forces are

Figure 4: Location of the silo group near the river Scheldt in the port of Antwerp (Belgium). The mean wind direction during the storm of 27 October 2002 was west-southwest as indicated by the arrow. The shaded area denotes the flat region in front of the group.

134 due to structural motion. Also combinations of these phenomena occur.

135 3. Methodology

136 In this section, the one-way and two-way simulations are described. Comparing their results provides some insight into the excitation mechanisms of the
 137 observed wind-induced vibrations. The calculation of the silo's deformation by
 138 a structural solver and of the wind by a flow solver are discussed in more detail
 139 in section 4. In the following paragraph, short notations for these solvers are
 140 already defined.

142 The aerodynamic pressures and shear stresses $\mathbf{P}(t_i)$ on the interface between
 143 the structure and the wind flow — i.e. on the surface shared by the structural
 144 calculation and the wind flow calculation — are determined in a wind flow
 145 simulation for time step t_i . The structural solver $\mathcal{S}$ calculates the structural
 146 response of the silo due to these aerodynamic loads $\mathbf{P}(t_i)$:

$$\mathcal{S}[\mathbf{P}(t_i)] = \mathbf{U}(t_i). \quad (1)$$

147 The response of the entire structure is calculated but only the displacements
 148 of the interface are passed back as $\mathbf{U}(t_i)$. The notation in this equation only

149 mentions information on the interface ($\mathbf{U}$ and $\mathbf{P}$). Obviously, also previous time
150 levels $t_{i-1}, t_{i-2}, \dots$ and additional boundary conditions are taken into account
151 when calculating the solution, but these are not shown to keep the notation
152 clear.

153 Based on the interface displacements, the flow solver $\mathcal{F}$ deforms the mesh in
154 the fluid domain close to the silo. Subsequently, the flow solver calculates the
155 wind in the entire fluid domain and returns the aerodynamic loading $\mathbf{P}(t_i)$ on
156 the interface:

$$\mathcal{F}[\mathbf{U}(t_i)] = \mathbf{P}(t_i). \quad (2)$$

157 Similarly, the dependence on previous time levels, on additional boundary con-
158 ditions and on the remainder of the fluid domain are implicitly understood.

159 3.1. One-way approach

160 In the one-way approach, the aerodynamic loads are first computed for a rigid
161 structure, followed by calculation of the resulting structural response. Conse-
162 quently, wind-structure interaction is not considered in the one-way approach.
163 Because the structure is not moving in the aerodynamic load calculation, only
164 turbulence-induced vibrations and part of the wake-induced vibrations are ac-
165 counted for in this approach. Interactions between the wake-induced excitation
166 and the structural motion as well as aeroelastic effects are not captured.

167 The flow solver $\mathcal{F}$ is used to determine the aerodynamic loading, $\mathbf{P}(t)$, acting
168 on the interface between structure and wind flow in every time step: $\mathcal{F}[\mathbf{0}] =$
169 $\mathbf{P}(t_i)$, with $\mathbf{0}$ referring to the zero displacements of the rigid structure. As
170 illustrated in figure 5, the resulting time history $\mathbf{P}(t)$ of aerodynamic loads
171 on the interface is subsequently applied as an external transient load on the
172 structure and the structural displacements are computed in the structural solver:
173 $\mathcal{S}[\mathbf{P}(t)] = \mathbf{U}(t)$.

174 Due to an abrupt application of wind pressures on the undeformed silo struc-
175 tures, a long period of transitional effects would be observed in the structural
176 response. To avoid such a transitional regime, a static loading step is intro-
177 duced first: $\mathbf{K}\mathbf{U}_0 = \mathbf{P}_0$. The pressures in the first time step of the aerodynamic

Figure 5: Schematic representation of the interaction between the flow solver $\mathcal{F}$ (white) and the structural solver $\mathcal{S}$ (grey) in the one-way partitioned simulation. The time-dependent aerodynamic loads $\mathbf{P}(t)$ are calculated with zero structural displacement. Subsequently, they are transferred to the structural solver for the calculation of the time-dependent displacement $\mathbf{U}(t)$, starting with initial displacement $\mathbf{U}_0$ from a steady calculation.

simulation $\mathbf{P}_0 = \mathbf{P}(t_1)$ are statically applied to the structure and the structural response $\mathbf{U}_0$ is used as an initial condition for the dynamic structural calculations. The effect of such preliminary static calculation has been found to be very effective to reduce initial transitional effects in the present simulations.

3.2. Two-way approach

The two-way simulations take into account the structural motion when calculating the wind flow. As opposed to the one-way approach, these two-way simulations are therefore WSI (or FSI) simulations in the true sense. In addition to the turbulence-induced and part of the wake-induced vibrations, these simulations also capture aeroelastic effects and interactions between the wake-induced excitation and the structural vibration. By comparing the results of the one-way and two-way simulations, it is possible to assess the importance of aeroelastic effects and/or interactions between the wake-induced excitation and the structural motion for the wind-induced vibrations.

In two-way simulations, the structural and flow solver are coupled in every time step as illustrated schematically in figure 6. A partitioned technique is applied which couples the black box flow solver with the black box structural

195 solver. Partitioned means that two independent solvers are used for the flow
 196 equations and for the structural equations, as opposed to the monolithic ap-
 197 proach which solves all equations together. Black box means that the source
 198 code of these solvers is not available and that Jacobians of the outputs with
 199 respect to the inputs cannot be obtained. Since the resulting aerodynamic
 200 loads $\mathbf{P}(t_i)$ and displacements $\mathbf{U}(t_i)$ typically differ slightly from the ones that
 201 were applied in the previous iteration within the same time step, consecutive
 202 flow and structural simulations have to be performed until equilibrium of load-
 203 ing and displacements is obtained on the interface between structure and wind
 204 flow.

Figure 6: Schematic representation of the interaction between the flow solver $\mathcal{F}$ (white) and the structural solver $\mathcal{S}$ (grey) in the two-way partitioned approach. In each time step t_i , the displacements $\mathbf{U}(t_i)$ and loading $\mathbf{P}(t_i)$ on the silo surface are exchanged multiple times between the flow solver and the structural solver. When these coupling iterations have converged, the following time step is started.

205 A multitude of coupling techniques have been proposed to solve FSI prob-
 206 lems in a partitioned way, as reviewed by Degroote (2013). In each time step,
 207 these techniques solve the flow equations and the structural equations multiple
 208 times to find the solution which satisfies the equilibrium conditions. For compu-
 209 tational efficiency, the number of coupling iterations has to be limited as much as
 210 possible. Therefore, the interface quasi-Newton technique with an approxima-
 211 tion for the inverse of the Jacobian of the coupled problem from a least-squares

212 model (IQN-ILS) is applied (Degroote et al., 2009). This root-finding algorithm
 213 solves the equilibrium equation

$$\mathcal{S}[\mathcal{F}[\mathbf{U}]] - \mathbf{U} = \mathbf{0} \quad (3)$$

214 with Newton-Raphson iterations, using a least-squares approximation for the
 215 inverse of the Jacobian of this equation. Since wind flow and structural response
 216 are calculated in black box solvers, this approximation is exclusively based on
 217 displacements of the fluid-structure interface in previous coupling iterations and
 218 time steps.

219 4. Numerical models of wind flow and structure

220 As discussed in section 3, separate black box solvers can be used for the
 221 calculation of the wind flow and of the structural response. Details on the
 222 numerical methods and settings used by these solvers are discussed hereafter.

223 4.1. Wind flow model

224 In the 3D CFD model, two different configurations are considered: a single
 225 silo and a group of 40 silos, all of which are mounted on a prismatic building
 226 as described in section 2. In the case of the single silo, the building is oriented
 227 at an angle of incidence of $\alpha = 45^\circ$ with respect to the incoming wind flow
 228 while an angle of $\alpha = 30^\circ$ is considered for the silo group configuration. The
 229 single silo case is studied in the light of comparing single silo and silo group
 230 results to assess the importance of the group effect on the overlying vibrations.
 231 Furthermore, the single silo is a computationally less expensive problem that
 232 can be used to study grid sensitivity of the simulations.

233 Several best practice guidelines are available in the literature for the CFD
 234 simulation of wind flows in urban environments, e.g. the AIJ guidelines (AIJ,
 235 2006; Tominaga et al., 2008) and the COST guidelines (COST Action C14, 2004;
 236 COST Action 732, 2007). Not only the size of the computational domain, but
 237 also the choice of appropriate boundary conditions, mesh and time step size as

238 well as the choice of convergence criteria for iterative processes are discussed in
239 these documents. These guidelines are followed as closely as possible.

240 *Numerical procedure*

241 A finite volume method is used in the CFD simulations for the discretization
242 of the governing incompressible Navier-Stokes equations. Large eddy simulation
243 (LES) resolves the large scale turbulent structures in the air flow. However,
244 LES simulations are computationally demanding for high Reynolds number
245 wind flows, especially if near-wall flows are calculated for a good prediction
246 of the aerodynamic forces on the silo walls. By contrast, a Reynolds-averaged
247 Navier Stokes (RANS) model is cheaper to simulate the near-wall flows. As
248 a compromise between these two options, delayed detached eddy simulations
249 (DDES) with $k - \omega$ SST as RANS model are performed in Ansys Fluent (Flu-
250 ent 14.5, 2012). This turbulence model has also been used in other studies
251 on similar objects and Reynolds numbers (Squires et al., 2008; Mannini et al.,
252 2011b; Gopalan and Jaiman, 2015). (D)DES models are referred to as hybrid
253 LES/RANS models because the RANS modelling of the boundary layer flow
254 in the near-wall region is combined with the LES approach in the separated
255 regions, where large unsteady turbulence scales are dominant. In the delayed
256 DES approach, a shielding function is used to ensure that RANS is applied in
257 the entire boundary layer since a sole geometrical separation of RANS and LES
258 regions based on mesh size has shown to be insufficient (Spalart et al., 2006).
259 For the shielding function, the blending functions of the SST turbulence model
260 are used (Menter et al., 2003).

261 For the discretization of the momentum equations a bounded central differ-
262 encing scheme is used. A second-order interpolation of the pressure, a second-
263 order upwind interpolation of the turbulent kinetic energy k and the specific
264 dissipation rate ω are applied. A bounded second-order implicit, uncondition-
265 ally stable, time stepping method has been selected. The SIMPLE algorithm
266 (Patankar and Spalding, 1972) is used for the pressure-velocity coupling between
267 the momentum and the continuity equations. In the COST guidelines, it is rec-

ommended that the residuals in the CFD solver should be reduced by at least four orders of magnitude. Therefore, the iterative process in (every coupling iteration within) every time step is truncated when the normalized residuals are all below 10^{-5} .

In the one-way simulations, an Eulerian, fixed grid description is used in the fluid solver. Modifications have to be made to account for a moving fluid grid when a two-way WSI simulation is carried out. Therefore, the flow equations are reformulated in an arbitrary Lagrangian-Eulerian (ALE) description (Donea et al., 1982, 2004). The mesh motion in the wind domain is determined by the motion of the deformable fluid-structure interface. For the simulations with a single silo, a smoothing technique (Batina, 1990; Löhner and Yang, 1996) is used to extend the displacements of the fluid-structure interface into the entire fluid domain. Conversely, for the silo group, Laplace equations are solved for the mesh displacement to handle the more challenging ALE mesh updates in the narrow gaps between adjacent silos. This implies that these diffusion equations for the mesh velocities of the fluid grid have to be solved iteratively in every coupling iteration. Approximately 10 iterations are required for every Laplace mesh update in the present application. This results in good grid quality for all occurring displacements of the silos and causes only a small increase in simulation time compared to the Eulerian formulation.

Computational domain and boundary conditions

The size of the computational domain is shown in figure 7 and is slightly larger than prescribed by guidelines (AIJ, 2006): e.g. height of the domain $6H > 5H$, blockage ratio $1.7\% < 3\%$, etc. The dimensions of the domain do not only depend on the zone of interest but also on the applied boundary conditions. The top boundary condition has to sustain the equilibrium ABL profiles. For this purpose, symmetry boundary conditions are applied which provide a good approximation of reality as long as the top boundary is located sufficiently far from the region of interest (COST Action 732, 2007). Symmetry boundary conditions are applied at the lateral boundaries as well while a constant pressure

Figure 7: Dimensions of the computational domain and global coordinate system, with origin at the bottom of the domain at the centre of the structure.

is applied at the outflow boundary. The walls of the building and the silo structures are modelled as no-slip walls.

A horizontally homogeneous unidirectional wind flow is applied at the inlet of the domain. Since no exact wind field data are available, approximative wind conditions are set up based on guidelines (AIJ, 2006; BIN, 2010; Tominaga et al., 2008; ANSI, 2010). Given the location of the silo group, the present case is classified in terrain category II of Eurocode 1 (BIN, 2010). The free field wind velocity is set to $u_{\text{ref}} = 31.8 \text{ m/s}$ at approximately mid-height of the silos, i.e. at $z_{\text{ref}} \approx 30 \text{ m}$ above ground level. This corresponds roughly to the peak wind velocities that were monitored in 2002 at the meteorological station in Deurne a few kilometers from the site. The highly turbulent wind flow regime around the group of silos is hence post-critical (Zdravkovich, 1997) at Reynolds number $\text{Re} = u_{\text{ref}} D / \nu = 1.24 \times 10^7$ with $\nu = 1.41 \times 10^{-5} \text{ m}^2/\text{s}$.

For the variation of the mean wind velocity with height $\bar{u}(z)$ in the atmospheric boundary layer (ABL, cfr. shaded area in figure 7), a power law profile as prescribed in the AIJ guidelines is used (AIJ, 2006; Tominaga et al., 2008).

314 The mean wind velocity u_{ref} at a reference height of $z_{\text{ref}} = 30$ m is used to fit
 315 the power law:

$$\overline{u}(z) = u_{\text{ref}} \left(\frac{z}{z_{\text{ref}}} \right)^{\beta}, \quad (4)$$

316 with β a constant depending on the terrain roughness which equals 0.14 for the
 317 considered terrain category (II, open country).

318 Note that an incompatibility of inflow data and wall boundary conditions
 319 at ground level may have an important impact on the preservation of the ho-
 320 mogeneity of the ABL flow (Blocken and Carmeliet, 2006; COST Action C14,
 321 2004; COST Action 732, 2007; Quinn et al., 2001; Zhang, 1994). This effect is
 322 limited to the lowest region of the ABL however (Castro, 2003). In the German
 323 guidelines (VDI-Richtlinie 3783, 2003), it is therefore recommended to place at
 324 least two nodes between the ground and the zone of interest. Considering the
 325 fact that the silo structures are mounted on a prismatic building, this effect is
 326 of no further consequence in the present simulations.

327 To simulate a 3D turbulent wind flow, realistic random wind field data have
 328 to be modelled at the inlet of the domain as well. In the present simulations,
 329 turbulence is synthetically generated with a spectral synthesizer method pro-
 330 posed by Smirnov et al. (2001), as implemented in Ansys Fluent (Fluent 14.5,
 331 2012). A power law profile for the turbulence intensity $I_u(z)$, based on the AIJ
 332 guidelines (Tominaga et al., 2008) is used as input for this spectral synthesizer
 333 method:

$$I_u(z) = 0.1 \left(\frac{z}{z_G} \right)^{-\beta-0.05}, \quad (5)$$

334 with $z_G = 350$ m the gradient height of the ABL in open country (terrain
 335 category II) (Tominaga et al., 2008).

336 *Discretization sensitivity analysis*

337 In the case of DDES simulations, it is advisable to get an indication of the
 338 sensitivity of the results to discretization cut-offs. In tables 1 and 2, the size of
 339 the computational domain is listed for several levels of grid refinement in the
 340 simulation of the flow around the single silo and around the entire silo group,

341 respectively. Most of the grid is block-structured, except for the part at the
 342 top of the silos. The maximal y^+ values along the circumference are around
 343 100, so wall functions are applied. At least 60 cells are present in the gaps
 344 between the silos of the group. It is obvious that an increase in number of grid
 345 cells results in a significant increase of computational efforts. It takes about 40,
 346 72 and 111 hours of computing time for the coarse, medium and fine meshes,
 347 respectively, to calculate 40 s of wind flow in the 3D simulation for a single silo.
 348 These calculations have been performed on 64 parallel cores, i.e. half of the cores
 349 of four quad-socket octa-core AMD Magny-Cours machines (Opteron 6136) at
 350 2.4 GHz with almost full use of the working memory of all machines (64 GB
 351 RAM per machine). For the simulation of the wind flow around the entire silo
 352 group on the coarse and fine grids, respectively 280 and 450 hours are required
 353 to simulate the same time frame of 40 s on the same 64 parallel cores.

Mesh	N_{circ}	N_{dom}
coarse	64	1 573 872
medium	80	4 552 486
fine	112	8 233 532

Table 1: Overview of the number of cells N_{dom} in the computational domain for the single silo
 simulations. Three stages of grid refinement are considered, based on the number of divisions
 N_{circ} on the circumference of the silo surface.

Mesh	N_{circ}	N_{dom}
coarse	64	8 276 472
fine	80	17 066 268

Table 2: Overview of the number of cells N_{dom} in the computational domain for the silo
 group simulations. Two stages of grid refinement are considered, based on the number of
 divisions N_{circ} on the circumference of the silo surface.

354 In view of the objectives of the present investigation, this inevitably implies

Figure 8: Detail of the coarse mesh of a single silo structure with the wind at an angle of incidence $\alpha = 45^\circ$.

that compromises between accuracy and required computational effort have to be made, especially for the two-way simulations where multiple coupling iterations have to be performed per time step. In this respect, it is important to assess discretization errors and take them into account for the interpretation of simulation results rather than pursuing extreme grid refinements to obtain a completely grid independent solution. Furthermore, it is noted that a simulated time frame of only 40 s is fairly short in wind engineering where typically response quantities are averaged over periods of 10 minutes or longer. Again, the length of these time intervals is limited by the high computational costs.

First, the single silo configuration is considered. A detail of the computational mesh (coarse grid) for the single silo is shown in figure 8, with incoming flow along the x -axis. The results for the mean and RMS values of the drag coefficients in x - and y -directions are summarized in table 3. A variability in the drag coefficients for the different grid sizes is observed. These discrepancies are due to differences in the predicted location of the separation point on the silo surface and, hence, the largest differences are observed for the mean drag

coefficient $\overline{C}_{dx}$ in the x -direction. It should be underlined that the accurate prediction of separation points on smooth, curved surfaces is a major challenge for every turbulence modelling technique in CFD.

Mesh	$\overline{C}_{dx}$	C_{dx}^{RMS}	$\overline{C}_{dy}$	C_{dy}^{RMS}
Coarse	0.426	0.021	0.025	0.061
Medium	0.359	0.018	0.018	0.052
Fine	0.302	0.017	-0.005	0.027

Table 3: Mean value and root mean square value of the drag coefficients C_{dx} and C_{dy} for the single silo with wind flow at an angle of incidence $\alpha = 45^\circ$ and for different mesh refinements.

For a selection of representative silos in the group, the drag coefficients in x - and y -directions are listed in table 4. Figure 9 furthermore shows the time history of C_{dx} and C_{dy} for the corner silos of the group. From table 4, it is observed that the cylinders at the front of the silo group (e.g. silos 1, 17, 25 and 33) are subject to larger drag forces than silos at the centre of the group (e.g. silos 30 and 38). Silos 1, 9, 17, 25 and 33 have the largest area exposed directly to the incoming flow (figure 2), resulting in the highest drag coefficients C_{dx} . Overall, it is concluded that the drag coefficients predicted on both meshes are in reasonably good agreement for the majority of the silos, including for silo 1 where the ovalling vibrations have been observed. Although the separation of the flow is much more geometrically determined for the entire silo group, difficulties with the prediction of separation are still observed for the transverse corner silos (silos 8 and 33 in figure 2) and for some of the upwind silos in the first row of the group. This difference between the results on both meshes at the transverse corner silos is mainly due to the prediction of the separation points on smooth, curved surfaces as in the single silo case.

Finally, also the influence of the time step on the accuracy of the simulations has been assessed by performing different simulations with a systematic reduction of the time step. This time step refinement has only been carried out for the single silo configuration. From the results summarized in table 5,

Figure 9: Time history of the drag coefficients (top) C_{dx} and (bottom) C_{dy} for the corner silos of the silo group (silo 1 - dashed black line; silo 8 - solid black line; silo 33 - dashed grey line; silo 40 - solid grey line) with wind flow at an angle of incidence $\alpha = 30^\circ$ and for (left) the coarse mesh and (right) the fine mesh.

it is concluded that a time step $\Delta t = 0.005$ s is sufficiently small. Although no explicit verification was made for the entire silo group, it can be reasoned that all physical flow phenomena for the silo group have larger length scales and hence longer periods which can be accurately captured by this time step. The COST guidelines (COST Action C14, 2004; COST Action 732, 2007) instruct that the choice of the time step is determined by the relevant frequencies in the flow: the highest frequency to be considered needs to be resolved with at least 10 to 20 time steps. When a time step size of 0.005 s is used, this means that frequencies of 10 Hz are still resolved. In the following, it will be shown that this is sufficiently accurate given the low natural frequencies of the silo structures and the low frequency content of the wind flow.

4.2. Structural model

The software package Abaqus (Abaqus 6.10, 2010) has been used to construct a finite element (FE) model of the silo structure which allows to calculate the

Silo	Mesh	$\overline{C}_{dx}$	C_{dx}^{RMS}	$\overline{C}_{dy}$	C_{dy}^{RMS}
1	Coarse	0.841	0.045	-0.253	0.022
	Fine	0.781	0.043	-0.268	0.022
5	Coarse	0.221	0.048	0.199	0.045
	Fine	0.233	0.057	0.192	0.043
8	Coarse	0.409	0.121	-0.094	0.154
	Fine	0.361	0.128	-0.269	0.195
17	Coarse	0.757	0.053	-0.381	0.031
	Fine	0.798	0.057	-0.411	0.045
25	Coarse	0.704	0.055	-0.269	0.043
	Fine	0.748	0.061	-0.281	0.050
30	Coarse	0.036	0.030	0.037	0.017
	Fine	0.038	0.031	0.043	0.024
33	Coarse	0.254	0.114	0.175	0.166
	Fine	0.403	0.072	0.059	0.096
38	Coarse	0.069	0.035	0.066	0.028
	Fine	0.043	0.034	0.064	0.033
40	Coarse	0.050	0.046	0.152	0.061
	Fine	0.042	0.048	0.104	0.066

Table 4: Mean value and root mean square value of the drag coefficients C_{dx} and C_{dy} for a selection of silos of the 8 by 5 silo group with wind flow at an angle of incidence $\alpha = 30^\circ$ and for the coarse and the fine mesh. The silos on the corners of the group are highlighted in the table.

structural response of the silos to applied aerodynamic pressures and shear stresses. This model is also used to determine the ovalling eigenmodes and corresponding natural frequencies of the silos.

Each silo in the group is made of 10 aluminium cylindrical sheets with a height of 2.5 m each (figure 10). At the top and bottom of the cylinder, a cone is welded to the cylinder at an angle of 15° and 60° with the horizontal plane, re-

Δt	C_{dx}^{RMS}	ΔC_{dy}
0.01 s	0.022	0.104
0.005 s	0.016	0.085
0.0025 s	0.016	0.082
0.000125 s	0.016	0.082

Table 5: Root mean square value of drag coefficient C_{dx} and amplitude $\Delta C_{dy} = C_{dy}^{\text{max}} - C_{dy}^{\text{min}}$ for the 3D single silo (fine mesh) and for different time steps.

spectively. Shell elements with linear FE interpolation functions are used for the entire structure. For the dynamic simulations, the unconditionally stable and second-order accurate Hilbert-Hughes-Taylor (HHT) method as implemented in the Abaqus FE solver is used.

The following material properties are used for aluminium: density $\rho = 2700 \text{ kg/m}^3$, Young's modulus $E = 67.6 \text{ GPa}$ and Poisson's ratio $\nu = 0.35$. Rayleigh damping is assumed and based on a constant damping ratio $\xi = 0.75\%$ for the two lowest eigenmodes. This is a realistic approximation since modal damping ratios ξ for this structure, determined during in situ measurements by Doms et al. (2006), were found to vary between 0.07% and 1.32%. These low modal damping values are typical for a welded aluminium structure. The silo is bolted to an octagonal steel framework at 4 points on the circumference of the cylindrical shell (figure 10).

To accommodate an easy transfer of the aerodynamic loads on the silo walls from flow solver to structural solver, the mesh of the FE model is chosen conforming to the mesh on the silo walls in the CFD simulations. As a result, three different structural models are used, i.e. one for each of the three CFD grids for a single silo (cfr. table 1).

Natural frequencies and ovaling modes

The mass normalized eigenmodes Φ and corresponding eigenfrequencies f_{eig} are determined by solving the generalized eigenvalue problem of the structure.

Figure 10: Geometrical representation of the silo structure with indication of the variation of the shell thickness t_s of the aluminium plates along the height z_s of the silo structure.

435 The eigenmodes corresponding to the lowest eigenfrequencies are summarized
 436 in table 6 and a selection of these modes is shown in figure 11.

Φ_j	(m, n)	$f_{\text{eig}j} [\text{Hz}]$	Φ_j	(m, n)	$f_{\text{eig}j} [\text{Hz}]$	Φ_j	(m, n)	$f_{\text{eig}j} [\text{Hz}]$
Φ_1	(1, 3)	3.96	Φ_7	(1, 5)	5.70	Φ_{13}	(2, 5)	8.19
Φ_2	(1, 3)	3.97	Φ_8	(1, 5)	5.71	Φ_{14}	(2, 6)*	8.62
Φ_3	(1, 4)	3.99	Φ_9	(1, 6)	7.72	Φ_{15}	(2, 4)	8.85
Φ_4	(1, 4)	4.11	Φ_{10}	(1, 6)	7.72	Φ_{16}	(2, 4)	9.10
Φ_5	(1, 5)	5.34	Φ_{11}	(1, 2)	7.83	Φ_{17}	(2, 6)	9.62
Φ_6	(1, 5)	5.35	Φ_{12}	(2, 5)	8.18	Φ_{18}	(2, 6)	9.72

Table 6: Natural frequencies f_{eig} of the lowest ovaling eigenmodes of the silo structure. The mode shapes indicated with an asterisk are a combination of two ‘pure’ ovaling shapes.

437 The mode shapes are of the ovaling type and are referred to by a couple
 438 (m, n) , where m denotes the number of half wavelengths in the axial direction

439 and n is the number of circumferential wavelengths. For an axisymmetric struc-
 440 ture most of the ovalling eigenmodes come in pairs: e.g. Φ_1 and Φ_2 are both
 441 classified as mode shapes (1,3) but are mutually orthogonal. The mode shapes
 442 indicated with an asterisk, e.g. $\Phi_{14} = (2,6)^*$ are referred to as ‘hybrid’ mode
 443 shapes. Such mode shapes are characterized by two combined ‘pure’ ovalling
 444 shapes at once, e.g. shapes (1,2) and (2,6) in the case of $\Phi_{14} = (2,6)^*$ (figure
 445 11d).

446 From the silo group vibrations observed during the storm in 2002, it is be-
 447 lieved that mainly ovalling modes (1,3) and (1,4) were excited by the wind field,
 448 corresponding to the lowest eigenfrequencies of the silo structure. Measure-
 449 ments during normal wind loading have also shown that eigenmodes with 3 or
 450 4 circumferential wavelengths have the highest contribution to the response of
 451 the silos (Dooms et al., 2006).

452 For the physical interpretation of the structural response, a more quantita-
 453 tive analysis is proposed in the following that allows to assess the modal con-
 454 tributions in the response. The deformation energy $E_d(t)$ is easily determined
 455 from the calculated structural response $\mathbf{U}(t)$ of the entire structure:

$$E_d(t) = \frac{1}{2} \mathbf{U}^T(t) \mathbf{K} \mathbf{U}(t), \quad (6)$$

456 where $\mathbf{K}$ represents the stiffness matrix of the structural FE model. The con-
 457 tributions of the different eigenmodes in the response are subsequently distin-
 458 guished by applying modal decomposition. By inserting $\mathbf{U}(t) = \Phi \alpha(t)$, with
 459 $\alpha(t)$ the modal coordinates, in equation (6), the deformation energy is decom-
 460 posed into modal contributions as follows:

$$E_d(t) = \frac{1}{2} \alpha^T(t) \Phi^T \mathbf{K} \Phi \alpha(t) = \frac{1}{2} \sum_{j=1}^{n_{\text{DOF}}} \omega_j^2 \alpha_j^2(t) = \sum_{j=1}^{n_{\text{DOF}}} E_{dj}(t) \quad (7)$$

461 where n_{DOF} is the number of degrees of freedom of the FE model. Based on this
 462 expression, the contribution $E_{dj}(t)$ of an individual mode j to the deformation
 463 energy $E_d(t)$ can be determined from the modal coordinates $\alpha(t)$.

Figure 11: (top) 3D isotropic view and (bottom) horizontal section at mid-height for a selection of ovaling eigenmodes of a silo: (a) mode $\Phi_1 = (1, 3)$ at 3.96 Hz, (b) mode $\Phi_4 = (1, 4)$ at 4.11 Hz, (c) mode $\Phi_5 = (1, 5)$ at 5.34 Hz and (d) mode $\Phi_{14} = (2, 6)^*$ at 8.62 Hz.

464 5. Wind-structure interaction simulation results

465 In this section, the wind-induced vibrations of the silos are analyzed using
 466 wind-structure interaction simulations. As described in section 3 both one-way
 467 and two-way simulations are performed for the single silo and the silo group
 468 configuration. Given the agreement between the results on the different grids
 469 in the previous section, the second finest grid is presented here. Simulations
 470 performed on other grids led to the same conclusions and are hence omitted for
 471 brevity. A time frame with the last 25 s is considered in all coupled simulations
 472 unless indicated differently.

473 5.1. Single silo simulations

474 One-way simulations

475 First, the flow pattern around the single silo as shown in figure 12 is consid-
476 ered. Streamlines are shown in a vertical and several horizontal planes across
477 the height of the structure. The flow has a highly three-dimensional character
478 and different flow patterns can be observed at different heights. Upstream of
479 the structure, near the ground, a horseshoe vortex is clearly formed in the flow
480 (figures 12top and a). The flow around the prismatic building is attached to
481 the surface on the windward side of the prism and separation occurs at the
482 corners of the building. At the connection between the prismatic building and
483 the cylindrical silo structure, the flow is deflected upwards and detaches from
484 the sharp edges of the building. These accelerated upward flows are deflected
485 sideways due to the vicinity of the cylindrical silo (figure 12b). Along the height
486 of the silo structure, the flow is separated at the lee side of the cylindrical sur-
487 face, generating a highly turbulent and narrow wake region, typical for high
488 Reynolds number cross-flows around cylinders. At the free end of the silo struc-
489 ture (figure 12d), the separated trailing vortex is mainly dragged downstream
490 and only slightly deflected downwards. The existing downwash effect has al-
491 ready disappeared at mid-height of the silo (figure 12c). As indicated by Park
492 and Lee (2004), the conical shape of the silo top might also explain the reduced
493 width of the wake formed near the free end of the cylinder. Downwash effects
494 are therefore thought to be limited at the present Reynolds number and little if
495 any interaction with the flow at midspan of the silo is observed. It could also be
496 argued that downwash effects can only have a very limited effect on the already
497 narrow and short wake region over the entire length of the silo structure.

498 In the one-way simulation of the single silo, a predominantly static structural
499 response with maximal displacements of approximately 0.04 m is found and
500 significantly smaller ovalling vibrations in the order of 0.01 m are observed.
501 These deformations are converted into nodal contributions to the deformation
502 energy $E_{dj}(t)$ which are shown as a function of time in figure 13 for the 20

Figure 12: Streamlines of the wind flow around a single silo structure after 40 s, colored according to the velocity magnitude, released from (top) a vertical plane $y = 0$ m and horizontal planes at (a) $z = 0.5$ m, (b) $z = 17.16$ m, (c) $z = 29.16$ m, and (d) $z = 41.16$ m.

503 structural eigenmodes with the lowest eigenfrequencies. Additional calculations
 504 accounting for geometrical nonlinearities did not reveal a significant effect of
 505 nonlinearities on the structural response.

Figure 13: Modal deformation energy $E_{dj}(t)$ of the first 20 mode shapes, computed from the structural response in the one-way simulation of a single silo: $\Phi_2 = (1, 3)$ (bold black line), $\Phi_4 = (1, 4)$ (thin black line), $\Phi_6 = (1, 5)$ (thin grey line), $\Phi_{14} = (2, 6)^*$ (bold grey line), $\Phi_{18} = (2, 6)$ (dashed black line), and the remaining mode shapes Φ_j (dashed grey lines, with small energy content).

506 Figure 13 shows that only a limited number of modes contribute significantly
 507 to the structural response of the silo. Typically, three time scales, named mean,
 508 resonant and quasi-static, are distinguished in the modal deformation energy
 509 $E_{dj}(t)$ (Holmes, 2015).

- 510 • The mean, time averaged modal deformation energy is related to the static
 511 excitation of a structural mode. Mode $\Phi_{18} = (2, 6)$, for example, is almost
 512 exclusively excited statically (dashed black line in figure 13).
- 513 • While a whole range of irregular oscillations seems to be present in the
 514 fluctuating parts of the response, regular oscillations of eigenmodes $\Phi_2 =$
 515 $(1, 3)$ (bold black line), $\Phi_4 = (1, 4)$ (thin black line) and $\Phi_6 = (1, 5)$ (thin
 516 grey line) at their respective eigenfrequencies can be clearly observed.
 517 This resonant response is mainly found for the eigenmodes with the lowest

518

natural frequencies.

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- All remaining oscillations are categorized as the background response of the structure. The fourteenth mode $\Phi_{14} = (2, 6)^*$, for example, is almost exclusively excited by low frequency fluctuations (bold grey line in figure 13). Because this is a one-way simulation, it is sure that these low frequency fluctuations originate from the wind, but it is difficult to discern between incoming flow and the silo wake. Such oscillations typically give rise to quasi-static swaying deformations of the silo, free of resonant effects.

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In the following, time averaged results are considered to facilitate comparison of results for one-way and two-way coupled simulations. Figures 14a and b show the time averaged $\overline{E}_{dj}$ and RMS values E_{dj}^{RMS} of the modal deformation energy for the one-way simulation of the single silo for the 50 eigenmodes with the lowest eigenfrequencies. The mean modal deformation energy $\overline{E}_{dj}$ (figure 14a) gives an indication of the static excitation of the eigenmodes while the RMS values E_{dj}^{RMS} (figure 14b) contain information on resonant and quasi-static motion.

Figure 14: (left) Mean value and (right) RMS value of the modal contributions to the deformation energy $E_{dj}(t)$ for the single silo in the one-way simulation. The deformation energy for the lowest 50 eigenmodes is plotted as a function of n while separate mode shapes $(1, n)$ are depicted as a circle ($\circ$), $(2, n)$ as a square ($\square$), $(3, n)$ as a diamond ($\diamond$), and $(4, n)$ as a cross ($\times$).

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The mean modal deformation energies in figure 14a are significantly larger

than the RMS values in figure 14b (shown on a different vertical scale). From these figures, it is observed that modes $\Phi_2 = (1, 3)$, $\Phi_6 = (1, 5)$ and $\Phi_{14} = (2, 6)^*$ are predominantly excited statically. This is of course related to the aerodynamic forces applied on the structure: high pressures at stagnation, low pressures in the attached boundary layer flows on the sides and a more or less constant pressure after separation. A snapshot of the resulting displacements is shown in figure 15a.

By comparing figures 14a and 14b for the mean and RMS value of the modal deformation energy, respectively, it is clear that structural vibrations are much smaller than the static displacements. According to figure 14b, the mode shapes that are excited dynamically are the eigenmodes with the lowest circumferential wavenumber n and only a half wavelength across the height ($m = 1$). It is noted that the RMS values characterize the magnitude of the dynamic response, regardless of the nature of the latter. For example, the RMS value of mode $\Phi_{14} = (2, 6)^*$ is due to quasi-static vibration while for modes $\Phi_2 = (1, 3)$ and $\Phi_6 = (1, 5)$ RMS values similar in magnitude correspond to resonant vibrations. This can be observed in figure 13 where the amplitudes of the oscillations at the corresponding eigenfrequencies are smaller for the former than for the latter two.

Two-way simulations

Two-way simulations are performed for the single silo to assess the change in structural response due to aeroelastic effects and/or interaction between wake-induced excitation and the vibration. In general, 5 IQN-ILS coupling iterations have to be performed in each time step to ensure equilibrium on the WSI interface. The computational effort required for the two-way simulations is therefore approximately 5 times larger than for the one-way simulations.

The time histories of the modal deformation energy in the one-way (figure 13) and the two-way simulation (figure 16) are compared. Furthermore, the averaged and RMS values of the response in the one-way and two-way simulation are compared (figures 14 and 17). It is observed that the static response and

Figure 15: Displacement of the single silo at $t = 15$ s in the one-way simulation. The structural displacements are mainly static and are amplified with a scale factor of 40.

Figure 16: Modal deformation energy $E_{dj}(t)$ of the first 20 mode shapes, computed from the structural response in the two-way coupled simulation of a single silo: $\Phi_2 = (1, 3)$ (bold black line), $\Phi_4 = (1, 4)$ (thin black line), $\Phi_6 = (1, 5)$ (thin grey line), $\Phi_{14} = (2, 6)^*$ (bold grey line), $\Phi_{18} = (2, 6)$ (dashed black line), and the remaining mode shapes Φ_j (dashed grey lines, with small energy content).

565 the RMS value of the deformation energy are similar in both simulations. This
566 is reflected in the similar static peak displacements of approximately 0.04 m in

Figure 17: (left) Mean value and (right) RMS value of the modal contributions to the deformation energy $E_{d_j}(t)$ for the single silo in the two-way simulation. The deformation energy for the lowest 50 eigenmodes is plotted as a function of n while separate mode shapes $(1, n)$ are depicted as a circle ($\circ$), $(2, n)$ as a square ($\square$), $(3, n)$ as a diamond ($\diamond$), and $(4, n)$ as a cross ($\times$).

both simulations. For eigenmode $\Phi_2 = (1, 3)$, the static and RMS value of the dynamic response are distributed differently over the two orthogonal mode shapes in the one-way and two-way simulations but with a similar total value.

In both the one-way and the two-way simulations, the RMS values of the deformation energy are one order of magnitude smaller than the corresponding static values. It is concluded from these observations that qualitatively similar results are found in the one-way and two-way simulation of a single silo, with the same modes contributing to the quasi-static and resonant response of the structure.

5.2. Silo group simulations

In order to study the effect of the group arrangement on the wind-induced vibrations, both one-way and two-way simulations have been performed for silos at different locations in the silo group. In the one-way simulations, all corner silos are flexible while in the two-way simulation, only the silo at the windward corner is flexible as this is where the largest vibration amplitudes were observed. The same methodology is applied as in the single silo case.

584 Velocity streamline plots of the flow pattern around the silo group are given
585 in figure 18. It is obvious that the flow pattern around the entire silo group has
586 a much more complex and turbulent nature than that around the single silo.
587 Nevertheless, some trends that were previously discussed are also observed for
588 the group configuration. The formation of a horseshoe vortex is for instance
589 clearly observed (figures 18top and a). The horseshoe vortex is observed at the
590 same location as in Shah and Ferziger (1997) for the wind flow around a cube
591 building with one face perpendicular to the incident wind. In this study, it
592 was found that the primary separation occurs at a saddle point located about
593 one obstacle height ahead of the obstacle. The horseshoe vortex is also much
594 higher than for the single silo configuration, deflecting the approaching wind
595 flow upwards from a larger upstream distance. Separation occurs at the sharp
596 edges at the transverse corners of the building, generating a large wake region
597 with irregular recirculation zones. In the region where the silos are located,
598 a generally similar pattern can be observed but comparing figures 18b and c
599 reveals some important differences. Although the flow is only partly attached
600 to the silo structures at the windward side of the silos with a small part of
601 the flow entering the silo array, the global picture remains similar as for the
602 bluff prismatic building where all flow is deflected sideways. At the transverse
603 corners of the silo group (silos 8 and 33), however, flow separation is only partly
604 geometrically triggered and separation occurs on the silo surfaces. At the top
605 of the silo group, the flow is deflected upwards and sideways. It only slightly
606 accelerates but separates from the edges at the top (figures 18top and d). No
607 specific point of reattachment on the top can be observed as for simple block-like
608 geometries in wind flow. This is mainly attributed to the open structure of the
609 silo array with wind flows emerging from the interstitial spaces and interaction
610 with the conical shape of the 40 silo tops. Similarly as for the single silo case,
611 the size of the wake is reduced near the free end of the group but the effect is
612 more limited. The wake behind the silo group is reduced less, creating a larger

613 flow resistance as compared to the single silo case.

614 The influence of the location of a silo in the group on the structural response
615 is investigated by considering the four corner silos: 1, 8, 33 and 40 (figure
616 2). Additional simulations showed that the response at these locations was
617 representative for all windward and leeward silos in the group.

618 First, the structural response of silo 1 at the windward corner of the silo
619 group is calculated. The mean and RMS values of the modal deformation energy
620 are shown in figures 19a and b, respectively. It can be clearly observed that the
621 static deformation of this silo is dominated by eigenmodes (1, 3) and (1, 4) (figure
622 19a). Other eigenmodes with low circumferential wavenumbers (n) are also
623 excited, but less pronounced. Roughly the same eigenmodes are also excited
624 dynamically as demonstrated by the RMS values of the modal deformation
625 energy (figure 19b). The RMS values for silo 1 are slightly larger than for the
626 single isolated silo. Note the different vertical scale of the RMS graphs compared
627 to the simulations for a single silo (figure 14).

628 Predominant static and dynamic excitation of modes (1, 3) and (1, 4) is also
629 seen in the response snapshots in figure 20. It is observed that the silo wall is de-
630 flected inwards due to the large positive pressures at the windward side. When
631 moving downstream along the silo wall, the attached boundary layer causes
632 suction and the shell is deformed outwards. The largest structural displace-
633 ments, however, are found in the small gaps between two adjacent silos. Due to
634 the larger wind velocities in these narrow passages, negative surface pressures
635 develop and the silos deform accordingly. The magnitude of the structural dis-
636 placements is as high as 0.07 m in these interstitial spaces. These displacement
637 values are large in comparison with the total distance of only 0.3 m between two
638 neighbouring silos. The vibration amplitudes, however, are significantly smaller
639 (approx. 0.01 to 0.02 m).

640 For the silos on the transverse corners of the silo group, i.e. silos 8 and 33,
641 the results of the one-way simulations are shown in figures 19c to f. For silos 8
642 and 33, the RMS value of the modal contributions is significantly larger than for
643 a single silo or silo 1 in the group. This is in agreement with the time history of

Figure 18: Streamlines of the wind flow around the silo group after 40 s, colored according to the velocity magnitude, released from (top) a vertical plane $y = 0$ m and horizontal planes at (a) $z = 0.5$ m, (b) $z = 17.16$ m, (c) $z = 29.16$ m, and (d) $z = 41.16$ m.

Figure 19: (left) Mean value and (right) RMS value of the modal contributions to the deformation energy $E_{dj}(t)$ in the one-way simulation of the silo group. The first row shows silo 1, the second row silo 8, the third row silo 33 and the last row silo 40. The deformation energy for the lowest 50 eigenmodes is plotted as a function of n while separate mode shapes $(1, n)$ are depicted as a circle ($\circ$), $(2, n)$ as a square ($\square$), $(3, n)$ as a diamond ($\diamond$), and $(4, n)$ as a cross ($\times$).

644 the drag coefficients for these silos in figure 9. It is interesting that also at these
645 locations eigenmodes $(1, 3)$ and $(1, 4)$ are predominantly excited, both statically

Figure 20: Displacement at $t = 10$ s of (a) silo 1, (b) silo 8, (c) silo 33, and (d) silo 40 of the one-way simulation of the silo group. The structural displacements are mainly static and are amplified with a scale factor of 40.

and dynamically. This is related to the fact that these modes have the lowest eigenfrequencies and are hence most susceptible to the low frequency content of the turbulent wind excitation. Furthermore, the vicinity of the neighbouring silos in a square arrangement and the resulting high wind velocities that are developed in the gaps between two adjacent silos automatically gives rise to the excitation of mode $(1, 4)$. Despite the differences in the RMS values of the modal contributions to the deformation energy between silos 8 and 33 on the one hand and silo 1 on the other hand, it should be noted that the displacements found on corner silos 8 and 33 are of the same order of magnitude as for silo 1 at the windward side, as illustrated in figure 20, mainly due to the dominance of the mean value in the deformation energy.

Finally, the results of the one-way simulation for the lee side corner silo 40 are shown in figures 19g and h. As opposed to the other corner silos, the modal deformation energy for this silo is negligibly small for all eigenmodes. The remarkable difference between the structural response at the lee side corner

661 (silo 40) and the other three corner silos (silos 1, 8 and 33) of the group is
 662 visualized in figure 20. The radial static displacements are only approximately
 663 0.01 m while vibration amplitudes are negligibly small for silo 40.

664 Overall, the patterns of the predicted vibration correspond well with the
 665 observed ovalling vibrations in the Antwerp silo group during the 2002 storm.
 666 Vibrations are observed at the windward side of the group and the modes that
 667 are preferentially excited seem to be those giving rise to the observed ovalling
 668 motion. In these one-way simulations, however, the magnitude of the vibration
 669 levels (approx. 0.01 to 0.02 m) is still much smaller than the ones observed
 670 (approx. 0.1 m) in October 2002.

671 *Two-way simulations*

672 Although the one-way simulations indicated which silos were subjected to
 673 ovalling vibrations, the resulting vibration amplitudes are smaller than observed.
 674 Therefore, a fully coupled WSI simulation is performed for the group configu-
 675 ration, taking into account aeroelastic effects and/or interactions between the
 676 wake-induced excitation and the vibration. In order to obtain results within a
 677 reasonable computation time, only a single flexible silo at the windward side of
 678 the group (silo 1) is considered while all other silos in the group are rigid.

679 At the start of the two-way simulation, a direct transfer of the large struc-
 680 tural displacements to the flow field inevitably leads to a long and significant
 681 transition in the fluid and structural response. The corresponding amplitudes
 682 of the vibrations are so large that the flexible silo collides with its neighbour-
 683 ing rigid silos due to the narrow gaps. To solve this issue, the aerodynamic
 684 forces that are passed from the flow solver to the structural solver are gradually
 685 increased during a limited period of time (5 s).

686 In general, approximately 5 IQN-ILS coupling iterations are required per
 687 time step. As a result, simulating 1 s of wind flow in this two-way simulation of
 688 the silo group requires about 70 hours of computing time.

689 Figure 21 depicts the modal deformation energy as a function of time for
 690 the two-way simulation of silo 1. The initial part of the simulation until $t = 5$ s

691 where the solution gradually evolves to the stationary regime should obviously
 692 be disregarded but from $t = 5$ s on the response of the structure to the full
 693 aerodynamic forces is obtained. The fluctuations in the deformation energy
 694 reach far beyond the corresponding levels in any of the one-way simulations. At
 695 approximately $t = 8$ s a peak is reached and the structural response decreases
 696 before rising again at approximately $t = 12$ s. This two-way simulation shows
 697 that WSI simulations are recommended to investigate ovalling vibrations in silo
 698 groups.

Figure 21: Modal deformation energy $E_{dj}(t)$ for the first 20 mode shapes, based on the structural response of the upwind silo 1 in the two-way simulation of the entire silo group: $\Phi_1 = (1, 3)$ (bold grey line), $\Phi_2 = (1, 3)$ (bold black line), $\Phi_4 = (1, 4)$ (thin black line), and the remaining mode shapes Φ_j (dashed grey lines, with small energy content).

699 Taking into account the difference in vertical scale in figures 22a and b and
 700 19a and b, it is observed that the result of the two-way simulation of silo 1
 701 (figures 22a and b) is distinctly different from the one in the one-way simulation
 702 (figures 19a and b). As opposed to the one-way simulations, the mean value and
 703 the RMS value of the modal contributions to the deformation energy have the
 704 same order of magnitude in the two-way simulations. The modal deformation
 705 energy graphs indicate a marked aeroelastic effect and/or interaction between
 706 the wake-induced excitation and the vibration in the structural response as a

707 result of changing wind flow patterns in vicinity of the silo structure. To distin-
 708 guish an aeroelastic effect from interaction between the wake-induced excitation
 709 and the vibration, the calculations would have to be repeated for higher wind
 710 flow velocities. Aeroelastic effects would have to remain present above the crit-
 711 ical velocity, whereas interaction between the wake-induced excitation and the
 712 vibration is expected to disappear when the wind velocity exceeds the resonant
 713 peak. However, repeating the analysis for different wind speeds is beyond the
 714 scope of this work. Hence, no statements on aeroelastic effect versus interaction
 715 between the wake-induced excitation and the vibration can be made based on
 716 the present study. In a study by Païdoussis et al. (1988) ovalling was identified
 717 as an aeroelastic flutter phenomenon using a model with two-dimensional flow
 718 around a single shell that is supported at both ends. As the silo group is only
 719 fixed at one end and the flow around it has been shown to be three-dimensional,
 720 it is not certain whether this conclusion by Païdoussis et al. (1988) holds for
 721 this silo group as well.

Figure 22: (a) Mean value and (b) RMS value of the modal contributions to the deformation energy $E_{dj}(t)$ for silo 1 in the two-way simulation of the silo group. The deformation energy for the lowest 50 eigenmodes is plotted as a function of n while separate mode shapes $(1, n)$ are depicted as a circle ($\circ$), $(2, n)$ as a square ($\square$), $(3, n)$ as a diamond ($\diamond$), and $(4, n)$ as a cross ($\times$).

722 To assess the magnitude of the structural vibrations in the two-way simula-
 723 tion, the time history of the radial displacements at two discrete points (A and
 724 B in figure 23) along the circumference and at mid-height of silo 1 is shown in

725 figure 24 with positive values indicating outward displacements. In the small
 726 gap between silos 1 and 9 (point A, figure 24a), the vibration amplitudes in-
 727 crease up to about 0.05 m. At the lee side of the silo (point B, figure 24b) the
 728 increase in the amplitude is slightly smaller but still very distinct. The vibra-
 729 tions in this simulation are significantly larger than in the one-way simulations
 730 and tend to the observed vibration amplitudes during the storm in 2002 (order
 731 of magnitude of 0.1 m). Furthermore, the dominant excitation of eigenmodes
 732 (1,3) and (1,4) is in line with observations.

Figure 23: Location of two discrete points A and B along the circumference and at mid-height ($z_s = 12.5$ m) of silo 1 in the group arrangement.

Figure 24: Radial displacements at two discrete points A and B (cfr. figure 23) along the circumference and at mid-height of silo 1 in the two-way simulation of the group arrangement.

733 6. Conclusions

734 The comparison between the one-way and two-way simulations did not re-
735 veal significant differences for the single silo case. By contrast, the vibration
736 amplitudes for the silo group are significantly larger in the two-way simulations
737 than in the one-way simulations. As the importance of two-way simulations
738 is difficult to estimate a priori, it is thus recommended to take the structural
739 displacement into account in the wind flow simulation for WSI simulations of
740 similar structures.

741 It is also concluded that the average and/or the RMS value of the wind load-
742 ing on the windward side of a silo group can be much larger than on a single
743 silo. This observed group effect is in agreement with the outcome of the Ferry-
744 bridge investigation, but appears on the windward side of closely spaced silos
745 as opposed to the leeward side of more widely spaced cooling towers. Further-
746 more, comparing the two-way simulations for the single silo with the two-way
747 simulations for the silo group demonstrates that the vibration amplitudes are
748 significantly larger for the group. So, both the Ferrybridge investigation and
749 this study indicate that objects in group should not be designed using wind
750 loading data or norms for a single object.

751 Finally, the two-way simulations of the silo group show results in agreement
752 with the observations during the storm. Extensive analysis of the grid size and
753 time step size gives an idea of the uncertainty on the results. However, the
754 duration of the simulations mentioned throughout this article and the required
755 computing power limit the use of the proposed modelling as engineering tool to
756 special investigations at present.

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764 **References**

765 Abaqus 6.10, 2010. User's Manual. Dassault Systèmes Simulia Corp.

766 AIJ, 2006. Recommendations for Loads on Buildings. Architectural Institute of
767 Japan.

768 ANSI, 2010. ASCE 7-10: Minimum Design Loads for Buildings and Other Struc-
769 tures. American National Standards Institute.

770 Batina, J., 1990. Unsteady Euler airfoil solutions using unstructured dynamic
771 meshes. AIAA Journal 28 (8), 1381–1388.

772 Bazilevs, Y., Hsu, M.-C., Kiendl, J., Wüchner, R., Bletzinger, K.-U., 2011. 3D
773 simulation of wind turbine rotors at full scale. Part II: Fluid-structure inter-
774 action modeling with composite blades. International Journal for Numerical
775 Methods in Fluids 65, 236–253.

776 Belloli, M., Collina, A., Rossa, L., Squicciarini, G., July 2011. Wind tunnel
777 tests on different erection stages of a cable stayed bridge. In: De Roeck,
778 G., Degrande, G., Lombaert, G., Müller, G. (Eds.), Proceedings of the 8th
779 International Conference on Structural Dynamics, EURODYN 2011. Leuven,
780 Belgium, pp. 1325–1332.

781 Billah, K., Scanlan, R., 1991. Resonance, Tacoma Narrows bridge failure, and
782 undergraduate physics textbooks. American Journal of Physics 59 (2), 118–
783 124.

784 BIN, December 2010. NBN EN 1991-1-4:2005/AC Eurocode 1: Actions on struc-
785 tures - Part 1-4: General actions - Wind actions (+ AC:2010). Belgisch Insti-
786 tuut voor Normalisatie.

787 Blevins, R., 1990. Flow-Induced Vibration, 2nd Edition. Van Nostrand Rein-
788 hold.

789 Blocken, B., Carmeliet, J., 2006. The influence of the wind-blocking effect by a
790 building on its wind-driven rain exposure. *Journal of Wind Engineering and*
791 *Industrial Aerodynamics* 94 (2), 101–127.

792 Castro, I., 2003. CFD for external aerodynamics in the built environment. *The*
793 *QNET-CFD Network Newsletter* 2 (2), 4–8.

794 COST Action 732, 2007. “Quality assurance and improvement of microscale me-
795 teorological models”. In: Franke, J., Hellsten, A., Schlünzen, H., Carissimo,
796 B. (Eds.), *Best practice guideline for the CFD simulation of flows in the urban*
797 *environment*. Office for Official Publications of the European Communities,
798 Luxembourg, pp. 1–52.

799 COST Action C14, 2004. “Impact of wind and storms on city life and built
800 environment”. working group 2: CFD techniques. In: Franke, J., Hirsch,
801 C., Jensen, A., Krüs, H., Schatzmann, M., Westbury, P., Miles, S., Wisse,
802 J., Wright, N. (Eds.), *Recommendations on the use of CFD in predicting*
803 *pedestrian wind environment*. Office for Official Publications of the European
804 Communities, Luxembourg, pp. 1–28.

805 Degroote, J., 2013. Partitioned simulation of fluid-structure interaction.
806 *Archives of Computational Methods in Engineering* 20, 185–238.

807 Degroote, J., Bathe, K.-J., Vierendeels, J., 2009. Performance of a new parti-
808 tioned procedure versus a monolithic procedure in fluid-structure interaction.
809 *Computers and Structures* 87, 793–801.

810 Donea, J., Guiliani, S., Halleux, J., 1982. An arbitrary Lagrangian-Eulerian
811 finite-element method for transient dynamic fluid structure interactions. *Com-*
812 *puter Methods in Applied Mechanics and Engineering* 33 (1-3), 689–723.

813 Donea, J., Huerta, A., Ponthot, J.-P., Rodríguez-Ferran, 2004. Arbitrary
814 Lagrangian-Eulerian methods. In: Stein, E., de Borst, R., Hughes, T. (Eds.),

815 Encyclopedia of Computational Mechanics. Volume 1: Fundamentals. John
816 Wiley & Sons, pp. 413–438.

817 Dooms, D., Degrande, G., De Roeck, G., Reynders, E., 2006. Finite element
818 modelling of a silo based on experimental modal analysis. *Engineering Struc-*
819 *tures* 28 (4), 532–542.

820 Fluent 14.5, 2012. User’s Guide. Ansys Inc.

821 Gopalan, H., Jaiman, R., 2015. Numerical study of the flow interference between
822 tandem cylinders employing non-linear hybrid URANS-LES methods. *Journal*
823 *of Wind Engineering and Industrial Aerodynamics* 142, 111–129.

824 Gorski, J., Mikulski, T., Ozieblo, M., Winkemann, K., 2015. Effect of geometric
825 imperfections on aluminium silo capacities. *Stahlbau* 84 (1), 52–57.

826 Hillewaere, J., Dooms, D., Van Quekelberghe, B., Degroote, J., Vierendeels, J.,
827 De Roeck, G., G. Degrande, G., 2012. Unsteady Reynolds averaged Navier-
828 Stokes simulation of the post-critical flow around a closely spaced group of
829 silos. *Journal of Fluids and Structures* 30, 51–72.

830 Hojjat, M., Stavropoulou, E., Gallinger, T., Israel, U., Wüchner, R., Bletzinger,
831 K.-U., 2010. Fluid-structure interaction in the context of shape optimization
832 and computational wind engineering. In: Bungartz, H.-J., Mehl, M., Schäfer,
833 M. (Eds.), *Fluid-Structure Interaction II. Modelling, Simulation, Optimiza-*
834 *tion*. Vol. 73 of *Lecture Notes in Computational Science and Engineering*.
835 Springer, pp. 351–381.

836 Holmes, J., 2015. *Wind Loading of Structures*, 3rd Edition. Taylor & Francis.

837 Löhner, R., Yang, C., 1996. Improved ALE mesh velocities for moving bound-
838 aries. *Communications in Numerical Methods in Engineering* 12 (10), 599–
839 608.

840 Mannini, C., Sbragi, G., Schewe, G., Borri, C., July 2011a. Determination of
841 flutter derivatives for a box-girder bridge deck through URANS simulations.

842 In: De Roeck, G., Degrande, G., Lombaert, G., Müller, G. (Eds.), Proceedings
843 of the 8th International Conference on Structural Dynamics, EUROODYN2011.
844 Leuven, Belgium, pp. 1473–1480.

845 Mannini, C., Soda, A., Schewe, G., 2011b. Numerical investigation on the three-
846 dimensional unsteady flow past a 5:1 rectangular cylinder. *Journal of Wind*
847 *Engineering and Industrial Aerodynamics* 99 (4), 469–482.

848 Menter, F., Kuntz, M., Langtry, R., October 2003. Ten Years of Industrial
849 Experience with the SST Turbulence Model. In: Hanjalić, K., Nagano, Y.,
850 Tummers, M. (Eds.), *Proceedings of the Fourth International Symposium on*
851 *Turbulence, Heat and Mass Transfer*. Begell House, Inc., Antalya, Turkey, pp.
852 625–632.

853 Michalski, A., Kermel, P., Haug, E., Löhner, R., Wüchner, R., Bletzinger, K.-U.,
854 2011. Validation of the computational fluid-structure interaction simulation
855 at real-scale tests of a flexible 29 m umbrella in natural wind flow. *Journal of*
856 *Wind Engineering and Industrial Aerodynamics* 99, 400–413.

857 Païdoussis, M., Price, S., Ang, S.-Y., 1988. Owalling oscillations of cylindrical
858 shells in cross flow: A review and some new results. *Journal of Fluids and*
859 *Structures* 2 (1), 95–112.

860 Païdoussis, M., Price, S., de Langre, E., 2011. *Fluid-Structure Interactions:*
861 *Cross-Flow-Induced Instabilities*. Cambridge University Press.

862 Païdoussis, M., Wong, D.-M., 1982. Flutter of thin cylindrical shells in cross
863 flow. *Journal of Fluid Mechanics* 115, 411–426.

864 Park, C.-W., Lee, S.-J., 2004. Effects of free-end corner shape on flow structure
865 around a finite cylinder. *Journal of Fluids and Structures* 19, 141–158.

866 Patankar, S., Spalding, D., 1972. A calculation procedure for heat, mass and mo-
867 mentum transfer in three-dimensional parabolic flows. *International Journal*
868 *of Heat and Mass Transfer* 15 (10), 1787–1806.

- 869 Pope, R., 1994. Structural deficiencies of natural draught cooling towers at UK
870 power stations part 1: failures at Ferrybridge and Fiddlers Ferry. Proceedings
871 of the Institution of Civil Engineers-Structures and Buildings 104 (1), 1–10.
- 872 Price, S., Païdoussis, M., Macdonald, R., Mark, B., 1987. The flow-induced
873 vibration of a single flexible cylinder in a rotated square array of rigid cylinders
874 with a pitch-to-diameter ratio of 2.12. Journal of Fluids and Structures 1 (3),
875 359–378.
- 876 Quinn, A., Wilson, M., Reynolds, A., Couling, S., Hoxey, R., 2001. Modelling
877 the dispersion of aerial pollutants from agricultural buildings – An evalua-
878 tion of computational fluid dynamics (CFD). Computers and Electronics in
879 Agriculture 30, 219–235.
- 880 Shah, K., Ferziger, J., 1997. A fluid mechanics view of wind engineering:
881 Large eddy simulation of flow pas a cubic obstacle. Journal of Wind Engi-
882 neering and Industrial Aerodynamics 67–68, 211–224.
- 883 Shellard, H., 1967. Collapse of cooling towers in a gale, Ferrybridge, 1 November
884 1965. Weather 22 (6), 232–240.
- 885 Smirnov, A., Shi, S., Celik, I., 2001. Random flow generation technique for
886 large eddy simulations and particle-dynamics modeling. Journal of Fluids
887 Engineering, Transactions of the ASME 123, 359–371.
- 888 Spalart, P., Deck, S., Shur, M., Squires, K., Strelets, M., Travin, A., 2006. A new
889 version of detached-eddy simulation, resistant to ambiguous grid densities.
890 Theoretical and Computational Fluid Dynamics 20 (3), 181–195.
- 891 Squires, K., Krishnan, V., Forsythe, J., 2008. Prediction of the flow over a
892 circular cylinder at high reynolds number using detached-eddy simulation.
893 Journal of Wind Engineering and Industrial Aerodynamics 96 (10–11), 1528–
894 1536.
- 895 Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa,
896 M., Shirisawa, T., 2008. AIJ guidelines for practical applications of CFD to

- 897 pedestrian wind environment around buildings. *Journal of Wind Engineering*
898 *and Industrial Aerodynamics* 96, 1749–1761.
- 899 Uernatsu, Y., Yasunaga, J., Koo, C., 2015. Design wind loads for open-topped
900 storage tanks in various arrangements. *Journal of Wind Engineering and In-*
901 *dustrial Aerodynamics* 138, 77–86.
- 902 VDI-Richtlinie 3783, 2003. Blatt 9 (Entwurf): Umweltmeteorologie. Prognos-
903 tische Mikroskalige Windfeldmodelle. Evaluierung für Gebäude- und Hin-
904 dernisumströmung. Verrein Deutscher Ingenieure.
- 905 Šarkić, A., Fisch, R., Höffer, R., Bletzinger, K.-U., 2012. Bridge flutter deriva-
906 tives based on computed, validated pressure fields. *Journal of Wind Engineer-*
907 *ing and Industrial Aerodynamics* 104–106, 141–151.
- 908 Žukauskas, A., Ulinskas, R., Katinas, V., Karni, J., 1988. *Fluid Dynamics and*
909 *Flow-Induced Vibrations of Tube Banks*. Hemisphere Publishing Corporation.
- 910 Weaver, D., Lian, H., Huang, X., 1993. Vortex shedding in rotated square arrays.
911 *Journal of Fluids and Structures* 7 (2), 107–121.
- 912 Zdravkovich, M., 1997. *Flow Around Circular Cylinders, Volume 1: Fundamen-*
913 *tals*. Oxford University Press.
- 914 Zhang, C., 1994. Numerical prediction of turbulent recirculating flows with a
915 $k - \varepsilon$ model. *Journal of Wind Engineering and Industrial Aerodynamics* 51,
916 177–201.
- 917 Zhao, Y., Cao, Q.-S., Su, L., 2013. Buckling design of large circular steel silos
918 subject to wind pressure. *Thin-Walled Structures* 73, 337–349.
- 919 Zhao, Y., Lin, Y., Shen, Y.-B., 2014. Wind loads on large cylindrical open-
920 topped tanks in group. *Thin-Walled Structures* 78, 108–120.