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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.

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.

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; Shellard, 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 (Fig. 1). During a storm in 2002 wind-induced ovalling vibrations with an amplitude of approximately 0.1 m have been observed on several empty

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

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, 5% of the diameter compared to approximately one diameter. This entails that the flow blockage effect for the silo group is much higher than for the cooling towers. Furthermore, the cooling towers are made of reinforced concrete as opposed to aluminium for the silo group, resulting in lower damping for the latter. The investigation of this incident with the cooling towers identified a tensile meridional failure within the shell fabric as dominant initial mode of failure. For the particular wind direction during the gale, the mean meridional force increased by 30% and the resonance force doubled, whereas the quasi-static fluctuating force remained more or less the same compared to an isolated tower (Pope, 1994).

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

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

In this paper, WSI simulations are performed to investigate the wind-induced ovalling vibrations of individual silos mounted in a group arrangement. Compared to our previous work related to this silo group (Hillewaere et al., 2012), a significantly different methodology is proposed. Our previous work only contained CFD simulations, with rigid structures. In this work, flexible structures are considered, with and without including the influence of their motion on the wind flow. The model of the silo group was 2D in our previous work and has been extended to 3D in this paper, which among other things entails including the atmospheric boundary layer. Consequently, only frequencies and circumferential mode shapes could be calculated in our previous work, without changes along the axis of the silo, and no magnitudes of the vibrations. In addition, the turbulence modelling has been improved to resolve a fraction of the turbulent fluctuations. Finally, the results in our previous work overestimated the excitation by the flow in the wake of the silo group because the simulations were 2D which preserves large vortices and prevents their break up.

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