Sustainable Energy Technologies and Assessments 11 (2015) 165–172

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Original Research Article

Structural analysis of an underwater energy storage accumulator

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ARTICLE INFO

Article history:
Received 1 September 2014
Revised 30 October 2014
Accepted 24 November 2014

Keywords:
Underwater compressed air energy storage
UWCAES
Vortex induced vibrations
Flexible structure
VIV

ABSTRACT

A full-scale three-dimensional simulation was conducted to investigate structural response of an underwater compressed air energy storage (UWCAES) accumulator to the hydrodynamic loads at Reynolds number of 2.3×10^5. The accumulator was assumed to be spherical, non-distensible and fixed to the bed of a water body via a cylindrical homogeneous isotropic elastic support. The simulation was carried out for three different supports with aspect ratios AR of 5, 10 and 20 where AR was defined as the ratio of the length to the diameter of the support. The effects of the aspect ratio on the frequency and amplitude of the vibrations of the solid structure induced by hydrodynamic loading were investigated. It was observed that the amplitude of the vibrations increases with the aspect ratio of the support, whereas the frequency decreases. The displacement of the spherical accumulator was illustrated on the X–Y plane for each case.

Introduction

The renewable energy industry has achieved considerable progress in offshore electricity generation through the development of offshore energy facilities, for instance Denmark is generating more than 30% of its total electric power by offshore wind farms [1,2]. However, it is still facing the challenge of energy storage to manage timely energy distribution in the most efficient way. Viable energy storage solutions could enable these resources to become dispatchable. One such potential solution is underwater compressed air energy storage (UWCAES) [3]. In this system, flexible accumulators are installed close to the bed of a deep water source. Surplus electrical energy is used to compress air into underwater accumulators. Hence, the stored air is under the hydrostatic pressure applied by the water and is ready to be released to drive turbo expanders to deliver power to the grid when desired. A few hybrid energy storage plants between UWCAES and other technologies have been also developed [4,5]. Underwater lift balloons have served as a suitable choice to perform as the accumulator unit of the UWCAES. To develop an efficient design for the accumulator unit of UWCAES, it is necessary to provide detailed physical insights into the interaction of the water flow and underwater balloons. As the first attempt to accomplish this, a two-way fluid–structure-interaction analysis is performed to investigate the effect of the aspect ratio of the cylindrical elastic support on the vortex induced vibrations of the accumulator structure. In addition, the information provided herein can be used to modify the shape and the cost analyses performed by Pimm et al. [6] where a force normal to the surface of the balloon owing to the differential pressure acting across the surface was the only acting force taken into account. In one of their most recent studies conducted at the European Marine Energy Centre in Orkney, Pimm et al. [7] discussed challenges associated with underwater accumulators including leakages causing the air hose and the accumulator to fill with water and tears occurring during the installation and operation. The structural vibrations induced by the crossing flow can severely affect the observed tears and leakages; hence, having insights into their frequency and amplitude can be very useful in choosing more appropriate valve connections and more long-lasting material for manufacturing balloons. Accordingly, the present study can be considered as one of the most demanding tasks to develop an optimal design for the foundation, support structures and valve connections of an underwater compressed air accumulator.

Sphere in cross-flow

Since the underwater energy storage balloon is assumed to be spherical, a brief review on some basic characteristics of flow over a sphere is due. Different flow patterns downstream of the sphere are summarized in Table 1. Studies on low Reynolds numbers are essentially interested in the creation and separation of the wake at the rear of the sphere. According to the literature [9–12], the onset of the wake behind the sphere is at a Reynolds number of

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http://dx.doi.org/10.1016/j.seta.2014.11.004
2213-1388/

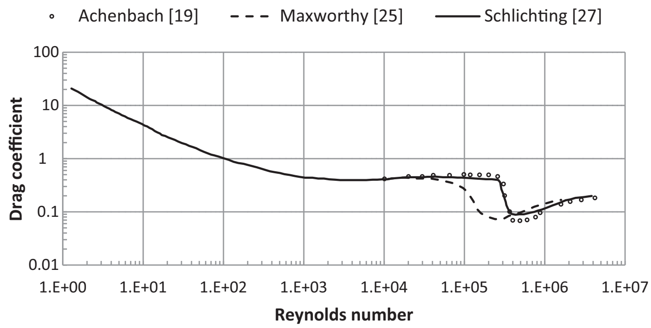
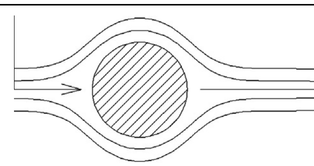
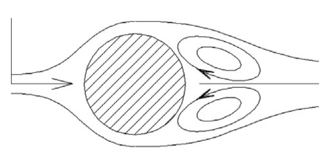
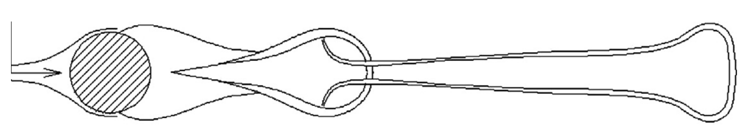
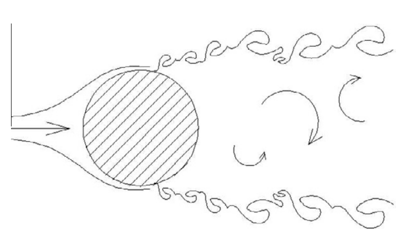


Fig. 1. Drag coefficient of sphere in uniform cross-flow; in subcritical regime, drag coefficient continuously decreases with Reynolds number, whereas in supercritical regime increases.

8–24. According to Taneda [12], at a Reynolds number of approximately 130, very low-frequency fluctuations are observed in the mentioned wake. Goldburg and Florsheim [15] found that the amplitude of these fluctuations increases to approximately 10% of the sphere diameter at a Reynolds number of 270. Once the Reynolds number exceeds approximately 270–400, a type of spiral instability appears causing hairpin-like vortices to be shed behind the sphere in a laminar unsteady regime [14–19]. At a Reynolds number of approximately 650–1000, a new instability is introduced to the flow causing axisymmetric shedding of vortex tubes in a quasi coherent fashion [19–24]. This mode is responsible for the distortion of the large-vortex structures, production of small scales and, eventually, transition to turbulence in the detached shear layers. Tomboulides et al. [23] and Tomboulides and Orszag [24] conducted DNS simulations and showed that as the Reynolds number was increased to Re = 1000, the shear layers became unstable after separation and small-scale turbulent structures were present in the wake. At a critical Reynolds number of approximately $Re_c = 2 \times 10^5$ (3×10^5 according to Achenbach [19]) the sphere wake becomes narrower. As is shown in Fig. 1, at this Reynolds number the drag coefficient experiences a significant decrease from approximately 0.4 to 0.09. The present simulation investigates flow over the spherical balloon at $Re = 2.3 \times 10^5$, i.e. a supercritical regime; therefore, a turbulence model must be applied. Standard k–ω turbulence model was utilized in the present paper. It is of note to mention that the critical Reynolds number crucially depends on the surface roughness and free stream turbulence [28,29]; in Fig. 1 the surface is approximately smooth and the free stream is laminar.

Table 1
Flow pattern downstream of a spherical bluff body.

Reynolds number range	Flow pattern [8]
Re < { 8, Nisi and Porter [9] 10, Rimon and Cheng [10] 20, Dennis and Walker [11] 24, Taneda [12]	
Re < { 210, Crivellini et al. [13] 270, Johnson and Patel [14] 270, Goldburg and Florsheim [15] 277, Natarajan and Acrivos [16] 300, Sakamoto and Haniu [17] 400, Clift et al. [18] and Achenbach [19]	
Re < { 280, Chrustetal et al. [20] 650, Sakamoto and Haniu [17] 800, Achenbach [19] and Kuchemann [21] 1000, Sakamoto and Haniu [22] 1000, Tomboulides et al. [23] 1000, Tomboulides and Orszag [24]	
Re < { $Re_{cr} = 2 \times 10^5$, Maxworthy [25] $Re_{cr} = 3 \times 10^5$, Achenbach [19] (Subcritical flow) $Re_{cr} = 3.7 \times 10^5$, Wang et al. [26]	
$Re > Re_{cr}$ (Supercritical flow)