Engineering Structures 57 (2013) 73–86

Contents lists available at ScienceDirect

Engineering Structures

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

Resonance mechanism of wind-induced isolated aqueduct–water coupling system

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ARTICLE INFO

Article history:
Received 20 February 2013
Revised 23 August 2013
Accepted 9 September 2013
Available online 13 October 2013

Keywords:
Isolated aqueduct bridge
Resonance mechanism
Aqueduct–water interaction
Wind-induced response

ABSTRACT

The resonance mechanism of wind-induced aqueduct–water coupling system installed with isolated bearings was studied using the Arbitrary Lagrangian–Eulerian (ALE) method and the Finite Element Method (FEM). A water sloshing model was used to analyze the dynamic properties of a U-shaped aqueduct–water coupling system. Simulation results show that the resonance can be eliminated under high-order-frequency excitation and may happen when the excitation frequency is close to the first-order water sloshing frequency. Though the isolated rubber bearings are helpful to improve the earthquake resistance capacity proposed by Zhang et al. (Zhang H, Liu L, Dong M, Sun H. Analysis of wind-induced vibration of fluid–structure interaction system for isolated aqueduct bridge. Eng Struct 2013;46:28–37), they reduce the structural stiffness, lengthen the structural vibration period and reduce the wind resistance performance of aqueduct structures.

1. Introduction

Aqueducts are usually built for conveying water from territories of water abundance to areas of water shortage. They can also be used as floods drainer, navigable shipping channel, river diversion facility, etc. In the past two decades, many large aqueducts have been widely built in China, e.g. in the South-to-North Water Transfer Project and Dongshen Water Supply Project, in order to relieve problems of uneven water resource distribution and regional water shortage. For example, Zhangyang aqueduct bridge is designed with the flux of 90 m^3/s while, in the project of aqueducts across Yellow River, among which a single aqueduct has the maximum flux of 250 m^3/s [1]. Because of the pressing need in real projects, study on the design and structural performance of aqueducts has gained increasing interests [2–6].

While the scale of aqueduct becomes larger, the study on aqueduct safety under dynamic loads turns to be an important subject since 1980s in China. Regardless of occasional earthquake effects, aqueducts still bear wind loads constantly. Dozens of aqueducts have been destroyed induced by winds in the past three decades in China leading to enormous economic loss [7]. At present, the wind resistance design of aqueducts is still being conducted referring to the building design code, in which wind loads are usually considered as static loads rather than dynamic loads. Nevertheless, the water–structure coupling effects under fluctuating wind loads might cause changes of the dynamic characteristics of aqueduct structures. Such fluctuating wind effects might not only shorten aqueducts' fatigue life, but also cause large amplitude sloshing of water and further lead to structural resonance which, in some cases, would increase the probability of structural damage.

Isolated bearings are usually installed on a structure in order to lengthen the vibration period and to dissipate the earthquake energy, so as to improve the structural dynamic performance in seismic design [8–12]. However, despite the wide application of isolated bearings in aqueducts (e.g., Zhangyang aqueduct [1], Dongshen aqueduct [8] and the aqueduct across Ming River [9] in China), studies of the influence of such bearings on the structural dynamic performance, especially on wind-induced properties, are insufficient, because the isolated bearings might reduce the structural stiffness and sometimes lead to structural failure due to large displacements caused by strong winds [8]. Therefore, the study on wind-induced properties of the aqueduct with isolated rubber bearings is becoming practically urgent and essential in the field of wind resistance design of actual hydraulic structures.

The hydrodynamic pressure and the interaction between water and structure should be considered in the dynamic analysis of aqueducts. According to the existing theory regarding small amplitude water sloshing, the high order resonance of the structure–water coupling system would occur under the excitation of harmonic waves with odd frequencies [13–15]. Hence, in real applications, the high order resonance has to be considered in the

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http://dx.doi.org/10.1016/j.engstruct.2013.09.014

Nomenclature

M	mass matrix
C	damping matrix
K	stiffness matrix
D	isolated bearing location matrix
c	horizontal damping of rubber bearing
k	horizontal stiffness of rubber bearing
u	displacement vector
$P_w(t)$	external fluctuating wind load vector
$P_f(t)$	fluid force vector acting on the structure
ρ	fluid density
v	fluid velocity
v_{ref}	referential fluid velocity
σ	Couchy stress tensor
κ	coefficient of fluid kinematic viscosity
p	fluid pressure
$G(\cdot)$	structure equation
$H(\cdot)$	fluid equation
$\tilde{\Gamma}$	free surface boundary
Γ	structure–fluid interface boundary
n	outward unit normal vector
τ	traction force
X	solution vector
$FEM(\cdot)$	finite element functions
$F(\cdot)$	coupled finite element function
r_τ	stress criterion
r_τ	displacement criterion
ε_τ	tolerance for stress convergence
ε_u	tolerance for displacement convergence
ε_0	small positive number
λ_d	displacement relaxation factor
λ_τ	traction relaxation factor
g	acceleration of gravity
$x_0(t)$	container displacement
a	container bottom width
V	summation of the simulated fluctuating wind speed and the average wind speed
h	water height
$\tilde{\omega}_n$	natural frequency of fluid in the container
ω	external force frequency
p_r^w	hydrodynamic pressure
F^w	overturning force
M^w	overturning moment
Z_c	point of application of the overturning force
W	Mooney–Rivlin strain energy density function
$\tilde{\sigma}$	Piola–Kirchhoff stress tensor
γ	Cauchy–Green strain tensor
P	wind pressure
$\bar{\rho}$	density of the atmosphere
Superscript i	time instant
Superscript Γ	structure–fluid interface
Subscript f	fluid domain
Subscript k	iteration index
Subscript s	solid domain

aqueduct bridge design, which accordingly leads to design difficulties and also brings hidden risks in practical projects. Obviously, it is important and necessary to validate the applicability of the theory to dynamic analysis of the aqueduct–water coupling system. Therefore, in this paper, we study the resonance characteristics of the aqueduct–water coupling system installed with isolated bearings, under harmonic excitations, using the Computational Fluid Dynamics (CFD) methods.

The coupling effects between aqueduct and water cannot be neglected in the dynamic analysis [16] since the fluid traction affects the structural deformations and the solid displacements, in turn, affects the fluid pattern. In general, there are two mainly categories of methods studying the aqueduct–water interaction and water sloshing [14,15,17–20]. One is the analytical method such as the additional mass method and the Housner model method [7,14,15], in which the water is regarded as an added mass and/or spring of the structure, ignoring the effects of water sloshing, which yields inaccurate calculation results. The other is the numerical computational methods, e.g., Lagrange Finite Element Method (FEM) [16], Boundary Element Method (BEM) [21] and Arbitrary Lagrangian–Eulerian (ALE) FEM [17–19], which considers the influence of nonlinearities caused by fluid sloshing on the structure. The study in [19] showed that the ALE method could express the moving boundary and adjust the distortion of mesh. Such a method gives a full consideration of the water sloshing with large amplitudes in solving nonlinear fluid–solid coupling problems, leading to wide applications in various fields, i.e., nuclear industry, aerospace industry, etc.

However, it is insufficient for quantitative study on the influence of hydrodynamic pressure on the stress filed variation and structural global stability under the fluctuating wind loads. Especially, the study on the structure–fluid interaction mechanism and dynamic properties of the aqueduct–water coupling system is limited. The geometrical and the material nonlinearities of the isolated aqueduct also make the random vibration based frequency method unsuitable for the wind-induced dynamic analysis. Hence, a time domain method was proposed in this paper to analyze the aqueduct–water coupling system. In order to fully take into account the impact of the isolated support on the wind-induced dynamic performance of the coupling system, a three-dimensional (3D) finite element model of an isolated aqueduct structure was presented for simulation.

Since the fluctuating wind could be treated as a steady Gauss stochastic process ignoring its initial unsteadiness [8,22], the ARMA method was proposed to simulate the fluctuating wind speed time histories [8]. The CFD methods were used to analyze the resonance response of aqueduct–water coupling system with rubber bearings under harmonic excitations. The dynamic characteristics and wind-induced response of the aqueduct–water coupling system were analyzed. The influence of the isolated bearings on the wind resistance performance of the aqueduct bridge were studied using the ALE method. This work aims to study the vibration mechanism of the aqueduct–water coupling system, which is helpful to understand the dynamic properties of the aqueduct induced by the fluctuating winds. It can also provide scientific basis for the wind-induced vibration control of isolated aqueducts.

This paper is organized as follows. Section 2 proposes the fundamental equations of fluid–solid coupling system and the solution method. Section 3 presents the small amplitude sloshing model for structural dynamic response analysis. Section 4 gives the numerical simulation analysis. The last part, Section 5, contains discussions and the final conclusions.

2. Fundamental equations

While analyzing the dynamic response of an aqueduct–water system installed with isolated rubber bearings, difficulty arises due to the geometric nonlinearity caused by large amplitude water