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Large eddy simulation and proper orthogonality decomposition of turbulent flow around a vibrissa-shaped cylinder

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ABSTRACT

The flow dynamics over a vibrissa-shaped cylinder at the sub-critical Reynolds number of 1.8×10^4 are comparatively investigated using the large eddy simulation (LES) approach, with particular emphasis on the wake structure and self-induced force. Three reference configurations with the same hydrodynamic diameters, i.e., a circular cylinder, an elliptical cylinder and a wavy cylinder, are compared with the vibrissa-shaped cylinder configuration. The results demonstrate that the fluctuation of lift force for the vibrissa-shaped cylinder is reduced by approximately 79.2% compared with that for the circular cylinder, and the predicted RMS magnitudes for the four configurations agree reasonably well with the experimental data. For the vibrissa-shaped cylinder, only one sharp peak with relatively low magnitude is observed at the characteristic frequency $fD/U_0 = 0.20$, and the wake shedding does not dominate the dynamics, while the vortex structures show significantly three-dimensional features. Meanwhile, the separation line of the recirculation zone shows a remarkable wavy structure that corresponds to the trailing geometrical surface with a spanwise shift of approximately a half-period of undulation. A proper orthogonal decomposition (POD) analysis is performed to explore the three-dimensional structures in the wake behind the vibrissa-shaped cylinder. The POD modes reveal a completely three-dimensional and periodically staggered arrangement along both the spanwise and streamwise directions. The spectra of the first two time coefficients reveal that the wake shedding processes on the *nodal* and *saddle planes* are not synchronous. Finally, the phase-averaging results show sequential processes of vortex shedding in the wake behind the vibrissa-shaped cylinder, and demonstrate marked differences between this and the other cylinders. Two symmetrical vortices are attached closely to the backward side of the vibrissa-shaped cylinder, resulting in smaller fluctuations of velocity and wall pressure, which in turn contribute to reducing the vortex-induced force and suppressing its vibrations.

1. Introduction

Recent studies have demonstrated that the ability of harbor seals (*Phoca vitulina*) to trace hydrodynamic trails is closely associated with suppression of their vibrissal vortex-induced vibration (VIV) as the seals move in a uniform flow (Hanke et al., 2010; Beem and Triantafyllou, 2015). As a seal approaches the wake far behind its upstream prey, its vibrissae exhibit an intensified structural vibration. Meanwhile, the cylindrical vibrissal structure, which is subjected to its own VIV, is surprisingly stationary during high-speed motion in a uniform flow (Schulte-Pelkum et al., 2007). This stationary quality indicates that the vibrissa's unique shape, which features an undulatory, asymmetric and elliptical geometry, is closely associated with the effective suppression of VIV (Hanke et al., 2010). Otherwise, the VIV would produce background noise, interfering with the seal's ability to detect weak signatures from the upstream prey. The three-dimensional surface geometry of the vibrissae was found to reduce the mean and fluctuation of self-induced forces (Hans et al., 2013). However, the Reynolds number for these structures, based on the seal's speed and the hydrodynamic diameter of each vibrissa, is normally the order of 10^2–10^3. Clearly, a comprehensive understanding of the turbulent flow around a vibrissa-shaped cylinder at a high Reynolds number would be highly desirable for potential industrial applications like wake detection (Witte et al., 2012; Beem et al., 2013).

A review of the literature in recent years reveals a growing interest in the wake flow over vibrissa-shaped cylinders.

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List of symbols

Main symbols

a, b	radii of the narrow vibrissal cross-section (**A**–**A**), mm
a_n	coefficient of the POD mode n
A	reference area of the cylinder, m^2
A – **A**, **B** – **B**	two nearly elliptical cross-sections for the *harbor* configuration
C_l	dimensionless lift coefficient
C_p	dimensionless pressure coefficient
c_ε,c_v	coefficient of dynamic one-equation subgrid model
D	hydrodynamic diameter, mm
$D_{\max}$, $D_{\min}$	large and small diameters for the wavy cylinder configuration, mm
k, l	radii of the wide vibrissal cross-section (**B**–**B**), mm
f	frequency, 1/s
F_y	transverse force acting on the wall surface, N
$\mathbf{k}$	vertical unit vector, normal to the free-stream direction
k_{sgs}	subgrid-scale kinetic energy, m^2/s^2
m	distance between two cross-sections; half-period of the undulation, mm
$\mathbf{n}$	normal unit vector pointing into the surface
n	number labeling a POD mode
$\underline{p}$	instantaneous pressure, Pa
$\overline{S}_{ij}$	rate-of-strain tensor, 1/s
St	Strouhal number, fD/U_0
t	time, s
$\mathbf{t}$	tangential direction to the surface
u	x component of instantaneous velocity, m/s
u_i	i component of instantaneous velocity, m/s
U_0	free-stream velocity, m/s
$\mathbf{v}$	y component of instantaneous velocity, m/s
v_{RMS}	RMS of longitudinal velocity fluctuation, m/s
w	z component of instantaneous velocity, m/s
y	cell-to-wall distance, m
y^+	non-dimensional wall distance

Greek symbols

α, β	angles for cross-sections **A**–**A** and **B**–**B**, degree
ε	$c_\varepsilon \frac{k_{sgs}^{3/2}}{\Delta}$,
δ_{ij}	Kronecker delta
$\overline{\Delta}$	grid-scale filter, $(\Delta_1\Delta_2\Delta_3)^{1/3}$
$\widehat{\Delta}$	test filter, $2\overline{\Delta}$
Δt	time-step, s
λ_n	eigenvalue of the POD mode n
ν	kinematic viscosity, m^2/s
ν_t	turbulent kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ_{ij}	subgrid-scale residual stress tensor, m^2/s^2
τ_w	wall shear stress, m^2/s^2
ω_z	cross-stream vorticity, s^{-1}

Abbreviations

DMD	Dynamic Mode Decomposition
GAMG	generalized geometric-algebraic multi-grid
HPC	high-performance computing
LES	large eddy simulation
LIC	line integral convolution
PIMPLE	merged PISO-SIMPLE
PISO	pressure implicit with splitting of operator
POD	proper orthogonal decomposition
RMS	root mean square
SGS	subgrid scale
SIMPLE	semi-implicit method for pressure-linked equations
TR-PIV	time-resolved particle image velocimetry
VIV	vortex-induced vibration

Hanke et al. (2010) performed a combined experiment and CFD simulation to study the wake flow dynamics behind harbor seal vibrissae at Reynolds numbers of 300 and 500. That study found that the mean drag force was reduced by approximately 40%. Hans et al. (2013) comparatively investigated the effects of geometrical surfaces on the self-induced force using four whisker-like geometries, and showed that geometries with axial undulations achieved a reduction of drag forces. A three-dimensional numerical investigation of a vibrissa, a circular cylinder and an elliptical cylinder at Reynolds numbers of 300 and 600 (Matz and Baars, 2012) confirmed that no apparent Karman vortex street appeared behind the vibrissa. Miersch et al. (2011) studied the hydrodynamic properties of harbor seal whiskers, and found that these whiskers could distinguish the vortex shedding frequencies produced in the upstream wake due to the high signal-to-noise ratio resulting from greatly reduced noise. Witte et al. (2012) examined the wake flow dynamics behind a harbor seal vibrissa at Reynolds numbers of 300 and 500 using Stereo-Micro-PIV and three-dimensional direct numerical simulation, respectively. The results verified that the wavy surface geometry of the vibrissa suppressed self-induced vibrations from the wake and damped the oscillating forces by 90% compared with those produced by a circular cylinder. Witte et al. also used proper orthogonal decomposition (POD) to identify the physical mechanism of force reduction. According to a phase-averaged flow field analysis, the vortex core of the vibrissa was significantly different from that of the circular cylinder. The vortex core in the wake of the vibrissa was formed further downstream, and the breakdown of the vortex structure occurred faster than in the case of the circular cylinder. These authors (Witte et al., 2012) emphasized the need for further research on the flow dynamics of vibrissae at higher Reynolds numbers to verify the basic mechanisms of vortex structures in the wakes of vibrissa-shaped cylinders. Recently, Beem et al. (2013) and Beem and Triantafyllou (2015) demonstrated the exquisite sensitivity of seal whisker-like sensors for the potential application of wake detection at Reynolds numbers $Re = 1060–20{,}670$. In summary, the literature contains numerous studies on the wake flow dynamics behind vibrissa-shaped cylinders at low Reynolds numbers. However, few studies can be found on the corresponding situation at high Reynolds numbers.

At high Reynolds numbers (approx. $10^4 < Re < 2 \times 10^5$ in the subcritical regime), the flow over a cylinder exhibits several complex features. These features include unsteady, large-scale, three-dimensional vortex shedding into the far wake, forming a vortex street, and the transition to turbulence in the wake region with subsequent turbulence-dominated flow. Moreover, both the drag coefficient and the RMS of the lift coefficient remain nearly constant in the subcritical regime (Yeon et al., 2016). Hence, in this regime, the benefits of a vibrissa-shaped cylinder for reducing self-induced forces deserve further study. Accordingly, this study explored the wake characteristics of air flow over a vibrissa-shaped cylinder at the subcritical Reynolds number of 1.8×10^4, based on a free-stream velocity of $U_0 = 17.76$m/s and a vibrissal hydrodynamic diameter of $D = 15$ mm. Particular attention has been paid to the differences in wake structures and self-induced forces between a vibrissa-shaped cylinder and three other cylinders with