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Interaction of a real seal whisker with the surrounding flow: Vortex shedding and vortex induced vibration

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Abstract

Certain species of seals are able to faithfully detect minute disturbances in ambient water solely using their whiskers, which is attributed to the whiskers' undulating three-dimensional (3D) morphology. While previous studies have examined effects of key morphology parameters on the wake using scaled-up whisker models, it is unclear how the wake behaves when induced by a real undulating seal whisker. Real seal whiskers usually have a diameter of about one millimeter and present variation in size and bending curvature along the length, which are not being considered in designing scaled-up whisker-like models. In addition, how the whisker orientation affects the induced wake and vortex shedding needs to be clarified. This study examines the wake flow characteristics generated by a real elephant seal whisker (of undulating morphology) and a California sea lion whisker (of smooth morphology) in laboratory water channels at Reynolds number of 390, using time-resolved PIV methods. Results indicate that the vortex shedding frequency is reduced for both the undulating and smooth whiskers, the energy spectral density is substantially increased at AOA = 90˚ than that at AOA = 0˚. Regardless of AOA, the energy spectral density is approximately 40% lower in the wake of the undulating whisker than that of the smooth whisker, indicating the favorable hydrodynamic feature of the undulating whisker. The extraordinary hydrodynamic traits of undulating seal whiskers are promising for renovating aero-propulsion flow components and designing high-sensitivity underwater flow sensors.

1 Introduction

Biomimicry has been adopted to create innovative solutions for a vast range of engineering applications. One potential nature-inspired design has come from seal whiskers, to improve flow sensors for autonomous underwater vehicles (AUVs). Hanke et al. (2010) found that harbor seals are able to track their prey by detecting even minute disturbance of the ambient water solely by using their whiskers, instead of visual and auditory sensing capability. The exceptional detection ability is desired for AUVs, because in dark, cramped, and unstable terrain AUVs are not able to maneuver using visual and sonar-based navigation.

The outstanding hydrodynamic capability of seals is attributed to the unique undulating three-dimensional morphology of the whisker, detailed in Rinehart et al. (2017). Another parameter is the whisker orientation with respect to the inflow direction: when the minor axis is aligned with the inflow, the angle of attack (AOA) of the whisker is 0˚. When the major axis is aligned with inflow the AOA is 90˚. Research has shown that this unique morphology suppresses vortex-shedding in the wake flow and thus reduces vortex induced vibrations (VIV), especially at AOA = 0˚. Beem and Triantafyllou (2015) found this allows the seal to sense very small fluctuations within the incoming flow, such as the wake of a fish, and in turn significantly enhance the seal's capability to track the fish.

Beem and Triantafyllou (2015), Rinehart et al. (2017), and others have studied the effects of the parameters of the whisker morphology on wake structure using idealized whisker-like models. Beem and Triantafyllou (2015) and Hans et al. (2014) have analyzed the vibrations of a whisker and the mechanics of a whisker to understand how a seal is able to track prey in the water. While these studies have focused on the wake effect of a single idealized whisker, a real seal whisker has a natural variation in length and size as well as a twist along the length of the whisker. It is not well understood how a real seal whisker changes wake flow, especially the vortex shedding and how it responds to the modified wake. The current study aims to understand the effect of a real seal whisker's morphology on the vortex shedding behavior. This work uses high-speed particle imaging velocimetry (PIV) to analyze the vortex shedding downstream of a real elephant seal whisker (undulating morphology) at a peak and trough location while comparing it to a California sea lion (smooth morphology) at Reynolds number of 400.

2 Experimental Setup

Wake behind the real whiskers is measured by a high-speed PIV system (see Figure 1b) which enables us to capture vortex shedding behavior induced by a seal whisker with sufficient temporal resolution. Properly aligning the light sheet with a real whisker sample is critical to get data at the desired measurement planes and interpret the results faithfully. The whisker was first attached to a 1/16 in diameter rigid rod and then mounted on a thin plate at the bottom of the water channel. The coordination of the optics tube and laser mounting mechanism allowed the light sheet to be aligned with a peak or trough or selected location, Figure 1a. Instantaneous vector fields from the snap-shot PIV tests were obtained with a window-based cross-correlation algorithm (DaVis 8.3, LaVision GmbH). A two-pass procedure was employed: initial interrogation window of 32 by 32 pixels followed by a reduced window of 16 by 16 pixels with 50% overlap in each pass.

The high-speed PIV system at the Biofluid and Biomimic Research Center (BBRC) at POSTECH, South Korea was used to analyze the vortex shedding behavior of the wake by both whiskers. The experimental set-up is shown in Figure 1b. The water channel is seeded with silver hollow spheres that have a mean diameter of 44 μm. The particle images were taken at peak and trough locations only in the horizontal plane at a rate of 5000 frames per second (fps), with a Fastcam SA1.1 Photron High Speed Camera and a Nikon ED AF Micro Nikkor 200 mm 1:4D Lens (fitted with a Nikon L37c 62 mm filter). The FOV of the particle images taken in the POSTECH water tunnel is 23.33 mm by 23.33 mm with the camera resolution of 1024 pixels by 1024 pixels. The conversion factor of 43.89 pixels/mm is used to transform the data from image plane to the physical plane. A total of 8000 images were captured for each measurement plane and analyzed using the window-based correlation method. The Cartesian coordinate system was the same as the 2D2C snap-shot PIV experiments. The measurement uncertainty is also similar to that of the snap-shot PIV tests. It is noted that no ensemble-averaging is performed for flow statistics computation, instead, behavior of the vortex shedding is the focus of the time-resolved PIV results.

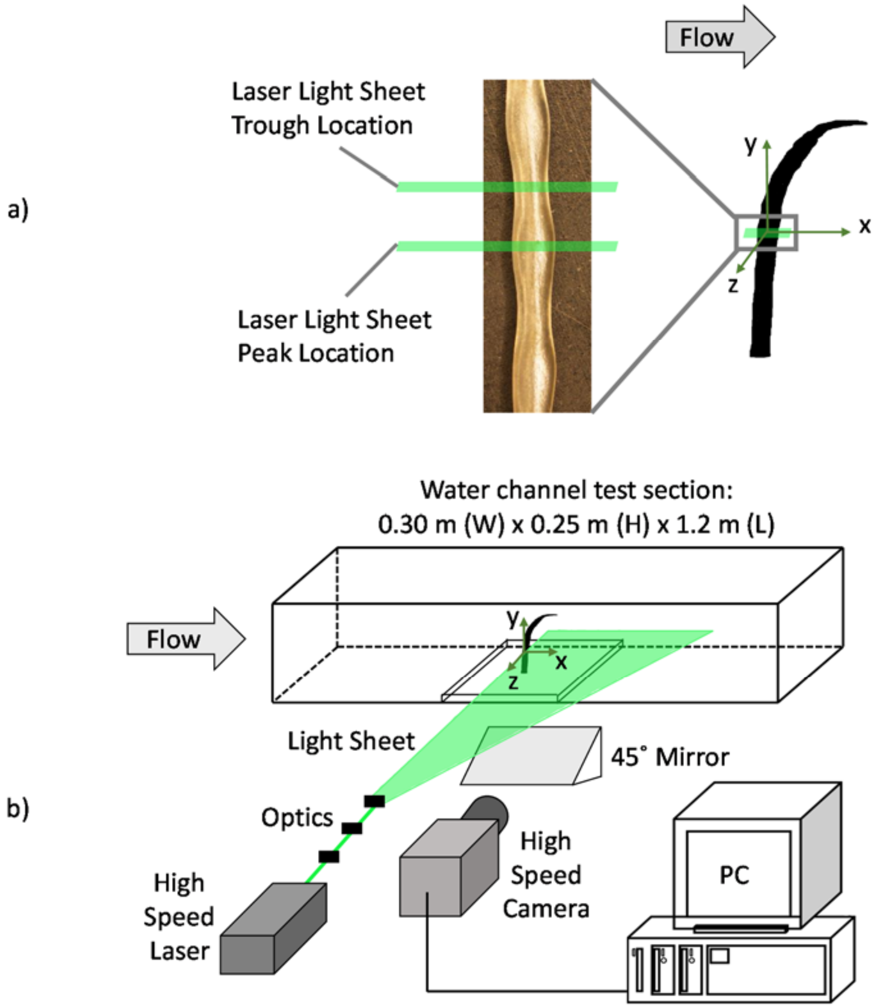

Figure 1: (a) Measurement planes at the peak and trough of an undulating whisker. (b) Schematics of the high-speed PIV measurement setup. The Cartesian coordinate is originated at the laser light sheet intersection of the single whisker. The x, y, and z coordinates correspond to streamwise, vertical, and spanwise directions and the velocities are u, v, and w, respectively.

3 Vortex Shedding

Spectral analysis was performed to examine the distribution of turbulent kinetic energy across a range of frequencies in the wake of the smooth and undulating whiskers, Figure 2. The spectra were calculated by taking the fast Fourier transform (FFT) of the instantaneous streamwise velocity at several locations of the separated shear layers. Localized high-energy signatures can be seen clearly at frequencies corresponding to periodic vortex shedding. A concentration of turbulent energy is indicated by the primary peak at the frequency of 108 Hz behind the smooth whisker, 150 Hz and 158 Hz at the peak and trough of the undulating whisker at an AOA = 0˚. Miersch et al. (2011) reported the frequency of seal and sea lion whiskers fall in the range of 47 to 193 Hz for a free-stream flow speed between 0.17 to 0.52 m/s. Our results are well aligned with this work. In addition, the energy spectral density is found to be 50% lower for the case of the undulating whisker, indicating reduced strength of vortex shedding. This result is consistent with suppressed wake generated by the undulating whisker, as well as recent work of Morrioson et al. (2016) and Kim and Yoon (2017).

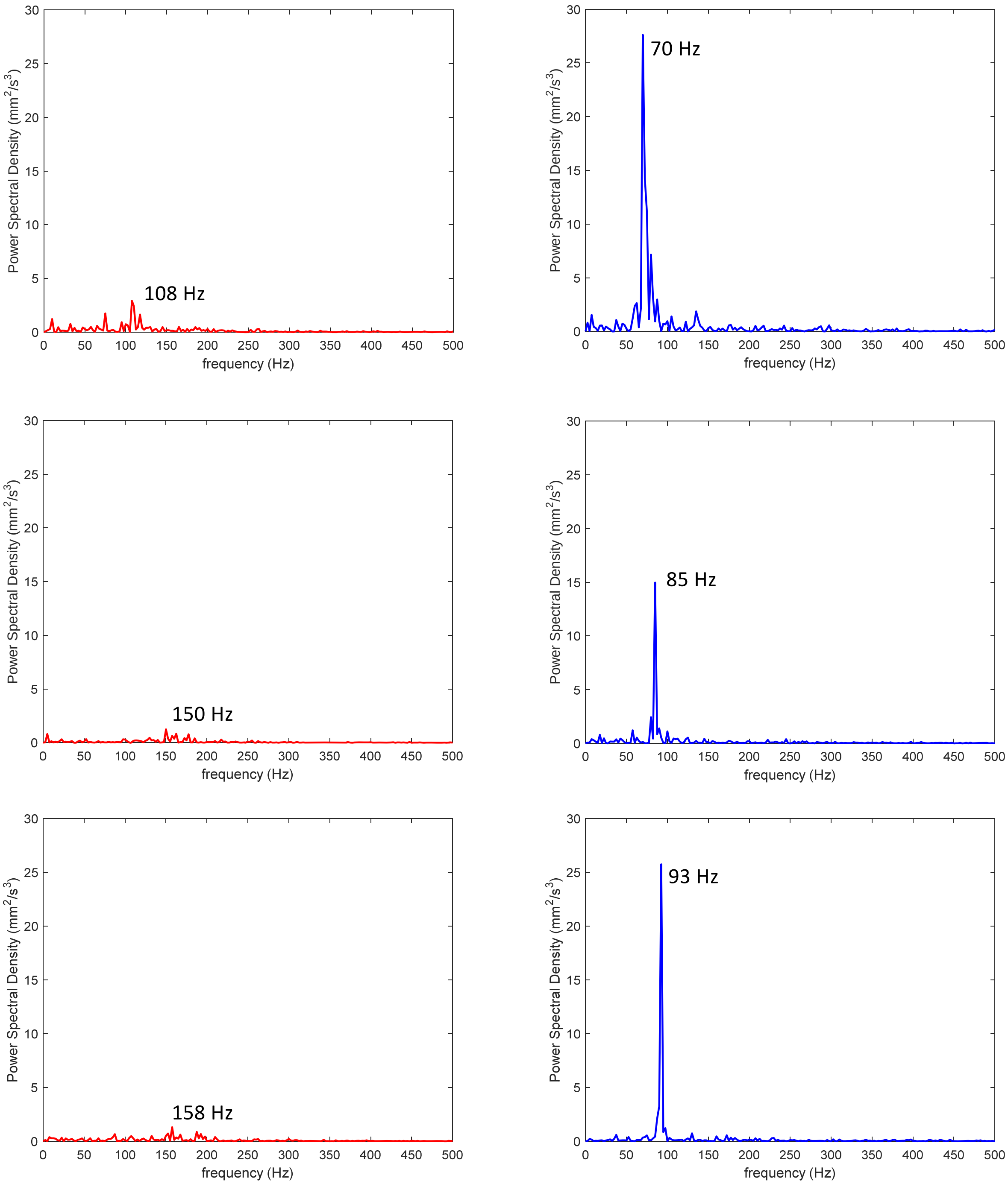

Figure 2: Power spectrum of the velocities at selected locations of the wake at Re = 390. The smooth whisker of a California Sea Lion (top), the Elephant Seal Whisker at the peak location (middle), and the Elephant Seal Whisker at the trough location (bottom). AOA = 0˚ (left) and AOA = 90˚ (right).

Once the AOA is changed to be 90˚, the primary peak frequency shifts to a lower value for all three positions. This agrees with the trend of vortex shedding frequency reported by Kim and Yoon (2017). It is even more interesting to note a dramatic jump in the energy spectral density for both smooth and undulating whiskers at AOA = 90˚. The energy spectral density is increased to 9 times higher for the smooth whisker. The increment of the energy spectral density of the wake of undulating whisker is even more noticeable: 12 times higher in the peak location and 19 times higher in the trough location. This result indicates the vortex shedding behavior is greatly affected by the AOA, which agreed to that in Murphy (2013).

Our data also shows evidence of a lower energy density in the wake of the undulating whisker, regardless the angle of attack, which is aligned with Kim and Yoon (2017). In short, when the whisker's orientation is well aligned with respect to the incoming flow, VIV can be remarkably reduced. However, when the major axis presents a large AOA to the inflow, VIV can be substantially magnified, as reported in Hans et al. (2014) and Beem and Triantafyllou (2015).

4 Conclusion

Measurements of the wake flow of a real undulating elephant seal whisker and a smooth sea lion whisker are conducted under well-controlled laboratory water channels. The turbulent statistics are achieved by a snap-shot PIV and the vortex shedding behavior is quantified by a high-speed PIV method. Spectral analysis of high-speed PIV data indicates the reduced power spectra density of vortex shedding behind the undulating whisker, compared to that of the smooth whisker, regardless of the AOA. However, changing the AOA from 0˚ to 90˚ substantially increases the energy spectral density for both whiskers, thus augmenting the vortex shedding significantly.

Ongoing work is to directly measure the smooth and undulating whisker vibration from the high-speed PIV images and to examine the relation of the dominant whisker vibration frequency to the frequency of the vortex shedding in the wake. New experimental data will be obtained at a higher Reynolds number of 2000, which is closer to the seal’s hunting regime. This will help to further understand the effect the Reynolds number has on the wake flow and the vortex shedding behavior, as well as provide further insights into seal-whisker-inspired engineering applications.

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