BI-STABLE STATES IN THE WAKE OF A FINITE-WIDTH DOUBLE BACKWARD FACING STEP

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ABSTRACT

The flow past a generic ship model is investigated numerically using well-resolved large eddy simulations at $Re = 8 \times 10^4$. The geometric configuration at the rear of the model is analogous to a double backward facing step, and it permits the occurrence of bi-stable flow states on each step; with an asymmetrical flow topology being observed in each of the flow states across the longitudinal midplane. The mean flow topology on the top step was observed to be anti-symmetrical to the flow topology on the bottom step, and the two flow states are anti-symmetrical to each other. By introducing a base cavity on the top step, the asymmetrical flow is suppressed on both the steps; leading to the elongation of the re-circulation bubble on each step, and a reduction in the drag coefficient. The wake behind the model is analysed, and occurrence of asymmetrical flow is attributed to the difference in the strength of the streamwise vortices along the lateral edges of the top step.

KEY WORDS: Wakes, bi-stability, backward facing step, flow control

1. INTRODUCTION

The air-wake of ships/frigates play a critical role in the flight movements of search and rescue helicopters. Recent experimental and numerical investigations ([1], [2], [3], [4], [5], [6], [7], [8], [9], [10] and others) have shown that the mean flow topology in the heli-deck area of the ship is asymmetrical across the longitudinal midplane of the ship, with the formation of a larger vortex on one side of the base and closer to it, while on the other side, a smaller vortex which is farther away from the base was observed. In experimental observations ([8]), this flow configuration is found to switch across the longitudinal midplane, leading to two "stable" flow states, similar to that observed behind squareback ground vehicles ([11], [12], [13], [14] and others). The switching phenomenon is known as bi-stability, and for the aforementioned ship models, the height-to-width ratio on the top step is 0.44, leading to the occurrence of the bi-stable flow states in the lateral midplane (see [15]). It may be emphasised that the phenomenon of bi-stability is random with small-scale disturbances triggering the switch from one flow state to the other, and to numerically simulate this phenomenon is computationally prohibitive on account of the long time-scales between switches.

Recent investigations by [16] using large eddy simulations (LES) and partially–averaged Navier–Stokes (PANS) equations, showed the existence of the two flow states in the flight deck region of an idealised ship/frigate model ([3]) as shown in figure 1(a). Flow states I and II were observed on meshes consisting of $\simeq 21.5$ million (mesh M2) and $\simeq 10$ million elements (mesh M1), respectively, with both meshes having adequately resolved the air-wake and the near-wall flow structures. In this study, we further investigate this

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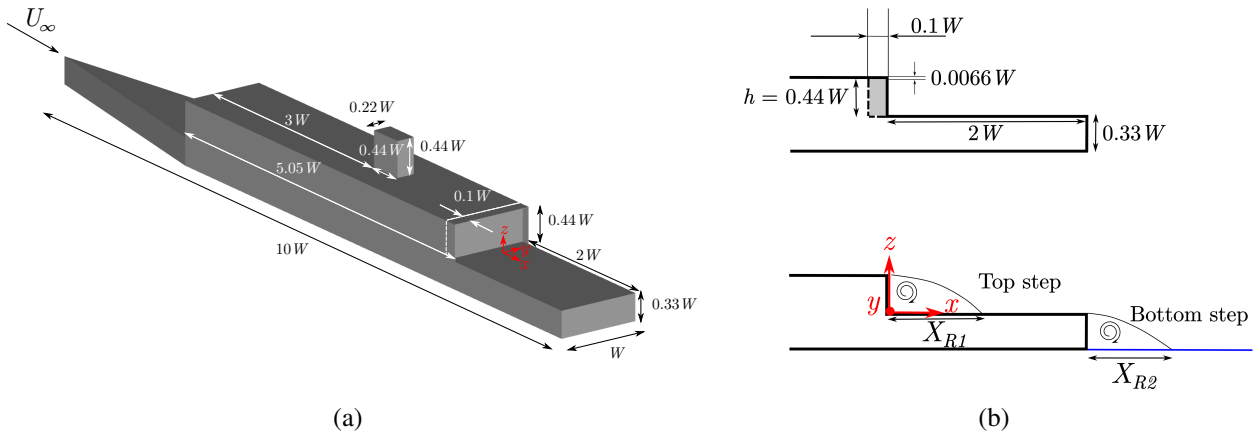
(a)

(b)

Fig. 1 (a) Schematic of the frigate model used in this study, with the base cavity at the top step in perspective view. (b) Top: side view detailing the dimensions of the base cavity. Bottom: schematic of the time-averaged velocity in the vertical midplane at the rear of the frigate, showing the two recirculation regions. Flow is from left to right in these images.

asymmetrical flow topology, and propose a passive flow control technique to mitigate it by creating a base cavity on the top step. The dimensions of this base cavity are shown in figure 1(b) and has a depth of $0.1W$ (where, W is the width of the ship), and was chosen such that the volume of the superstructure of the ship was not significantly reduced and/or the area for the flight movements are not significantly compromised. Also, the chosen depth is such that it is within the range of drag minima observed when base cavity is used in bluff body flows (see [17], [18], [19]). The computational mesh size for the base cavity case is similar to mesh M1. For a detailed description of the spatial resolution studies, velocity profiles, flow visualisation around the ship, the reader is referred to [16]. The outcome of this study can be applied to a wide range of engineering applications such as the design of buildings, automotive applications etc. Section §1.1 briefly details the results from the LES for the two flow states and the base cavity case. This is followed by conclusions in §2.

1.1 Results

Figures 2(a) - 2(c) show the mean flow topology in flow state I, II and for the base cavity case in plan view. Clearly discernible is the asymmetrical flow topology on the top step in each of the two flow states, while an anti-symmetrical flow topology top that observed on the top step is observed in the lateral plane of the bottom step. The two flow states are anti-symmetrical. It may be noted that the height-to-width ratio of the top and bottom steps are 0.44 and 0.33, respectively, and these ratios permit bi-stable flows in the lateral planes (see [15]). However, when the base cavity is used, the mean flow is symmetrical about the vertical midplane, with the vortices on each step being equidistant from the base. Furthermore, the base cavity elongates the length of the recirculation bubble, thereby leading to the formation of the vortices further away from the base, leading to a lower drag coefficient (also see [18], [19]). This is confirmed when the contours of the pressure coefficient are plotted on the vertical faces of the two steps (figures 2(d) - 2(f)), where higher pressure coefficient is observed when the base cavity is used as compared to that observed in the two flow states.

Upon examining the vorticity contours downstream of the ship at a distance of $0.2W$ from the stern, the asymmetry in the two flow states is prominent, with the plane slicing through the larger vortex on the bottom step observed in figures 2(a) and 2(b). Also discernible is the longitudinal vortex observed along the lateral edges of the top step. In flow state I, this longitudinal vortex is stronger on the left hand side on account of the shorter recirculation bubble on the top step permitting flow from the sides to feed into the longitudinal vortex, while on the opposite side, the longitudinal vortex is weaker. This scenario is reversed in flow state II, and for the base cavity case, the longitudinal vortices are of equal strength. The downwash on the side of the larger/stronger streamwise vortex occurs further downstream (also evidenced by the higher pressure on the
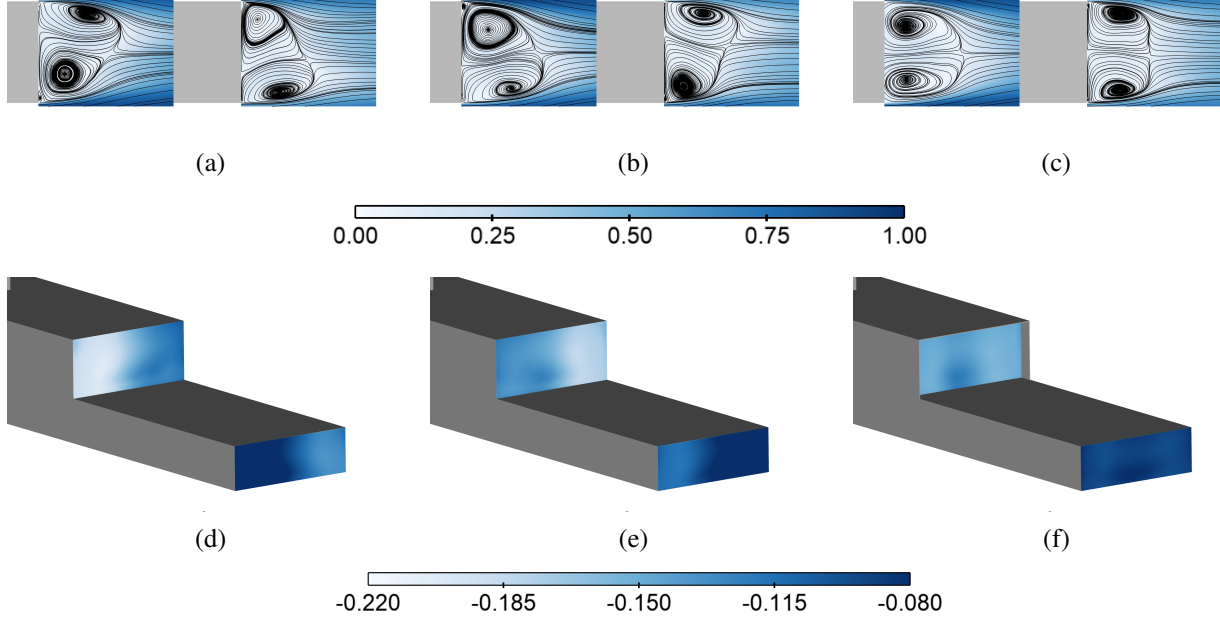
Fig. 2 (a) - (c) Visualisation of the contours of the normalised time-averaged velocity overlaid by streamlines in plan view. The plane on the left of each image is at $Z/W = 0.22$ and the plane on the right is at $Z/W = -0.2$. (d) - (f) Visualisation of the contours of the pressure coefficient (C_p) on the vertical faces of the ship in perspective view. Flow state I - (a), (d); flow state II - (b), (e), (g) and, base cavity case (c), (f), (i). Flow is from left to right in (a) - (c), and from top left to bottom right in (d) - (i).

bottom vertical face), resulting in an asymmetrical flow topology behind the bottom step.
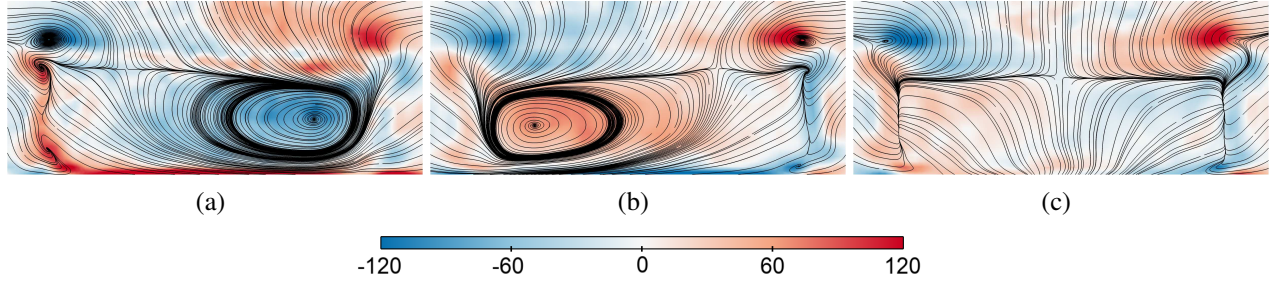

Fig. 3 Visualisation of the contours of the time-averaged streamwise vorticity (ω_x) overlaid with streamlines in the wake of the ship model for flow state I; flow state II - (b), and the base cavity case - (c) at a distance of $X/W = 2.2$. The images are captured from a point directly downstream of the ship, looking upstream. The planes extend $\pm 0.6W$ in the lateral direction, and from $Z/W = -0.33$ to $Z/W = 0.167$ in the vertical direction.

2. CONCLUSIONS

The air-wake of a generic ship model which is analogous to a double backward facing step was investigated using LES, with the geometric configuration of the ship permitting bi-stable flow. An asymmetrical mean flow topology is observed behind each of the two flow steps; with the flow topology on the top step being anti-symmetrical to the bottom step. Furthermore, the two flow states are anti-symmetrical to each other. By the use of a base cavity on the top step, the bi-stable flow is suppressed, with the formation of a pair of symmetrical vortices behind each flow step. The unequal strength of the longitudinal vortex along the lateral edges of the

ship was found to be responsible for the asymmetry on the bottom step. The use of such passive flow control devices would not only provide a uniform flow topology in the wake for flight operations, but also lead to a reduction in the drag coefficient, resulting in cost savings for the marine industry.

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