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# Asymmetric distributions in pressure/load fluctuation levels during blade-vortex interactions

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A B S T R A C T

The separation distance ($h/c$) between vortex and blade is a critical parameter in blade-vortex interaction, which strongly affects the magnitudes of induced pressure fluctuations (peak-to-peak values) and noise on helicopters. Parallel blade-vortex interaction (BVI) was studied in a subsonic wind tunnel to better understand the flow physics of BVIs with small $h/c$ values and further improve the current BVI alleviation schemes. A vortex was generated by a sudden pitch motion applied to an airfoil through a pneumatic system. As the vortex interacted with a downstream target airfoil in a parallel manner, the vortex dynamics and induced loads were studied. The induced pressure/load fluctuations were obtained from the unsteady pressure data on the target airfoil, and the flow fields during the interaction were visualized using particle image velocimetry (PIV). Despite the fact that a symmetric airfoil was studied, the pressure data clearly displayed an asymmetric distribution in fluctuation levels above and below the chord line ($h/c$=0). Maximum pressure and load fluctuations occurred when the vortex passed on one side of the symmetric airfoil with small $h/c$, rather than in the head-on case ($h/c$=0). This side of the airfoil is defined as the strong fluctuation side, with the opposite side defined as the weak fluctuation side. PIV data revealed that this phenomenon was directly related to the asymmetry in velocity field induced by the vortex. The load fluctuation level also exhibited weak dependence on the decay in vortex strength due to both viscous- and inviscid-type interaction with the airfoil. However, the role of vortex decay became insignificant at higher Reynolds number due to lower decay rate. These findings cleared some confusion in previous studies and suggested that the magnitude of BVI fluctuations could be reduced by passing the airfoil below a clockwise vortex or above a counter-clockwise vortex.

## 1. Introduction

Blade-vortex interaction (BVI) usually has detrimental effects on helicopter performance because it induces pressure fluctuations on the blade surface, which results in structural vibration and impulsive noise. This problem is most severe during maneuver and landing that poses limitations on the helicopter performance as well as its applications in urban environments. Typically, the interaction occurs between a tip vortex and a rotor blade while the vortex orientation can be parallel, perpendicular or more generally oblique to the blade. Parallel BVI, defined with the vortex axis being parallel to the blade span, has received the most attention in BVI research mainly due to the following two reasons: 1. Both numerical analysis (Windnall, 1971) and experimental

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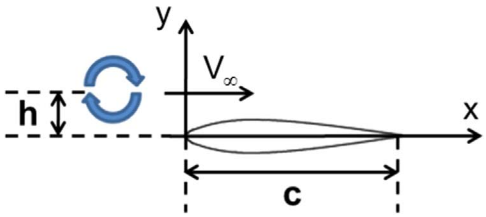


**Fig. 1.** Definition of separation distance ($h/c$).

results (Nakamura, 1981; Lorber, 1991) showed that parallel interactions produced the highest amplitude of impulsive noise among all type of interactions; 2. It is relatively easy to set up experiments and numerical simulations for the parallel case.

The separation distance between vortex and blade ($h/c$, as defined in Fig. 1) has been identified as a critical parameter that determines the severity of pressure fluctuation and noise, according to previous studies on parallel BVI (Caradonna et al., 1984; Horner et al., 1993; Kitaplioglu and Caradonna, 1994). (Note that the term "fluctuation" refers to the peak-to-peak value throughout the paper.) The pressure fluctuation and noise levels are largest for head-on interactions ($h/c$=0) and they drop rapidly as $h/c$ increases. Therefore, a number of modern BVI alleviation techniques were designed to reduce BVI noise by increasing the separation distance, including higher harmonic control (Splettstoesser et al., 1997; Yu et al., 1997), individual blade control (Yu et al., 1997), active trailing edge flap control (JanakiRam et al., 2009; Glaz et al., 2009) and leading edge blowing (Weiland and Vlachos, 2009). However, these control schemes usually come with performance penalties and extra cost in power. To further optimize the control scheme within its limited flexibility, it is necessary to fully understand the effects of $h/c$ on BVI. Despite the extensive research efforts made in this field, knowledge of the interaction is incomplete, especially for cases with small $h/c$ values.

Previous studies of parallel BVI have generally stated that the magnitudes of induced pressure fluctuation and noise were inversely related to separation distance. However, a closer look at some of the previous data revealed that this statement might not be true for small $h/c$ values. In fact, asymmetric distributions of pressure/load fluctuation levels with respect to the chord line ($h/c$=0) for a symmetric airfoil were noticeable (i.e., different peak-to-peak pressure values when a vortex passes over different sides of a symmetric airfoil with the same $h/c$). For example, blade loading and noise data from Booth Jr. (1990) showed that the fluctuation levels actually decrease as $h/c$ approaches zero. Booth Jr. attributed this behavior to bursting of the vortex during its collision with the leading edge. Horner et al. (1993) studied the effects of $h/c$ for three different vortex strengths during parallel BVI. For the strongest vortex, the maximum fluctuation occurred at $h/c$=0.1 with the distribution of fluctuation level being asymmetric about $h/c$=0. No discussion was provided concerning this phenomenon. Later, a similar phenomenon was observed by Kitaplioglu and Caradonna (1994) in their large-scale rotor tests. Their unsteady pressure data showed that the highest pressure peak was present for $h/c$=−0.125 ($Zv/C$=0.125 based on the coordinate system defined in their study). However, it was speculated in their discussion that this asymmetric distribution was an error caused by inaccurate measurements of vortex location. In summary, the above results have shown that the effects of separation distance on BVI are actually different from common knowledge as $h/c$ approaches zero, and the flow physics behind this behavior are still not well understood.

A preceding study (Peng and Gregory, 2015) was performed to investigate vortex dynamics, especially the vortex strength decay, during parallel BVI with small $h/c$ values ($|h/c| < 0.3$). The results show that BVI generally has two main stages: interaction between vortex and leading edge (vortex-LE interaction), and interaction between vortex and boundary layer (vortex-BL interaction). A vortex loses its strength during BVI in close proximity due to both viscous effects such as the shear stress near the surface and inviscid effects such as the adverse pressure gradient near the leading edge. The amount of loss in vortex strength increases as separation distance decreases. Vortex-LE interaction is often dominated by inviscid decay but will become a viscous-type interaction if there is enough separation distance. Vortex-BL interaction is inherently dominated by viscous effects, so the decay rate is dependent on Reynolds number. Also, vortex sense has great impact on vortex-BL interaction because it changes the velocity field and shear stress near the surface, showing a clear sign of asymmetry in decay rate about $h/c$=0. The above findings serve as basis for the current study and will help in understanding some of the observed phenomena.

The current research complements the previous studies on parallel BVI with a focus on the flow physics during interactions with small separation distance ($|h/c| < 0.3$). The present work concentrates on the outcome of BVI (pressure/load fluctuations) rather than the fundamental vortex dynamics studied in the previous work (Peng and Gregory, 2015). Due to the asymmetric phenomenon discussed previously, it is necessary to include test cases with both positive and negative $h/c$. The vortex-induced flow field near the leading edge, as well as its relation to the resulting pressure/load fluctuations, are studied in detail using both particle image velocimetry (PIV) and fast pressure transducers. The findings will clarify some confusion in previous studies, provide guidance for further improving noise control schemes, and possibly lead to new ideas for BVI alleviation.

## 2. Experimental setup

All experiments in the current study were performed in the Battelle Subsonic Wind Tunnel at The Ohio State University with a home-built vortex generation system (see Peng and Gregory (2015) for detailed information). Starting vortices were generated by an airfoil with sudden pitching motion and allowed to interact with a target airfoil downstream. The previous study has shown that the properties of the generated vortex have good repeatability for the range of freestream velocity encountered in the current study. The fluctuation levels in location, vortex size and vortex strength are 3%, 10% and 5%, respectively. Also, the velocity profiles of the