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Towards understanding the effects of freestream turbulence on separation bubble dynamics beyond integral parameters

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SUMMARY:
The effects of freestream turbulence (FST) scale and intensity on the behaviour of a turbulent separation bubble are investigated through the lens of "Active-Scales" of turbulence. That is, the spectral range in which both the baseline flow and the FST share turbulent energy. Particular emphasis is placed on understanding the role of very large scales of FST with respect to observed changes they cause in the fluctuating surface pressure within the separation bubble

Keywords: separation bubble, freestream turbulence, bluff body flow

1. INTRODUCTION

The effects of freestream turbulence (FST) on the bluff body separation bubble have been studied extensively (Castro and Haque, 1987; Cherry et al., 1984; Hillier and Cherry, 1981; Kiya and Sasaki, 1983a). The result of the interactions is fundamentally important to wind engineering since the r.m.s and peak pressures generated within the bubble produce critical design conditions. Hence there is imperative that the wind engineering community and wind tunnel operators have a firm fundamental comprehension of the mechanisms which produce these conditions at both prototype and model scales. However, the interactions of these turbulent flows are extremely complex since both are multi-scale, 3D, and unsteady (Saathoff and Melbourne, 1997). Investigators have historically sort to scale the argumentation of the base flow (that of the unperturbed bubble) by FST using parameters I_{u} and $L_{\mathrm{u}}^{\mathrm{x}}$. These are both integral parameters such that their spectral scale-energy relations are lost. This of course simplifies the ensuing scaling arguments, yet it also forgoes the opportunity to understand the scale-to-scale interactions between flows.

Recently there has been renewed interest in the concept of "Active-Scales" (Morrison and Kopp, 2018) whereby the energy within a range of FST scales is physically important to the interactions between the flows. The concept is one of frequency-dependent receptivity: the separation bubble will be constructively and/or destructively receptive to interaction at scales of similar size/frequency to that produced by its inherent instabilities. The same conceptual reasoning motivated Melbourne's S-parameter (Melbourne, 1979); i.e., the magnitude of the spectral energy at the size of the shear layer is essential to the behaviour of the shear layer dynamics, and hence the flow can be usefully scaled using this metric. The Active-Scales concept recognises the presence of multiple instabilities within the baseline flow and hence assumes a corresponding range of FST scales which must be matched in order to reproduce the receptivity effects and the concomitant design pressures between the model and prototype. Morrison and Kopp, 2018 suggest this range is $0.1 \leq St_D \leq 2$. Further research is required to confirm this range and understand the basic nature of the interacting scales, particularly at large scales/low-frequencies.

Thus the present investigation seeks to understand the role of the FST through the lens of Active-Scales and the spectral energy of FST. Emphasis is placed on the importance of the very large scales and their sustained influence on r.m.s pressure within the separation bubble.

2. BASELINE AERODYNAMICS

To elucidate the mechanisms of turbulent interaction and comprehend the impact of FST scale, a thorough understanding of baseline unsteadiness is required. For the canonical separation bubble forming from a $2D$ sharp-edged body with very low levels of FST (i.e., “smooth"), the literature has focused on three primary modes of unsteadiness arising from inherent instabilities: the Kelvin-Helmholtz (KH) or shear layer mode, a so-called pseudo-periodic “shedding” mode (S), and a low-frequency “flapping” mode (F). The shedding mode is the most energetic (Kiya and Sasaki, 1983b). More recently, Fang et al., 2022 revealed that the shedding mode is at least 3 distinct nested modes at $St_D = 0.23, 0.18$ and 0.10. Both shedding and flapping modes scale with the dimensions of the bubble, or the reattachment length, x_R, where in smooth flow $x_R/D \approx 4.6$. As $I_\mathrm{u} \rightarrow 0.15$, $x_R/D \rightarrow 1.4$ (Akon and Kopp, 2016; Saathoff and Melbourne, 1997). Their respective frequencies are summarised in Table 1 in terms of the blunt plate frontal dimension, D, and the reattachment length, x_R. While the KH, S, and F modes have garnered the most attention, it is also important to recognise the presence of $3D$ instabilities, primarily hairpin vortex (Cimarelli et al., 2018; Sasaki and Kiya, 1991).

The KH instability is Reynolds number dependent (Lander et al., 2018; Moore et al., 2019) since the front face boundary layer remains laminar at separation. However, for $Re > 10^5$, the boundary layer thickness is $\mathscr{O}(0.001D)$ and the KH vortices are likely relatively unimportant to the overall dynamics of the bubble (Bearman and Morel, 1983; Gartshore, 1973). Using the scaling arguments of Lander et al., 2018 with $St_{D,VK} = 0.134$ (which remains approximately constant over a large range of Re), one finds $St_{D,KH} = 0.024Re^{0.6}$. The shear layer instability of the separation bubble exhibits different dynamics than for bluff bodies where a wake can form. Indeed, the shear layer vortices convect from separation and successively amalgamate (pairing) to become large-scale pseudo-shedding vortices. The implication is a range of vortices of increasing size scaling between the KH mode and shedding mode.

Table 1. Observed non-dimensional frequency scales for the shedding and flapping modes of the separation bubble from a $2D$ blunt plate. Values in parentheses $(\cdot)$ are for high intensity turbulent flow ($I_\mathrm{u} > 0.15$) assuming the reattachment length shrinks to $x_R/D = 1.4$ (Akon and Kopp, 2016) from $x_R/D = 4.6$ in smooth flow (Kiya and Sasaki, 1985).

Shedding (S)		Flapping (F)		Study
$St_{S,D} = \frac{f_S D}{U_\infty}$	$St_{S,x_R} = \frac{f_S x_R}{U_\infty}$	$St_{F,D} = \frac{f_F D}{U_\infty}$	$St_{F,x_R} = \frac{f_F x_R}{U_\infty}$	
0.13 (0.43)	0.60	0.026 (0.086)	0.12	(Kiya and Sasaki, 1985)
0.23 (0.76)	1.06	0.025 (0.086)	0.12	
0.18 (0.59)	0.83			(Fang et al., 2022)
0.1 (0.32)	0.46			

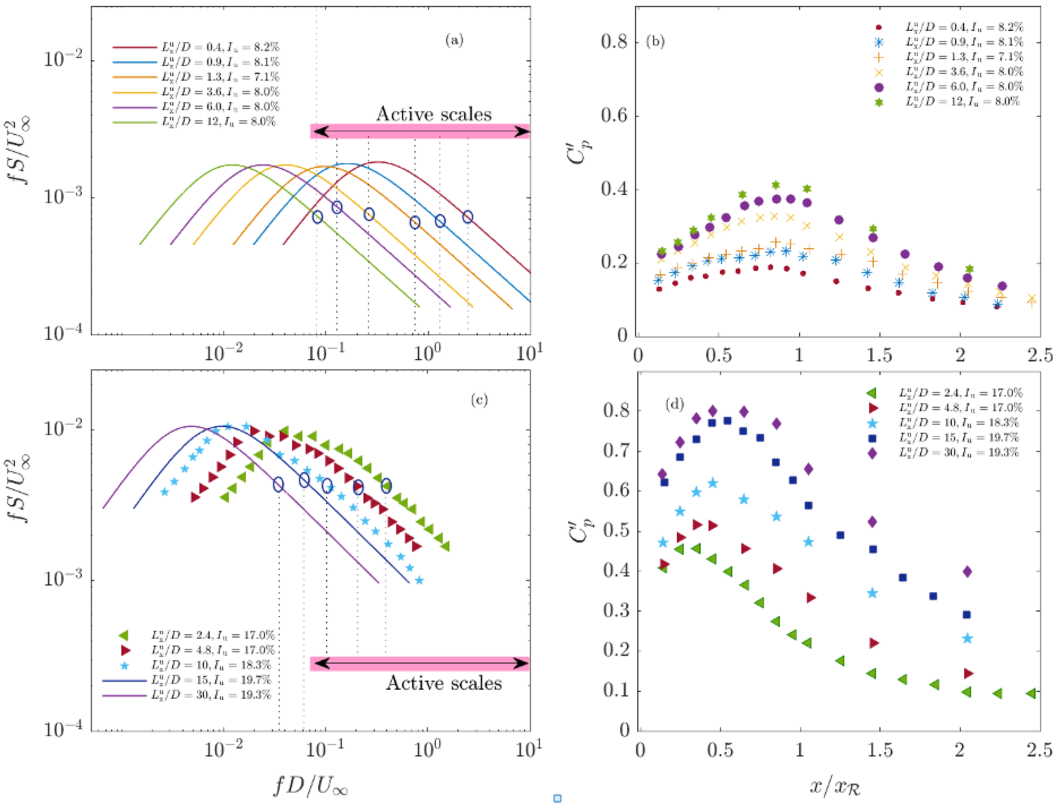

Figure 1. (a, b), $I_u \approx 0.08$ while (c, d) are for $I_u \approx 0.18$. Data in (a, c) are longitudinal velocity spectra while (b, d) are distributions of r.m.s pressure through the bubble. All data from (Li and Melbourne, 1999).

It is apparent that within the separation bubble, there exists a broad range of frequencies associated with the inherent instabilities of the baseline flow. Following Table 1, the range of Active-Scales is taken as $0.086 \leq St_D \leq 10$ with the low-frequency is limited by the flapping mode of the bubble scaled with a shortened x_R for high-intensity turbulent FST. The high-frequency is taken as Melbourne's S-parameter value, noting this both underestimates the true St_{KH} for moderate Re_D (for 5×10^4, $St_{D,KH} \approx 16$) while overestimates with respect to convincing arguments made by Morrison and Kopp, 2018.

3. RESULTS

In figure 1, data from Li and Melbourne, 1999 are presented anew. In (a, b), $I_u \approx 0.08$ while (c, d) are for $I_u \approx 0.18$. The left plots (a, c) are longitudinal velocity spectra while on the right (b, d) are distributions of r.m.s pressure through the bubble, with the x-axis normalised by x_R estimated from (Akon and Kopp, 2016). Superimposed on (a) and (c) is the range of Active-Scales identified in section 2. Markers indicate data extracted from the manuscript while continuous lines are computed with the I_u and L_x^u and the von-Kármán spectrum.

Figure 1 (a, c) shows the effect of increasing L_x^u/D at constant I_u is to shift the spectrum to the low-frequencies. Importantly, in figure 1 (c), the shift from $L_x^u/D = 2.4$ to 30 results in a factor 4 reduction in the spectral energy across a large proportion of the inertial subrange, i.e., for $fD/U_\infty > 0.1$.

That is, across a large portion of the Active-Scales identified in section 2 ($0.086 \leq St_D \leq 10$). The shift also adds energy at much lower frequencies. Curiously, these are at much larger scales than that identified as potentially active in the flow. Despite this redistribution of spectral energy away from the Active-Scales, the dramatic influence of increasing $L_{\mathrm{x}}^{\mathrm{u}}/D$ on the r.m.s. pressure distributions, C_p', is shown in Figure 1 (b, d). The open circles and dashed vertical lines in figure 1 (a, c) draw attention to the spectral energy at $L_{\mathrm{x}}^{\mathrm{u}}/D$ for each flow condition. For both constant I_{u} cases it is apparent that the spectral energy at the integral scale remains effectually constant and that $L_{\mathrm{x}}^{\mathrm{u}} \approx \lambda_{\mathrm{m}}/2\pi$ where λ_{m} is the wavelength, U_∞/f, for which the logarithmic spectral density exhibits its peak (Tieleman et al., 1996). The paper will provide further interpretation and scaling arguments to illuminate the salient characteristics of the above observations.

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