14TH EUROPEAN TURBULENCE CONFERENCE, 1–4 SEPTEMBER 2013, LYON, FRANCE

OPEN-LOOP CONTROL OF AN AXISYMMETRIC TURBULENT WAKE USING HIGH-FREQUENCY PERIODIC JET BLOWING

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Abstract We show that high-frequency periodic jet blowing can be used to increase the base pressure of a bullet-shaped body with a turbulent axisymmetric wake by as much as 35%. A detailed investigation of the effects of forcing is made using random and phase-locked 2C PIV, and modal decomposition of dynamic pressure measurements on the base of the model. In contrast to other studies using periodic jet forcing, for example those discussed in [1], this control strategy does not target specific local or global wake instabilities. Instead, the high-frequency jet creates a row of closely spaced vortices which appear to act as a buffer between the wake and separating flow, thereby inhibiting the entrainment of fluid from the separating boundary. The resulting pressure recovery is proportional to the strength of the vortices produced by the jet, and is accompanied by a broadband suppression of base pressure fluctuations associated with **all** modes. We will show that the optimum forcing frequency is roughly six times the frequency of the shear layer mode, where excitation of the shear layer mode approaches unity gain. We also observe that despite being subject to an axisymmetric perturbation, the forced wake does not exhibit statistical axisymmetry.

EXPERIMENTAL SETUP

The experiments were performed in the Donald Campbell closed-circuit wind tunnel in the Deparment of Aeronautics. The working section measures 1.5 m x 1.2 m x 3.0 m with a contraction ratio of 4.92:1. A schematic of the experimental setup is shown in Figure 1. The freestream velocity was maintained at 15 ms^{-1} providing a turbulent boundary layer at separation with a ratio of body diameter to momentum thickness (D/θ) of 75. The Reynolds number based on diameter, Re_D, is 200,000. A high-fidelity speaker mounted inside the model is used to generate a pulsed jet of variable frequency and amplitude. The jet issues in the freestream direction from a 2.0 mm wide annular orifice located 1.0 mm below the trailing edge. The base of the model is instrumented with 64 static pressure tappings and 12 Endevco 8507C transducers which were sampled at 225 Hz and 40 kHz respectively. Spatially resolved, random and phase-locked 2C PIV measurements were performed on the upper and lower separating shear layers simultaneously, and the jet was calibrated using a single hot-wire CTA system.

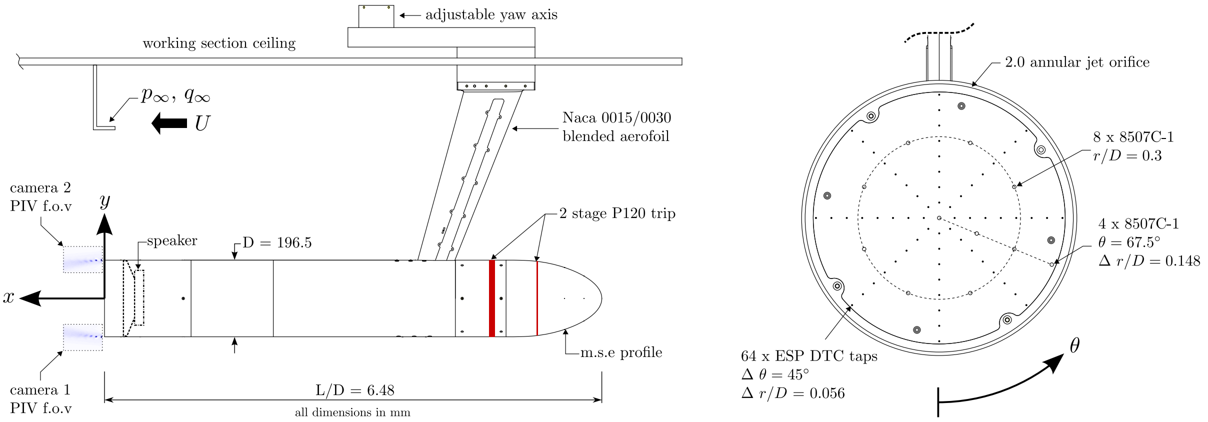


Figure 1. Schematic of the experimental setup. Each view is independently to scale.

RESULTS AND DISCUSSION

Figure 2 shows the change in mean base pressure coefficient as a function of forcing amplitude and frequency, where $C_p = \frac{p-p_\infty}{0.5\rho U_\infty^2}$. The change in base pressure coefficient is averaged over time and space and expressed as a percentage of the unforced case. The dimensionless forcing frequency is $St_\theta = f\theta/U$ and the dimensionless forcing amplitude is $C_\mu = \frac{u_j^2 A_j}{U_\infty^2 A}$, where u_j is the amplitude of the jet perturbation, A_j is the area of the jet orifice, and A is the area of the base of the model. This response map has two key features. At $St_\theta \lesssim 0.08$, there is a pressure 'bucket', where the jet perturbation reduces the base pressure due to strong coupling with the shear layer mode. This phenomenon is well

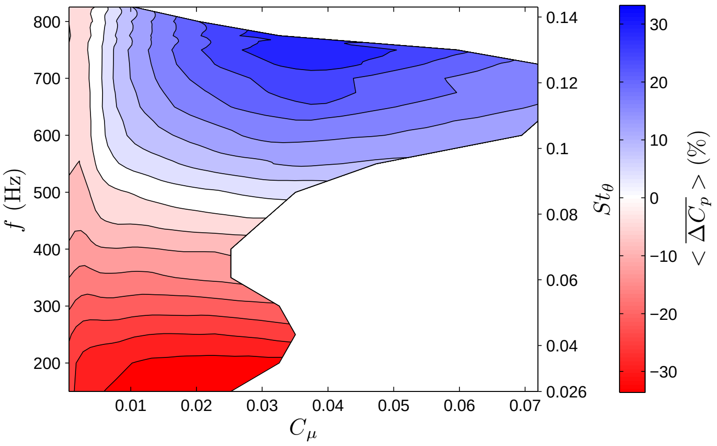
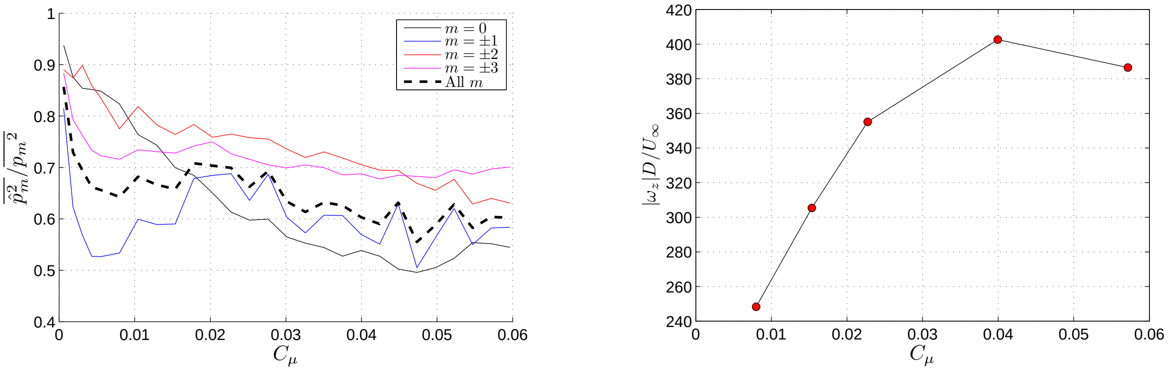


Figure 2. Change in base pressure coefficient as a function of forcing amplitude and frequency.



(*a*) (*b*)

Figure 3. a) Comparison of mean square pressure fluctuations for each mode shape as a function of forcing amplitude, $St_\theta = 0.13$. b) Peak vorticity of the primary vortex as function of forcing amplitude, $St_\theta = 0.13$.

understood and has been previously discussed in [2, 3]. At higher forcing frequencies there is a pressure ‘peak’, within which it is possible to significantly raise the base pressure and consequently reduce the drag of the body. This effect does not appear to have been noticed previously [2]. For this geometry we observe a maximum pressure recovery of 33% at $C_\mu = 0.036$ and $St_\theta = 0.13$.

Figure 3 (a) shows the pressure fluctuation energy for each mode shape (normalised by the baseline case) as a function of forcing amplitude ($St_\theta = 0.13$). These energies are computed from a 2D decomposition of the dynamic pressure measurements at $r/D = 0.3$. As the forcing amplitude is increased, the pressure fluctuation energy decreases. The suppression of energy occurs across all modes with no bias towards any particular wavenumber, indicating a strong non-linear coupling between all the wake modes and the axisymmetric perturbation. Temporal energy spectra (not shown) reveal that the attenuation is also spread over the complete spectrum. Figure 3 (b) shows the peak vorticity of the first vortex created by the jet, $|\omega_z| D / U_\infty$, as a function of forcing amplitude at $St_\theta = 0.13$. Initial increases in the forcing amplitude strengthen the primary vortex up to $C_\mu \approx 0.4$ where the vortex saturates. At higher forcing amplitudes the primary vortex breaks down into multiple structures reducing its peak vorticity. There is a strong correlation between the magnitude of the pressure recovery and the primary vortex strength, both of which saturate at $C_\mu \approx 0.4$.

References

[1] H. Choi, W. Jeon and J. Kim. Control of flow over a bluff body. *Annu. Rev. Fluid Mech.*, 40:113-39, 2008.
[2] J.F. Morrison and A. Qubain. Control of an axisymmetric turbulent wake by a pulsed jet. *ETC 12*, 2010.
[3] A. Qubain. Active control of a turbulent bluff body wake. PhD Thesis, Department of Aeronautics, Imperial College London 2009.