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Influence of synthetically generated surface structures on hydraulic profile performance

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1. Introduction and motivation

Surface texturing is a passive control of boundary layer behaviour on hydraulic profiles without changing their basic profile (curvature, thickness, position of maximum thickness etc). This work evaluates synthetically generated dimple textures applied to a cambered hydrofoil to:

1) mitigate separation and reduce drag under off‑design conditions,
2) keep on‑design penalties minimal.

We combine scale‑resolving CFD with a controlled design of texture families to test these modifications on a single isolated hydrofoil with perspective application for hydraulic machinery components (runner/impeller blades, guide vanes).

Unlike prior work, this study examines a broader range of dimple geometries and their impact on drag and separation under both optimal and off-design conditions. The study also highlights the importance of texture placement and depth, challenging the assumption that all textured surfaces reduce drag consistently across different flow regimes, as noted by Raayai-Ardakani and McKinley [1]. Furthermore, this research investigates the role of dimple geometry in reducing both friction and pressure drag components, extending earlier work [2] by Tay et al., which primarily focused on frictional drag reduction on flat surfaces. While previous studies, like Van Weersch [3], have observed positive effects on turbulent boundary layers, this study provides a more nuanced exploration of how texture depth and placement influence flow separation and overall performance in hydraulic systems.

2. Reference geometry and texture families

The canonical non-symmetrical NACA 2412 hydrofoil was analysed at $Re = 6.56\times10^5$ (based on water as working fluid and chord as length scale), for two incidence angles representative of design and off‑design operation: $\alpha = 8°$ (near‑optimal angle) and $\alpha = 12°$ (stronger adverse pressure gradient). Span and chord used for force normalisation were $b = 0.0375$ m and $c = 0.12$ m.

Five layouts to decouple scale, placement, and shape were tested (A: circular dimples, d/D = 10%, full coverage, B: circular, d/D = 5%, full coverage, C: circular, d/D = 5%, leading edge (LE) clear with texture starting at $x/c \approx 0.33$, D: circular, d/D = 5%, trailing edge (TE) clear, E: elliptical dimples, d/D = 5%, full coverage, matched pitch to B (shape effect isolation), see Figs. 1 and 2.

Global pitch in both directions ensured manufacturable spacing and comparable areal coverage across designs; the $d/D \approx 5\%$ range targets shallow cavities that limit form (pressure) drag while still altering near‑wall transport.

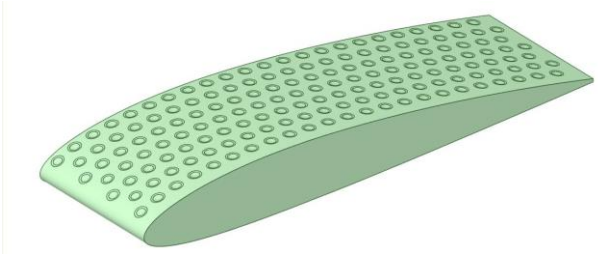

Fig. 1. Hydrofoil with dimple texture “A”

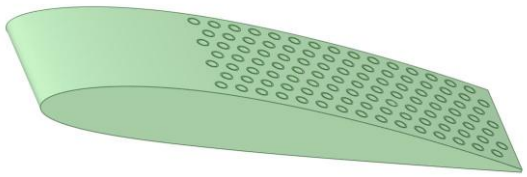

Fig. 2. Hydrofoil with partial dimple texture “C”

3. Methodology and results

Simulations were performed in ANSYS Fluent (2023 R2) using a hybrid SBES (RANS–LES) approach to capture unsteady separation and the cavity-driven vortex dynamics. A multi-block mesh with near-wall refinement was set to meet $y^+ \approx 1$ (see Fig. 3 for surface mesh detail). An implicit coupled pressure–velocity solver with second-order spatial schemes (pressure: second order; momentum: bounded central; turbulence scalars: second-order upwind) was used. Inlet velocity was prescribed according to $Re = 6.56 \times 10^5$, and outlet pressure was set constant, spanwise periodicity was prescribed on sides.

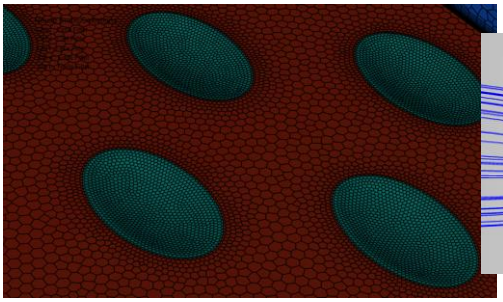

Fig. 3. Surface mesh

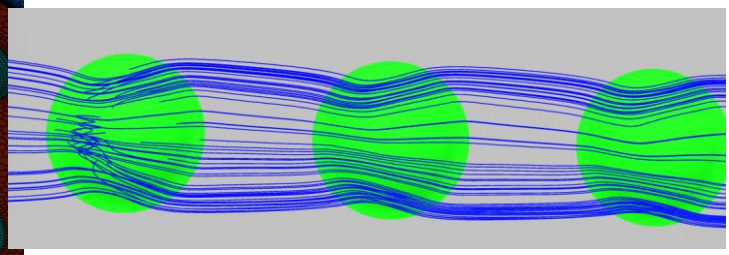

Fig. 4. Near-wall streamlines (hydrofoil “C”)

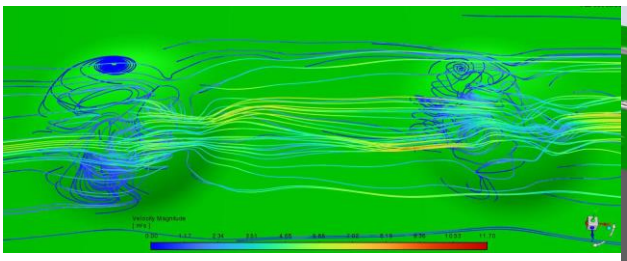

Fig. 5. Near-wall streamlines (hydrofoil “A”), incidence angle 8 degrees

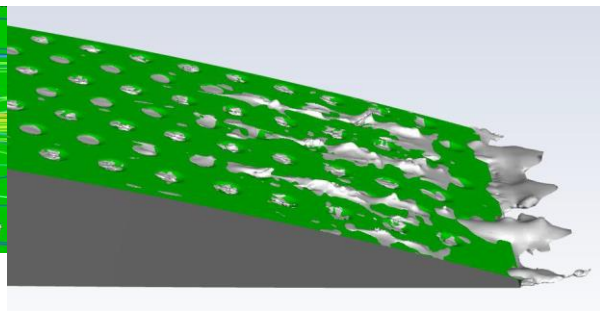

Fig. 6. Pockets of separated flow (grey, hydrofoil “A”), incidence angle 8 degrees

Validation was carried out using smooth NACA 2412 matching historical data: $c_d = 0.0196$ at $\alpha = 8°$ versus ≈0.020 measured; $c_d = 0.0333$ at $\alpha = 12°$ versus ≈0.035 measured, supporting the fidelity of the setup.

Textured performance at $\alpha = 8°$ (design-like) showed that added form drag from cavities dominated modest friction changes, yielding small penalties for well-tuned textures. The least penalising layout was C (LE-clear, d/D = 5%) with $\Delta c_d = +1.45\%$ relative to smooth. Other outcomes were B: +3.60%, D: +3.55%, E: +3.58%; A (10%) incurred ≈ +12%, indicating excessive depth is detrimental.

For textured performance at $\alpha = 12°$ (off‑design) the separation was mitigated. C achieved $\Delta c_d = -6.9\%$; D and E also reduced drag (−2.15% and −4.48%). Decomposition indicated reductions in both pressure and friction components, consistent with a smaller/shorter separation bubble and locally energised near‑wall flow above the dimples.

Looking at the results from perspective of flow physics interpretation it can be concluded that unsteady recirculation inside shallow dimples generates streamwise‑biased secondary motions that modulate the buffer/log layer. When $d/D \approx 5\%$ and the LE is clear, the pattern keeps on‑design penalties small yet delays or weakens separation under stronger adverse pressure gradients. Deeper cavities or LE coverage trigger premature mixing and added form drag without compensating off‑design benefits.

4. Key findings and conclusion

Hydrofoil with clear leading edge (LE) and shallow dimple texture ($d/D \approx 5\%$) delivers the most favourable balance, i.e. near‑neutral drag at $\alpha = 8°$ (≈+1–4%) and measurable reductions off‑design at $\alpha = 12°$ (≈−2% to −7%) and hence presents the best compromise. Regarding depth sensitivity it can be stated that increasing depth to $d/D = 10\%$ notably increases form (pressure) drag at design incidence and is not recommended unless severe separation occurs. It was assessed in the simulations that dimple placement matters: clearing the LE ($x/c \lesssim 0.33$) protects on‑design performance; TE clearance is a viable alternative when manufacturing or structural constraints apply but yields slightly smaller off‑design gains. It was also shown that shape is secondary within the tested range. Elliptical vs circular dimples provided smaller differences than those due to depth and placement.

Synthetically generated dimple textures provide a low‑intrusion passive control to extend the usable incidence range of hydraulic profiles. The recommended configuration (LE‑clear, $d/D \approx 5\%$) offers robust off‑design savings with minimal design point penalties. However their transfer to guide vanes and runner/impeller blades must be further investigated under conditions of nonuniform, highly disturbed inflow and rotational effects. Future work should focus on experimental validation (current manufacturing based on advanced 3d prototyping techniques or laser beam texturing, can realise shallow dimple fields, specify radius blends and areal coverage), expand the Reynolds number range, and also assess influence on cavitation (cavitation inception, cavitation cloud dynamics, erosion) and finite span effects.

Acknowledgement

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References

[1] Raayai-Ardakani, S., McKinley, G. H., Geometric optimization of riblet-textured surfaces for drag reduction in laminar boundary layer flows, Physics of Fluids 31 (5) (2019) 053601.
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[3] Van Weersch, Y., On the turbulent drag reduction of a dimpled sur-face under a pressure gradient, Master thesis, TU Delft, 2017.