Spectral/hp element methods as a digital twin for turbomachinery applications

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Outline

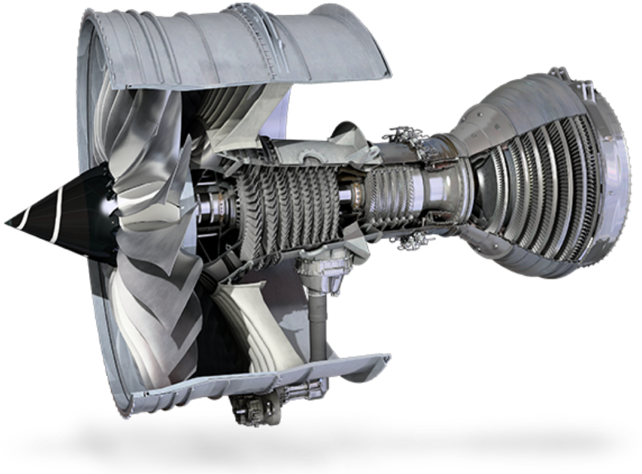
- Motivation.
- Computational approach.
- Test case 1: resolution study of T106A with clean inflow at Re = 88450.
  - Effect of increasing polynomial order.
- Test case 2: representative industrial LPT with inflow disturbances at Re = 111200.
  - Momentum forcing near the leading edge.
  - Random Fourier method for synthetic turbulence generation at the inlet.
- Conclusions.

Motivation

1. Advanced scale resolving DNS and LES CFD simulations as a feasible aero-thermal performance prediction tool.

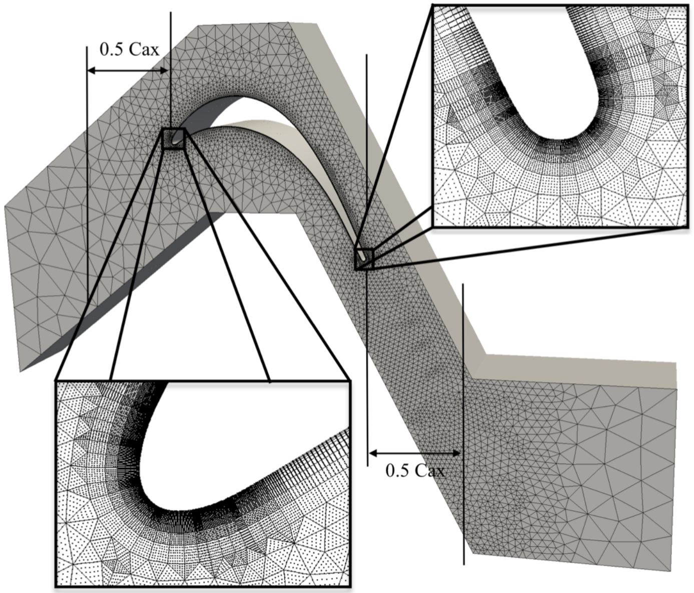
2. Fast-paced technological progress in High Performance Computing.

3. The Nektar++ software framework platform fulfils the key requirements.

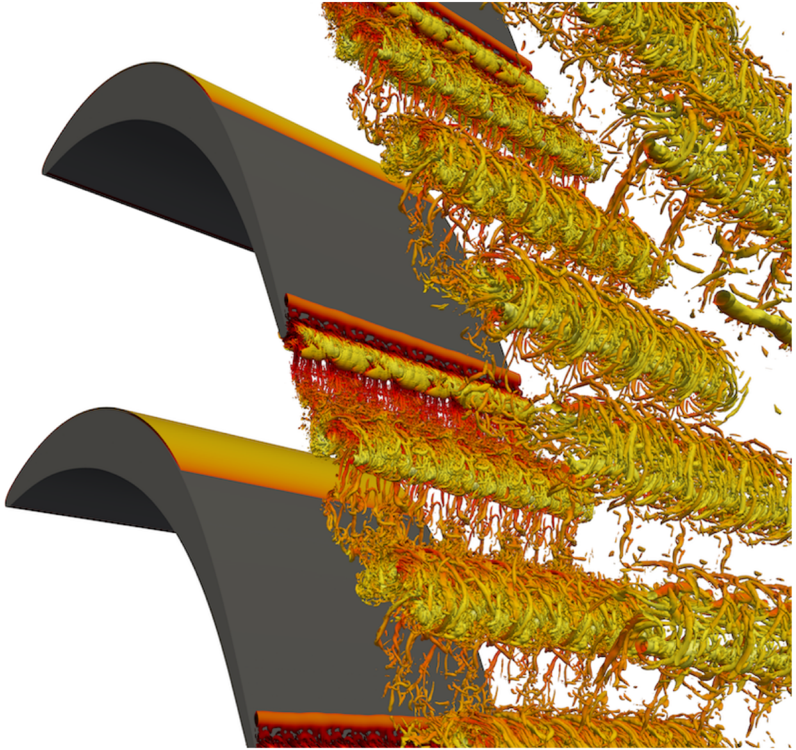


Rolls-Royce Trent 1000

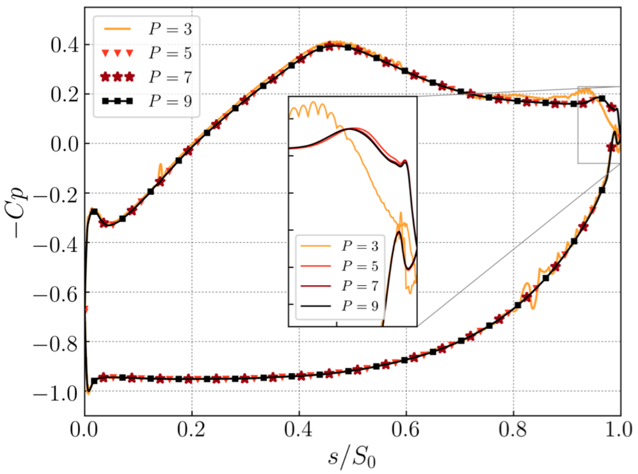
Test case and computational approach

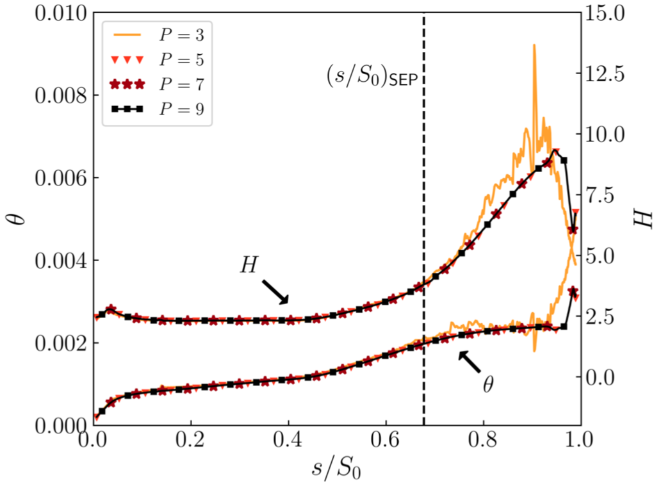


Computational base mesh of the T106A blade and (zoomed) high-order LE and TE mesh with $P = 7$.



P-refinement on blade statistics





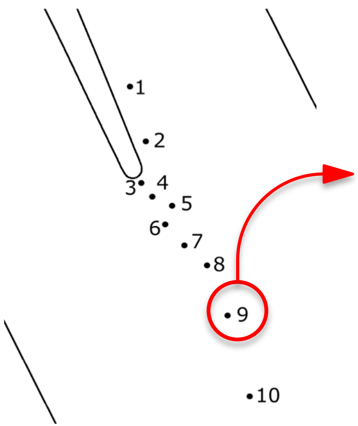
Left: time- and spanwise-averaged pressure distribution.

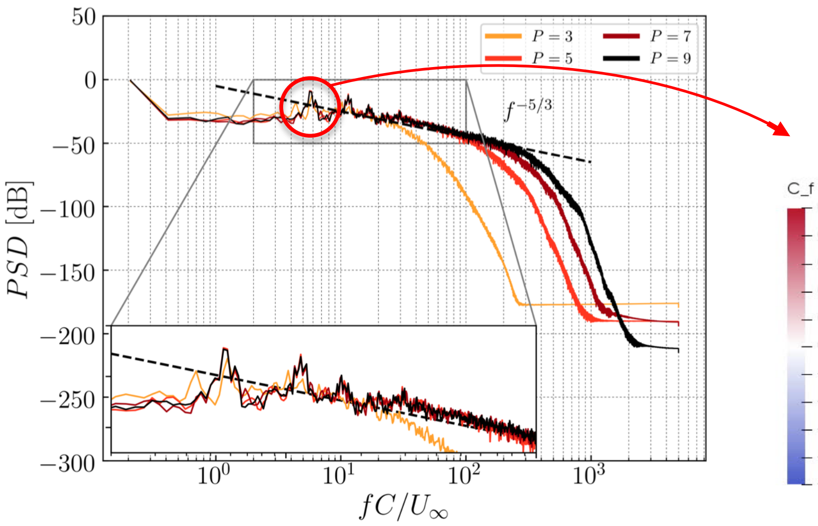
Right: Evolution of momentum thickness (θ) and shape factor (H) along the suction surface (740 stations).

PROPERTY	P=3	P=5	P=7
C_P	0.0367	0.00262	0.000939
C_F	0.196	0.00797	0.00221
$(S/S_0)_{SEP}$	0.0221	0.00400	0.000512
Θ	0.216	0.0131	0.00361
H	0.153	0.0118	0.00305

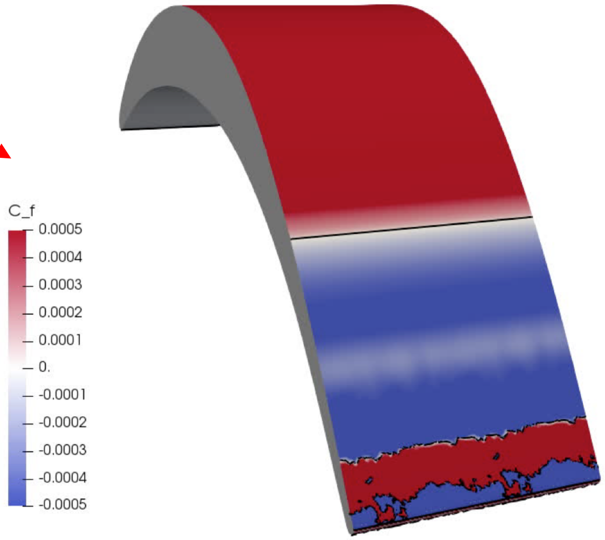
Table on the left: RMS of the relative error with respect to case P=9.

P-refinement on velocity spectra





PSD of streamwise velocity in the turbulent wake.

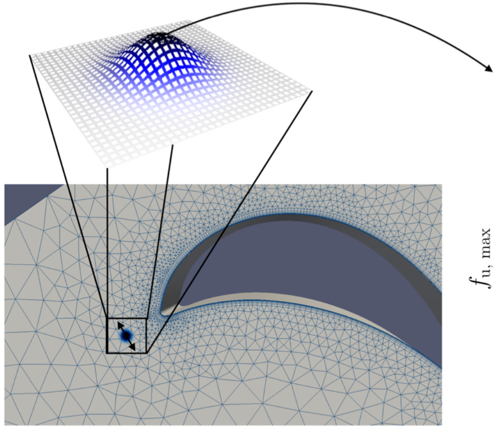


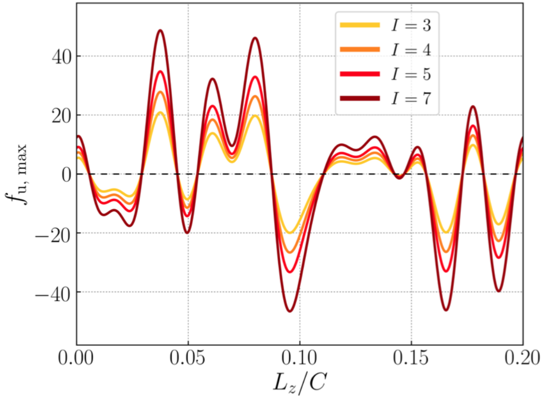
Skin friction coefficient map

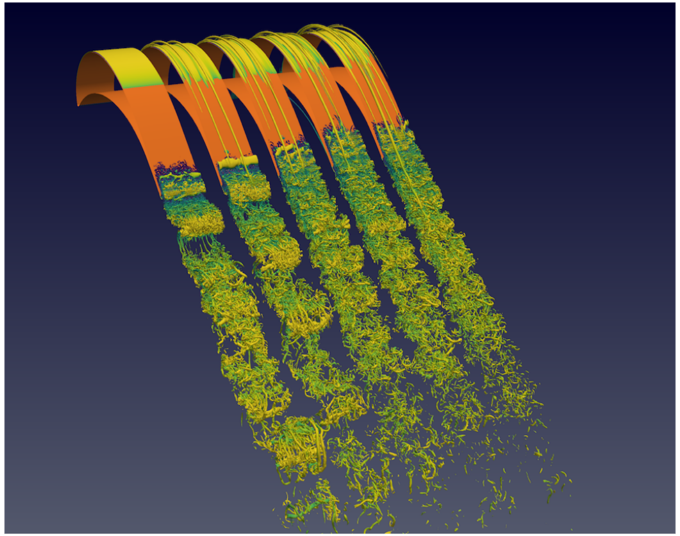
However…

- The cascade with clean inflow behaves like an extremely silent wind tunnel.
- The presence of low levels of physical noise is necessary to trigger a more realistic transition and reattachment mechanism.
- Two approaches are investigated:
  - Momentum forcing near the leading edge
  - Random Fourier method for synthetic turbulence generation at the inlet

Momentum forcing near the LE





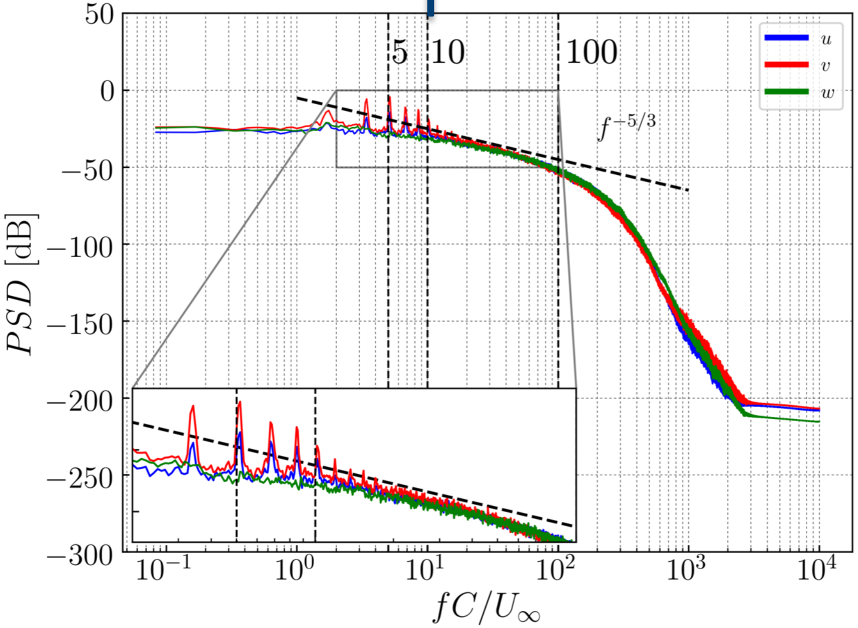


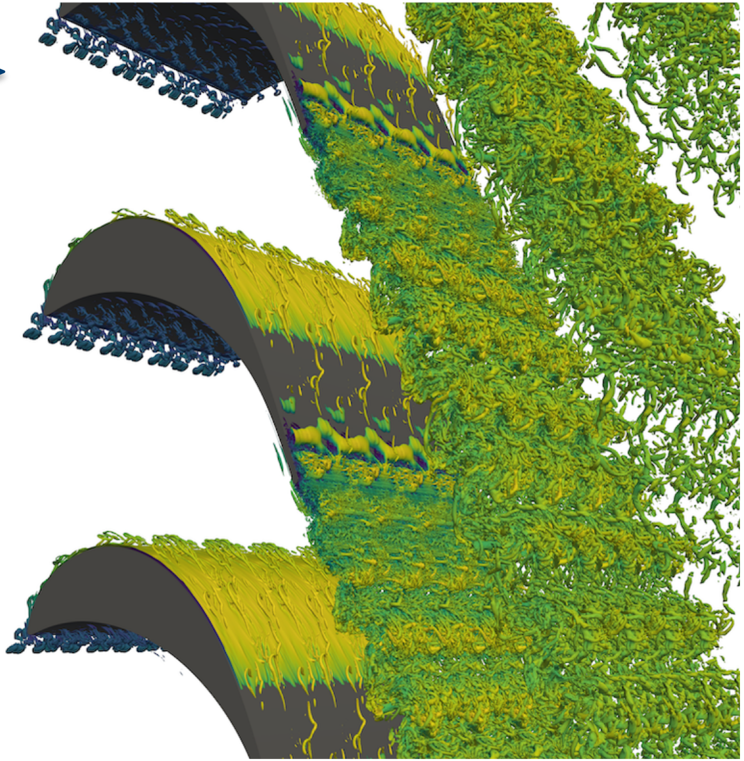
$$\mathbf{f_u}(x,y,z,t) = \begin{cases} I(t) \cdot \dfrac{g(z)}{\int_0^{L_z} \sqrt{g(z)^2}} \cdot \alpha \cdot e^{\frac{-\left[(x-x_c)^2+(y-y_c)^2\right]}{\delta^2}} \\ I(t) \cdot \dfrac{g(z)}{\int_0^{L_z} \sqrt{g(z)^2}} \cdot \beta \cdot e^{\frac{-\left[(x-x_c)^2+(y-y_c)^2\right]}{\delta^2}} \\ 0 \end{cases}$$

$$g(z) = \sum_{i=1}^{N_{\text{body}}} A_i \sin\left(\frac{2\pi}{L_z} iz + \phi_i\right)$$

Time-varying bodyforcing

$$I(t) = I \cdot \sin(2\pi f C / U_\infty t)$$





Synthetic inflow turbulence

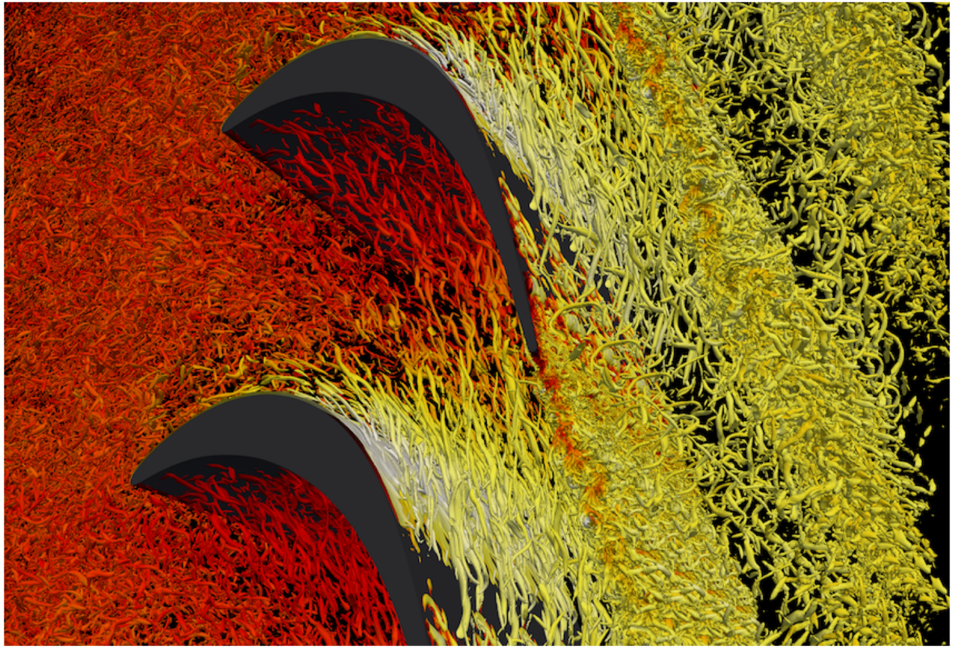
$$E(\kappa) = \alpha \frac{u_{rms}^2}{\kappa_e} \frac{(\kappa/\kappa_e)^4}{[1+(\kappa/\kappa_e)^2]^{17/6}} e^{[-2(\kappa/\kappa_\eta)^2]}$$

$$\hat{u}^n = \left(E(|\kappa_j^n|)\Delta\kappa\right)^{1/2}$$

$$u_i'(x_j) = 2\sum_{n=1}^{N_{\text{turb}}} \hat{u}^n \cos(\kappa_j^n x_j + \psi^n)\sigma_i^n$$

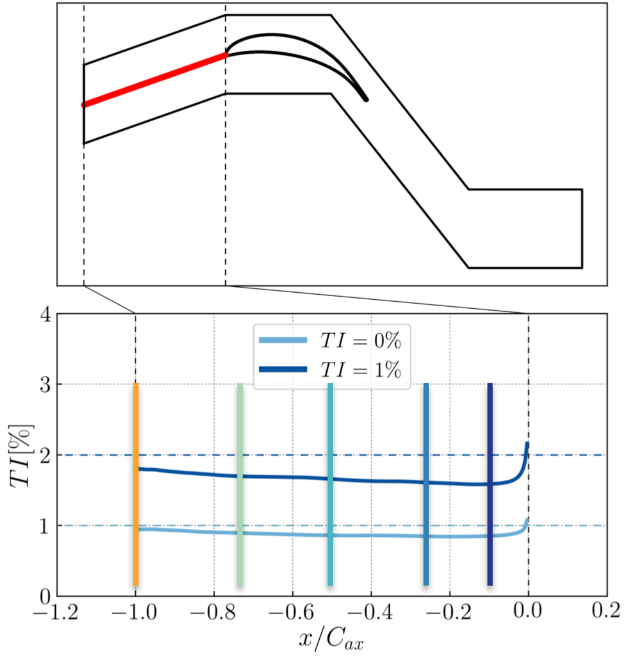
$$a = e^{-\Delta t/\mathcal{T}} \qquad b = \sqrt{1-\left(e^{-\Delta t/\mathcal{T}}\right)^2}$$

$$(u_{i,in}')^t = a(u_{i,in}')^{t-\Delta t} + bu_i'$$

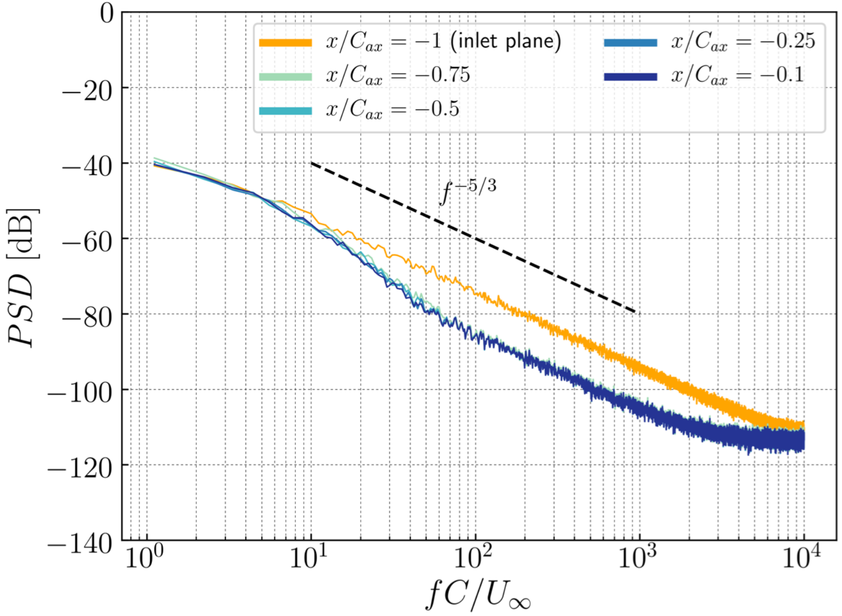


L. Davidson. Using isotropic synthetic fluctuations as inlet boundary conditions for unsteady simulations. Advances and Applications in Fluid Mechanics 1.1 (2007), pp. 1-35.

Turbulence intensity evolution

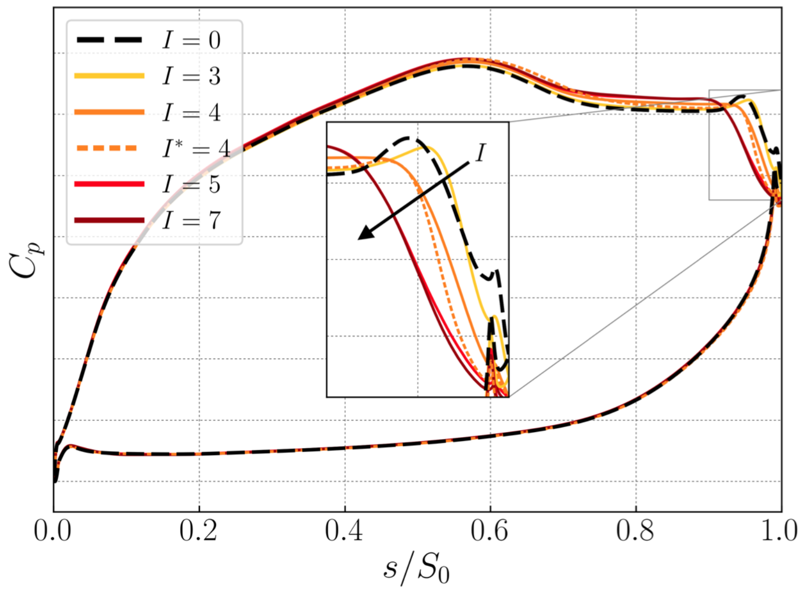


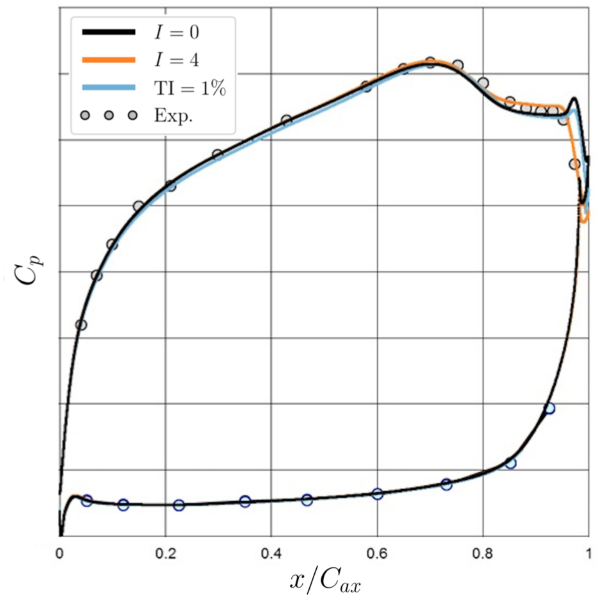
TKE evolution in the development region of the domain.



Streamwise velocity spectrum in various stations

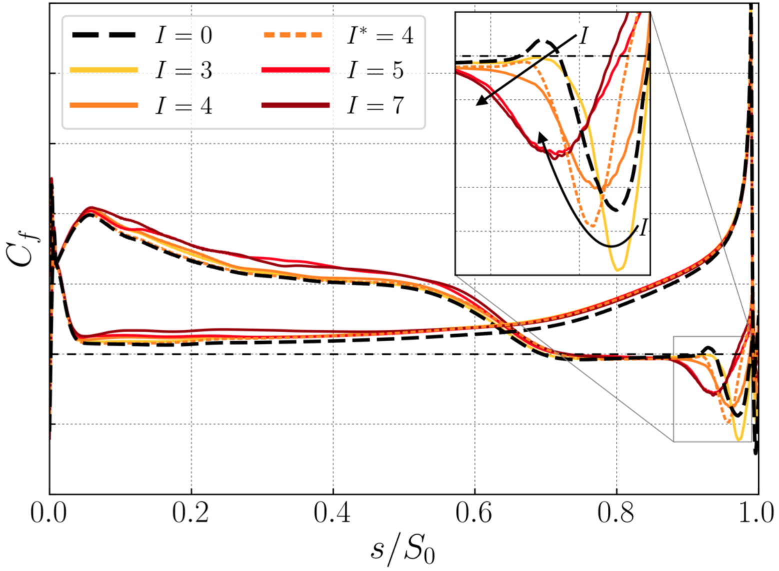
Pressure distributions

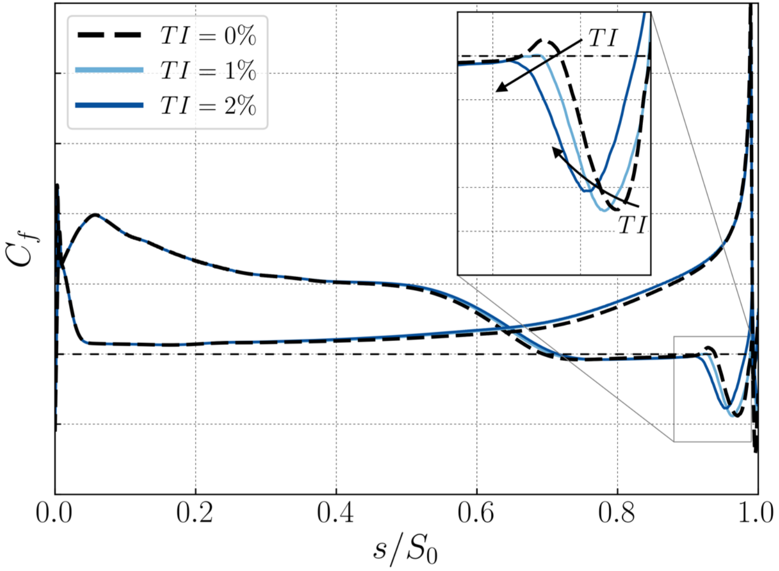




Pressure coefficient with increasing bodyforcing intensity (left), and comparison with experimental data and inflow turbulence approach (right).

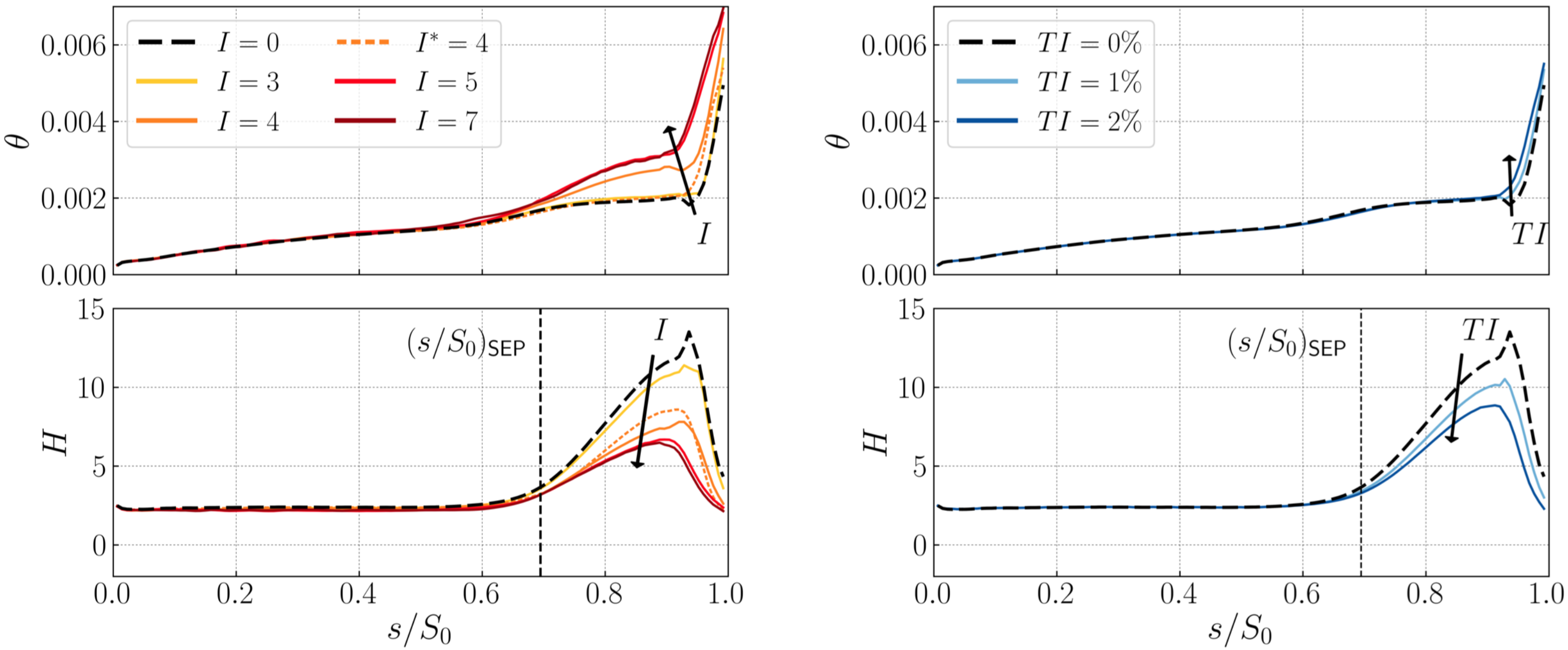
Skin friction coefficient





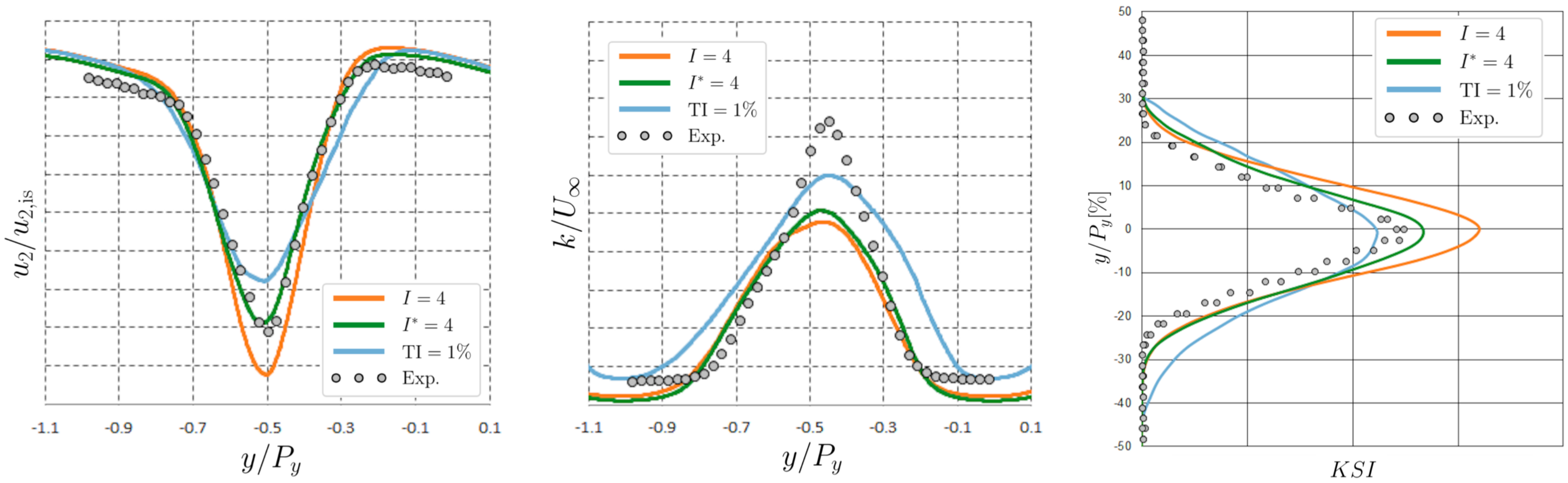
Skin friction coefficient with increasing bodyforcing intensity (left) and synthetic inflow turbulence (right).

Boundary layer parameters



Boundary layer parameters with increasing bodyforcing intensity (left) and synthetic inflow turbulence (right).

Wake profiles



Comparison agains experimental data: velocity wake (left), turbulent kinetic energy (middle) and KSI (right).

Conclusions

- Towards Digital Twin/ Virtual Wind Tunnel → High Order Methods. This work shows how to tackle the problem.
- P-refinement is demonstrated to be a powerful tool to achieve results convergence on a range of statistics.
- Comparison between inflow disturbance mechanisms:
  - Momentum forcing: more “artificial” and cheaper method, proven useful investigation tool
  - Synthetic inflow turbulence: more robust and expensive method.

Thank you for your attention

Cassinelli A., Montomoli M., Adami P., Sherwin S. J., 2018. "High fidelity spectral/*hp* element methods for turbomachinery". ASME Paper No. GT2018-75733.

Cassinelli A., Xu H., Montomoli M., Adami P., Diaz R. V., Sherwin S. J., 2018. "On the Effect of Inflow Disturbances on the Flow Past a Linear LPT Vane Using Spectral/*hp* Element Methods". ASME Paper No. GT2019-91622.

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