Low-Noise Blade Design Optimization for a Transonic Fan Using Adjoint-Based MDO Approach

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Overview

To Enrich the Multidisciplinary Design Capabilities in Turbomachinery

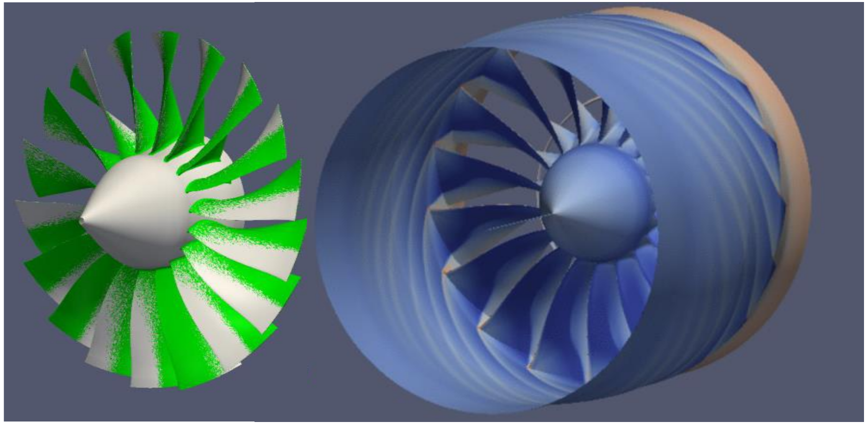
- Develop **adjoint** sensitivity analysis for **transonic fan aeroacoustics**
- Target the **buzz-saw noise**
- Build an adjoint-based, **MDO** workflow for transonic fan blades

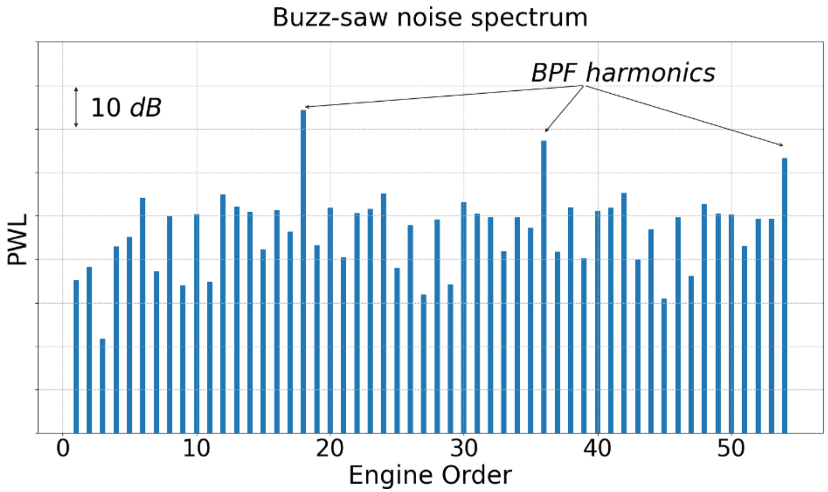
Adjoint-Based Optimizations of an Industrial Research Fan

- Aeroacoustic design optimization
- Aerodynamic design optimization
- Bi-objective design optimizations
- Mechanisms for performance improvements

Buzz-saw noise

- Spiral shock trains from each blade
- Nonlinearity: decay; interactions between EO tones
- **Rotor-locked**





Using full-annulus domain for optimization?

Adjoint for fan aeroacoustics

- Noise objective definition

$$(\boldsymbol{U}, \boldsymbol{x}) \longrightarrow \boxed{\bar{\boldsymbol{I}}(\theta, r) \equiv \frac{1}{T}\int_T \boldsymbol{I}(\boldsymbol{x}_S, t)dt = \frac{1}{2\pi}\int_0^{2\pi} [p' + \rho_0 \boldsymbol{u}' \cdot (\boldsymbol{u}_0 + \boldsymbol{V}_\Omega)] \left[\boldsymbol{u}' + \frac{p'}{\gamma p_0}(\boldsymbol{u}_0 + \boldsymbol{V}_\Omega)\right] d\theta} \longrightarrow \boxed{W = 2\pi \int_{r_{\min}}^{r_{\max}} \bar{\boldsymbol{I}}(r) \cdot \boldsymbol{n} dr} \longrightarrow PWL \equiv J(\boldsymbol{U}, \boldsymbol{x})$$

- Adjoint formulization in the rotating frame of reference

  Linearization of J: flow adjoint source $\frac{\partial J}{\partial \boldsymbol{U}}$, geometric adjoint source $\frac{\partial J}{\partial \boldsymbol{x}}$

- Discrete steady adjoint equation

$$\left(\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{U}}\right)^{\top} \boldsymbol{\phi} = \left(\frac{\partial J}{\partial \boldsymbol{U}}\right)^{\top}$$

Assumption:
$\boldsymbol{R}(\boldsymbol{U}, \boldsymbol{x}) = \boldsymbol{0}$

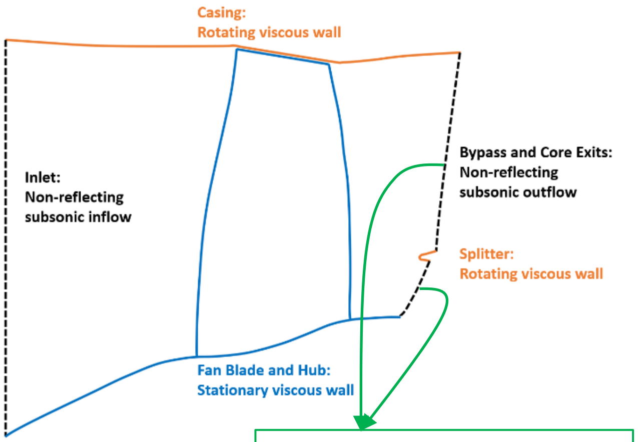
- Adjoint mesh sensitivity

$$\frac{\delta J}{\delta \boldsymbol{x}} = \boldsymbol{\phi}^{\top}\left(-\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{x}}\right) + \frac{\partial J}{\partial \boldsymbol{x}}$$

- Design sensitivity = Mesh sensitivity * Mesh deformation

Case under investigation

- Rolls-Royce VITAL Fan
- Minimize: $\{PWL, 1\text{-}\eta\}$
- Subject to: Specified $(\dot{m}, PR)$
- CFD setups

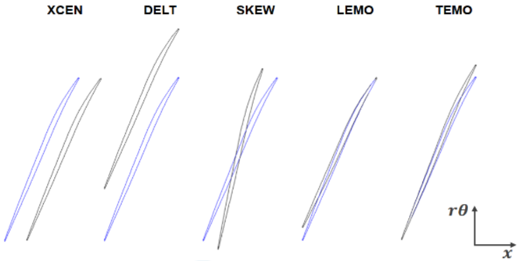


Fixed exit capacities

- Geometry parameterization

7 engineering parameters defined at 5 radial locations (25%, 50%, 75%, 87.5%, 100%)

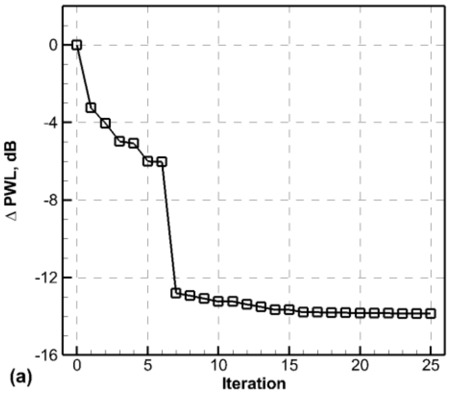
XCEN	Axial sweep, mm
DELT	Circumferential lean, degree
SKEW	Re-staggering, degree
LEMO	Leading edge re-cambering, degree
TEMO	Trailing edge re-cambering, degree
LEBP	Chord position for LEMO blending, dimensionless
TEBP	Chord position for TEMO blending, dimensionless



blue: datum
black: DPs applied

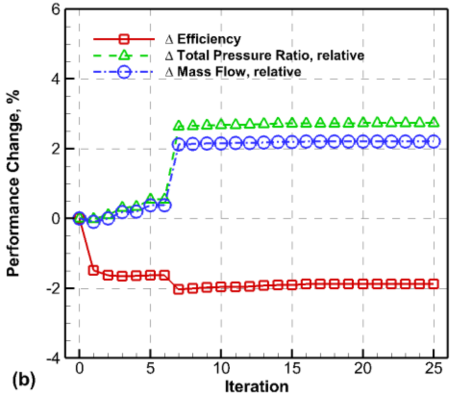
Aeroacoustic optimization

- Unconstrained

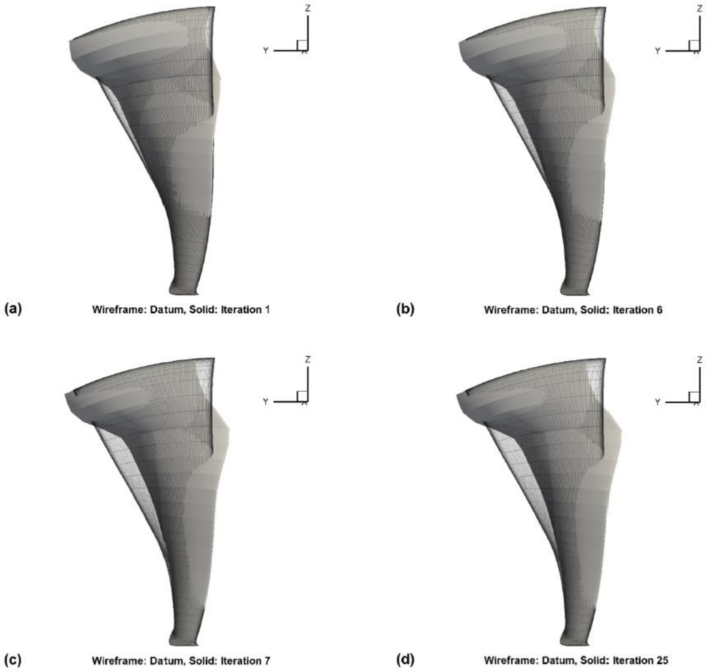


An impressive noise reduction (14 *dB*)

Operating point shifted
Efficiency penalty

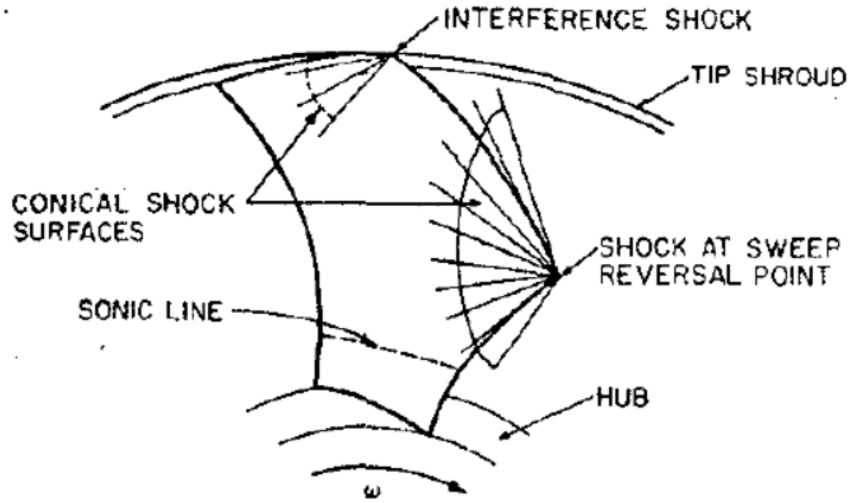


- Blade shape comparison



Aeroacoustic optimization (Cont.)

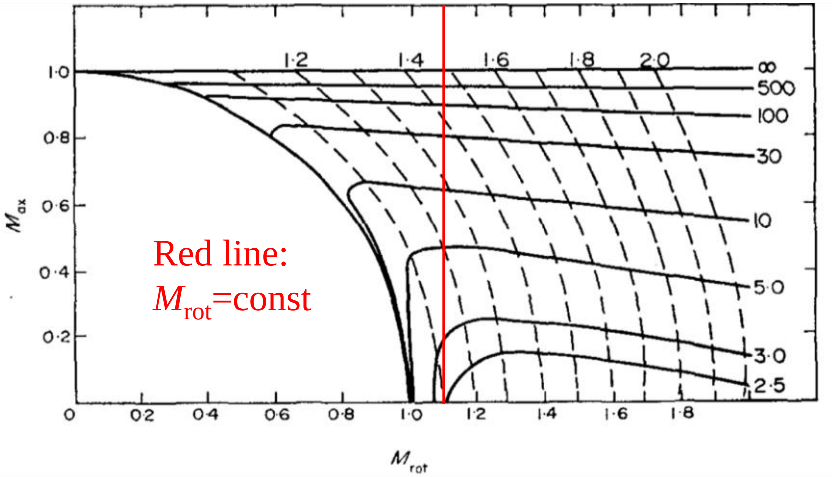
- Compound leading-edge sweep
  Manipulate shock generation



Bliss et al, 1976

- Increased blade passage area
  Enhance nonlinear attenuation

Time of flight: $\frac{a_0 t}{\lambda} = \frac{x}{s} \boxed{\frac{M_{rel}^4}{\sqrt{M_{rel}^2 - 1}} \{M_{rot} - \sqrt{M_{rel}^2 - 1} \cdot M_{ax}\}^{-2}}$



Hawkings, 1971

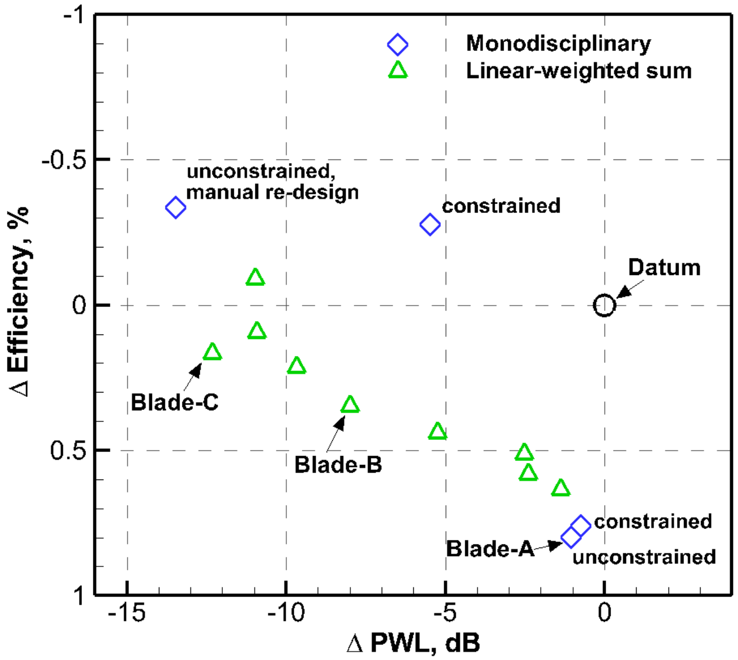
Aeroacoustic optimization (Cont.)

- Fan operating point recovery $-0.25\% \le \frac{PR - PR_{\text{datum}}}{PR_{\text{datum}}} \le 0.25\%$
  - Conduct a constrained optimization
  - Manually redesign the unconstrained optimized blade

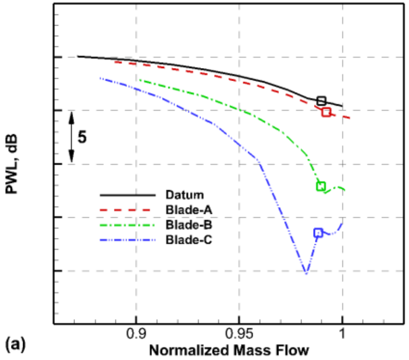
	Uncons.	Manual redesign	Cons.
$\Delta\, PWL$	-14 dB	-13.5 dB	-5.5 dB
$\Delta\, \eta$	-1.9 %	-0.34 %	-0.28 %
$\Delta\, PR \,/\, PR_{\text{datum}}$	+2.7 %	+0.05 %	+0.19 %
$\Delta\, \dot{m} \,/\, \dot{m}_{\text{datum}}$	+2.2 %	+0.03 %	+0.15 %

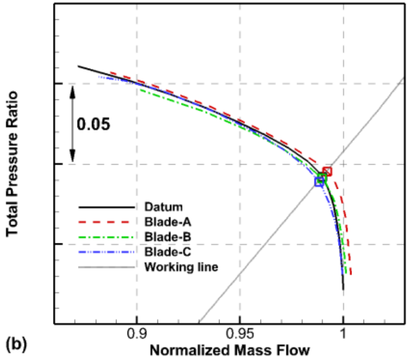
MDO result

- Noise-efficiency tradeoff

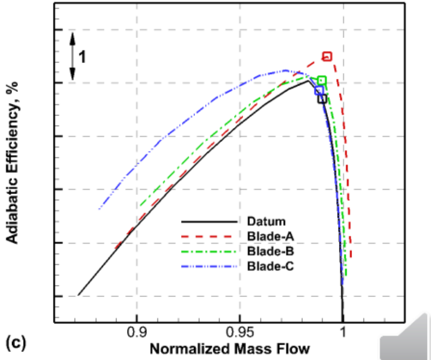


- Off-design performance





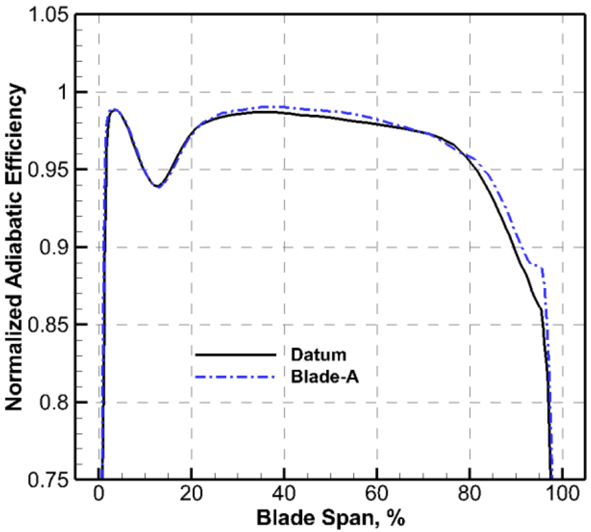
Performance improvements achieved over the entire operating range

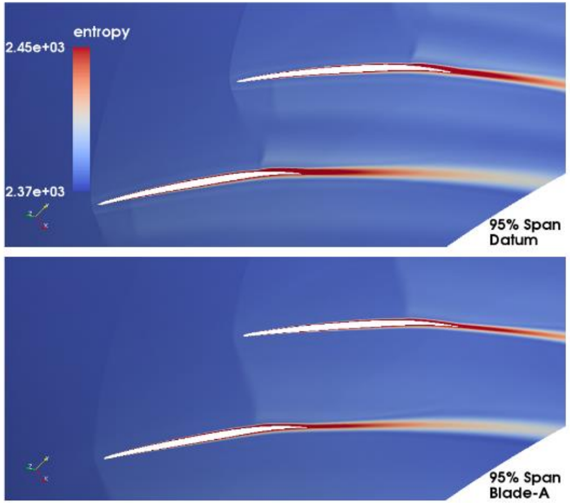


(c)

Blade-A

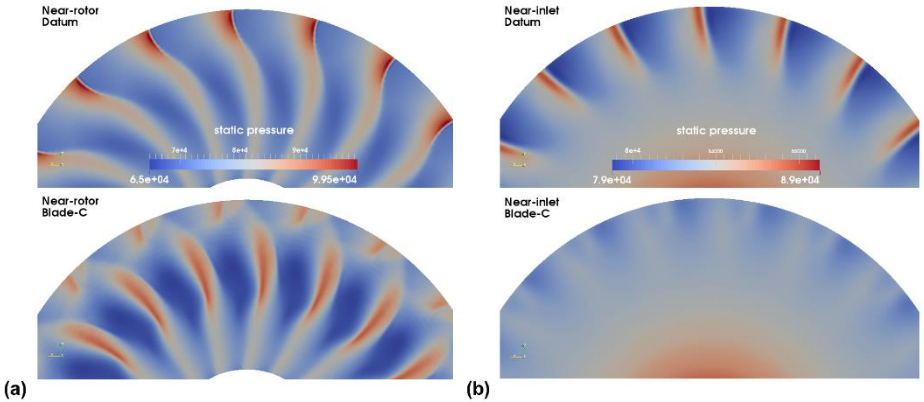
- Efficiency benefit mainly due to flow field improvement near the tip region
- Reduced direct shock loss and the viscous loss caused by shock-boundary layer interaction





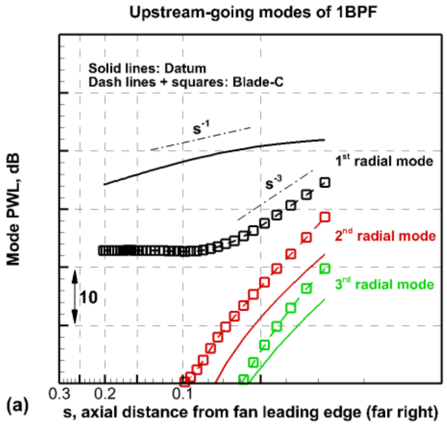
Blade-C: Wavesplitting analysis

- Enhanced coupling between the shock field and high-order duct modes
- At the rotor face, acoustic energy was transferred to high-order duct modes that are cut-off. Therefore, much less acoustic energy can propagate to the upstream far-field.



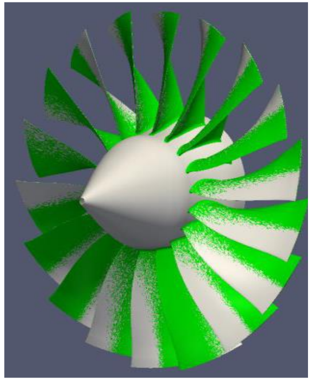
Shock distributions at two axial cut planes

Wavesplitting analysis

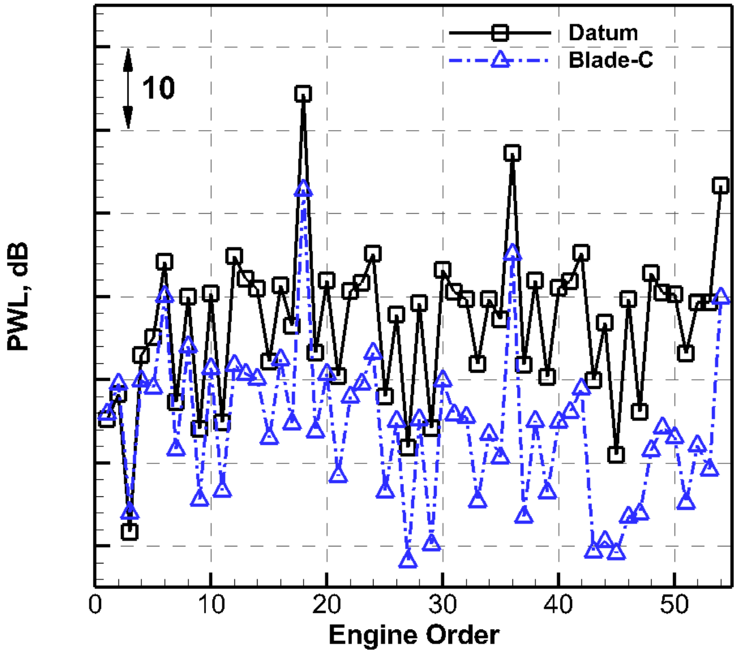


Blade-C: Buzz-saw noise

- Buzz-saw tones are broadly reduced.



Full-annulus calculation with stagger angle variations applied to each blade



Conclusions

- Adjoint sensitivity analysis for transonic fan aeroacoustics
- Adjoint-based MDO workflow for transonic rotors
- Methodology successfully applied to the aeroacoustic & aerodynamic optimizations of an industrial research fan
- Significant performance improvements achieved
- Enhancing the coupling between the flow field and high-order duct acoustic modes through blade shaping is good for noise source level reduction

Thanks for your attention!

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