# Numerical Investigation of Abradable Coating Wear Through Plastic Constitutive Law

Application to Aircraft Engines

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#### Outline

#### Introduction

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# **Problem statement**

#### Technologies for improved efficiency

- light and composite materials
- few turbine and compressor stages with higher conicity
- aerodynamically improved blade designs
- higher operating temperatures



#### CFM56- CFM International

# New strategy: use of abradable coatings

- minimal operating clearance for improved compression rates
- capable of undergoing structural contacts through wear
- unexpected diverging behaviors?

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# **Problem statement**

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#### modeling of abradable coating wear in aircraft engines

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#### Referenced mechanisms

- abrasion, erosion, corrosion, adhesion, fretting
- drilling, grinding, turning, milling
- high speed tangential velocities

# Abradable properties

- strength to withstand gas turbine environment
- wear characteristics to minimise incurring blade wear

# Current knowledge and modeling

- Wear: experimental and empirical  $\rightarrow$  Archard's law
- Machining : kinematic relationships
- CPU-intensive numerical approaches in the FEM framework



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#### Assumptions

- A single blade in contact
- Statically distorted casing on a 2-nodal diameter shape

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- No friction
- No thermomechanical coupling

### Solution method

- Blade dynamics reduction through Craig-Bampton technique
- Abradable coating wear through quasi-static plastic constitutive law
- Time-marching solution method





Equations	of motion		
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$$\int_{\Omega_1} \rho_1 \ddot{\mathbf{u}}_1 \delta \mathbf{u}_1 \, \mathrm{dV} + \int_{\Omega_1} \bar{\bar{\sigma}}_1(E_1) : \delta \bar{\bar{\epsilon}}_1 \, \mathrm{dV} = - \int_{\Gamma_c} t_N \delta g \, \mathrm{dS} \quad \leftarrow \text{ blade}$$
$$\int_{\Omega_2} \bar{\bar{\sigma}}_2(E_2, E_T, \sigma_Y) : \delta \bar{\bar{\epsilon}}_2 \, \mathrm{dV} = \int_{\Gamma_c} t_N \delta g \, \mathrm{dS} \quad \leftarrow \text{ abradable coating}$$

Equations	of motion		
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$$\begin{aligned} &\int_{\Omega_1} \rho_1 \ddot{\mathbf{u}}_1 \delta \mathbf{u}_1 \, \mathrm{dV} + \int_{\Omega_1} \overline{\bar{\sigma}}_1(E_1) : \delta \overline{\bar{\epsilon}}_1 \, \mathrm{dV} = -\int_{\Gamma_c} t_N \delta g \, \mathrm{dS} & \leftarrow \text{blade} \\ &\int_{\Omega_2} \overline{\bar{\sigma}}_2(E_2, E_T, \sigma_Y) : \delta \overline{\bar{\epsilon}}_2 \, \mathrm{dV} = \int_{\Gamma_c} t_N \delta g \, \mathrm{dS} & \leftarrow \text{abradable coating} \end{aligned}$$

#### Finite element discretization

$$egin{array}{lll} \mathsf{M}\ddot{\mathsf{u}} + \mathsf{D}\dot{\mathsf{u}} + \mathsf{K}\mathsf{u} + \lambda &= \mathbf{0} &\leftarrow \mathsf{blade} \ \lambda &= \mathsf{F}_\mathsf{int} &\leftarrow \mathsf{abradable} \end{array}$$

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$$\int_{\Omega_1} \rho_1 \ddot{\mathbf{u}}_1 \delta \mathbf{u}_1 \, \mathrm{dV} + \int_{\Omega_1} \bar{\bar{\sigma}}_1(E_1) : \delta \bar{\bar{\epsilon}}_1 \, \mathrm{dV} = -\int_{\Gamma_c} t_N \delta g \, \mathrm{dS} \quad \leftarrow \text{blade}$$
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Finite element discretization

#### Contact conditions

$$\begin{split} \mathsf{M}\ddot{\mathsf{u}} + \mathsf{D}\dot{\mathsf{u}} + \mathsf{K}\mathsf{u} + \lambda &= \mathbf{0} \quad \leftarrow \text{ blade} \\ \lambda &= \mathsf{F}_{\text{int}} & \leftarrow \text{ abradable} \end{split} \qquad \qquad \lambda \geqslant 0, \quad \mathbf{g} \geqslant 0, \quad \lambda \mathbf{g} = \mathbf{0} \end{split}$$

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Equations	of motion		
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$$\int_{\Omega_1} \rho_1 \ddot{\mathbf{u}}_1 \delta \mathbf{u}_1 \, \mathrm{dV} + \int_{\Omega_1} \bar{\bar{\sigma}}_1(E_1) : \delta \bar{\bar{\epsilon}}_1 \, \mathrm{dV} = -\int_{\Gamma_c} t_N \delta g \, \mathrm{dS} \quad \leftarrow \text{blade}$$
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Finite element discretizationContact conditions $M\ddot{u} + D\dot{u} + Ku + \lambda = 0$  $\leftarrow$  blade $\lambda \ge 0$ ,  $g \ge 0$ ,  $\lambda g = 0$  $\lambda = F_{int}$  $\leftarrow$  abradable

Explicit time stepping technique: central finite differences

$$\ddot{\mathbf{u}}_n = \frac{\mathbf{u}_{n+1} - 2\mathbf{u}_n + \mathbf{u}_{n-1}}{h^2}, \quad \dot{\mathbf{u}}_n = \frac{\mathbf{u}_{n+1} - \mathbf{u}_{n-1}}{2h}$$

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# Abradable constitutive law: plasticity

## Assumptions

- Uni-axial plasticity in compression only
- Isotrope hardening: •

$$f(\sigma,\alpha) = \sigma - (\sigma_Y + K\alpha)$$

Linear additive law:

$$\varepsilon = \varepsilon^{\mathbf{e}} + \varepsilon^{\mathbf{p}}$$
$$\sigma = \mathbf{E}\varepsilon^{\mathbf{e}}$$

#### Integration

- Kuhn & Tucker conditions
- Prediction-correction incremental approach: Return Map algorithm
  - if  $f^{\rm p} \leq 0$ , admissible prediction
  - if  $f^{p} > 0$ , correction of prediction



plastic constitutive law



Proposed a	algorithm		
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1. Displacement prediction by neglecting contact constraints

$$\mathbf{u}_{n+1,p} = \left[\frac{\mathbf{M}}{h^2} + \frac{\mathbf{D}}{2h}\right]^{-1} \left( \left(\frac{2\mathbf{M}}{h^2} - \mathbf{K}\right) \mathbf{u}_n + \left(\frac{\mathbf{D}}{2h} - \frac{\mathbf{M}}{h^2}\right) \mathbf{u}_{n-1} \right)$$

- 2. **Determination** of  $g_{n+1,p}$  by identifying all abradable elements  $i \in I$  being penetrated by the blade
- 3. Abradable internal forces computation  $\mathbf{u}_{n+1,p} \rightarrow \varepsilon_{i \in I} \rightarrow (\sigma_{i \in I}, \alpha_{i \in I}) \rightarrow \mathbf{F}_{int}$  $\varepsilon_{i \in I}^{p} \rightarrow \text{abradable profil update}$
- Displacements correction consistent with abradable internal forces (~ contact forces)

$$\mathbf{u}_{n+1} = \mathbf{u}_{n+1,p} - \left[\frac{\mathbf{M}}{h^2} + \frac{\mathbf{D}}{2h}\right]^{-1} \mathbf{F}^{\mathsf{c}}$$

Model con	vergence		
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#### Modal convergence

- Craig-Bampton reduction technique
- frequency deviation

$$\Delta f = \frac{|f_f - f_r|}{f_f} < 0.1\%$$

- initial size :  $\sim$  80,000 dof
- final size : 109 dof



First five modes of the blade



Model con	vergence		
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First five modes of the blade



CB componant modes



CB static modes

Model conv	vergence		
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#### Time-step convergence

- Conditionally stable explicit time-stepping scheme: very small time-step
- Blade displacement convergence
- Abradable wear profile convergence

Model convergence	
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#### Time-step convergence

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Modal inte	eractions		
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Modal inte	eractions		
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Ω low ductility – after ten rounds

0.2

0.3

0.4

0.1

Ω high ductility – after ten rounds

0.2

0.3

0

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0ò

0.1

0.4

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#### Summary

- Available numerical tool accounting for macroscopic peudo-wear mechanisms
- Convergence + low CPU features
- Possibility of experimental measure for abradable identification
- Wear + clearance opening  $\rightarrow$  New phenomena compared to the usual unilateral contact framework
- Detection of unexpected high levels of vibration at critical velocities in agreement with first experimental results

#### Future work

- Addition of friction
- More contact and wear interfaces (~ more CB interface nodes)
- More realistic plastic constitutive laws
- New scenarios of interaction