Modal nudging of aerospace structures

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Outline

- Nonlinearities in design process
- Modal nudging
  - Concept
  - Stiffened structure example
- Limitations
- Current/future work
- Summary
Well-behaved nonlinear structures

- Instabilities ≠ structural failure
- Large deformations in material linear elastic range: Novel functionality and lighter structures
- Well-behaved nonlinearities can be robustly controlled

Improved structural efficiency through the incorporation of well-behaved nonlinearities in the design process

[1] shellbuckling.com
Modal nudging

Nonlinear response tailoring method based on post-buckling information

Original structure → Nonlinear post-buckling response information → Small change in geometry → Improved structural response:

- Load-carrying capacity
- Stiffness/compliance
- Sensitivity to imperfections


Modal nudging of aerospace structures
1. Identify isolated stable region of interest.
2. Extract deformation mode $u_{\text{state}}$.
3. Superpose to initial geometry $x_0$.
4. Restart analysis using nudged geometry $x$.
5. If necessary, increase nudging factor $\eta$. Repeat from 3.

Steps and results

- Clamped edge
- Clamped edge
- Original structure

Modal nudging of aerospace structures
Steps and results

1. Identify isolated stable region of interest.

2. **Extract deformation mode** \( \mathbf{u}_{\text{state}} \).

3. Superpose to initial geometry \( \mathbf{x}_0 \).

4. Restart analysis using nudged geometry \( \mathbf{x} \).

5. If necessary, increase nudging factor \( \eta \). Repeat from 3.

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**Graph:**

- **Load, \( \lambda/\lambda_c \):** 0 to 3
- **End-shortening, \( d/d_c \):** 0 to 9
- **Higher load-carrying solution**
- **Region of interest**
- **Stable orig. path**
- **Unstable orig. path**
- **Critical point**

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**Modal nudging of aerospace structures**
Steps and results

1. Identify isolated stable region of interest.
2. Extract deformation mode $\mathbf{u}_{\text{state}}$.
3. Superpose to initial geometry $\mathbf{x}_0$.
4. Restart analysis using nudged geometry $\mathbf{x}$.
5. If necessary, increase nudging factor $\eta$. Repeat from 3.

$$\mathbf{x} = \mathbf{x}_0 + \eta \bar{\mathbf{u}}_{\text{state}}$$

$\eta$: nudging factor
$\eta \sim$ thickness
$\bar{\mathbf{u}}_{\text{state}}$: normalised $\mathbf{u}_{\text{state}}$
Steps and results

1. Identify isolated stable region of interest.
2. Extract deformation mode \( \mathbf{u}_{\text{state}} \).
3. Superpose to initial geometry \( \mathbf{x}_0 \).
4. **Restart analysis using nudged geometry \( \mathbf{x} \).**
5. If necessary, increase nudging factor \( \eta \). Repeat from 3.

\[
\mathbf{x} = \mathbf{x}_0 + \eta \bar{\mathbf{u}}_{\text{state}}
\]

- \( \eta \): nudging factor
- \( \eta \sim \text{thickness} \)
- \( \bar{\mathbf{u}}_{\text{state}} \): normalised \( \mathbf{u}_{\text{state}} \)

Modal nudging of aerospace structures

[Diagram showing load-shortening relationship with stable and unstable paths, critical point, and nudged capacity.]
Limitations and Current/future work

Manufacturability

Modal nudging

Feature nudging

Aerodynamic surface change

Geometrical surface change

NA change

Modal nudging of aerospace structures
Summary

• Modal nudging is a robust method for improving structural efficiency
• Negligible increase in mass → Improvement in load carrying capacity/stiffness
• Effective for stiffened structures and can be adapted for different cases
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