Advances in Aeroelastic Prediction and Design Optimization for Next-Generation Aerospace Vehicles

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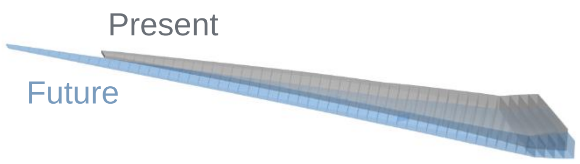
Georgia Institute of Technology

20th International Forum on Aeroelasticity and Structural Dynamics
The Hague, The Netherlands
June 19, 2024

Georgia Tech

The next generation of aerospace vehicles

An explosion of innovation



Higher-aspect-ratio wings

Strut- and truss-braced wings

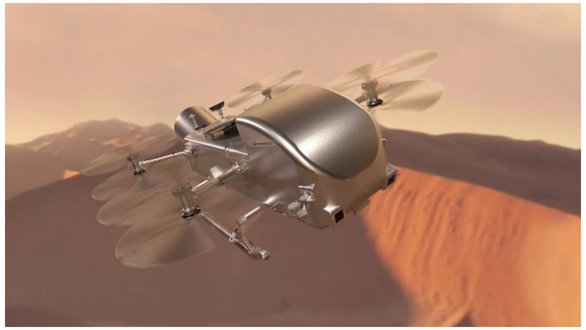
Lower- and zero-emission technologies

Distributed propulsion configurations

Commercial supersonic vehicles

High-speed vertical take-off landing vehicles

Urban air mobility operations



Planetary exploration rotorcraft

Image sources: NASA & Boeing, Airbus, DLR (top); NASA, Leonardo, Archer (bottom)

The next generation of aerospace vehicles

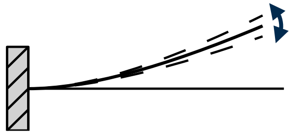
An explosion of aeroelasticity challenges

Aeroelastic behavior changes with amplitude

More than inertial, elastic, and aerodynamic forces

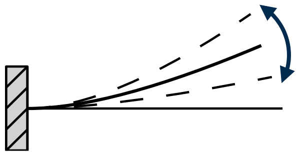
Limited design insights and guidelines

Static amplitude

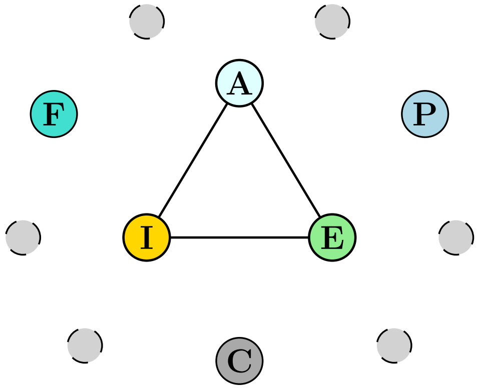


The equilibrium state matters

Dynamic amplitude



New phenomena come into play



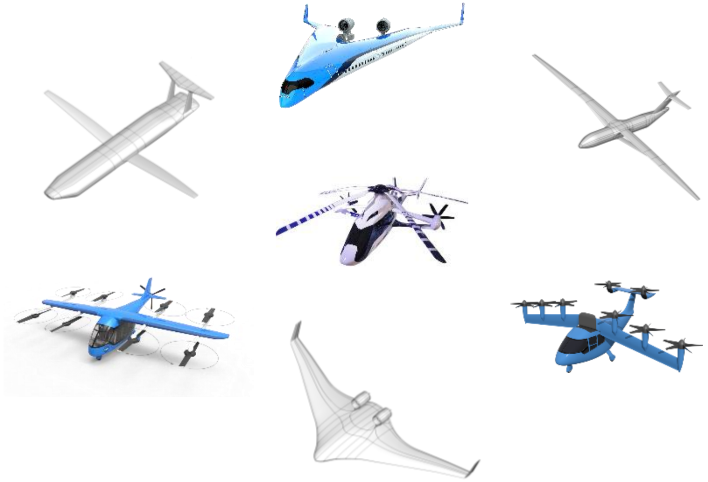


Image sources: NASA & Boeing, Airbus, DLR, Leonardo, Archer (top); NASA, Airbus, TU Delft, and Hwang and Martins, *AIAA Paper 2012-5605*, 2012 (bottom right)

The next generation of aerospace vehicles

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Need for

Reliable aeroelastic predictions to understand new physical mechanisms

Design methodologies that leverage aeroelastic predictions to make parameter choices

Image sources: NASA, Boeing, Airbus, DLR, Leonardo, Archer (top)

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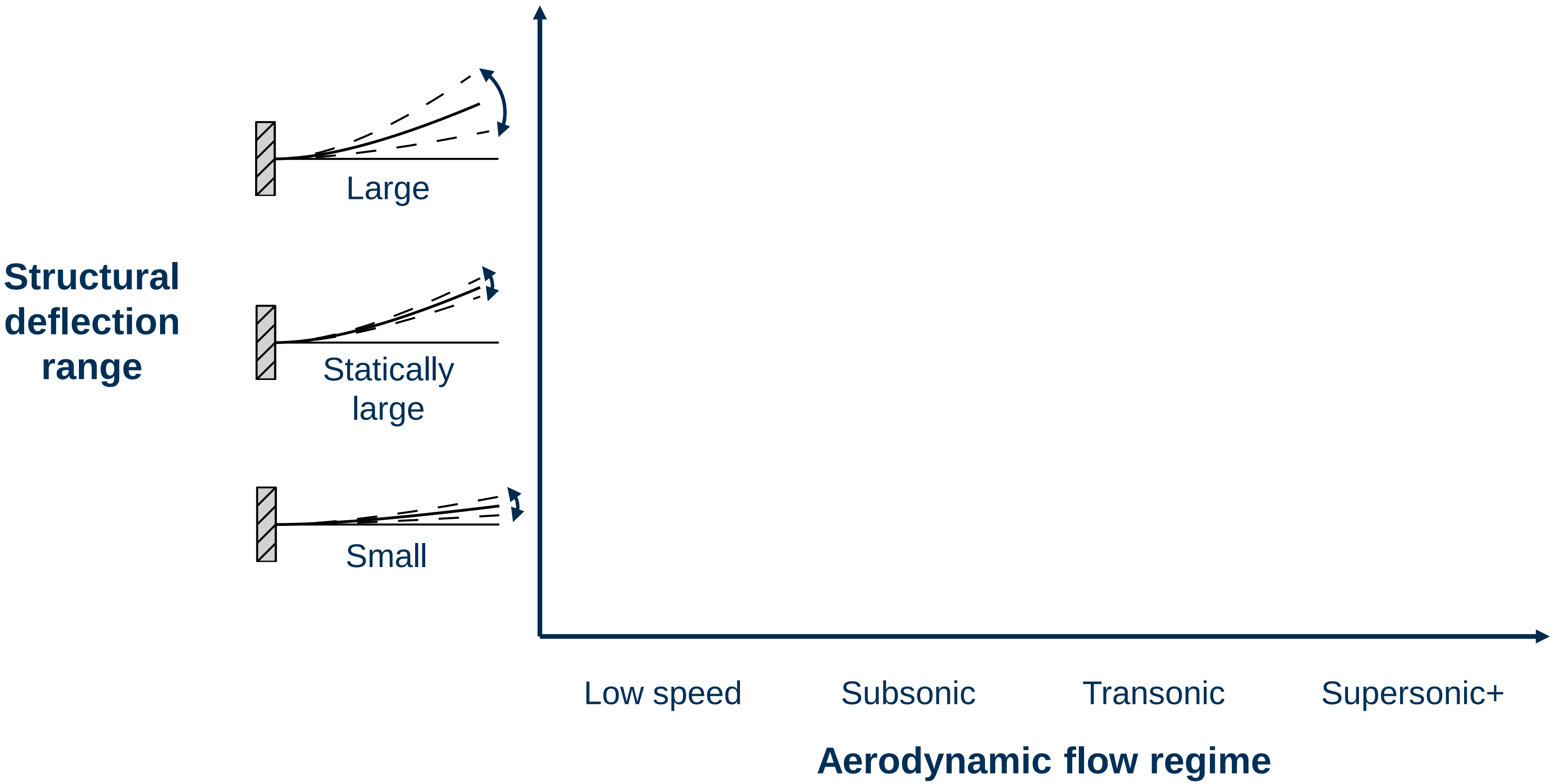
Aeroelastic prediction

When the aeroelastic behavior changes with amplitude

How can we effectively model the physical phenomena of interest?



Metrics of interest

- Static structural response
- Modal characteristics
- Static aeroelastic response
- Flutter boundary
- Limit-cycle oscillations
- Gust response
- Maneuver response
- Ride quality
- Handling qualities
- …

Aeroelastic prediction

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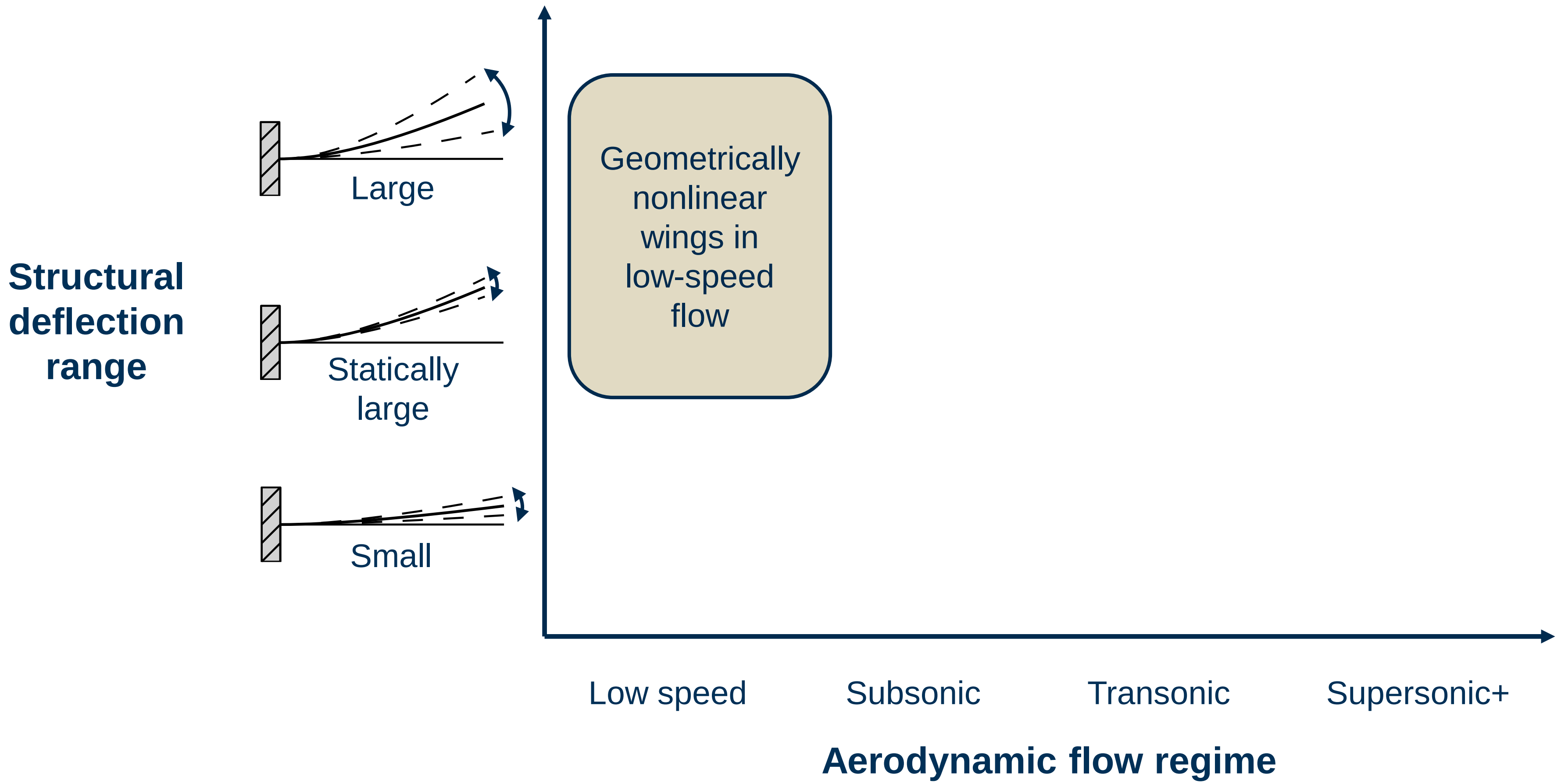

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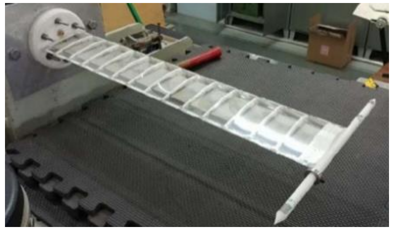
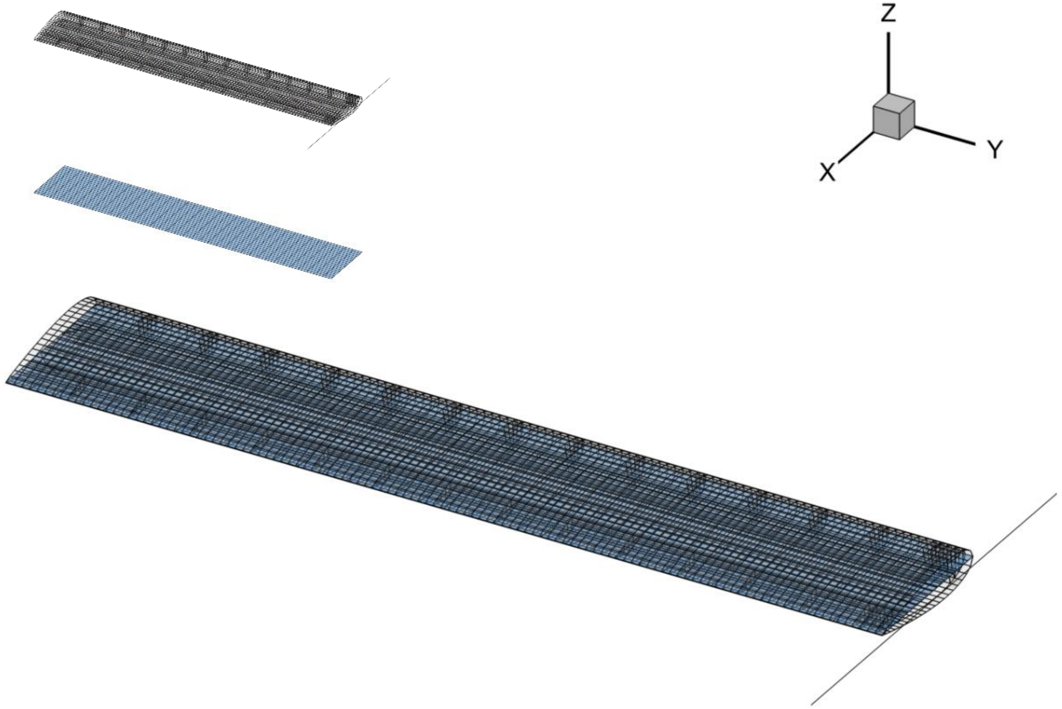
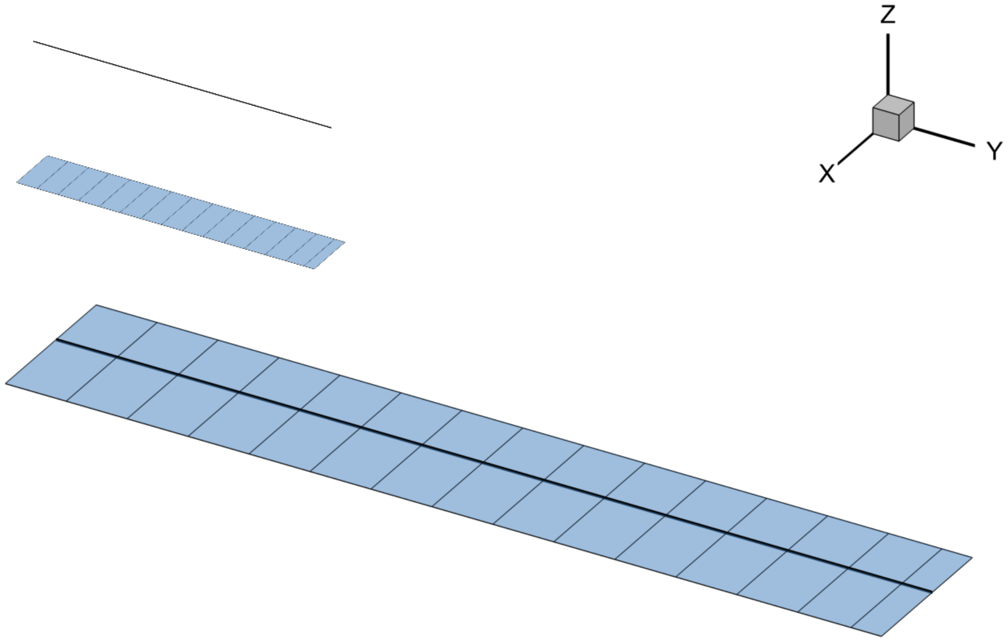
Aeroelastic prediction

Geometrically nonlinear wings in low-speed flow: modeling test case





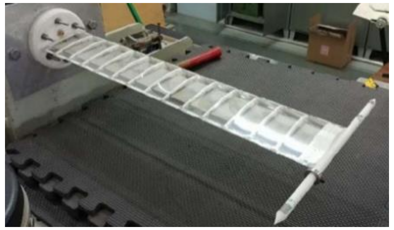


High-order model	**Low-order model**
Detailed FEM + VLM or DLM	Beam model + corrected strip theory
(42k structural DOFs + 648 aerodynamic panels)	(60 structural DOFs + 15 aerodynamic strips)

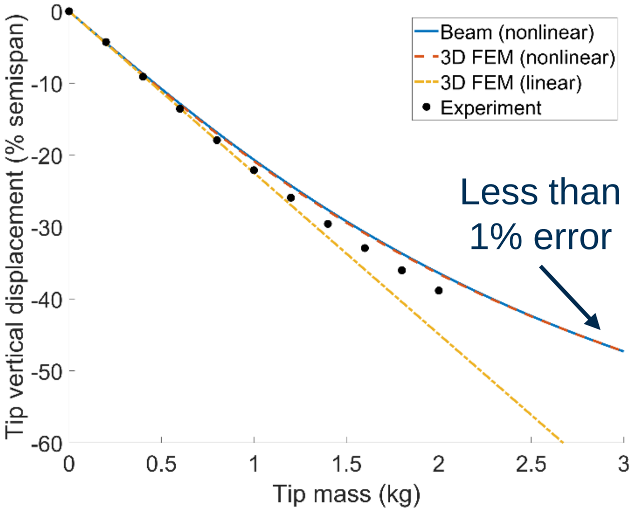
Experimental model details: Avin et al., *AIAA J.*, 2022; Image: Aeroelasticity Lab, Technion
Numerical models details: Riso and Cesnik, *J. of Aircr.*, 2023 & *J. Fluids and Struct.*, 2023; Data: https://github.com/UM-A2SRL/AePW3-LDWG.git

Aeroelastic prediction

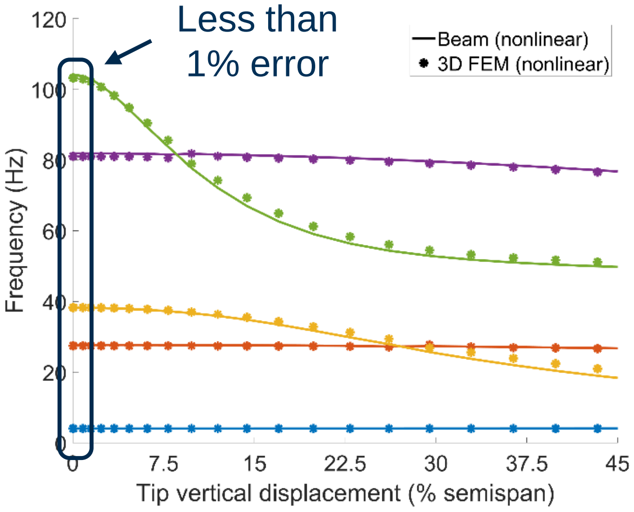
Geometrically nonlinear wings in low-speed flow: takeaways



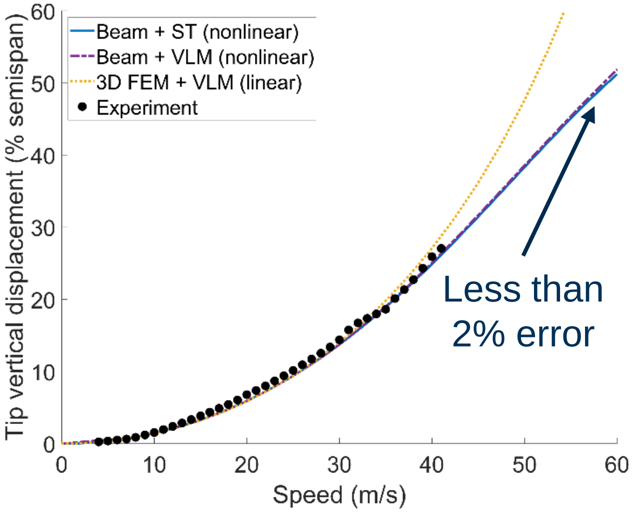
Static structural response



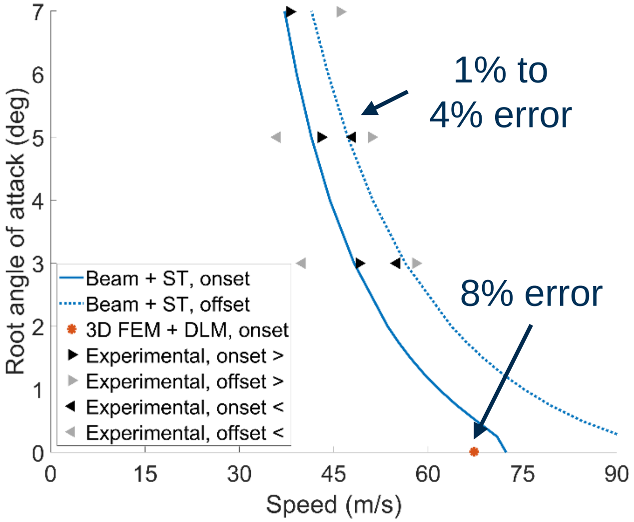
Modal characteristics



Static aeroelastic response



Flutter boundary



Beam model predicts global structural metrics with practically same accuracy as 3D FEM

Beam model + strip theory predicts global static aeroelastic metrics within 2% of higher-order models based on 3D steady aerodynamics

Flutter onset errors up to 8% reduce at larger deflection as geometrical nonlinearities take over

Geometrical nonlinearities alone miss subcritical behavior (in this case)

Image: Aeroelasticity Lab, Technion

Full study: Riso and Cesnik, *J. Aircr.*, 2023 & *J. Fluids Struct.*, 2023; Data: https://github.com/UM-A2SRL/AePW3-LDWG.git

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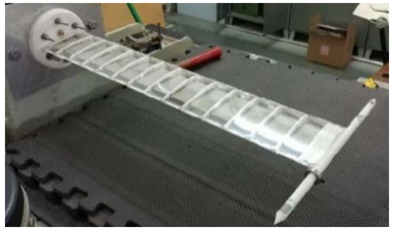

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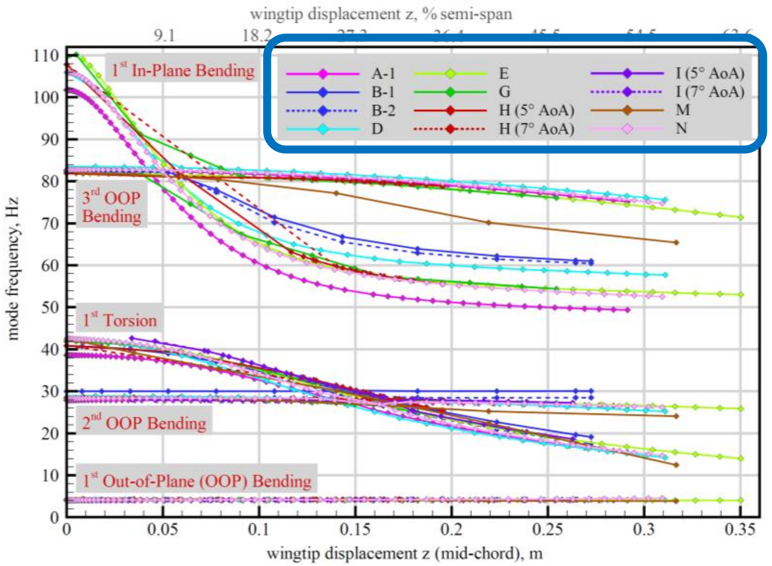

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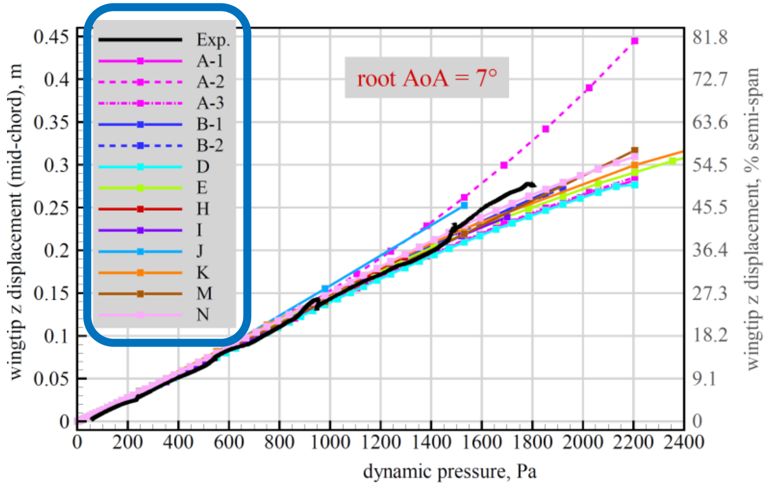

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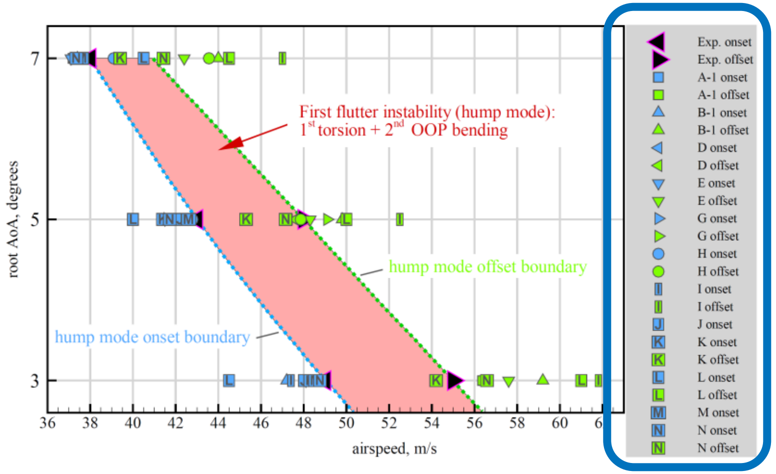

20+ researchers, 10+ approaches

Synergistic experimental-computational, computational-computational, and experimental-experimental collaborations

are essential to advancing aeroelastic prediction

Image: Aeroelasticity Lab, Technion
Full study: Ritter et al., *AIAA SciTech Forum*, 2024; AePW3 details: https://nescacademy.nasa.gov/workshops/AePW3/public/

Aeroelastic prediction

When the aeroelastic behavior changes with amplitude

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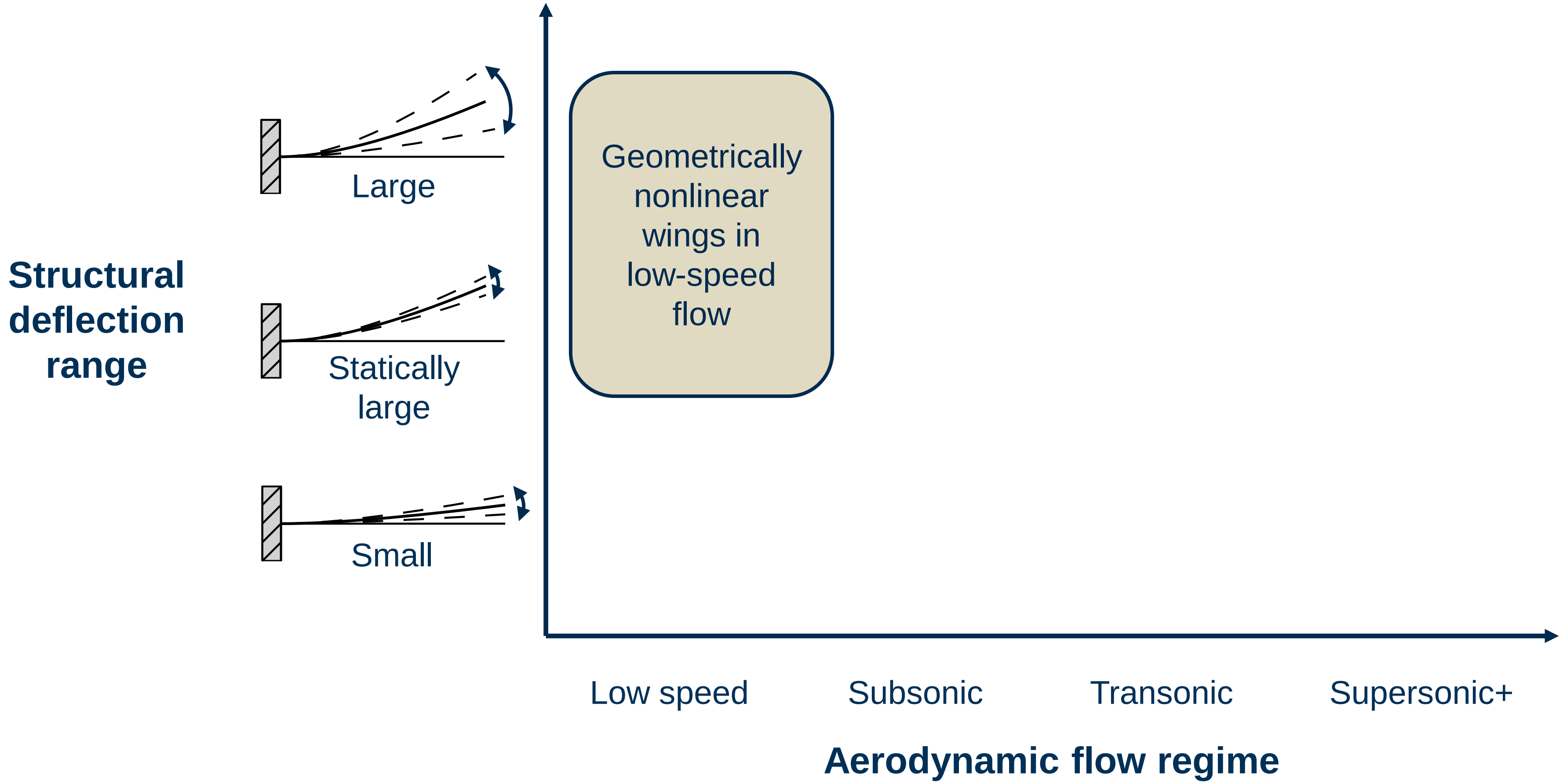

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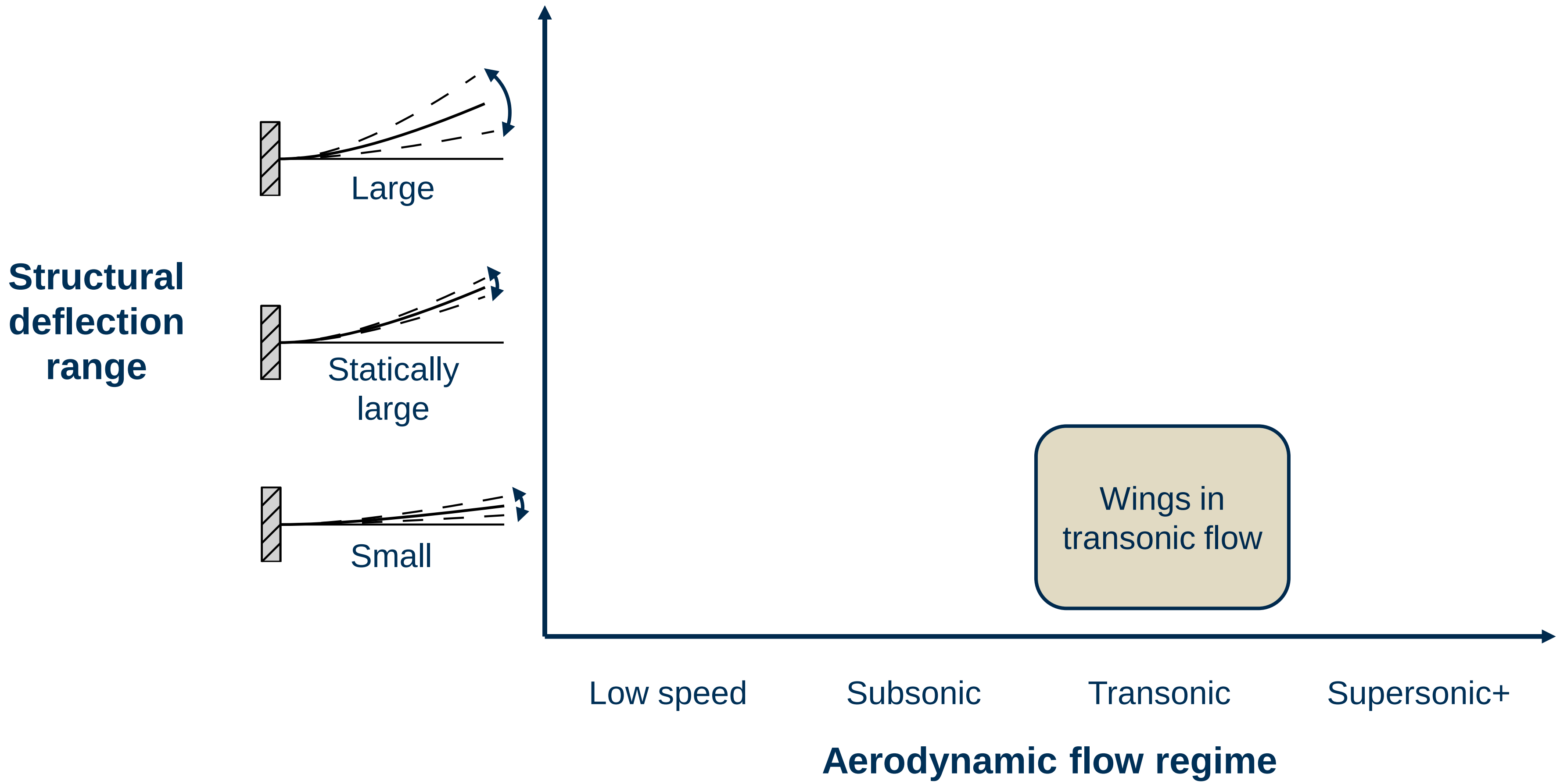

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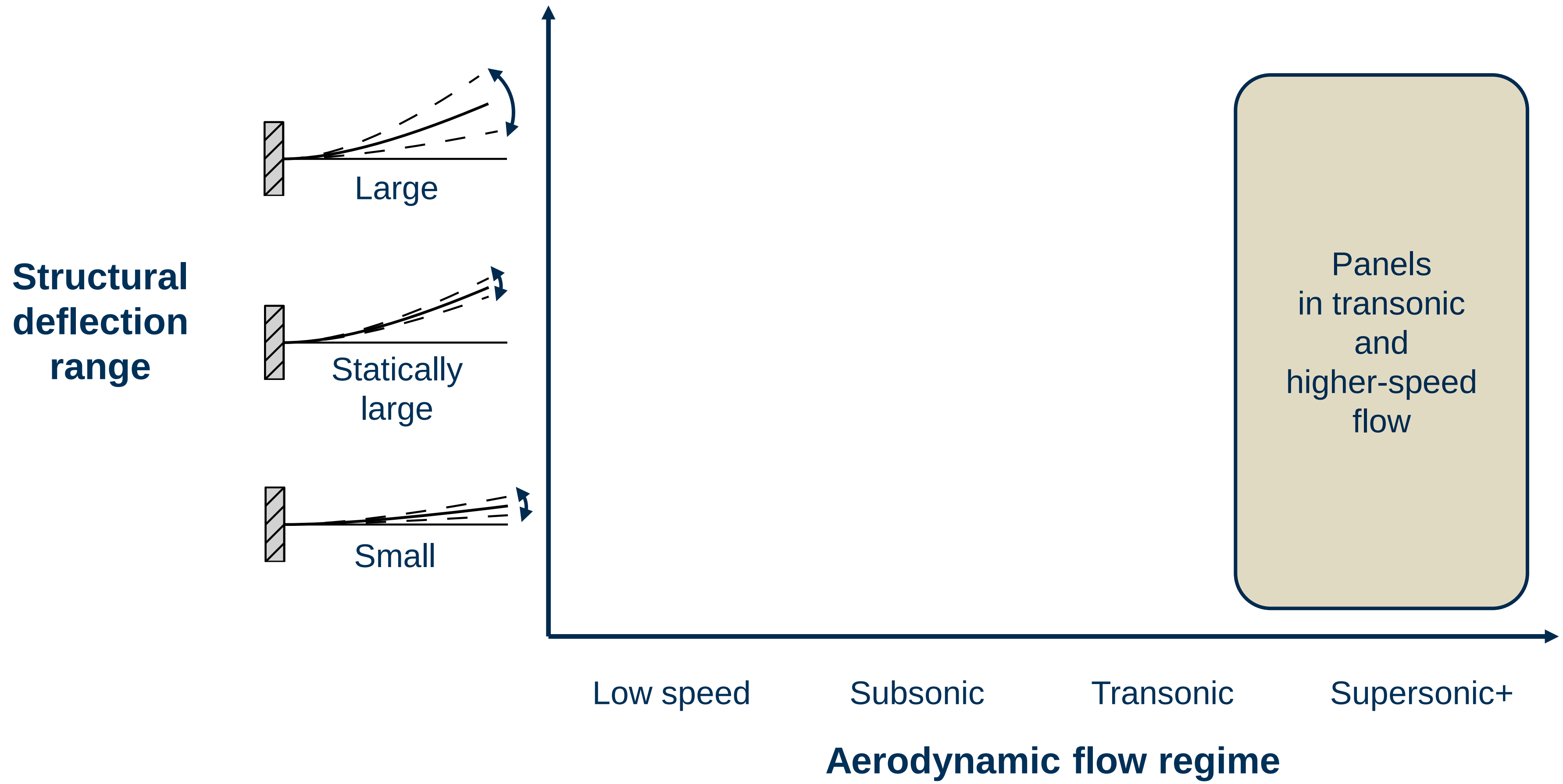

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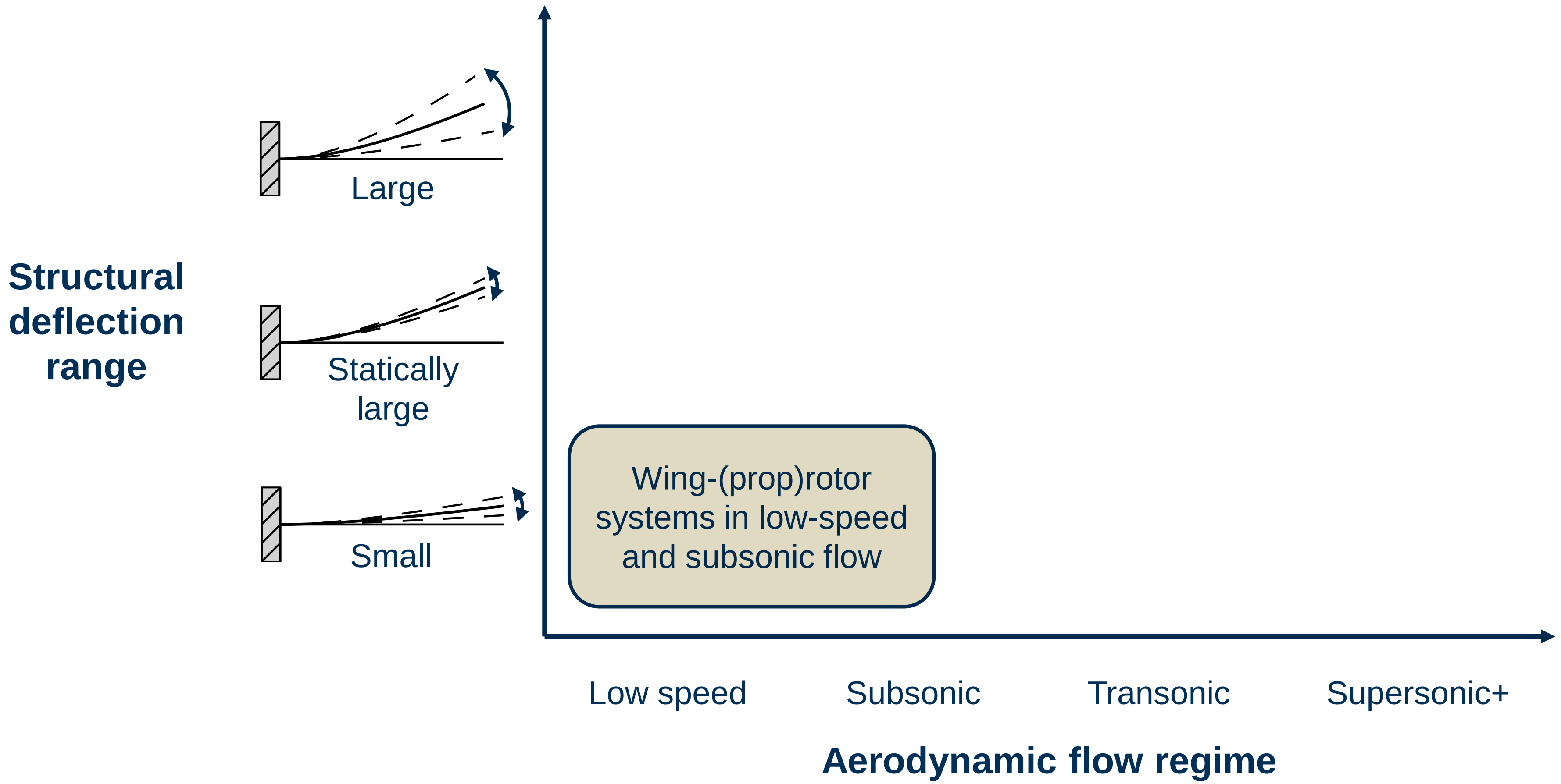

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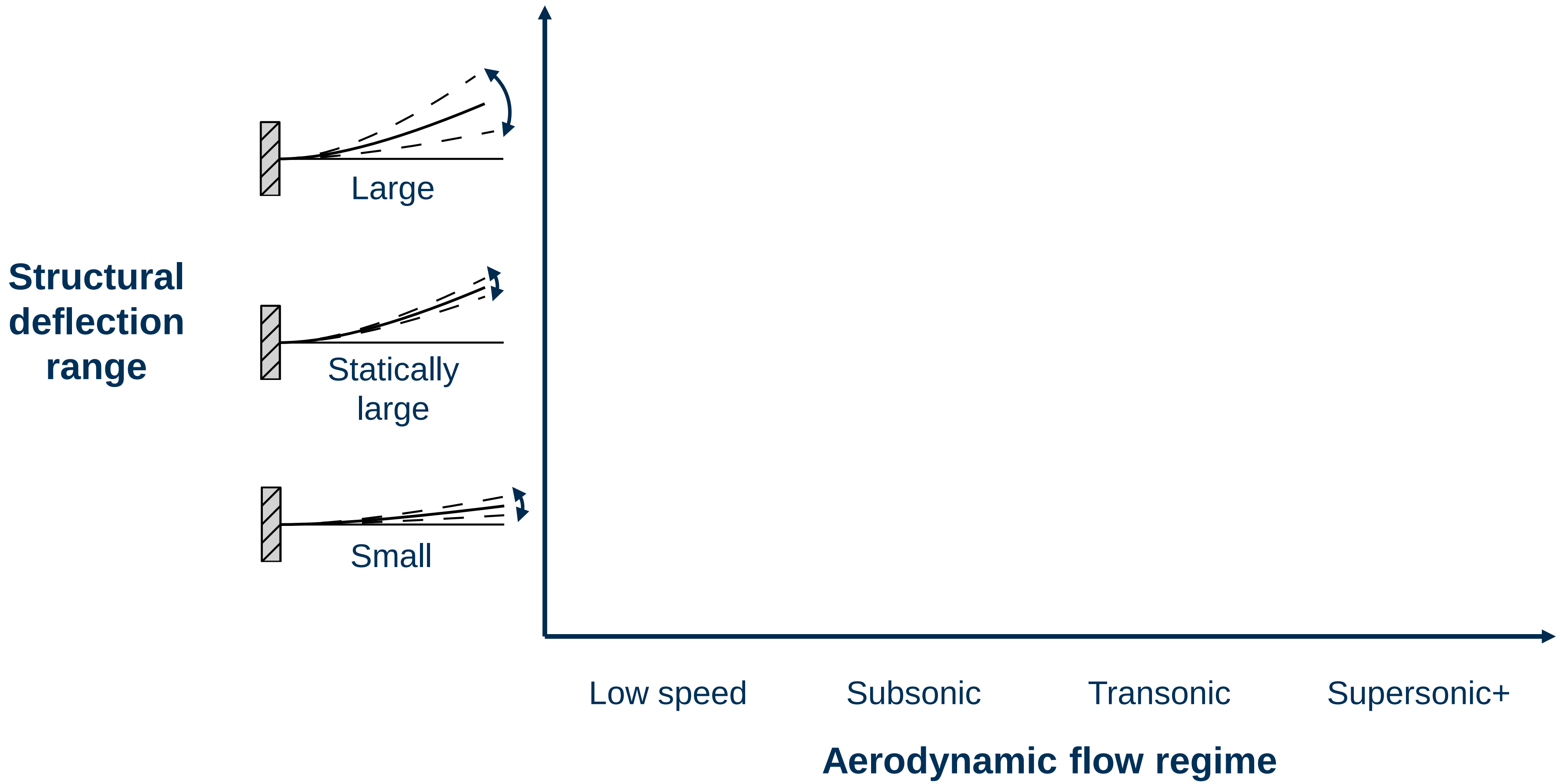

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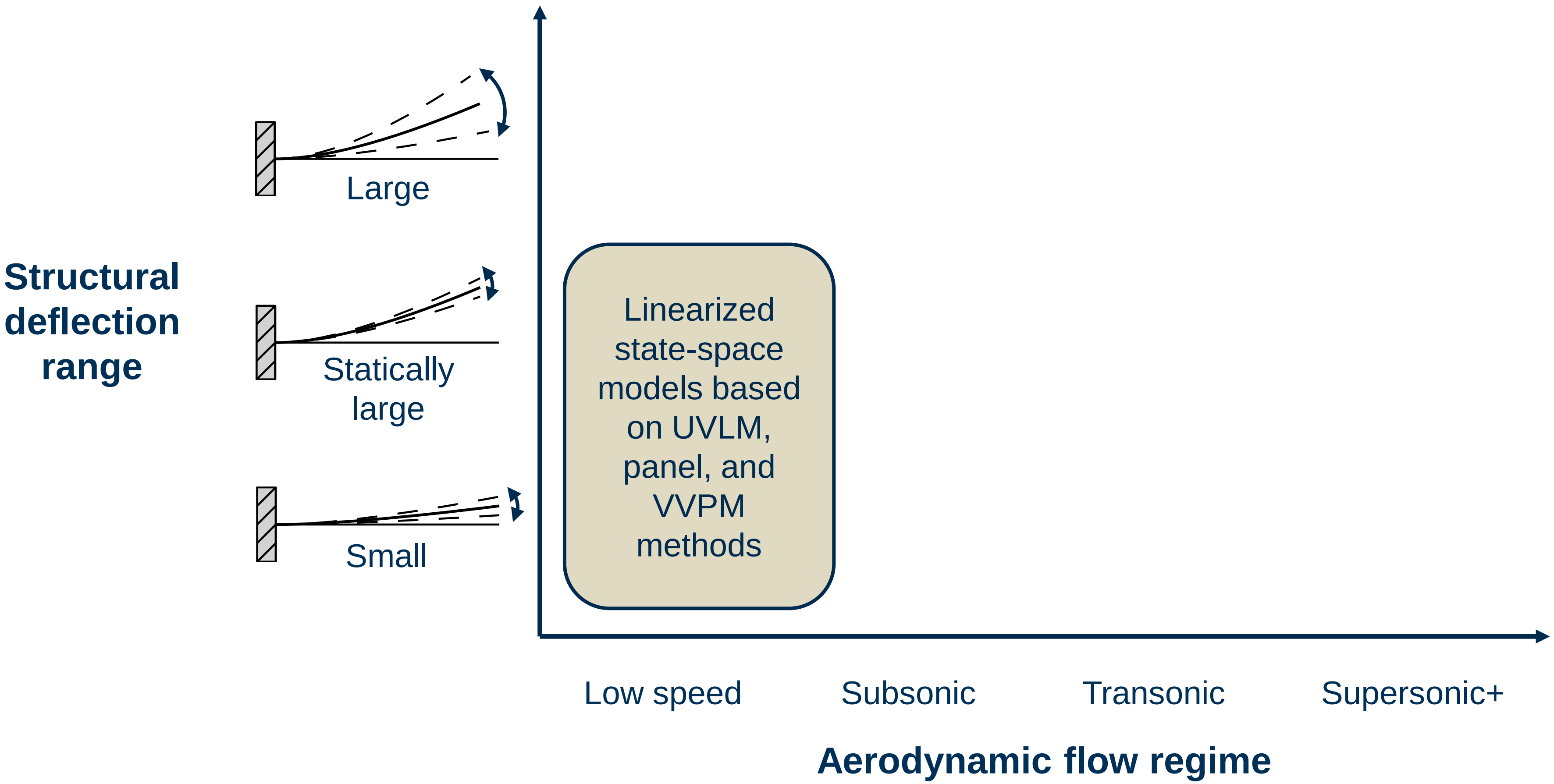

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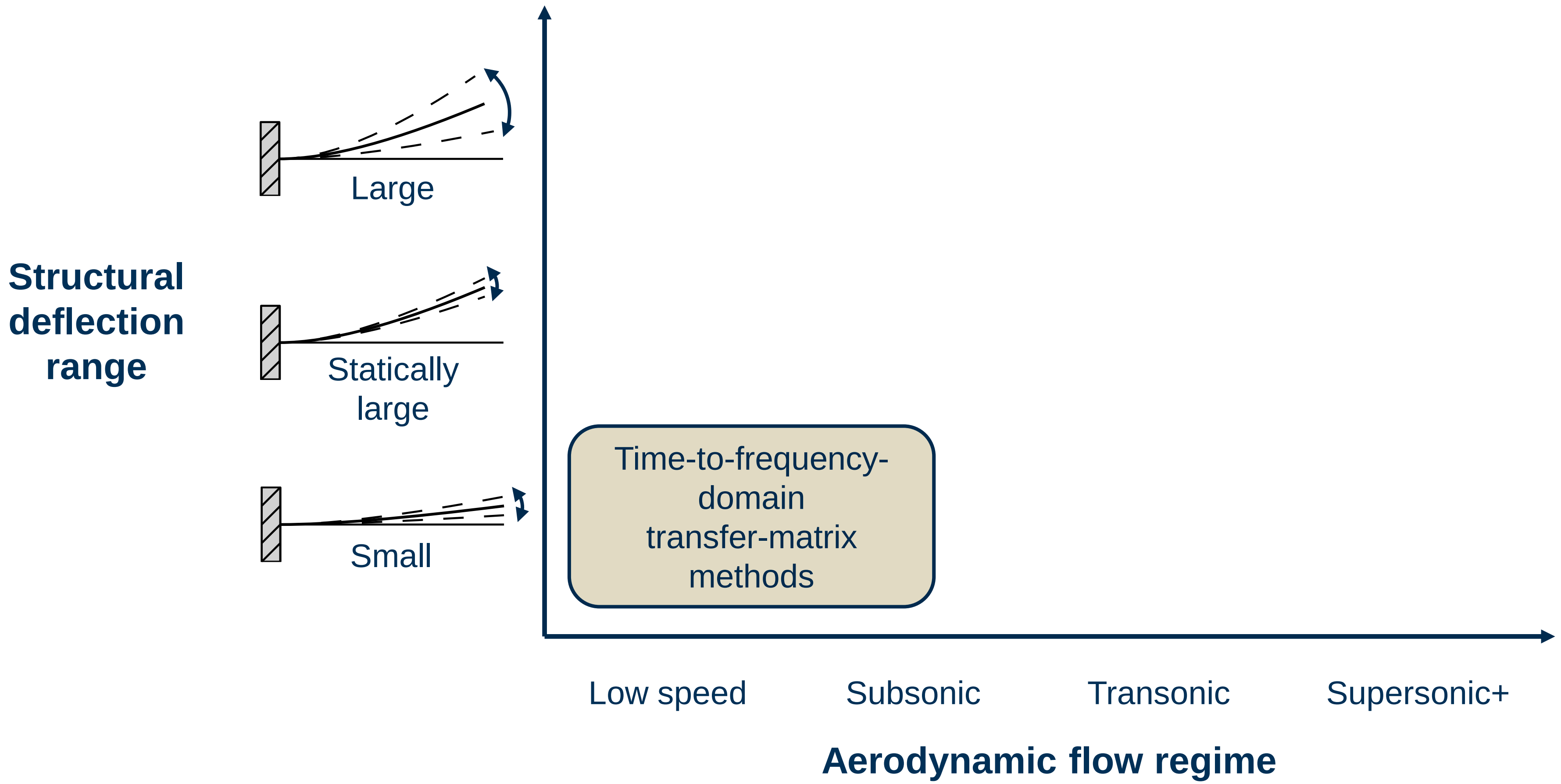

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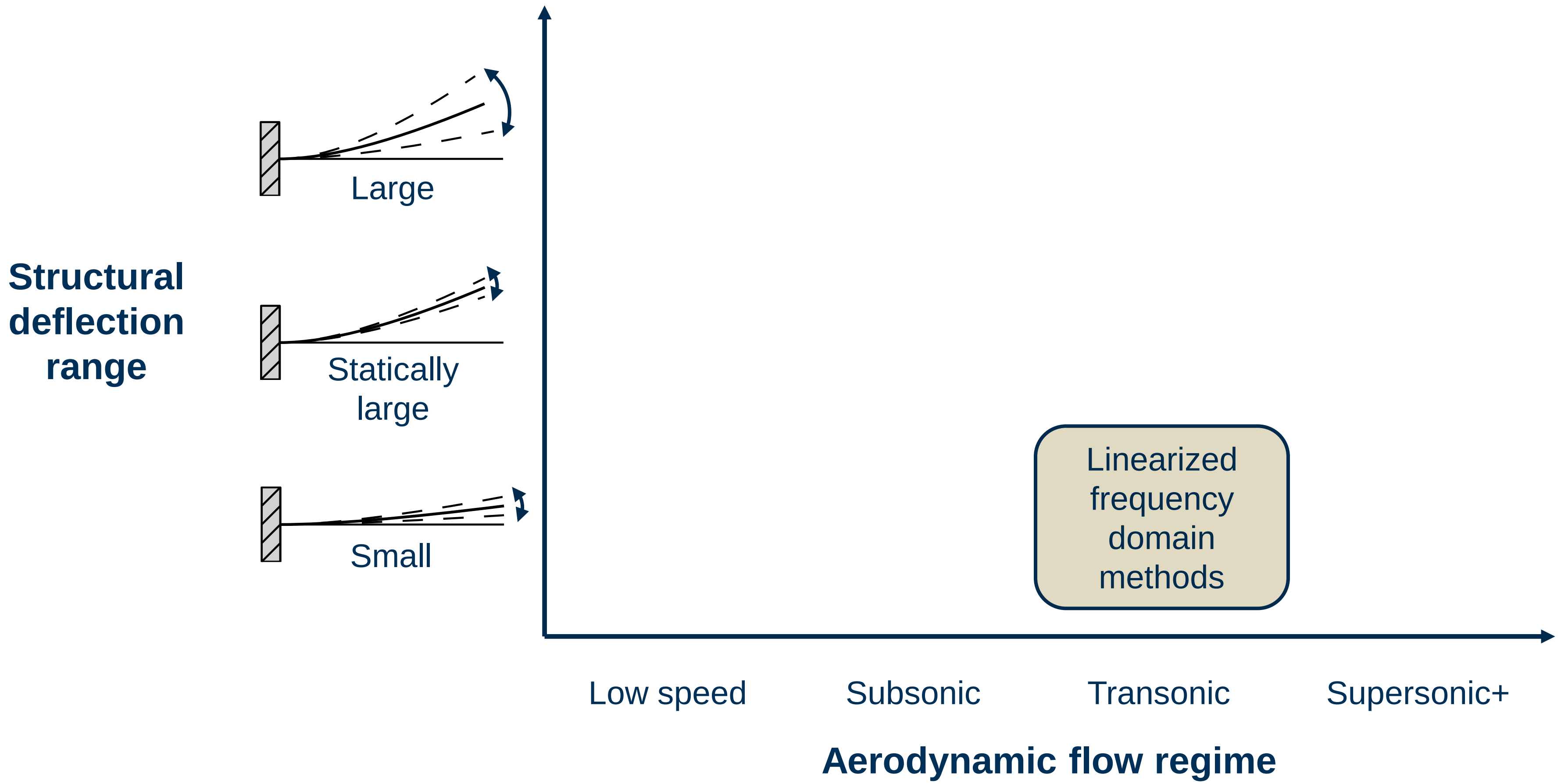

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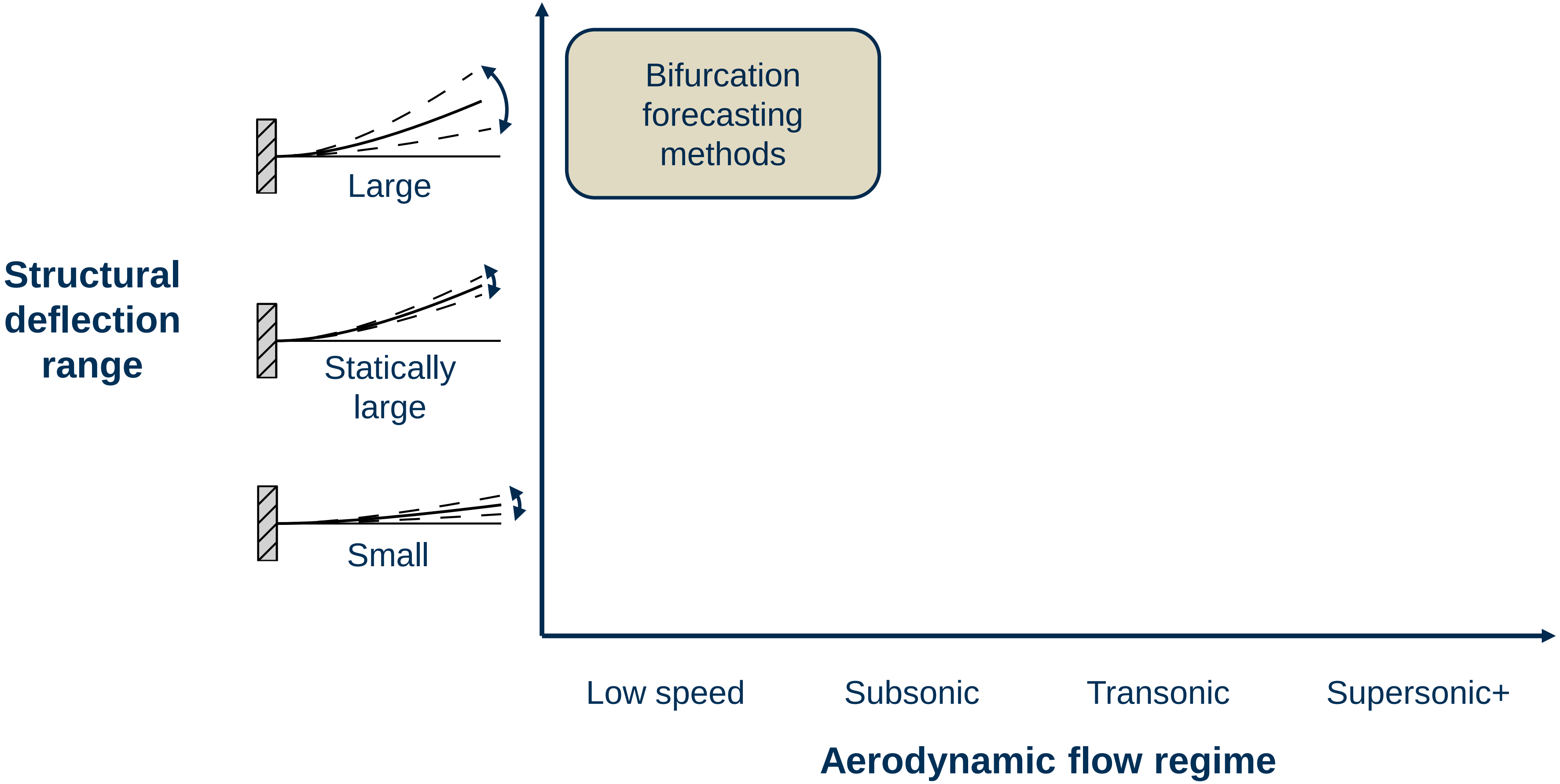

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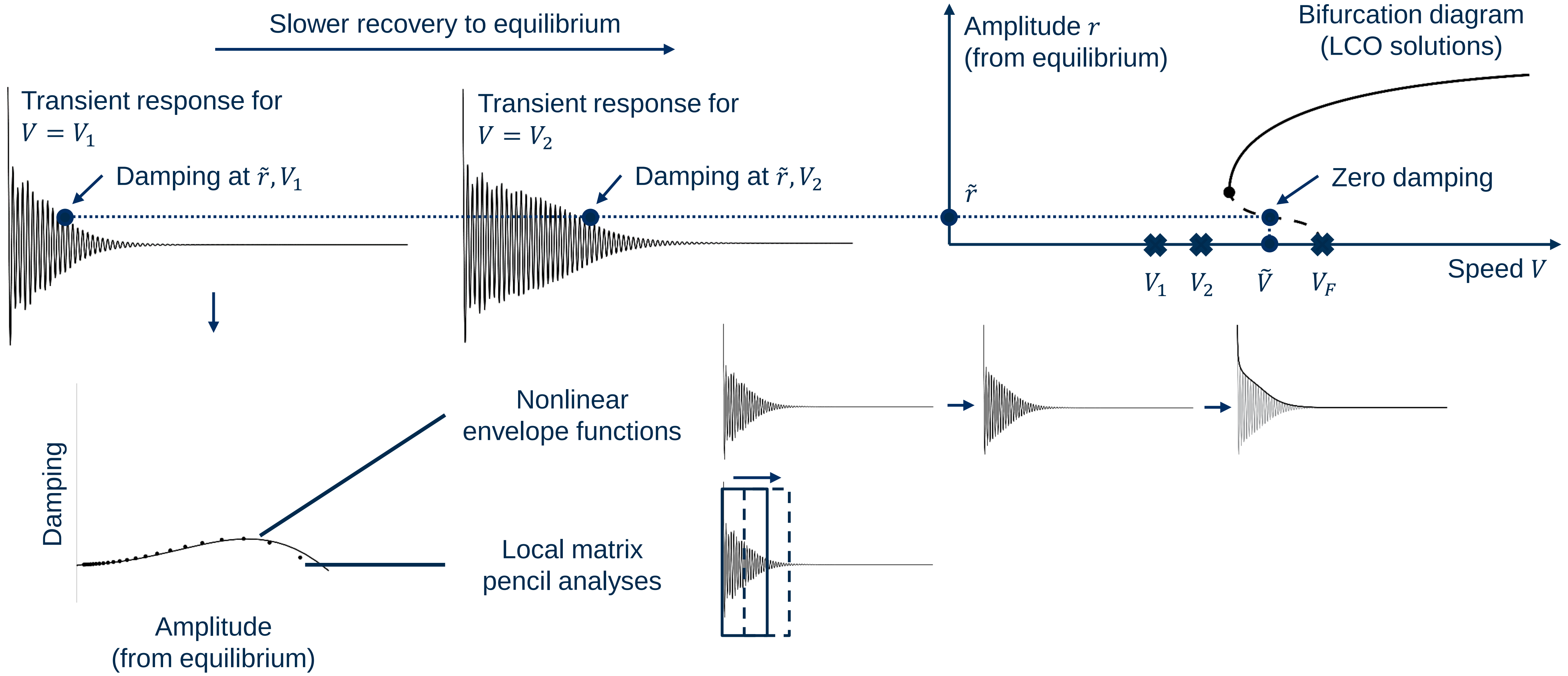
Aeroelastic prediction

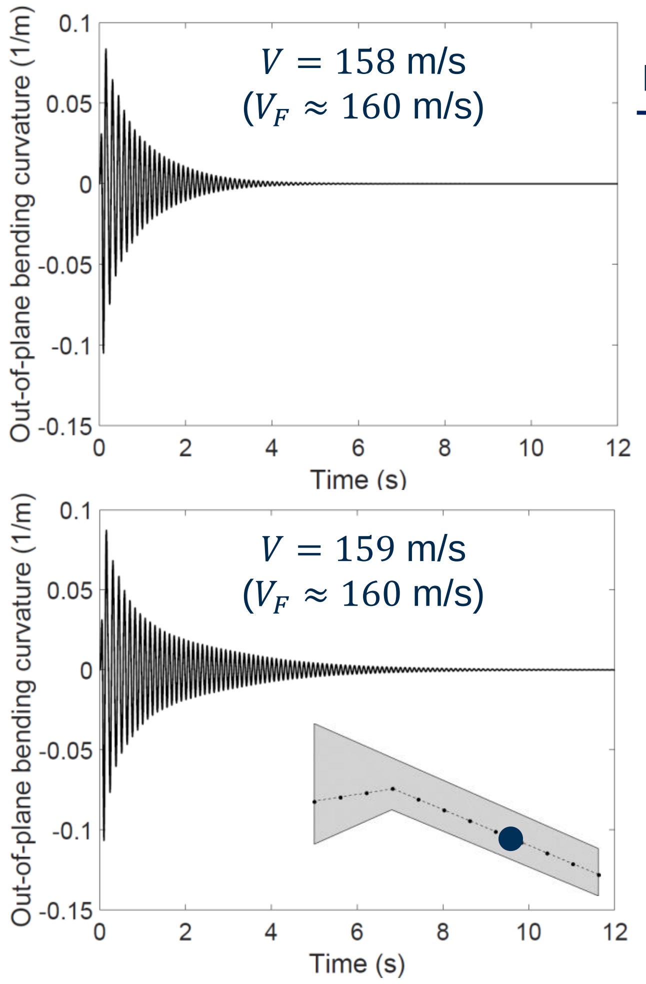
Limit-cycle oscillation (LCO) prediction via bifurcation forecasting: approach

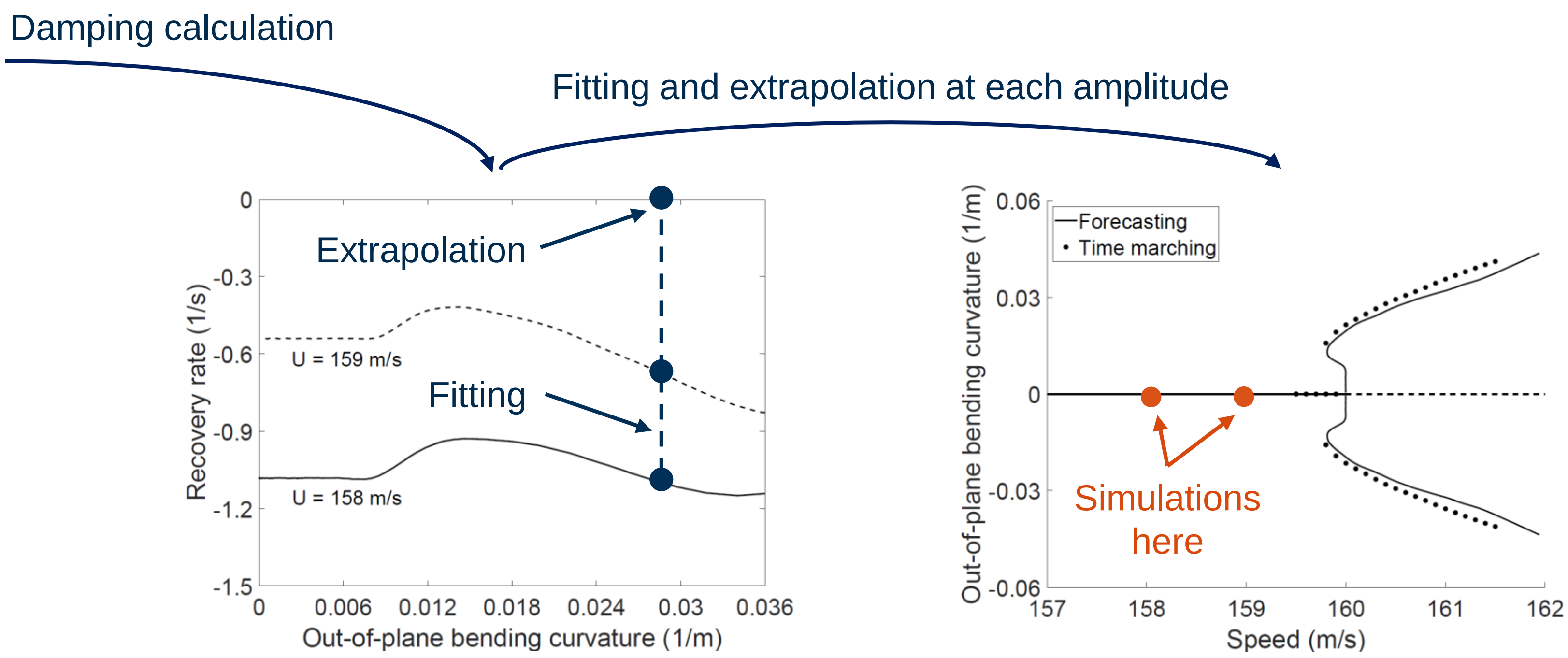


Formulation details: Lim and Epureanu, *Phys. Rev. E*, 2011 & Ghadami et al., *J. Comput. Nonlinear Dyn.*, 2016 (single parameter), Riso et al., *J. Fluids Struct.*, 2021 (multiple parameters)
Local matrix pencil analysis details: Golla et al., *AIAA SciTech Forum*, 2024 & *AIAA J.*, 2024 (under review)

Aeroelastic prediction

Limit-cycle oscillation (LCO) analysis via bifurcation forecasting: takeaways



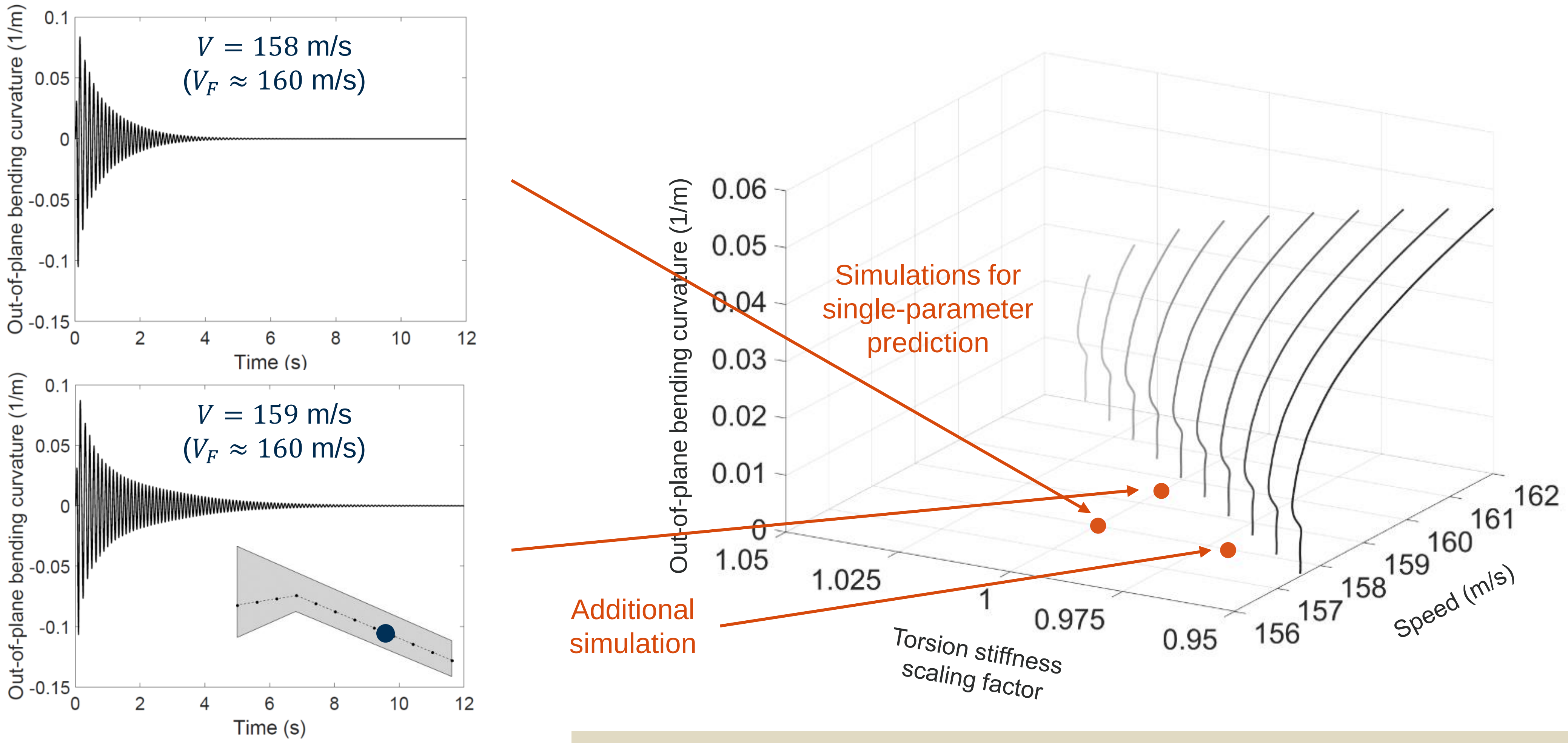


Amplitude-dependent damping extrapolation enables output-based LCO predictions using as few as two pre-flutter transient responses

Full study: Riso*, Ghadami*, et al., *AIAA J.*, 2020 (* = equal contribution)

Aeroelastic prediction

Limit-cycle oscillation (LCO) analysis via bifurcation forecasting: takeaways

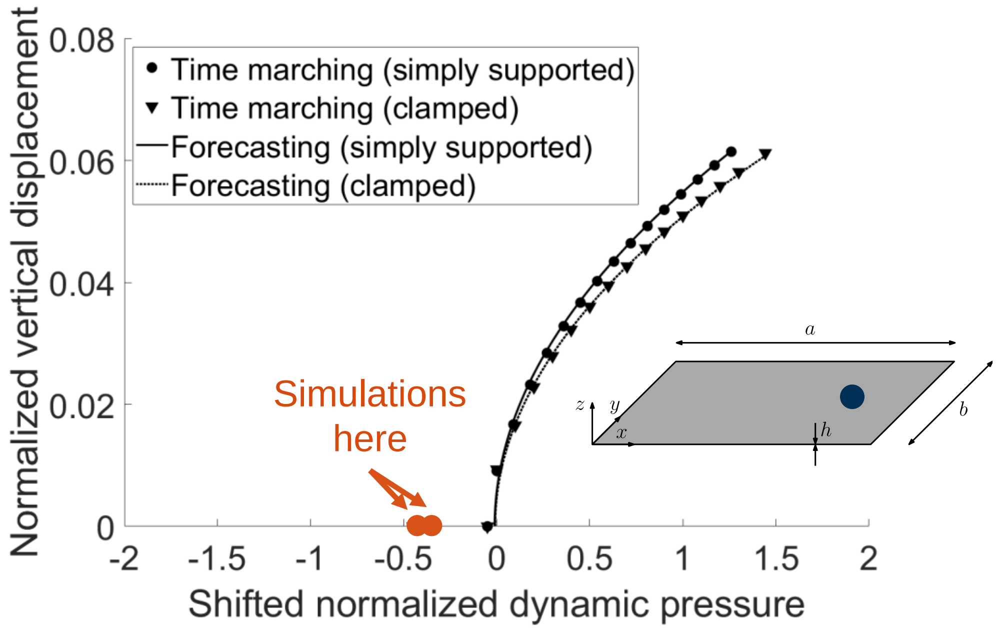


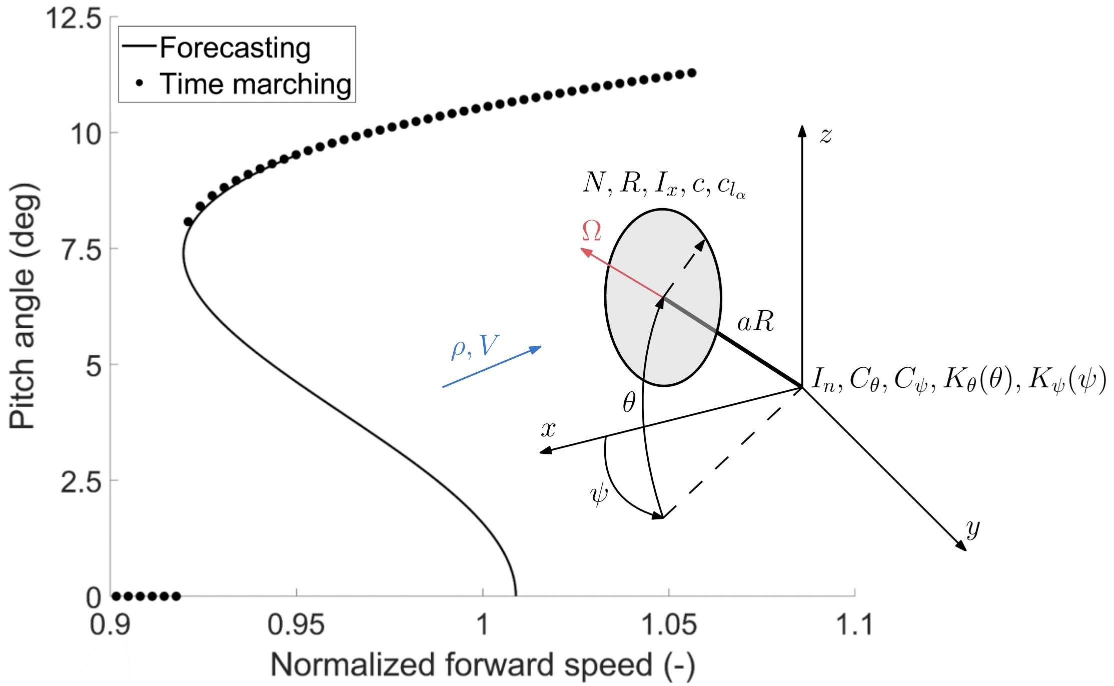
Amplitude-dependent damping extrapolation enables output-based LCO predictions considering multiple varying parameters

Full study: Riso et al., *J. Fluids Struct.*, 2021

Aeroelastic prediction

Limit-cycle oscillation (LCO) analysis via bifurcation forecasting: takeaways





Amplitude-dependent damping extrapolation enables output-based LCO predictions across a variety of systems

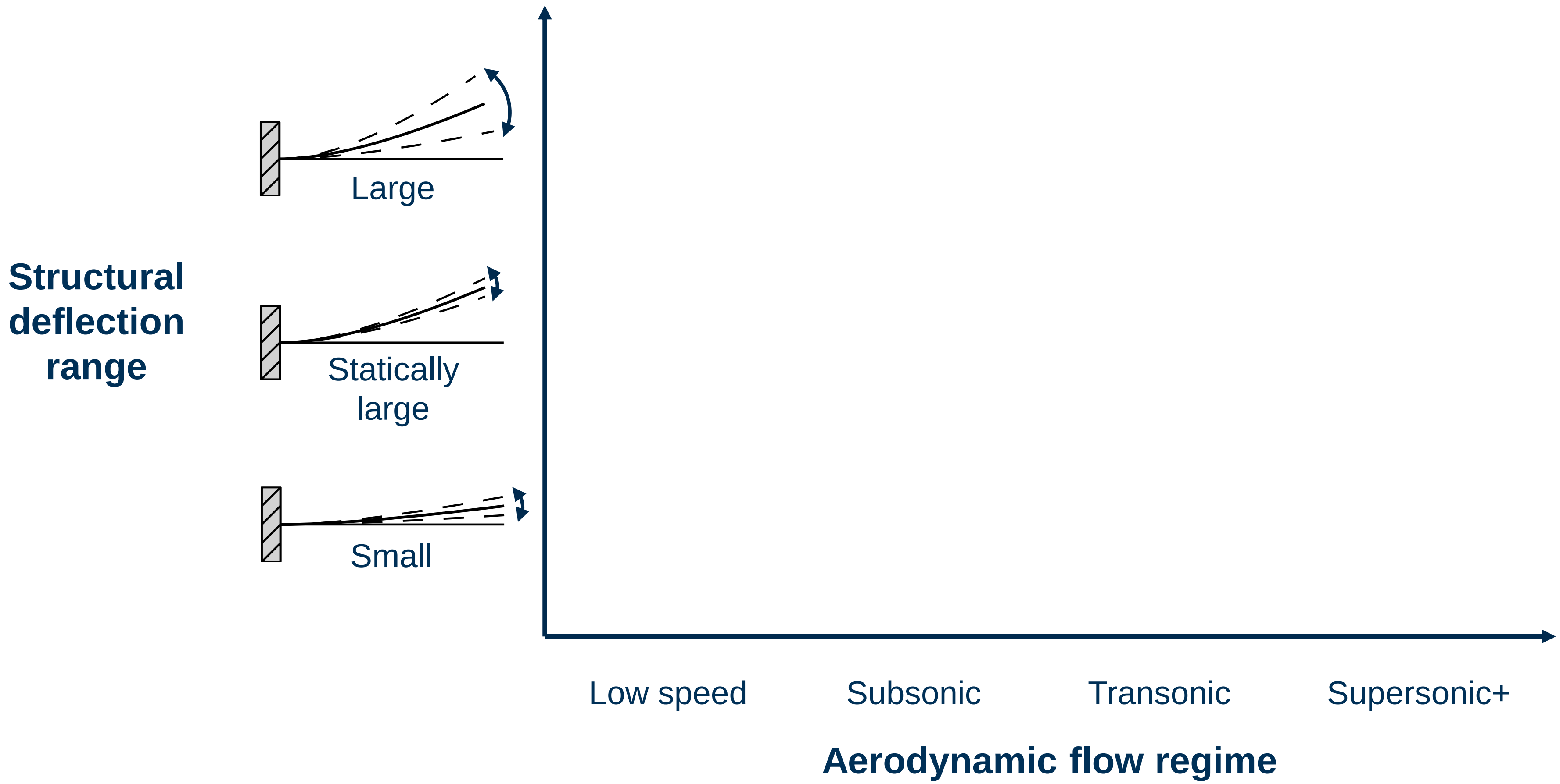
Predictions enhanced by leveraging knowledge of stability scenario from eigenvalue analyses

Full panel study: de Dominicis and Riso, *AIAA SciTech Forum,* 2024 & *AIAA J.*, 2024 (accepted, to appear)
Full propeller whirl study: Gali et al., *J. Fluids Struct.*, 2023 & Riso, 6th *Decennial VFS Aeromechanics Specialists Conference*, 2024

Design optimization

When the aeroelastic behavior changes with amplitude

How can we leverage aeroelastic predictions for design?



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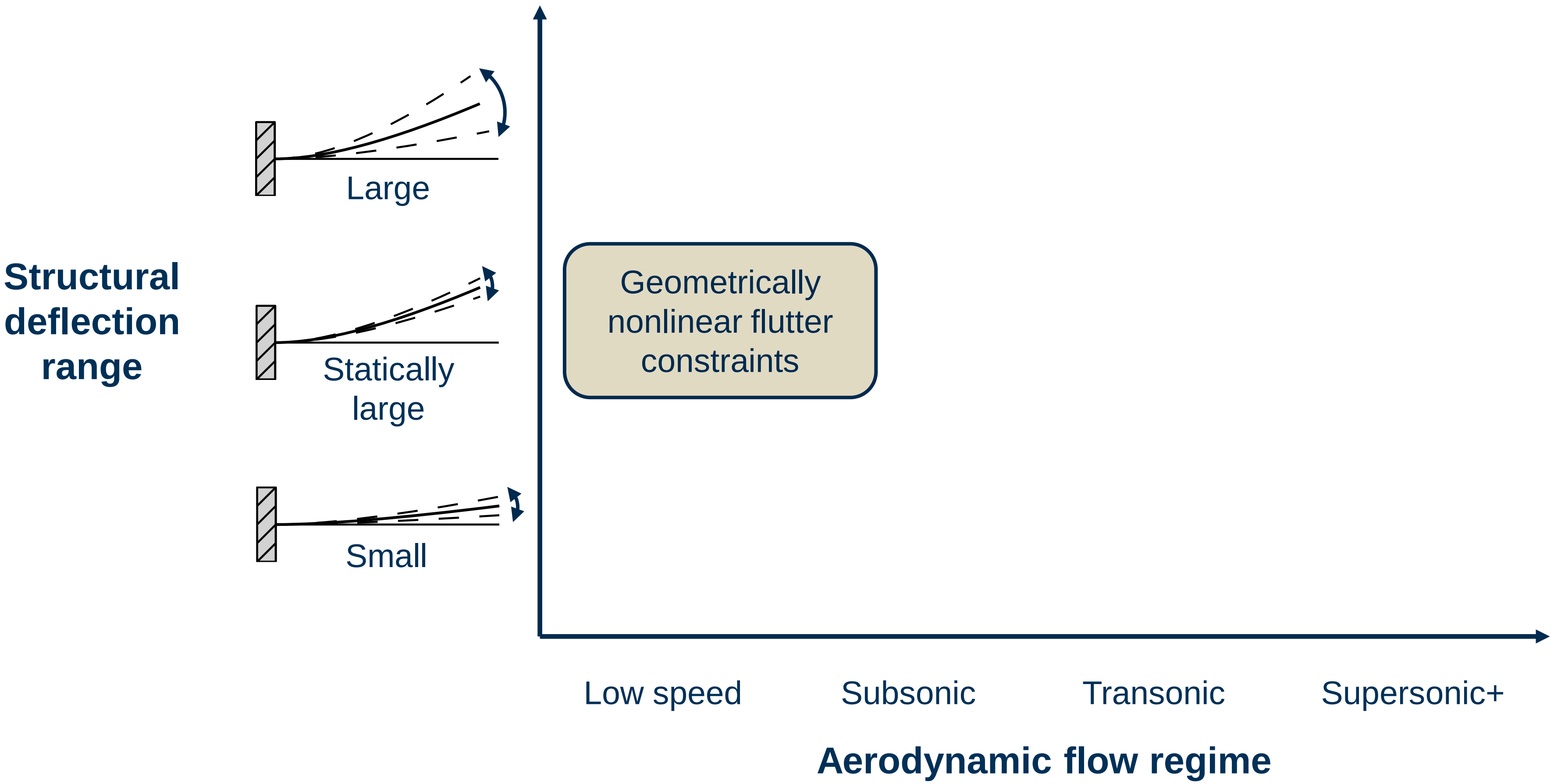

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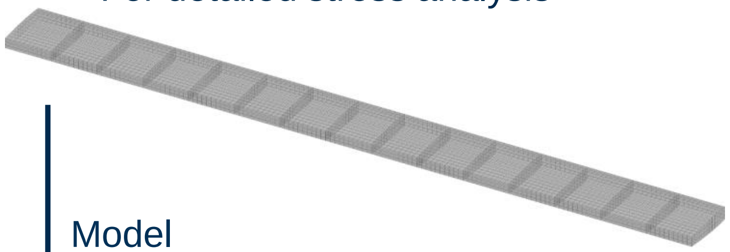
Review paper: Jonsson et al., *Prog. Aerosp. Sci.*, 2019

Design optimization

Geometrically nonlinear flutter constraint: approach and takeaways

3D FEM
For detailed stress analysis



Model order reduction

Beam model
For local eigenvalue analyses

Stress constraints

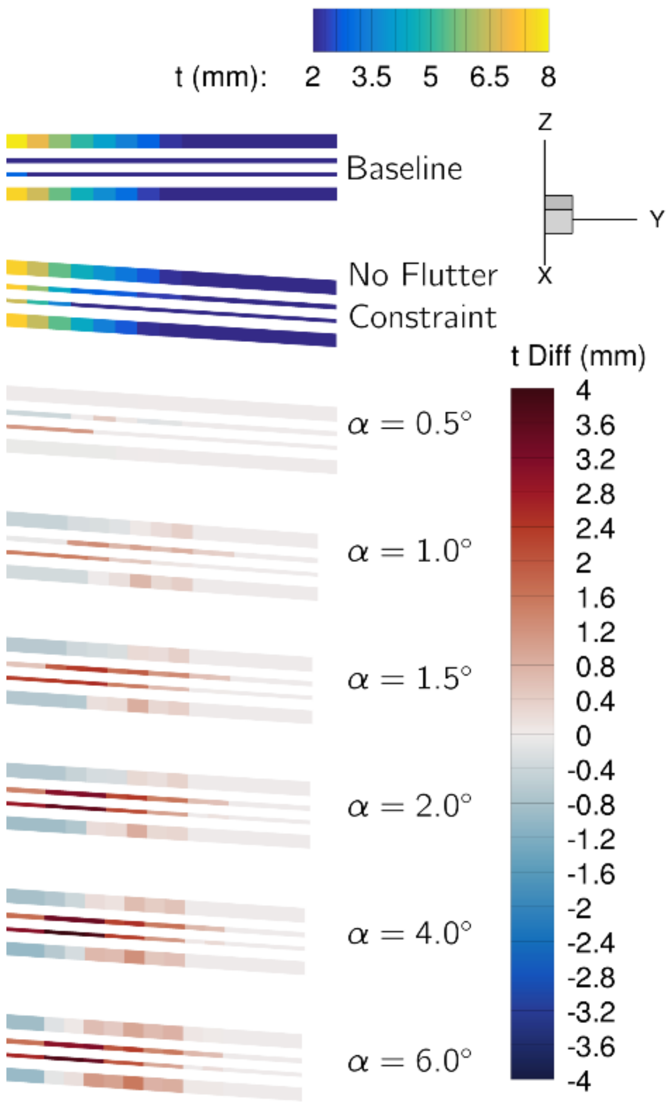
KS aggregates of local stresses

Flutter constraint

KS aggregate of damping values at each equilibrium state

Design optimization

Design solution



Optimizer leverages knowledge of damping variation with equilibrium state to prevent flutter by reducing static deflections

Full study: Jonsson et al., *AIAA J.*, 2023 & Gray et al., *AIAA J.*, 2023; Left images: Gray et al., *IFASD*, 2022

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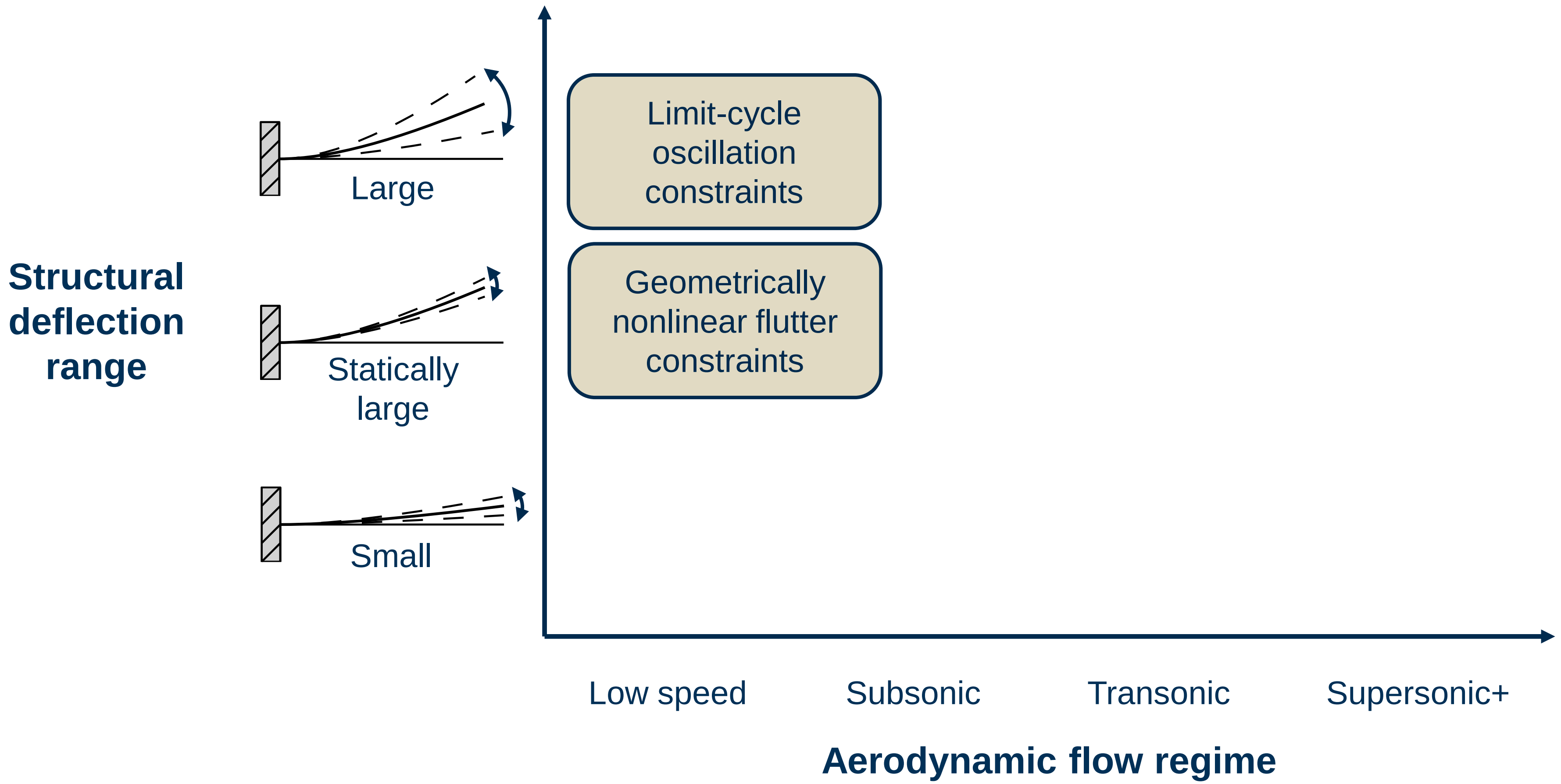

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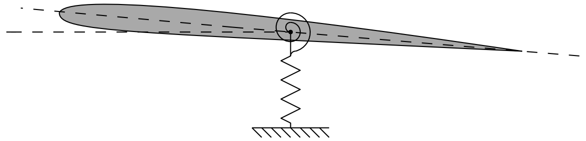
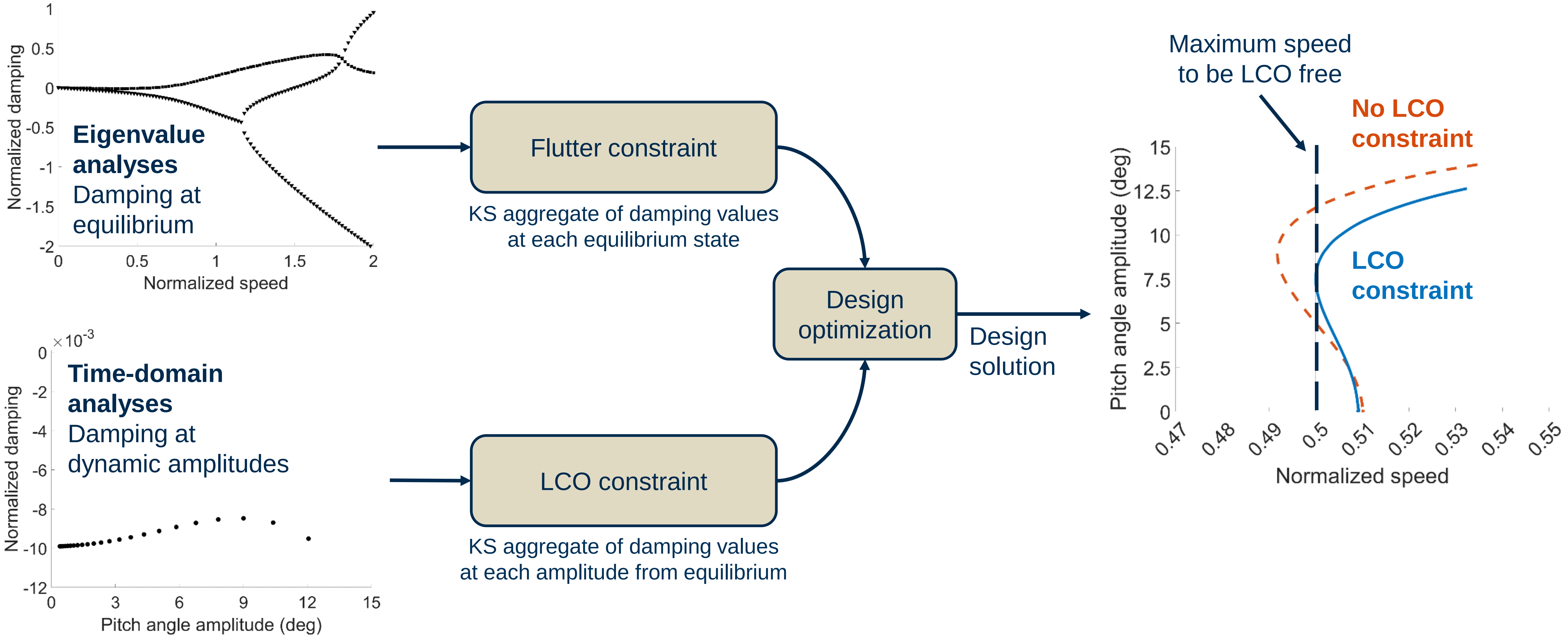


Design optimization

Limit-cycle oscillation (LCO) constraints: approach and takeaways



Optimizer leverages knowledge of damping variation with dynamic amplitude to prevent LCOs without computing bifurcation diagrams

Full study: Riso et al., *AIAA J.*, 2023 & Golla et al., *AIAA SciTech Forum*, 2024

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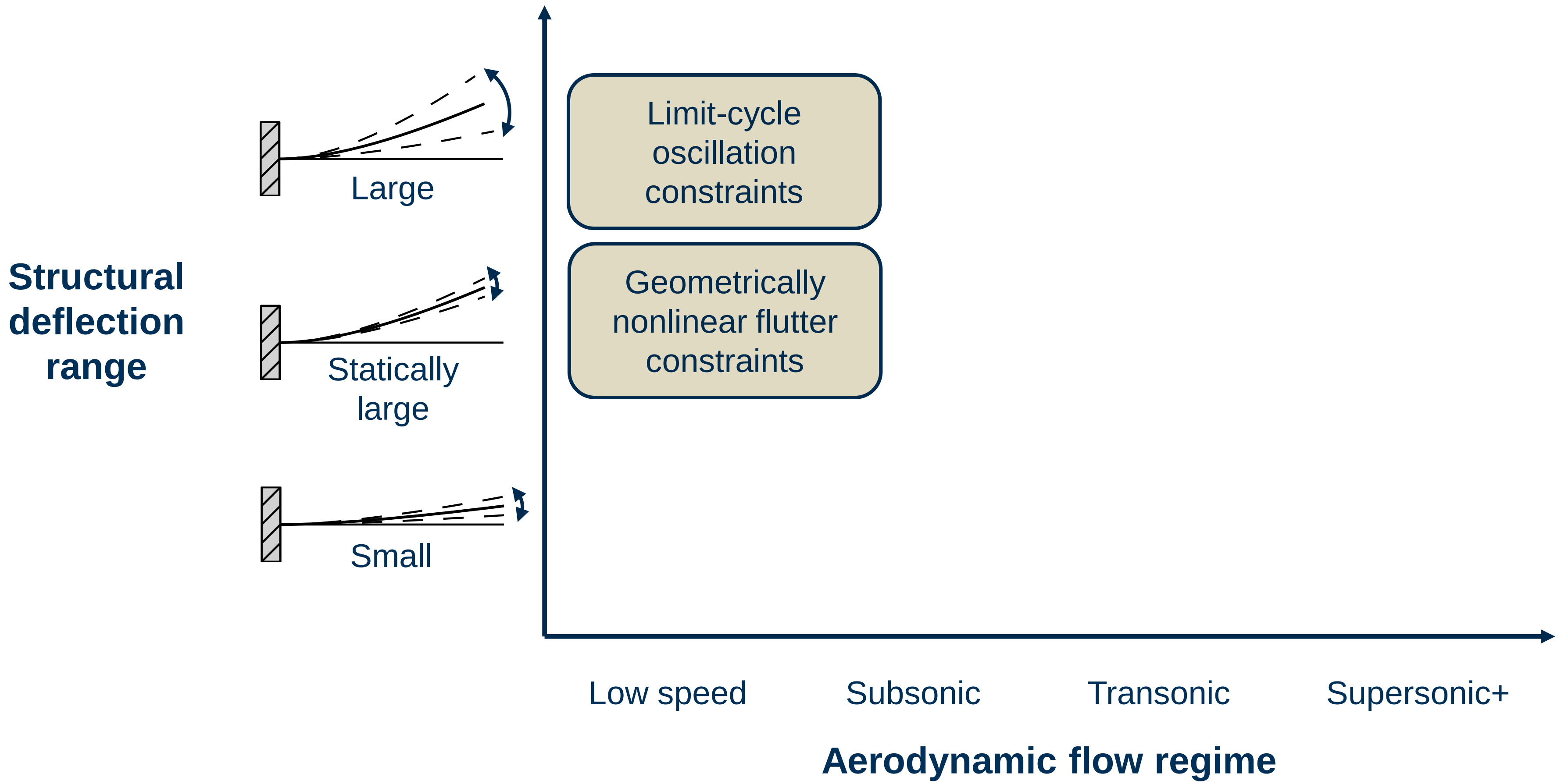

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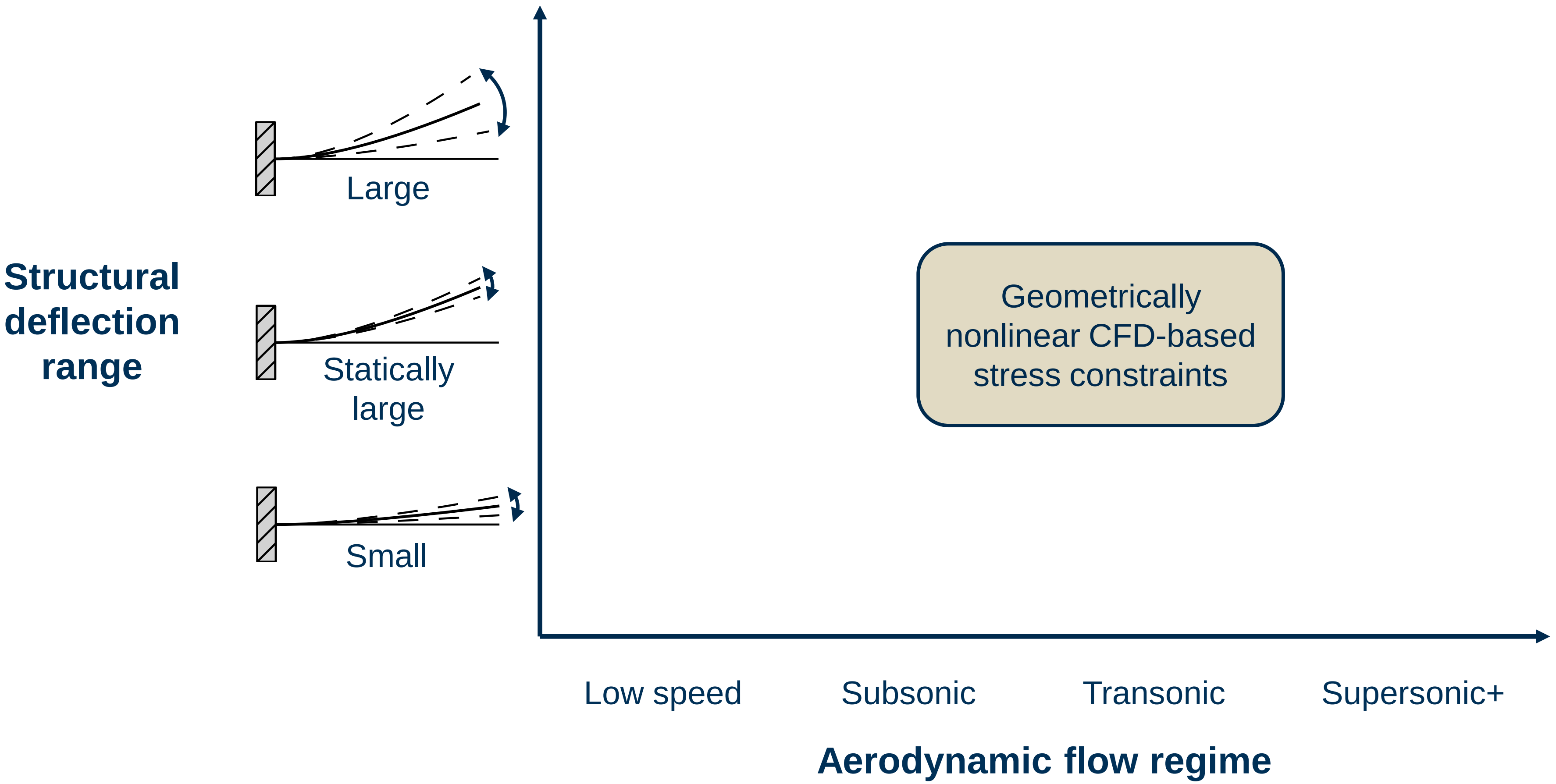

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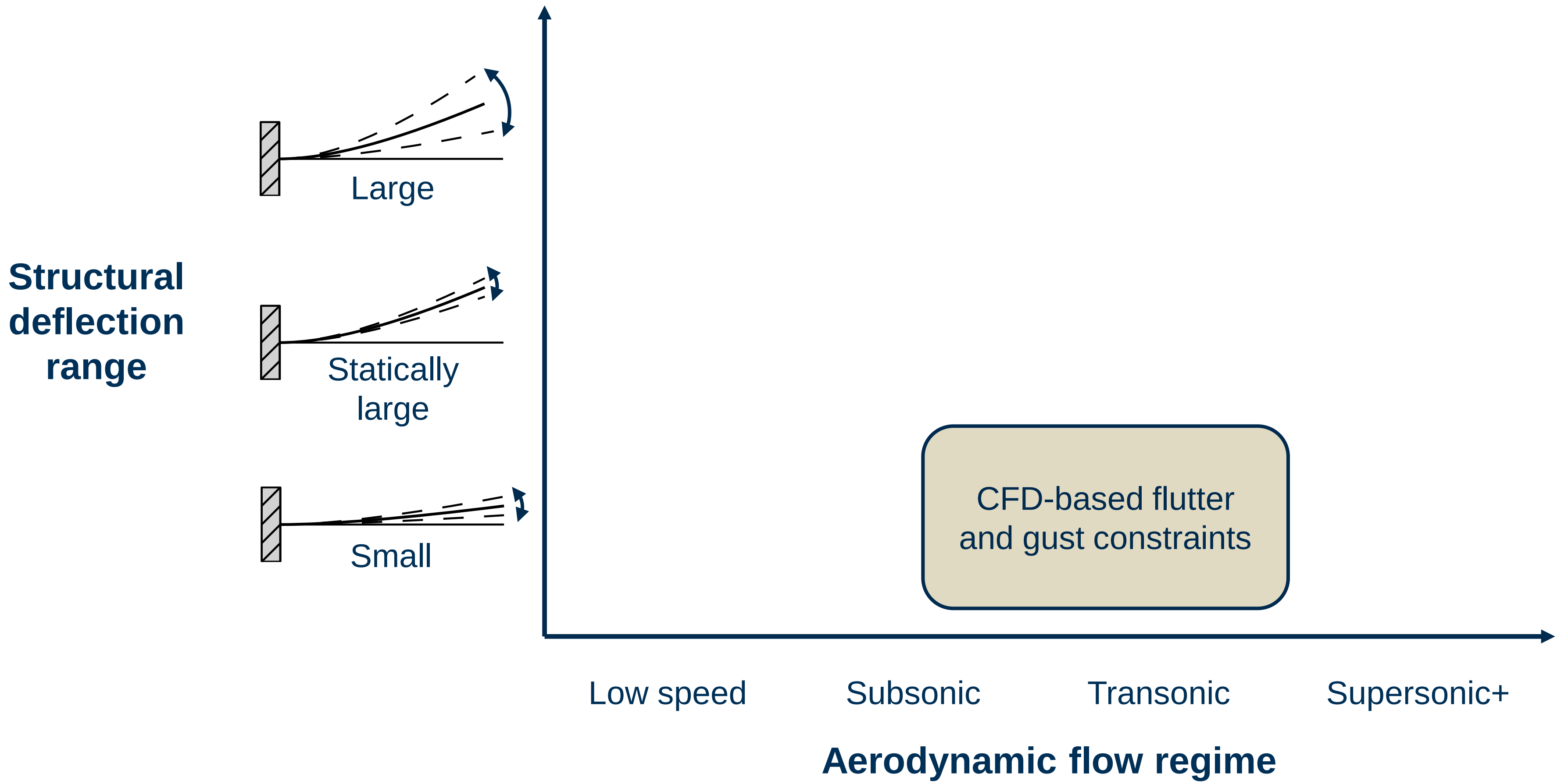

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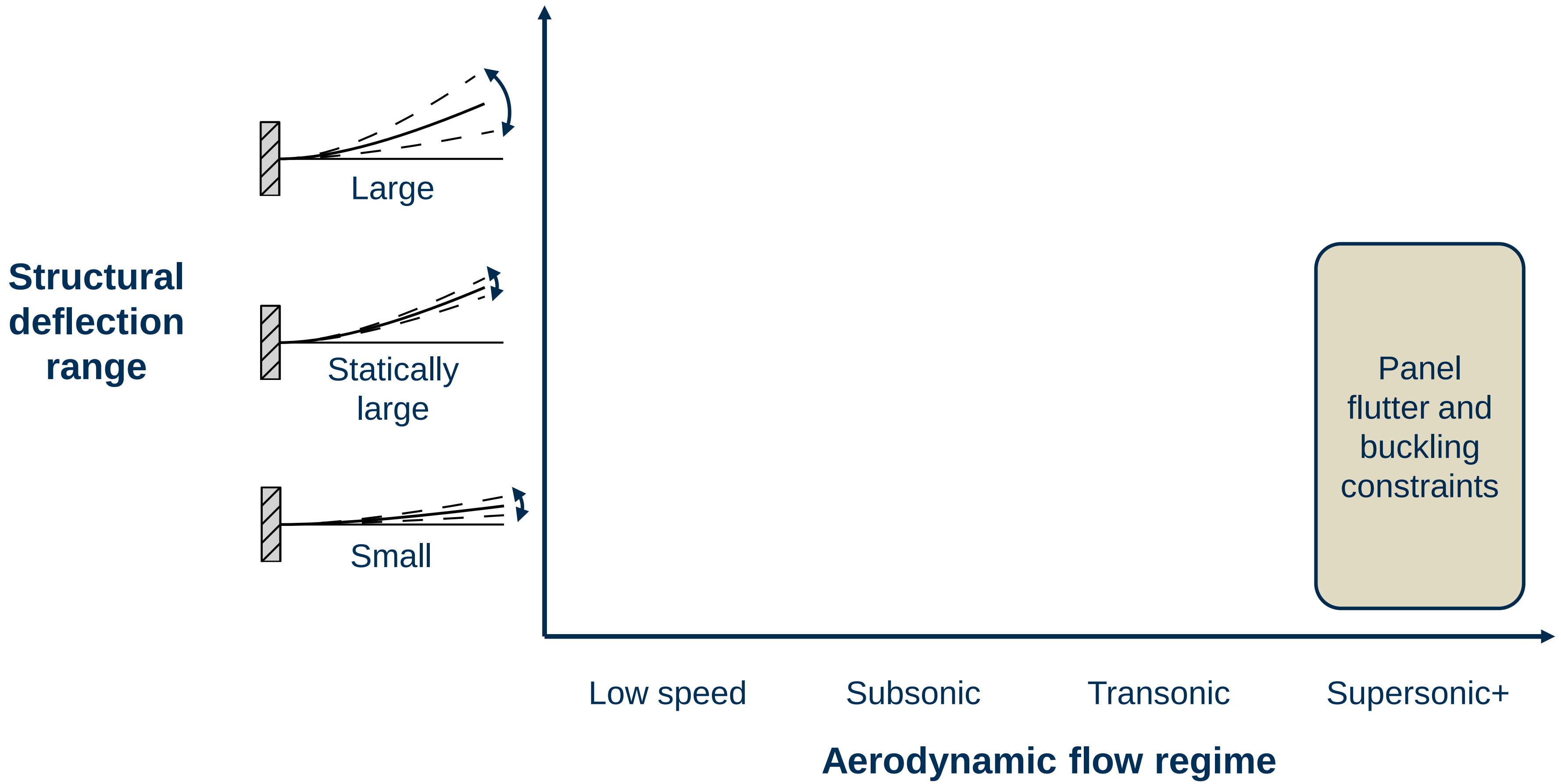

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- Ride quality
- Handling qualities
- …

The next generation of aerospace vehicles

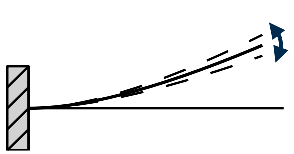
An explosion of aeroelasticity challenges

Aeroelastic behavior changes with amplitude

More than inertial, elastic, and aerodynamic forces

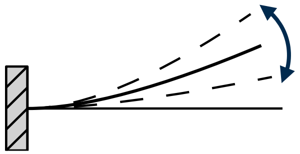
Limited design insights and guidelines

Static amplitude

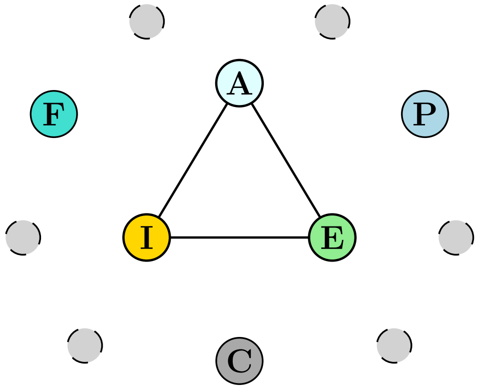


The equilibrium state matters

Dynamic amplitude



New phenomena come into play



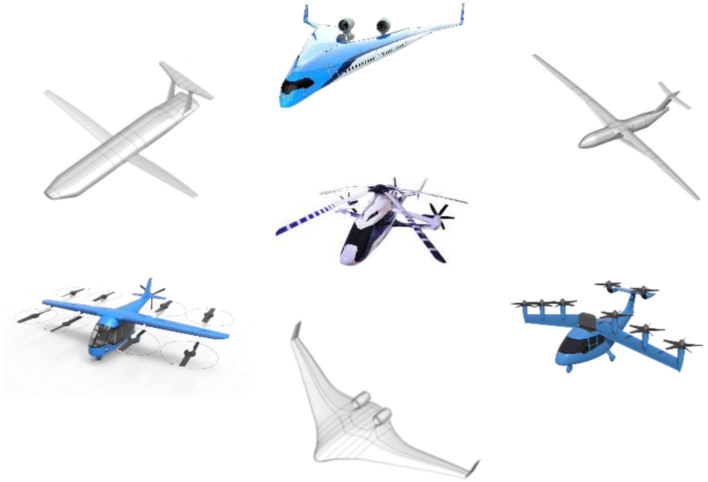
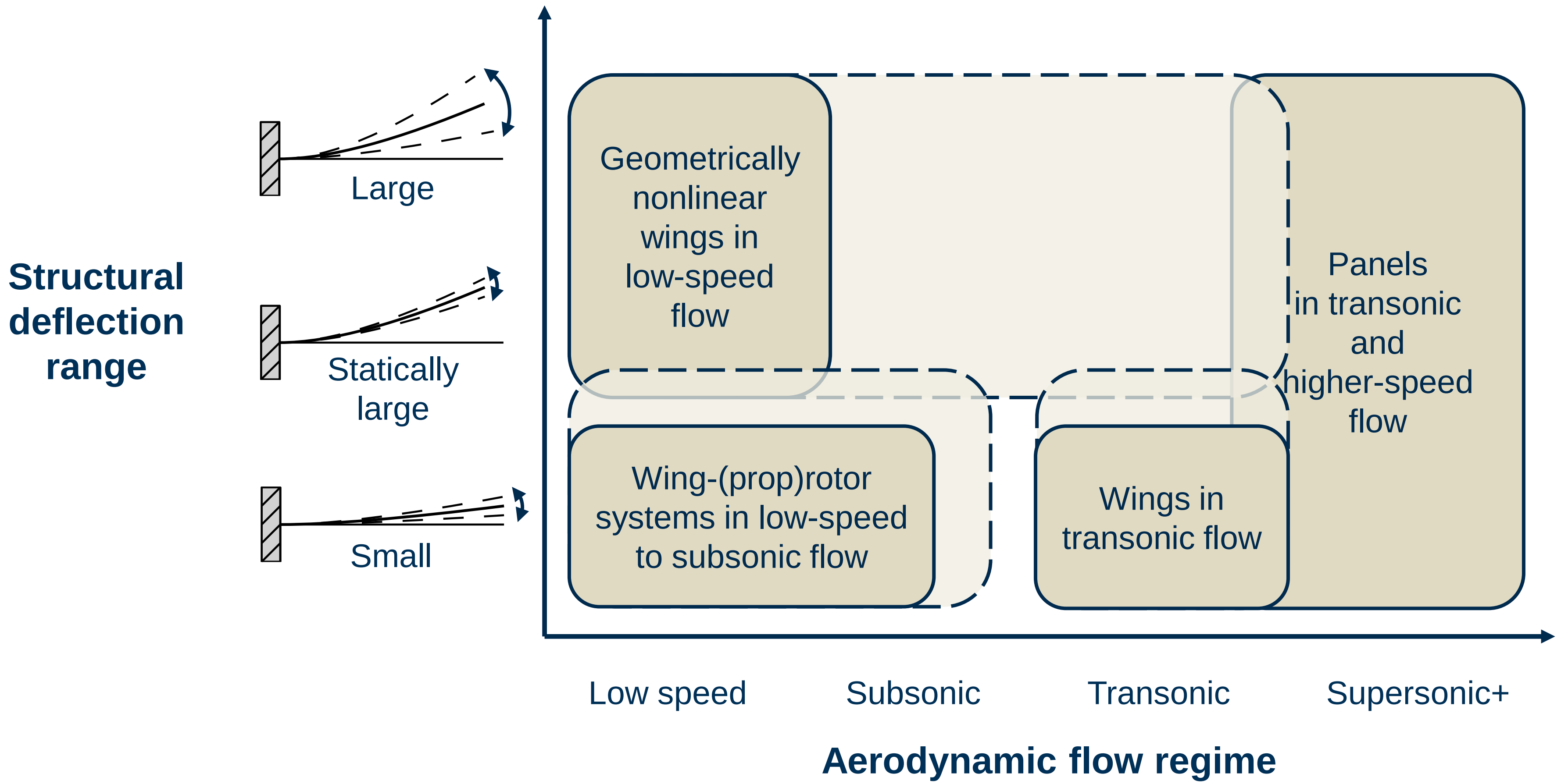


Image sources: NASA, Boeing, Airbus, DLR, Leonardo, Archer (top); NASA, Airbus, TU Delft, and Hwang and Martins, *AIAA Paper 2012-5605*, 2012 (bottom right)

The next generation of aerospace vehicles

An explosion of aeroelasticity challenges

How do we effectively model physical phenomena where multiple nonlinearities interact?



Metrics of interest

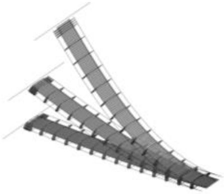
- Static structural response
- Modal characteristics
- Static aeroelastic response
- Flutter boundary
- Limit-cycle oscillations
- Gust response
- Maneuver response
- Ride quality
- Handling qualities
- …

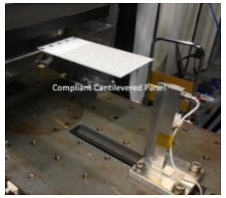
The next generation of aerospace vehicles

An explosion of aeroelasticity challenges

How do we keep basic research and practical design efforts connected?

What we want to fundamentally understand





What we want to design, build, and fly

Canonical shared test cases of increasing complexity for prediction and design optimization

Success metrics – what do “accurate” and “efficient” mean and for which use case?

Best practices and worst practices too

Reproducible results

Image sources: AePW3 (top left), NASA, Boeing, and Airbus (top right)

The next generation of aerospace vehicles

An explosion of aeroelasticity challenges

How do we integrate foundations and latest developments in aeroelasticity education?

What we want to fundamentally understand

What we want to design, build, and fly

Intentional workforce development for research and production

Constraints → **What we teach** ← **Unsteady boundary conditions**

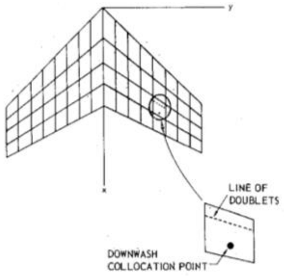
Constraints

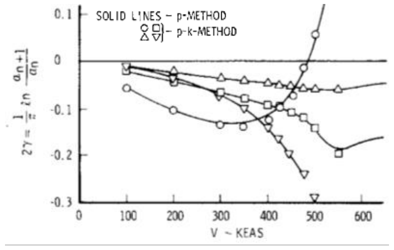
Limited time

Limited courses (if any)

Mostly graduate-level courses

What we teach





Unsteady boundary conditions

Post-pandemic teaching and learning

AI invasion

Image sources: AePW3 (top left), NASA, Boeing, and Airbus (top right); Albano and Rodden, *AIAA J.*, 1969; Hassig, *J. Aircr.*, 1971 (bottom middle); Harvard, OpenAI (bottom left)

The next generation of aerospace vehicles

An explosion of aeroelasticity ~~challenges~~ opportunities

Aeroelastic behavior changes with amplitude

More than inertial, elastic, and aerodynamic forces

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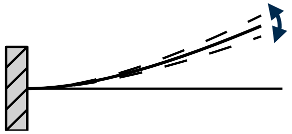
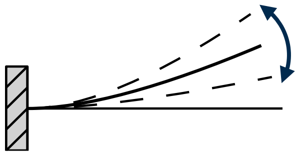
Static amplitude



The equilibrium state matters

Dynamic amplitude



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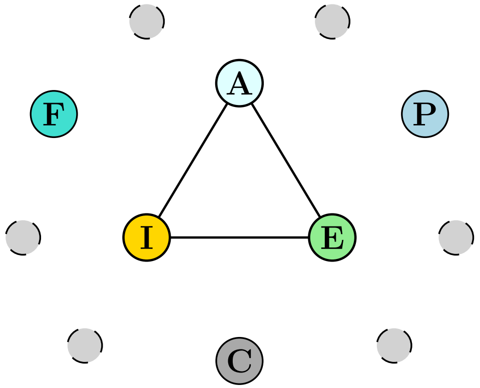


Image sources: NASA, Boeing, Airbus, DLR, Leonardo, Archer (top); NASA, Airbus, TU Delft, and Hwang and Martins, *AIAA Paper 2012-5605*, 2012 (bottom right)

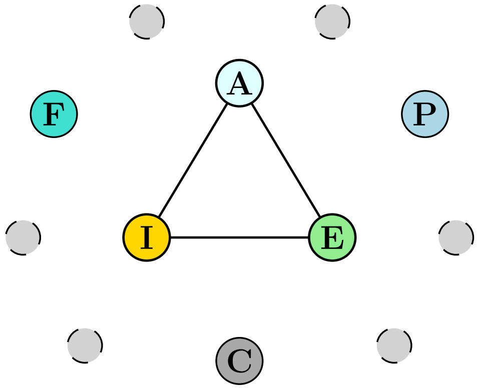
The next generation of aerospace vehicles

An explosion of aeroelasticity ~~challenges~~ opportunities

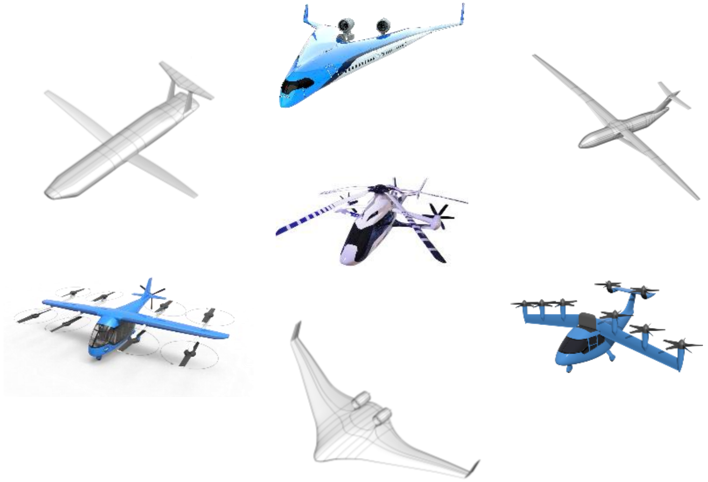
Aeroelastic behavior changes with amplitude

A new dimension for aeroelastic tailoring

More than inertial, elastic, and aerodynamic forces



Limited design insights and guidelines



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The next generation of aerospace vehicles

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Mutual benefits between traditionally disjoint disciplines

Image sources: NASA, Boeing, Airbus, DLR, Leonardo, Archer (top); NASA, Airbus, TU Delft, and Hwang and Martins, *AIAA Paper 2012-5605*, 2012 (bottom right)

The next generation of aerospace vehicles

An explosion of aeroelasticity ~~challenges~~ opportunities

Aeroelastic behavior changes with amplitude → A new dimension for aeroelastic tailoring

More than inertial, elastic, and aerodynamic forces → Mutual benefits between traditionally disjoint disciplines

Limited design insights and guidelines → Aeroelasticity can play a key role in shaping new designs

Image sources: NASA, Boeing, Airbus, DLR, Leonardo, Archer (top)

Reference list

Aeroelastic prediction

References

- Avin et al., *AIAA Journal*, 2022. DOI: https://doi.org/10.2514/1.J060621
- Riso and Cesnik, *Journal of Aircraft*, 2023. DOI: https://doi.org/10.2514/1.C036869
- Riso and Cesnik, *Journal of Fluids and Structures*, 2023. https://doi.org/10.1016/j.jfluidstructs.2023.103897
- Ritter et al., *AIAA SciTech Forum*, 2024. DOI: https://doi.org/10.2514/6.2024-0419

Additional resources

- Pazy wing models and results. https://github.com/UM-A2SRL/AePW3-LDWG.git
- Third Aeroelastic Prediction Workshop. https://nescacademy.nasa.gov/workshops/AePW3/public/
- Workshop on High Aspect Ratio Wing Technologies. https://cassyni.com/s/ar20plus/seminars

LCO prediction

References

- Lim and Epureanu, *Physical Reviews E*, 2011. DOI: https://doi.org/10.1103/PhysRevE.83.016203
- Ghadami and Epureanu, *Journal of Computational and Nonlinear Dynamics*, 2016. DOI: https://doi.org/10.1115/1.4033920
- Riso, Ghadami, Cesnik, and Epureanu, *AIAA Journal*, 2020. DOI: https://doi.org/10.2514/1.J059024
- Riso, Cesnik, and Epureanu, *Journal of Fluids and Structures*, 2021. DOI: https://doi.org/10.1016/j.jfluidstructs.2020.103201
- Gali, Goehmann, and Riso, *Journal of Fluids and Structures*, 2023. DOI: https://doi.org/10.1016/j.jfluidstructs.2023.103986
- Riso, *6th Decennial VFS Aeromechanics Specialists' Conference*, 2024 (available on Research Gate)
- de Dominicis and Riso, *AIAA SciTech Forum, 2024.* DOI: https://doi.org/10.2514/6.2024-0190
- de Dominicis and Riso, *AIAA Journal*, 2024 (to appear, available on Research Gate)

Geometrically nonlinear flutter and LCO constraints

References

- Jonsson, Riso, Lupp, Martins, Cesnik, and Epureanu, *Progress in Aerospace Sciences*, 2019. DOI: https://doi.org/10.1016/j.paerosci.2019.04.001
- Jonsson, Riso, Bahia Monteiro, Gray, Martins, and Cesnik, *AIAA Journal*, 2023. DOI: https://doi.org/10.2514/1.J061575
- Gray, Riso, Jonsson, Martins, and Cesnik, *AIAA Journal*, 2023. DOI: https://doi.org/10.2514/1.J062127
- Riso, Cesnik, and Epureanu, *AIAA Journal*, 2023. DOI: https://doi.org/10.2514/1.J062012
- Golla, Kennedy, and Riso, *AIAA SciTech Forum*, 2024. DOI: https://doi.org/10.2514/6.2024-2413