INFLUENCE OF MIXED BOUNDARY CONDITIONS ON THE INSTABILITY OF PLATES IN UNIFORM FLOW

Benjamin K. Morris[1], Eetu A. Kohtanen[1], R. Benjamin Davis[1]

[1]College of Engineering
University of Georgia
220 Riverbend Road, Athens, GA 30602 USA
ben.davis@uga.edu

Keywords: aeroelasticity, vortex lattice method, landing gear, flutter, divergence

Abstract: The landing gear door of a business jet recently experienced flutter during takeoff. In the present work, a flat plate with a hinged edge boundary condition and a small interior region with a pinned boundary condition is considered as an idealized model of a landing gear door. Aeroelastic stability of the plate is predicted using the vortex lattice method (VLM) for the entire range of possible actuator placements. Results show that the location of the actuator on the door's surface significantly alters the critical velocity, type of instability (flutter or divergence) and the structural mode that becomes unstable.

1 INTRODUCTION

Recently, the landing gear door of a business jet was observed to experience flutter during takeoff. The door is geometrically complex, involving a hinge along one chordwise edge, an actuator attachment, as well as variable thickness and curvature. Blades and Cornish [1] analyzed the aeroelastic instability of a business jet landing gear door using a Navier-Stokes computational fluid dynamics solver and the exact door geometry. To better understand the fundamental aeroelastic behavior of the system, this study idealizes the door as a hinged flat plate with an interior patch of translationally fixed nodes to simulate the attachment of a stiff actuator. While the effect on critical flutter speed of plates is well understood for many key parameters including mass ratio, aspect ratio, and boundary conditions [2, 3], the aeroelastic stability of plates with unusual boundary conditions, such as those considered here, has rarely been studied. In this paper, the critical flutter and divergence speeds are predicted for a representative plate geometry across a full range of postulated actuator placements. The results can be used as guidelines in the aeroelastic design of hinged plate-like structures having an additional stiff support.

2 THEORY

An unsteady, linear vortex lattice model (VLM) is coupled with a structural plate model as described in Gibbs [4]. One edge of the plate is hinged, allowing rotation about the x-axis but constraining all other degrees of freedom. Other edges of the plate are unconstrained. Additionally, a rectangular area on the interior of the plate with a width (Δx) and height (Δy) equal to 5% of the chord and span, respectively, is fixed in all translational degrees of freedom while allowing rotation about all axes (similar to a ball joint). The location of the rectangular area within the plate is varied across the simulations. The system geometry is shown in Fig. 1.

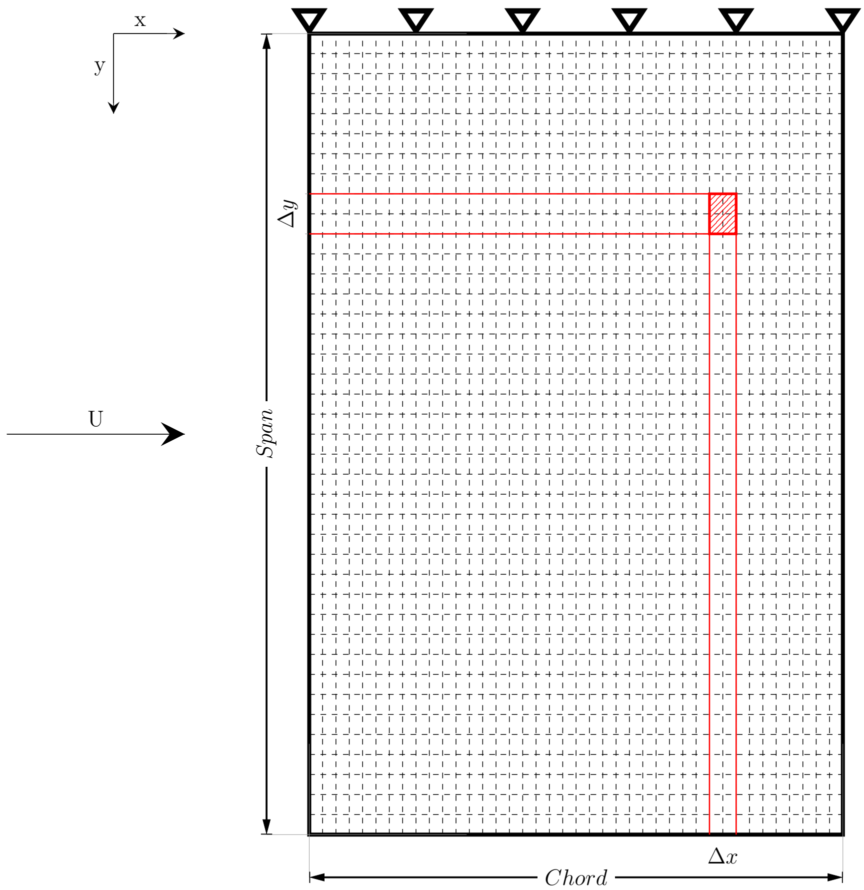

Figure 1: System geometry of the flat plate with a fixed boundary condition in all degrees of freedom except for rotation about the x-axis at 0% span, and a boundary condition fixed in all translational degrees of freedom, as indicated by the red region. The grid overlay indicates the 2.5% chordwise and spanwise spacing between simulation cases and is also coincident with the finite element mesh.

Boundary conditions are introduced to the VLM implicitly by including mode shapes from an *in vacuo* structural finite element model. Typical mode shapes from a finite element model are shown in Fig. 2. The assumed placement of the actuator tends to change the natural frequencies and mode shapes of the plate considerably, particularly for the higher-order modes (3^{rd} mode and above).

The fluid theory is based on incompressible potential flow. Hence, the fluid is assumed to be irrotational and inviscid. While it is impossible to study phenomena such as limit cycle oscillations with a linear model, there is no limitation to analyzing critical flutter speeds. The model uses a rectangular mesh with element dimensions dx and dy as shown in Fig. 3. For each element there is an associated horseshoe vortex that begins at quarter chord of the element and extends to infinity.

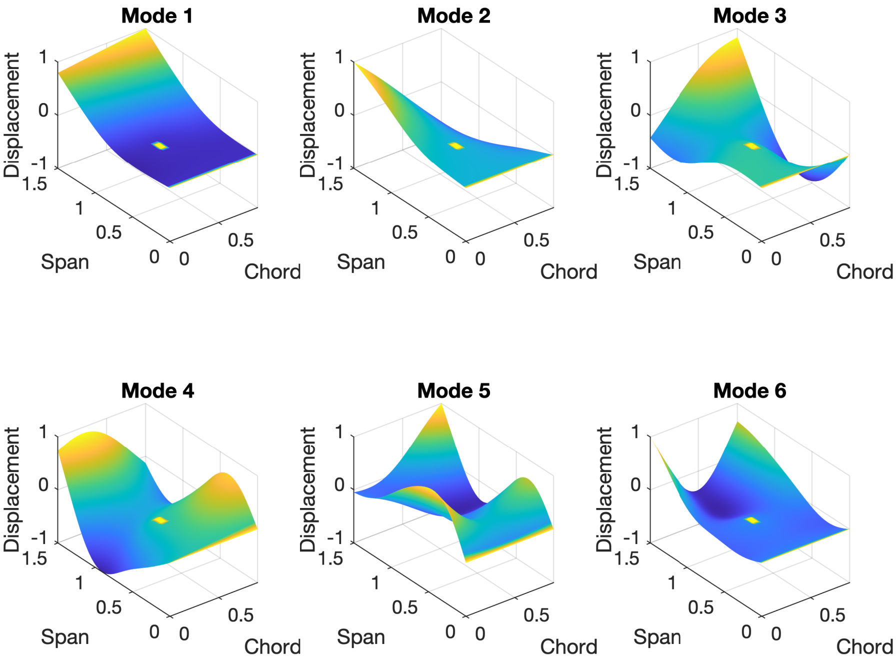

Figure 2: Mode shapes for the 40% chordwise, 40% spanwise actuator placement. The location of the fixed nodes is indicated by the yellow square. Analogous mode shapes exist for the other chord and spanwise locations of the fixed cluster. Note that the order of the mode shapes may change for different fixed node positions. All mode shapes are normalized to a unit amplitude.

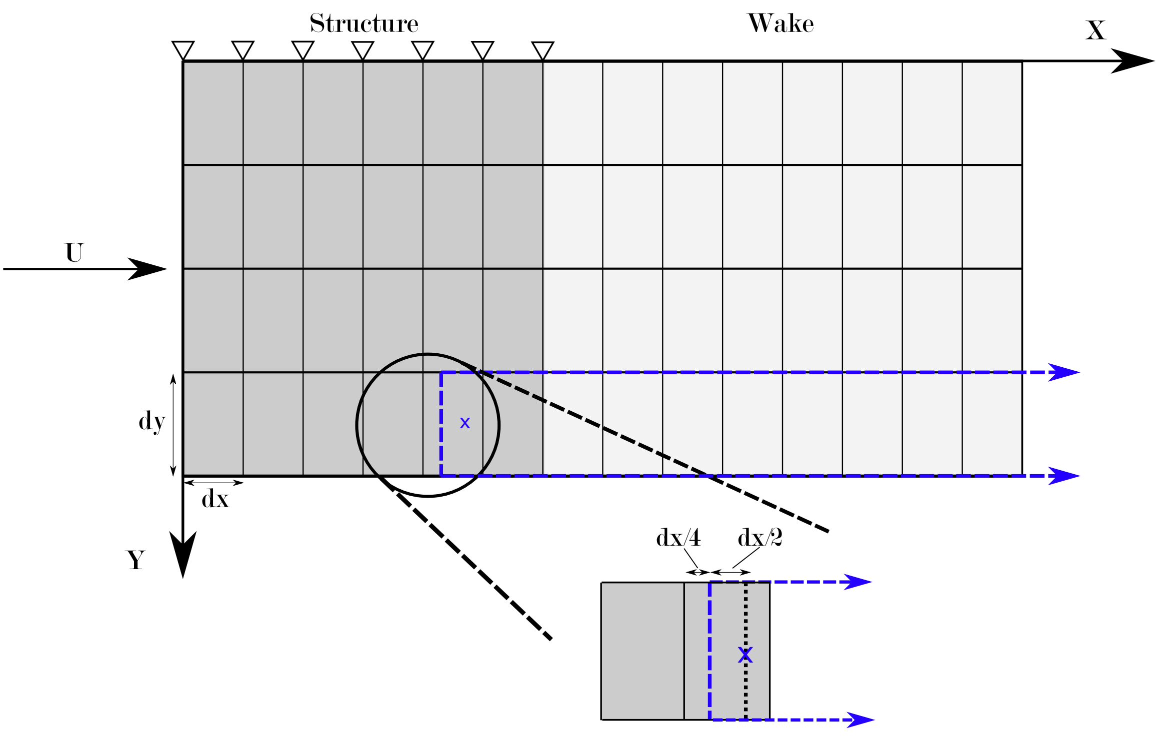

Figure 3: Sample mesh of a hinged plate. For each element there exists an associated horseshoe vortex as displayed at the quarter chord of the fifth element on the bottom row. The red "x" indicates the location of the collocation point.

There are two ways in which the structure and the fluid are coupled. First, all vortices induce downwash according to the Biot-Savart Law. The downwash at the collocation points, or the three-quarter chord of the elements, must conform to the structural velocity, i.e., no flow is allowed to penetrate the structure. Additionally, the fluid adds a forcing term to the structural equation of motion. All relationships are transformed into discrete state-space form, and arranged into a single linear matrix equation

$$[\kappa]\boldsymbol{\Theta}^{n+1} + [\Omega]\boldsymbol{\Theta}^{n} = 0, \tag{1}$$

$$[\kappa] = \begin{bmatrix} [\sigma] & -[\beta] \\ -[C_1] & [D_1] \end{bmatrix}, \tag{2}$$

$$[\Omega] = \begin{bmatrix} [\xi] & [0] \\ -[C_2] & [D_2] \end{bmatrix}, \tag{3}$$

where Θ is a vector containing the state space variables as well as the vortex strengths. The superscript n denotes the time step. The vortex relations including the fluid boundary condition on the plate are captured in $[\sigma]$, $[\xi]$, and $[\beta]$. The structural equation of motion as well as the state space relations are embedded into $[C_1]$, $[C_2]$, $[D_1]$, and $[D_2]$. Note that since Eq. (1) is linear, the system of equations is solved using eigenanalysis. The eigenvalues are then used to compute the structural frequencies as well as the damping ratios.

3 NUMERICAL RESULTS AND EXPERIMENTS

The instability characteristics of plates subjected to a flowing fluid depend on non-dimensional parameters including the mass ratio, μ, and the aspect ratio, H. The mass ratio is defined as the ratio of the structural mass to fluid mass obtained by circumscribing a cylinder on the plate chord, and is given as $\mu = 4\rho_s h/(\pi\rho_f b)$, where ρ_s and ρ_f are the structural and fluid densities, h is the plate thickness, and b is the plate chord. The aspect ratio is defined as $H = a/b$, where a is the plate span. In the present work, a plate with properties loosely reflecting those of a typical landing gear door is selected with the parameters of $\mu = 25$ and $H = 5/3$. The values of a and b are chosen to be 1.5 m and 0.9 m, respectively. The plate material in nominally aluminum, with a Young's modulus (E) of 70 GPa, a Poisson's ratio (ν) of 0.3, and a density (ρ) of 2700 kg/m^3. The fixed node cluster locations are spaced uniformly across the chord and span in 2.5% increments from 2.5% to 97.5% chord and span.

The plate goes unstable when either the damping of a mode becomes negative, or when one of the natural frequencies becomes zero. These conditions correspond to flutter and divergence, respectively. In the figures to follow, the assumed flow speed is incremented past the point where the plate goes unstable by either mechanism for different fixed node cluster positions. In Fig. 4, the instability type and critical velocity, U_{cr}, are shown for varied chordwise cluster locations using a representative spanwise location of 30%. At very low chord, the critical flutter velocity increases slightly with chordwise location. As the fixed node cluster moves farther from the leading edge towards mid-chord, the flutter velocity decreases. Near mid-chord, the flutter velocity again increases. At these mid-chord locations, as velocity is increased far beyond flutter, the damping of the associated mode begins to increase toward zero, indicating that the unstable mode is a "hump mode" that re-assumes stability at higher flow speeds. As the fixed nodes are assumed farther downstream, however, the plate goes unstable by divergence. Typically, the flutter predicted when the fixed node cluster is upstream of mid-chord corresponds to the second mode, but higher-order modes may flutter when the fixed node cluster is at high spanwise locations. As the fixed points move further towards the trailing edge, the divergence speed decreases drastically.

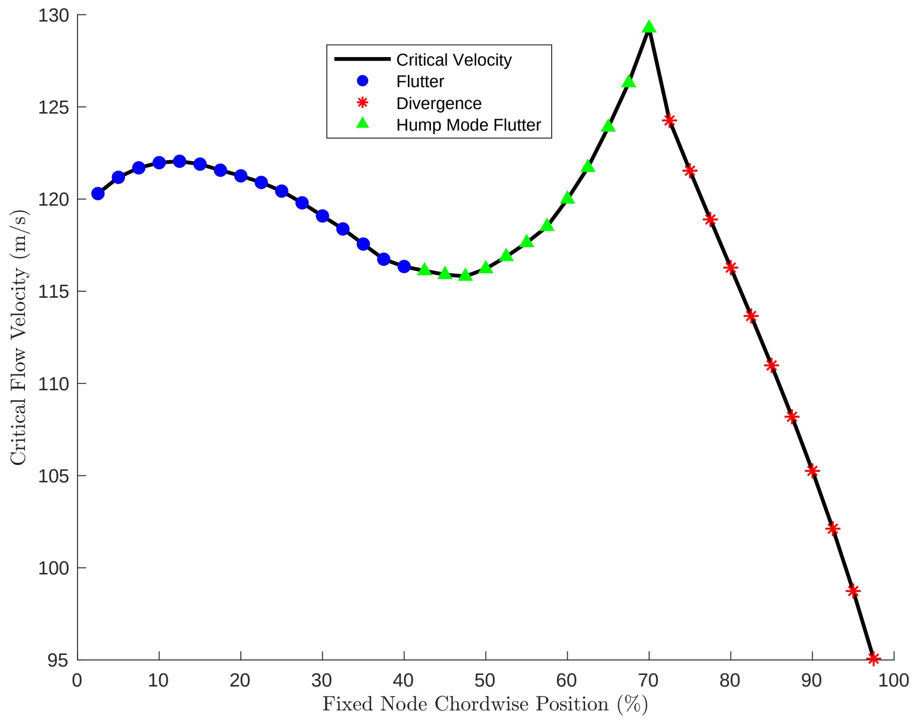

Figure 4: Representative critical velocities across the chord of the plate at a fixed span of 30%. At a given span, the plate generally flutters (blue circles) when the patch of fixed nodes is upstream of mid-chord and diverges when it is downstream of mid-chord. (red stars). The flutter is associated with a hump mode when the cluster is near mid-chord. Hump modes occur when a given eigenvalue branch goes unstable via flutter and then restabilizes at higher flow speeds.

The behavior shown in Fig. 4 is typical for the majority of spanwise locations. Between a span of 55% and 85%, however, higher order modes demonstrate instability. Fig. 5 shows the first instability and the corresponding mode number for every tested chord and spanwise position. Between spanwise positions of 55% and 65%, the 4^{th} mode flutters, between spanwise positions of 65% and 77.5%, the 3^{rd} mode flutters, and between spanwise positions of 80% and 85%, the 5^{th} mode flutters.

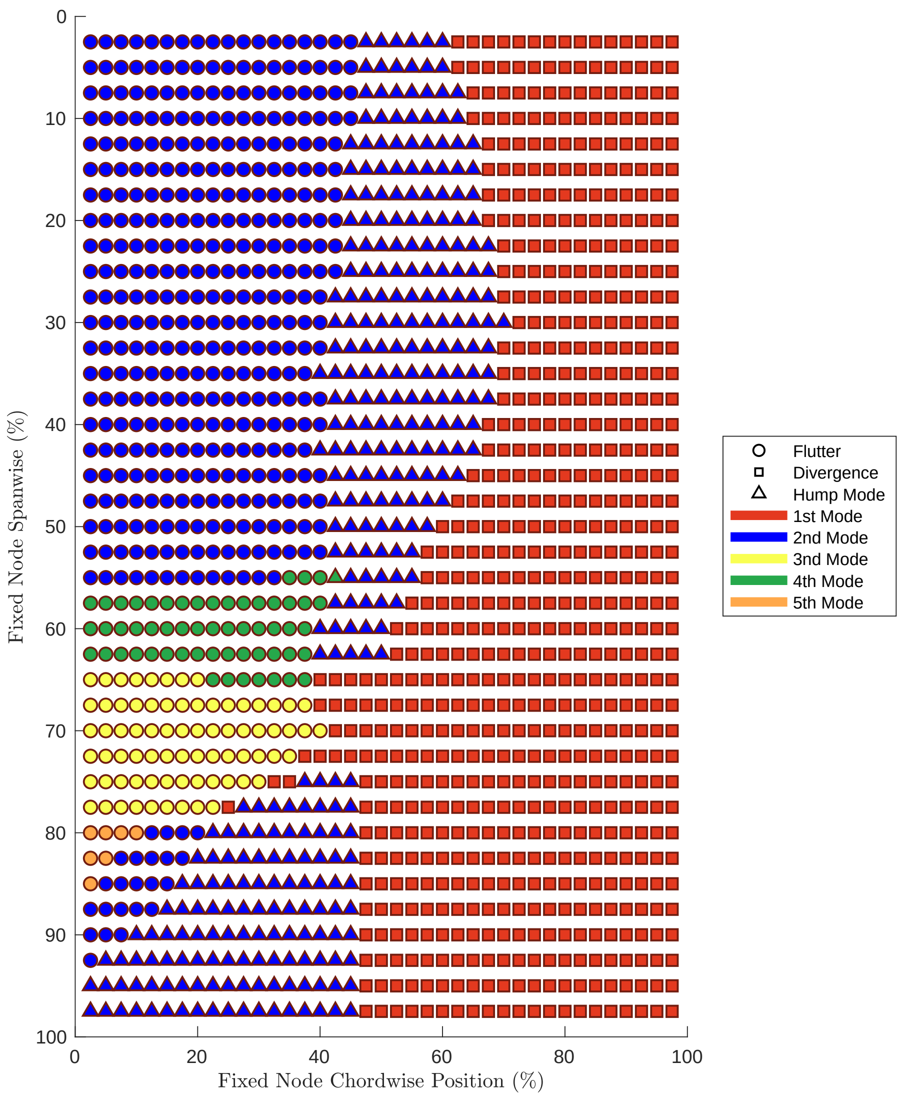

Figure 5: First instability type (marker shape) and the corresponding unstable structural mode (marker color) for a full range of fixed node cluster positions.

The critical velocity is shown for each fixed cluster position in Fig. 6 along with the flutter-divergence boundary. The instability speed tends to increase for cluster positions away from the hinge. Higher critical velocities occur at certain locations in the flutter region when high-order modes undergo flutter. The critical velocity for the high-order mode flutter can be signifcantly greater than the critical velocities with the actuator assumed at the same spanwise position, but at other chordwise positions. At high span, the flutter-divergence boundary rests near 50% chord, but at low span, the boundary lies at greater than 50% chord and changes with span. The drastic changes in mode order and frequency for different cluster positions is believed to greatly contribute to the rich landscape of instability behavior observed here.

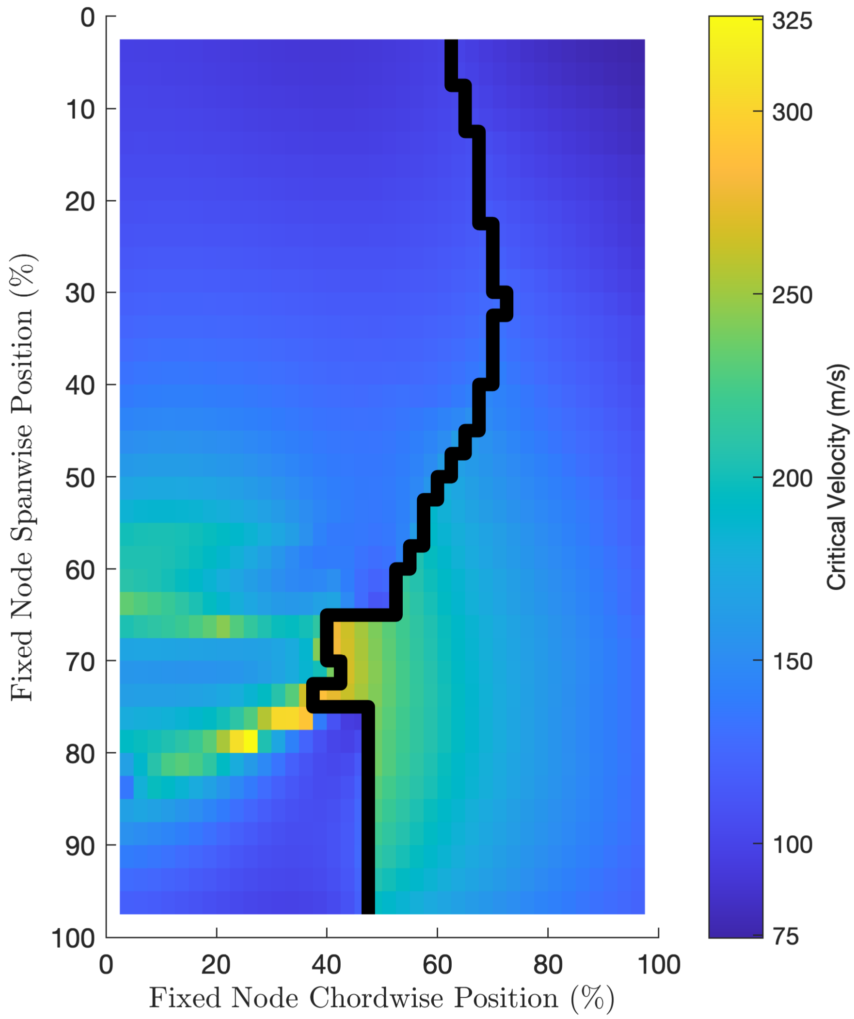

Figure 6: Critical velocity for a full range of fixed node cluster positions. The black line overlay shows the boundary between flutter (left) and divergence (right).

4 CONCLUSIONS AND FUTURE WORK

The spanwise and chordwise locations of a fixed node cluster have a significant effect on the instability characteristics of a hinged plate. This indicates that the actuator position on more complex plate-like geometries in flowing fluid may be an important design parameter to move the critical instability speed sufficiently far away from design speeds. For the flat plate studied here, a clear flutter-divergence boundary exists at approximately 50% chord, where actuator positions nearer the leading edge are associated with flutter and actuator positions closer to the trailing edge are associated with divergence. Additionally, the critical velocity is highest near this boundary. The parameter space worthy of analysis is vast, and further studies are needed to analyze the effects of the fixed node clusters more generally. Numerical studies involving a wide range of non-dimensional parameters including mass ratio, plate aspect ratio, fixed node cluster aspect ratio, and reduced velocity are planned.

5 REFERENCES

[1] Blades, E. and Cornish, A. (2015). Aeroelastic stability predictions of a business jet landing gear door using high fidelity fluid-structure interaction tools. In *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. p. 0173.

[2] Gibbs, S. C., Wang, I., and Dowell, E. H. (2012). Theory and experiment for flutter of a rectangular plate with a fixed leading edge in three-dimensional axial flow. *Journal of Fluids and Structures*, 34, 68–83.

[3] Gibbs IV, S. C., Wang, I., and Dowell, E. H. (2014). Stability of rectangular plates in subsonic flow with various boundary conditions. *Journal of Aircraft*, 52(2), 439–451.

[4] Gibbs, S. C. (2012). *Linear Aeroelastic Stability of Beams and Plates in Three-Dimensional Flow*. Master's thesis, Duke University.

COPYRIGHT STATEMENT

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the IFASD-2019 proceedings or as individual off-prints from the proceedings.