T-tail flutter analysis using Edge

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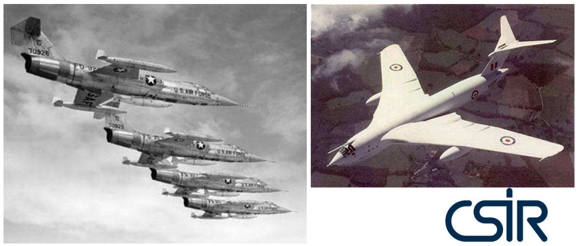
The problems with T-tail aeroelasticity are well known:

- The horizontal tail plane (HTP) is subject to significant in-plane motion
- In-plane aerodynamic loads and loads due to in-plane motion need to be considered
- The unsteady aerodynamic loads depend on the steady loads and on the static deformation of the airframe



Limitations of the Doublet Lattice Method

The Doublet Lattice Method (DLM), which is the most common means of calculating generalised forces for aeroelastic analysis, does not calculate all the required unsteady aerodynamic forces for T-tails. The following additional forces are typically added to DLM results:

- a lateral component of the lift force caused by angular displacement of the tailplane in roll,
- a rolling moment caused by angular displacement of the swept tailplane in yaw,
- a rolling moment caused by angular velocity of the tailplane in yaw, and
- a rolling moment caused by lateral velocity of the tailplane.

These forces are typically estimated empirically or calculated using strip theory

Advantages of FSI

CFD codes in general do not require special treatment to calculate the loads that the DLM doesn’t. Transonic flow can also have a significant effect on T-tail flutter and the only accurate means of modeling this effect is using CFD – either in time-domain simulations or for calculating generalized aerodynamic forces for small harmonic oscillations about the trim state. The Edge code is suited to both these applications and is therefore an attractive alternative to the DLM-based methods for T-tail flutter analysis.

However, the linear modal displacement model in Edge can lead to erroneous results. The use of a parabolic modal displacement model offers much greater accuracy.

The parabolic modal displacement model

The essence of the parabolic modal displacement model is that the linear expression for the displacement of a point on a structure

$$\mathbf{x}(t)=\sum_{i=1}^{n} q_i(t)\mathbf{u}_i$$

is replaced by a quadratic expression

$$\mathbf{x}(t)=\sum_{i=1}^{n} q_i(t)\mathbf{u}_i+\sum_{i=1}^{n}\sum_{k=1}^{n} q_i(t)q_k(t)\mathbf{g}_{ik}$$

where the q_i are the generalised coordinates, the $\mathbf{u}_i$ are the linear mode shape components and the $\mathbf{g}_{ik}$ are the quadratic mode shape components

Implementation in Edge

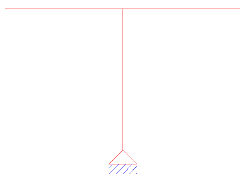
For this evaluation exercise, only the DMOCOUPL routine was modified to interpret some modes as quadratic mode shape components (the order of the modes is assumed to be all linear mode shape components, followed by all quadratic mode shape components).

The solution of the structural equation of motion was modified accordingly.

This approach is obviously very costly in terms of memory, since a modal mesh deformation is associated with each quadratic mode shape component. There are much more efficient implementation options, but they would require more extensive code changes.

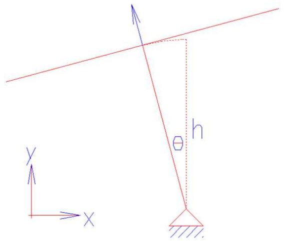
T-tail problem No. 1

The need to consider the quadratic mode shape components in T-tail flutter analysis is illustrated by the example of a T-tail with height *h*, hinged at its base with torsional stiffness K_t, and mass moment of inertia I_{zz} about the hinge. The hinge line is parallel to the flow.



T-tail problem No. 1

We consider the case of an HTP generating an upward trim load of constant magnitude *F*, with the HTP (and the force) rolling with the fin. The trim load acts at the junction of the fin and the HTP.



T-tail problem No. 1

The force will have no effect on the dynamics of the T-tail because the force always acts through the hinge line. When we analyze the T-tail using Lagrange's equation and a linear modal displacement model, we get a different result.

Lagrange's equation applied to the T-tail simplifies to:

$$I_{zz}\ddot{\theta} + K_t\theta = Q$$

Where θ is the angular deflection of the fin and Q is the generalized force defined by

$$\delta W = Q\delta\theta$$

T-tail problem No. 1

δW is the virtual work that would be performed by the applied force if the fin was displaced through a virtual angular deflection $\delta\theta$. The virtual work is given by the dot product of the force and the virtual displacement, viz.

$$\delta W = \mathbf{f} \cdot \delta\mathbf{x}$$

According to the linear modal displacement model, the displacement and virtual displacement of the top of the fin are given by

$$\mathbf{x} = (-h\theta, 0)$$
$$\delta\mathbf{x} = (-h, 0)\delta\theta$$

T-tail problem No. 1

The force is approximately equal to

$$\mathbf{f} = (-\theta F, F)$$

The virtual work is equal to

$$\delta W = \mathbf{f} \cdot \delta\mathbf{x} = (-\theta F, F) \cdot (-h, 0)\delta\theta = hF\theta\delta\theta$$

And Lagrange's equation becomes

$$I_{zz}\ddot{\theta} + (K_t - hF)\theta = 0$$

Therefore the T-tail is predicted to diverge if the product of the applied force and the fin height exceeds the torsional stiffness, which is wrong.

T-tail problem No. 1

According to the parabolic modal displacement model, the displacement and virtual displacement of the top of the fin are given by

$$\mathbf{x} = \left(-h\theta, -\tfrac{1}{2}h\theta^2\right)$$
$$\delta\mathbf{x} = (-h, -h\theta)\delta\theta$$

The virtual work is equal to

$$\delta W = \mathbf{f} \cdot \delta\mathbf{x} = (-F\theta, F) \cdot (-h, -h\theta)\delta\theta = 0$$

The steady trim load is therefore predicted to have no effect on the dynamics of the T-tail. This is the correct result except that in reality there will be roll damping.

Numerical example

For this example the dimensions and mass and stiffness of the hypothetical T-tail was chosen as:

Fin height: 0.3 m

HTP span: 0.5 m

Fin and HTP chord: 0.1 m

Mass moment of inertia: 0.052178 kg.m²

Modal frequency: 5 Hz

We consider three HTP incidences: zero, -6º and +6º

DLM solutions

The standard DLM (i.e. without additional loads) ignores the steady load and predicts virtually no effect of HTP incidence on the aeroelastic behaviour of the T-tail.

The DLM with additional loads, in particular the side force due to roll of the HTP, predicts a strong dependence of aeroelastic behaviour on HTP incidence.

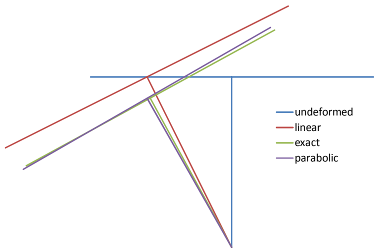
A T-tail DLM, which calculates all the additional loads and also accounts for the parabolic modal displacement, yields the same result as the standard DLM.

Edge solution

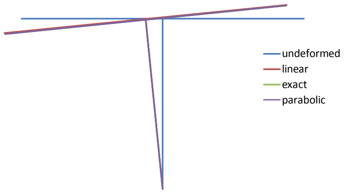
A grid was generated with the base of the fin, i.e. the hinge line, on the axis of a cylindrical domain with a diameter of 2m. Due to the axial symmetry of the setup, rotation of the T-tail should not change the pressure distribution on the T-tail. In reality, due to some a-symmetry in the grid, this was not quite achieved.

The analyses consisted of a steady solution, followed by a prescribed, sine-squared, disturbance of 0.03 radians (corresponding to 10 mm lateral displacement at the fin top), followed by a coupled time-domain simulation.

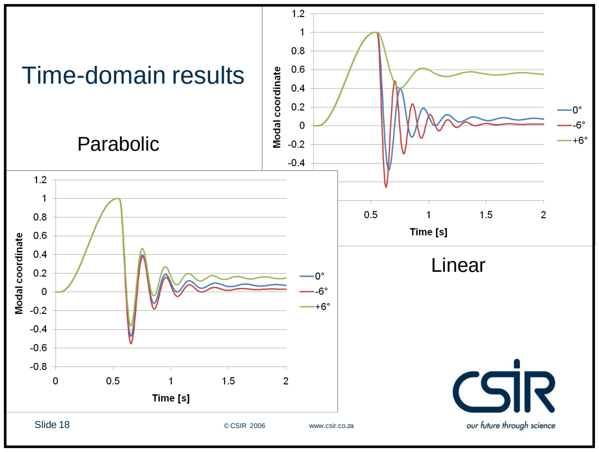
Parabolic vs. Linear modal displacement 0.5 radians / 30°



Parabolic vs. Linear modal displacement 0.1 radians / 6°



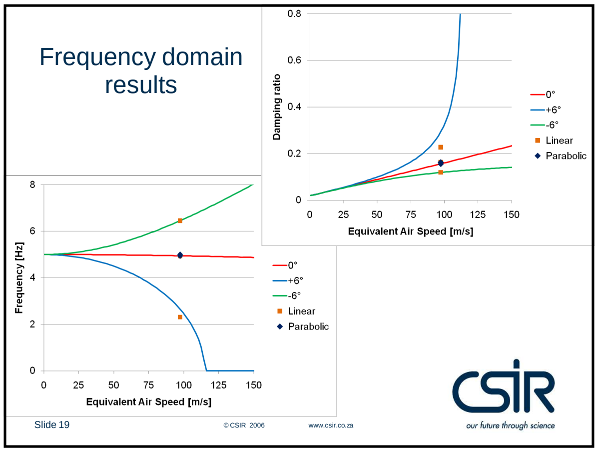
Time-domain results



Parabolic

Linear

Frequency domain results



Acknowledgements

The authors wish to acknowledge the contributions of Jonathan Smith for assistance with the implementation of the quadratic mode shapes in Edge and Rene Heise of CSIR for the modeling of the T-tail example cases.

Conclusion

We have a permanent disclaimer on our CFD computer room door that reads:

"The purpose of simulation is insight, not numbers."
Oscar Buneman 1986

A more cynical person, e.g. the first author, might have replaced "insight" with "colours". T-tail flutter analysis using FSI offers a good opportunity to get the colours (pressure distribution) right and the numbers (generalized forces) wrong. In the academic world this is of little consequence, but in industry the numbers are also important. Anyone using FSI for T-tail flutter analyses would be well advised to ensure that the method used provides the correct answers (numbers, not colours) to T-tail problem No. 1.