Flutter in the Sky

In engineering terms, flutter means a vibration that amplifies. Flutter has destroyed bridges, such as the infamous Tacoma suspension bridge, and it challenges designers of high-performance aircraft. As recently as September 1997, wing flutter — partly the result of faulty structural maintenance — caused an F-117A Nighthawk, the first operational "stealth" plane, to lose most of one wing and crash at an air show.

"Flutter can be catastrophic and must be avoided at all cost," says Charbel Farhat, who directs the University of Colorado’s Center for Aerospace Structures. For about 10 years, Farhat has worked to develop sophisticated computational methods for predicting the "flutter envelope" of high-performance aircraft and to encourage wider use of these methods in industry. Through a collaborative program with Edwards Air Force Base, he’s been trying out his methods on the F-16 fighter.

“We do blind tests," explains Farhat. "We develop the simulation technology and try it on the aircraft. Then they fly it to get actual flight data, and we see how we’re doing." In the spring of 2001, "friendly user” time on the prototype Terascale Computing System allowed him to improve the resolution of the F-16 model and achieve his best results to date.

THE FLUTTER ENVELOPE
Most of us have experienced in-flight turbulence, but we may not have looked out the window to see the wings shimmy as the plane encounters a turbulent patch. Made of flexible material, aluminum or composite, modern high-speed aircraft experience stress in the range of 40,000 pounds per square inch. When these structures vibrate, the engineering question is whether the air will absorb the vibration or amplify it into flutter. The answer depends, says Farhat, on three things — speed, altitude, and stiffness and mass of the structure.

To calibrate these interactions, the design process aims at accurately predicting the plane’s flutter envelope — a curve that plots speed versus altitude. "At a given altitude," says Farhat, "it tells you the speed not to exceed, even if the engines can do it, because any perturbation is going to be amplified." Even for supersonic fighters, however, which must be designed for aggressive, high-speed maneuvers, relatively uncomplicated analytical techniques — which can be solved with "linear” mathematics — give reliable flutter predictions at subsonic and supersonic speeds.

The problem comes in the transition from subsonic to supersonic flow — from about Mach 0.85 to almost Mach 1. Linear methods can’t reliably predict flutter in this transitional regime, and the aircraft industry for years has relied on wind-tunnel testing. To model flutter, however, unlike aerodynamics, the scale model has to reproduce the stiffness properties of the full-scale plane and vibrate in scale with reality. To build one model, test it, interpret the data, and plot five points that describe the curve of the transonic flutter envelope, says Farhat, takes at minimum a year.

A THREE-FIELD FORMULATION
As computational technology improves, it has become feasible to turn to more sophisticated modeling techniques. Flutter involves the interaction between flow and structure, and to realistically predict it requires solving equations of motion for the structure simultaneously with those for the fluid flow, which turns the mathematics into a complex "nonlinear" problem.

Computational fluid-dynamics problems are solved by overlaying the structure with a fine-mesh grid that gives coordinates in space at which to calculate forces. The nonlinear, coupled approach requires that the fluid also be represented as a computational mesh, with exchange of energy between the air and the vibrating structure calculated at the intersections between these two grids.

Difficulties arise, however, because structural vibration necessarily changes the shape of the grid, potentially introducing serious error into the calculation unless the structure grid can simultaneously be redrawn at each microsecond time-slice, which is impractically cumbersome. To circumvent this problem, Farhat has developed methods, implemented in a simulation technology called AERO, that treat the movement of the computational mesh as a third field that interacts with the structure and the fluid.

To validate his innovative "three-field formulation," Farhat has simulated flutter on the F-16. Using a 32-processor SGI Origin 2000 system, AERO modeled a clean-wing F-16 configuration — without underwing attached weapons — for one point on the flutter envelope. This took about four hours of computing time, demonstrating that AERO can be a practical simulation tool. Comparison with flight-test data showed reasonably good accuracy, within about 15 percent.

A series of runs on the prototype Terascale Computing System, however, demonstrated what can be gained with faster processing. The
TCS ran AERO roughly twice as fast per processor, and using all 256 processors the overall capability increased by another factor of eight. This made it feasible to use a fluid mesh with 1.5 million grid points, nearly four times more detailed than the earlier simulations. The change brought agreement with flight-test data to within five percent.

Farhat notes his simulations have dealt with only one F-16 configuration, and many others must be correlated with flight data, but the results are encouraging. “This shows that better computational capability can substantially improve our technology.”

More information: http://www.psc.edu/science/farhat.html