Chapter 6

Concluding Remarks

6.1 Summary

In this dissertation a rather complete model of general unsteady aeroelastic behavior has been developed. The approach is to consider the structure, the flowing air, and in some cases the control system as elements of a single dynamical system and to numerically integrate all of the governing equations interactively and simultaneously in the time-domain. Since the present analysis provides the solution in the time domain, it is not restricted to periodic motions or linear equations of motion. In contrast with solutions performed in the frequency domain, time-marching schemes allow the modeling of subcritical aeroelastic behavior as well as aeroelastic behavior after the onset of flutter as long as the effective angles of attack are not large enough to produce stall. As a consequence, these schemes can be a very effective tool for the design of flutter-suppressing control systems. Because the equations are solved numerically structural nonlinearities do not present a problem; the aerodynamic model is inherently nonlinear.

The general unsteady vortex-lattice method, a generalization of the familiar vortex-lattice method for steady, incompressible flows, was used to predict the aerodynamic loads. A major contribution of the present work was to further refine the vortex-lattice method and to write a new, user-friendly, object-oriented computer code in Fortran 90. The technique accounts for the aerodynamic nonlinearities associated with angles of attack, static deformation, vorticity-dominated flow, and unsteady behavior; and is valid for arbitrary angles of attack, planforms, and motions as long as massive stall and vortex-bursting in the near vicinity of the body do not occur. The new vortex-lattice model of the flowfield contains the fuselage, engines, pylons, tail assembly, and wings with ailerons. It is capable of capturing the aerodynamic interference among all the components of the complete configuration. The vorticity distribution in and the shape of the wakes are determined as part of the solution. Because vorticity in the wakes now was generated on and shed from the wing and/or bodies earlier, the history of the motion is stored in the wakes.

In the present work, the structural models for the bridges were simple; the roadbed was considered a rigid plate and the supports were condensed into a single equivalent spring for the translational motion and a single equivalent spring for the rotational motion. In some cases, the connection between the roadbed and the control was elastic and the structure had internal damping.

In the case of aircraft, the structural model included only the wing. The entire wing was modeled as a cantilever beam fixed to the rigid fuselage. The elastic, linear, and structurally undamped wing was free to bend about two axes, twist, and elongate. The mass center of each section did not coincide with the elastic axis; thus there was dynamic coupling between flexural and torsional modes. The equations of motion were discretized by using the finite-element method.

Another major contribution of this work was to develop a technique for combining the vortex-lattice and finite-element methods. The principle of virtual work, long in use as a basis for determining the nodal forces in finite-element methods, was extended to transfer the aerodynamic loads to the structural grid. The structural deformation of the wing was expressed as an expansion in terms of its free-vibration modes, and the time-dependent coefficients in this expansion were used as the generalized coordinates of the entire dynamical system. To effect the numerical simulations, Hamming's fourth-order predictor-corrector method was adapted to the present problem in order to avoid evaluating the aerodynamic loads at fractional time steps and to accommodate aerodynamic loads that are proportional to the acceleration.

For the case of the bridges, the present simulation predicts the onset of flutter in good agreement with earlier work, and clearly shows the merger of the structural frequencies. The merged frequency lies between the two frequencies that correspond to the structure without flow. The simulation also shows that the responses at subcritical wind speeds are decaying and clearly contain two frequencies. There is no damping in the structural model yet the motion decays. Obviously, there is some aerodynamic damping, which is the result of the structure transferring energy to the flowing air. This damping is provided by the aerodynamic model although viscosity does not appear explicitly. The airstream represents an infinite sink, or in the case of flutter an infinite source, of energy. At subcritical speeds of the freestream, energy is transferred from the structure to the flowing air; while at supercritical speeds, the transfer is in the opposite direction.

As the speed of the freestream increases, the two frequencies in the response approach each other; they merge at the onset of flutter. The motion does not suddenly change from decaying to growing but becomes organized; indeed, this developing organization is a clear warning that the bridge is about to go into flutter. When the supporting springs are linear the response of the system appears to approach a limit cycle. However, the amplitude of the apparent limit cycle and to a much lesser extent the frequency depend on the initial conditions. Most likely, therefore, the response is not truly a limit cycle, but either a very slightly stable or a very slightly unstable focus. When the springs are nonlinear, the response of the nonlinear system is a true limit cycle.

When used to suppress the wind–excited vibrations of suspension bridges, the present simulation strongly suggests that flutter is easy to control. In fact, the present scheme can most likely be improved substantially. The present simulation suggests that flutter can be readily suppressed at wind speeds 25% above the critical speed for the uncontrolled bridge.

For the case of the wing of the Cessna Citation X, the present simulation predicts aeroelastic behavior that is in good agreement with the experimental work performed by Cessna. At subcritical wind speeds, the numerical simulation predicts the decay of the motion in all but the third mode. Each of the modes, except the third, reaches its static equilibrium position. The reason the amplitude of the third mode does not decay is that there is practically no damping in this mode. The structural model does not include any damping. The general unsteady vortex-lattice method does provide damping, but mostly in the bending and torsion modes. At low angles of attack, there is considerable "cross contamination" of one mode by the others; that is, one modal amplitude contains significant energy at many frequencies. At higher angles of attack, the motion becomes more organized, with each mode tending to have its energy concentrated around one frequency. The present results suggest that it is possible to induce flutter at a fixed Mach number by increasing the angle of attack; thus, we conclude that the wing at the higher angle of attack is closer to flutter than the one at the lower angle of attack. As the flutter boundary is approached, the motion begins to organize, concentrating energy around a few frequencies.

As the wind speed increases at a constant angle of attack, the dimensionless frequency of the first torsion mode (the fourth mode) decreases considerably while that of the first bending mode (the first mode) increases very slightly, and the two frequencies merge at or near the onset of the instability. This merger, which is one of the principal characteristics of flutter, is captured by the current numerical simulation. Moreover, apparently, all initial conditions produce the same motion after a long period. These results strongly suggest that there is a limit cycle. The structural model does not include any nonlinearity; therefore, in these simulations the nonlinearities of the aerodynamic model are responsible for the limit cycles.

As a final remark we observe that the present simulation is very promising because the solution is calculated in the time domain by numerically integrating all the equations simultaneously and interactively. This approach has advantages over the classical methods because it can predict subcritical, critical, and supercritical aeroelastic behavior. The approach is ideally suited to handle nonlinear aerodynamic and structural models as well as nonlinear control systems. It realistically predicts the merger of frequencies near the onset of flutter and the existence of limit-cycle oscillations, which have been observed in many experiments.

6.2 Future Work

The aerodynamic model used in this work is restricted to incompressible flows and, hence, one very significant improvement in the present simulation would be to replace this aerodynamic model with one that can accurately capture the effects of compressibility. The present method cannot model the flowfield when massive stall occurs; hence another significant improvement would be to replace the current model with one that includes viscous effects, which are essential for modelling separation. For two dimensional flows the random-walk method is very appealing. Changing the aerodynamic model is straightforward because of the modular structure of the program.

A significant improvement would be to consider the flexibility of the roadbed in the model of the bridge. There is a need to investigate the effects of changing the placement of the wing(s), the use of other control schemes such as those based on concepts from neural networks, the influence of perturbations (turbulence) in the wind speed and direction, and the effect of a delay in the response of the wing to a command.

The present simulation can be used almost as is for future work in the following topics:

- Gust response.
- Flutter suppression.
- Aileron flutter.
- Tail and pylon flutter.
- Unsteady ground effects.
- Static aeroelasticity (e.g., aileron reversal and divergence).
- Inclusion of the elasticity of the fuselage, tail assembly, and pylon.
- Incorporation of improved structural models of the wing that can simulate large (nonlinear) deflections and rotations as well as material nonlinearities.
- Incorporation of smart structures to suppress flutter and reduce gust responses.
- Inclusion of stores.