10.
Conclusions and propositions for future work

10.1. Conclusions

The modeling and control law design of the aerodynamic control of long-span bridge flutter by control surfaces in the form of winglets positioned below the bridge deck has been studied. A time domain model of unsteady aerodynamic forces acting on the deck has been obtained through rational functions, according to the “minimum state” technique proposed by Karpel [25]. The minimum state approximation is used by Karpel to construct state-space aeroelastic control equations with flight-condition dependent coefficients. The same approach was used in this thesis, by writing the equation of motion of the entire aeroservoelastic system consisting of the bridge deck and the control surfaces subjected to wind forces in the state space form.

Accuracy of the rational functions approximation is obtained in part by a least-squares optimization technique. The lag terms which permit an approximation of the time delays inherent in unsteady aerodynamics were found via a nonlinear non-gradient optimizer proposed by Nelder & Mead [47]. The rational functions serving as an approximation of the unsteady aerodynamic forces were obtained by means of a FORTRAN program written by Masukawa [43], and used throughout this thesis. Although the equation of motion is augmented by new aerodynamic states, the flutter problem can be reduced to a linear frequency-independent state-space form. The representation of the equation of motion in a state-space form allowed the shaping of the closed-loop dynamics of the system through conventional (see Chapter 6) and variable (see Chapter 7) techniques of output feedback control.

The optimal control of linear time-invariant systems by a conventional-gain output control with respect to a quadratic performance criterion has been presented in Chapter 6, and was based mainly on an article written by Levine & Athans [41] and applied to the present problem by Wilde & Fugino [98]. The optimal control problem was posed with the additional constraint that the control vector $\mathbf{u}(\mathrm{t})$ representing rotations applied to the winglets is a time-invariant function of the output vector $\mathbf{y}(\mathrm{t})$ representing variables that can be measured in situ, being available for feedback, i.e., $\mathbf{u}(\mathrm{t}) = -\mathbf{K}\,\mathbf{y}(\mathrm{t})$, rather than a function of the state vector $\mathbf{x}(\mathrm{t})$. The performance criterion is then averaged, and algebraic necessary conditions for a minimized $\mathbf{K}^*$ are determined. The feedback gain matrix is obtained in an iterative way through the solution of Lyapunov and Silvester algebraic equations, which are different forms of Riccati equations. Conventional (static) optimal output gain control provides a suitable control design for the suppression of flutter when the control gains are determined for high mean wind velocity. However, since the system dynamic properties vary considerably with mean wind velocity, this control law cannot be as effective as a variable-gain output feedback procedure over a wide range of wind velocities.

The flexibility of shaping closed-loop dynamics for different wind velocities has been obtained in Chapter 7, by application of a variable-gain output feedback procedure proposed by Halyo et. al. [17] and implemented by Wilde & Fugino [98]. This is an extension of the conventional optimal output gain control procedure and is basically a gain-scheduling method. The derivation of the necessary conditions for the minimization of the overall quadratic performance criterion has been set in a firm mathematical formulation, as shown in Chapter 7. The variable-gain design for aerodynamic control of deck flutter offers the possibility of varied control strategies at different wind velocities.

At wind speeds below the flutter velocity, the stabilizing aerodynamic forces are commanded to add aerodynamic damping to the structural modes of the bridge, while for high wind ranges a significant amount of aerodynamic stiffness is produced in order to drive the natural frequencies of pitching and heaving modes away from each other to prevent coupling, a phenomenom characteristic of classical two degrees of freedom flutter. The variable-gain control results in a procedure that is optimal in the average sense over a wind range specified a priori. The inconvenience of the variable-gain approach is that it lacks a systematic way for the selection of the weighting functions. The selection of the weighting functions are decided by trial and error computations and the designer cannot be sure whether the obtained gains are the most efficient ones or not. The present author has introduced a procedure which shows, step by step, a sure way to obtain the matrix $\mathbf{K}_0 = [\ [\mathbf{KI}]\ [\mathbf{K0}]\ ]$ of variable gains, which is a function of the weights fixed previously. The procedure makes the matrices $\mathbf{P}$ and $\mathbf{L}$ [see equations (7.38) and (7.39)] for the operating points positive definite, thus avoiding the process of trial and error of choosing an initial $\mathbf{K}_0$ from which the final $\mathbf{K}_0$ evolves.

The objectives of this thesis, outlined in the first chapter, were met, and the practical results were presented along Chapters 6 to 8.

Numerical simulations have shown that the aerodynamic control of flutter by active surfaces can stabilize a long bridge for any desired wind velocity, either by conventional (Chapter 6) or variable-gain (Chapter 7) output feedback control procedures.

It was shown that, as a general rule, the winglets rotate in opposite directions and different amplitudes to stabilize the deck against flutter.

The great advantage of this technique in comparison to structural suppression methods is the source of the stabilizing forces, as already remarked by Ostenfeld and Larsen [53]. In aerodynamic control the vibration of the bridge excited by wind is suppressed by the stabilizing forces also generated by wind flow. The control forces are not produced by mechanical devices, but induced by rotation of the control surfaces. On the other hand, the magnitude of the control aerodynamic forces change at the same rate as the external wind forces.

However, the implementation of the method is relatively complex, requiring two or three parallel control systems to safeguard reliability, since the failure of the controller may result in the collapse of the bridge.

10.2. Propositons for future work

10.2.1. Adaptive Controller

The natural continuation of the present thesis would be the design of an adaptive controller. The general idea behind Model Reference Adaptive Control (MRAC, also know as MRAS or Model Reference Adaptive System) is to create a closed loop controller with parameters that can be updated to change the response of the system. The output of the system is compared to a desired response from a reference model. The control parameters are updated based on this error. The goal is for the parameters to converge to ideal values that cause the plant response to match the response of the reference model.

Using MRAC, it would be possible to choose a reference model that would respond quickly to a step input with a short settling time. In the present thesis, a controller would be built that would adapt itself to rotate the winglets like the model.

This involves modifying the control law used by a controller to cope with the fact that the parameters of the system being controlled are slowly time-varying or uncertain.

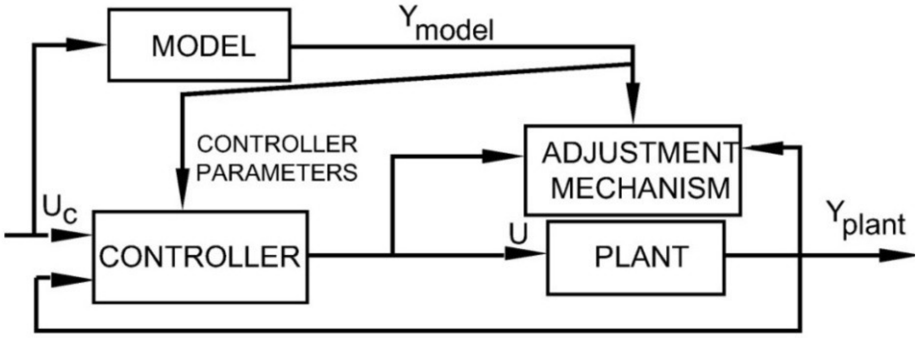

Figure 10-1- Model Reference Adaptive Control (MRAC)

Adaptive control is different from robust control in the sense that it does not need a priori information about the bounds on these uncertain or time-varying parameters. Robust control guarantees that if the changes are within given bounds the control law needs not be changed, while adaptive control is precisely concerned with control law changes.

10.2.2. Effects of turbulence and aerodynamic nonlinearities

The linear model presented in this thesis is not suited for capturing the emerging concerns in bridge aerodynamics introduced by aerodynamic nonlinearities and turbulence effects. These issues may become critical for bridges with aerodynamic characteristics sensitive to the effective angle of incidence.

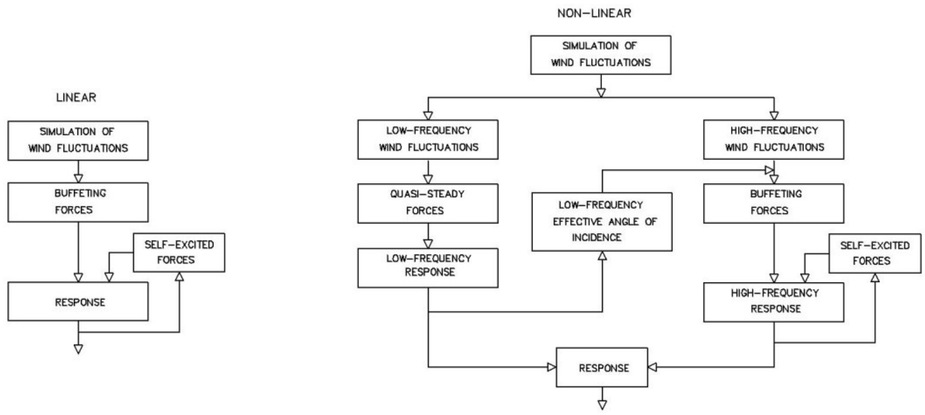

Figure 10-2 – Linear and proposed nonlinear analysis framework

Chen & Kareem [6] present a nonlinear aerodynamic force model and associated time domain analysis framework for predicting the aeroelastic response of bridges under turbulent winds.

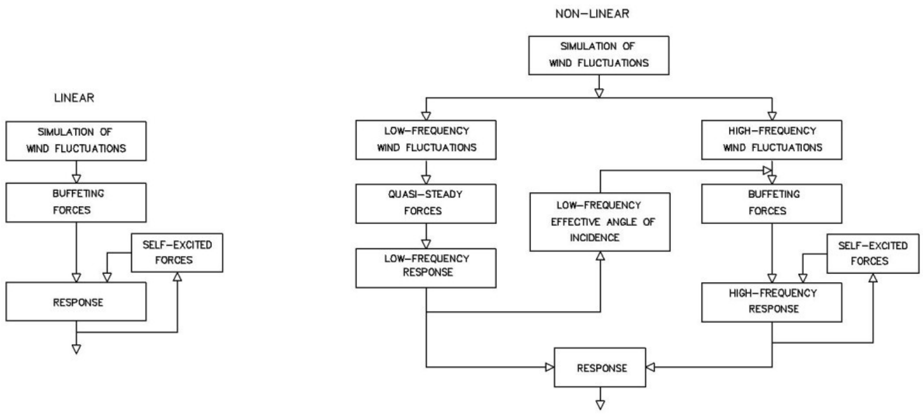

Figure 10-2 shows a comparison of models for linear and nonlinear analysis of instability phenomena related to wind effects in long span bridges.

The influence of mean wind angle of incidence on the aeroelastic modal properties and the associated aeroelastic response, as well as the sensitivity of bridge response to nonlinear aerodynamicas and low-frequency turbulence may be examined in future research along these lines.