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Vortex induced vibration control for long span bridge nonlinear systems

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Abstract

Vortex induced vibration control for long span bridge is studied. A nonlinear, coupling and uncertain dynamic model of the long span bridge is considered. Because it is difficult to design the controller for the long span bridge vibration control system, the nonlinear and coupling uncertain control system is simplified, and a linear model is obtained. Then, based on sliding mode control approach, an optimal controller is designed for the long span bridge. Numerical simulations illustrate the effectiveness of the proposed controller.

Keywords: vortex, vibration control, nonlinear systems

1. Introduction

Vortex induced vibration is a typical flow-structure interference phenomenon which causes an unsteady flow pattern due to vortex shedding at or near the structure's natural frequency leading to resonant vibrations [1, 2, 3]. Vortex Induced Vibration is an important issue in the aerodynamic performance of long span bridges, and is typically connected to premature fatigue damage and to the serviceability of a bridge.

The analysis of the existing wind environment in the bridge is based on the theory of the near ground boundary layer [4, 5, 6]. The existing standard span bridge or other small span bridge, because of its strong stiffness and overall stability, the wind is basically stable when the wind is blown over, and the effect of wind on the structure is only the form of static wind pressure [7, 8, 9]. The bridge stiffness and overall stability are relatively low as the bridge continues to develop in the large and flexible direction. At this time, the stability of a bridge not only depends on the static wind stability and the seismic analysis, and the wind resistance checking and analysis is particularly important. In addition, the choice of bridge location for large span bridges is mostly difficult to cross large rivers, deep mountains, lakes and sea areas, and strong wind environment requires high wind resistance for bridges [10].

The theoretical mechanism of Vortex-induced Vibration is much more complicated than other types of wind induced vibration, and the difficulty of research and analysis is also larger than that of other types. Vortex induced vibration includes two attributes: self-excited vibration and limiting amplitude forced vibration [11, 12]. The flow of air flow is separated from the non-streamlined structure, so the vortex is generated on both sides of the bridge structure, and the structure is dissymmetrical. The different air flow types and velocity will make the surface air pressure on both sides of the structure disagree, and the overall aerodynamic force can be regarded as the transverse wind force exerted on the bridge structure. That is the vortex induced force, vortex induced force will stimulate the crosswind vibration structure etc. During vortex induced vibration, vortex induced resonance of bridge structure will occur when the frequency of vortex shedding step by step to a certain modal frequency of bridge structure. Vortex induced vibration often occurs at a relatively low speed, especially for large span and lightweight bridge structures.

2. Dynamical system

The vortex induced force models include simple harmonic force model, lift oscillator model, empirical linear model, empirical nonlinear model and generalized empirical nonlinear model. Compared with other models, the empirical nonlinear model not only reflects the nonlinear properties of the vortex induced force, but also explains the limiting and self-excitation characteristics of the vortex excited vibration. In 1986, Scanlan and so on established an empirical nonlinear model to describe the vortex - induced force, and then further deepened and perfected the empirical nonlinear model. For the empirical nonlinear model, the concept of the Van der Pol oscillator is applied to the nonlinear aerodynamic self-excitation by introducing a three order term.

$$m(\ddot{y}+2\xi\omega_0\dot{y}+\omega_0^2 y)=\frac{1}{2}\rho U^2 D\left[Y_1(1-\varepsilon\frac{y^2}{D^2})\frac{\dot{y}}{U}+Y_2\frac{y}{D}+C_L\sin(\omega t+\varphi)\right], \quad (1)$$

in which, m is the structure quality; ξ is the damping ratio; ω_0 is the vertical bending vibration frequency of the structure; ρ is the air density; U is the wind velocity; D is the structure transverse wind dimension; y is the vertical response of the vortex excited vibration; the coefficient Y_1, Y_2, C_L, and ε epsilon are undetermined parameters, which need to be fitted to the observed values.

In 2004, Ge and Li established a new two-dimensional vortex excited vibration model by introducing the concept of vortex moving velocity, which explained the law of vibration change in the range of frequency locking:

$$m(\ddot{y}+2\xi_b\omega_b\dot{y}+\omega_b^2 y)=\frac{1}{2}\rho U^2 BC_{vb}\sin(\sqrt{\omega_s\omega_m}\ t), \tag{2}$$

in which, m is the mass of the main beam of a unit length; y is a vertical displacement; ξ_b is a vertical bending damping ratio; ω_b is a vertical bending frequency; C_{vb} is a vertical bending vortex excitation parameter; ω_s and ω_m are respectively the frequency of vortex shedding circle frequency and swirling circle frequency.

3. Vibration control and simulation

The system (2) is rewritten in the state-space representation:

$$\dot{\boldsymbol{x}}(t)=\boldsymbol{Ax}(t)+\boldsymbol{Bu}(t), \tag{3}$$

The approach of control is adopted as following

$$\begin{aligned} s &= Cx, \\ \dot{s} &= C\dot{x}=\text{slaw}, \end{aligned} \tag{4}$$

in which, slaw is reaching law.
And the control law is as following:

$$u=(CB)^{-1}(CAx+s), \tag{5}$$

Then We design the Matlab program to simulate the control effect. Vortex induced vibration control for long span bridge nonlinear systems is carried out by Matlab program design platform, which includes two m-files: main program. m and subprogram. m. The main program is as following:

```
clear all;
close all;
global M A B C eq k para
ts=0.001;
T=3.5;
TimeSet= [0: ts:T];
c=15;
C=[c, 1];
para=[c];
[t,x]=ode45 ('sub’,TimeSet,[0.5 0.5],[],para);
x1=x(:,1);
x2=x(:,2);
s=c*x (:, 1)+x(:,2);
if M==2
  for kk=1:1:T/ts+1
    xk=[x1(kk);x2(kk)];
    ski(kk)=c*x1(kk)+x2(kk);
    slaw(kk) =-eq*sign (sk(kaki))-k*sk(kaki);
    u (kk)=inv(C*B)*(-C*A*xk+slaw(kk));
  end
end
figure (1);
plot(t,x(:,1),'k');
xlabel('time(s)');
ylabel('x1');
figure(2);
plot(t,x(:,2),'k');
xlabel ('time(s)');
ylabel ('x2');
if M==2
  figure(3);
  plot(t,u,'k');
  xlabel('time(s)');
  ylabel ('u');
end
```

Subprogram is as following:

```
function dx=Dynamic Model (t, x, flag,para)
global M A B C eq k
a=25;
b=133;
c=para (1);
s=c*x (1) +x (2);
A= [0 1; 0 -a];
B= [0; b];
M=2;
Eq=5;
if M==1
  rin=1.0;
  slaw=-eq*sign(s);
elseif M==2
  k=10;
  slaw=-eq*sign(s)-k*s;
elseif M==3
  k=10;
  alfa=0.5;
  slaw=-k*abs(s) ^Alfa*sign(s);
elseif M==4
  k=1;
  slaw=-eq*sign(s)-k*s^3;
end
u=in(C*B)*(-C*A*slaw);
dx =zeros (2, 1);
dx(1) =x(2);
dx(2) =-a*x(2)+b*u;
```

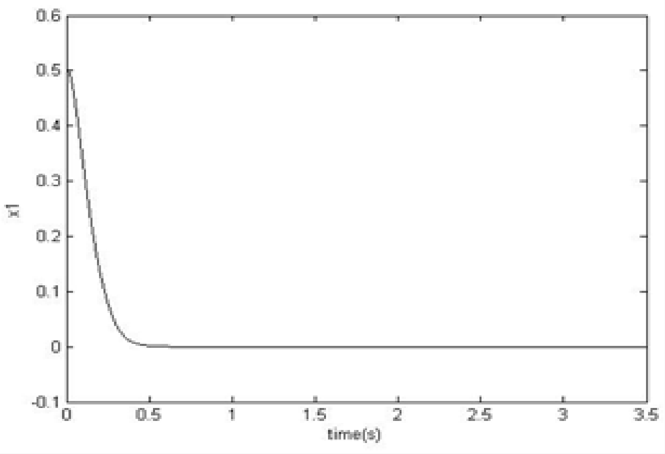

Fig 1: Curve of x_1.

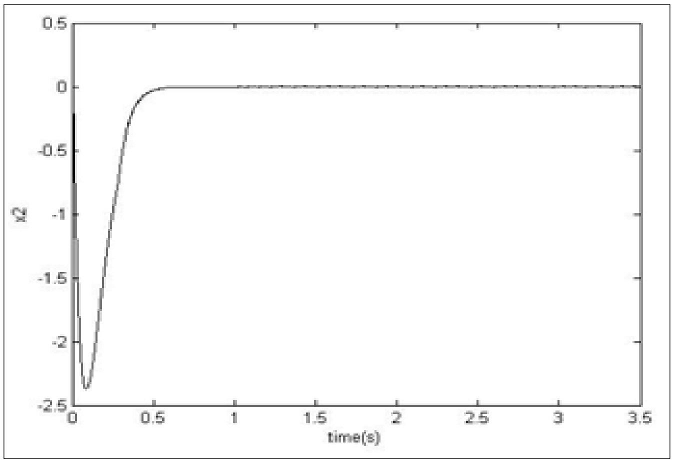

Fig 2: Curve of x_2.

The velocity and direction of the wind and the spatial distribution of the wind will be influenced by the turbulence of the near boundary layer, which makes them exhibit very strong non-constancy and randomness, and the results of them are shown in fig 1. and fig.2.

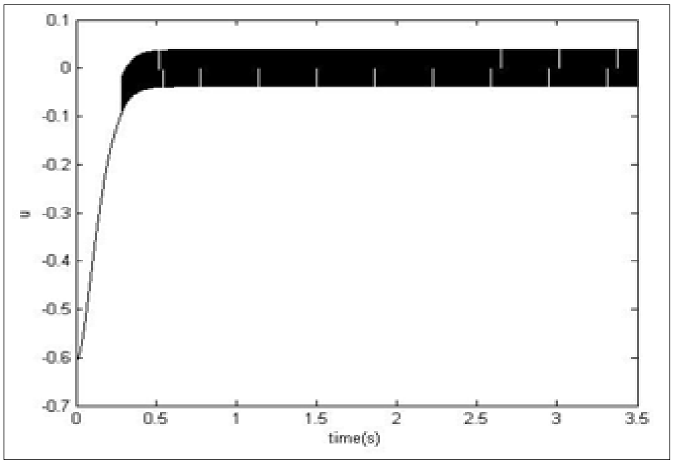

Fig 3: Curve of *u*.

The main section of the bridge is a blunt body, so the natural wind and the vortex will be separated when the natural wind is wrapped with pulsating wind, which makes the bridge section bear complex forces, and the control force is shown in fig3.

4. Conclusions

When the wind passes through the bridge section, it will stimulate the vibration of the bridge. The small vibration and deformation of the bridge in turn affect the wind environment around the bridge section, making the wind change the force of the bridge section continuously, which makes the bridge complicated and wind-induced vibration, so that the wind and the bridge structure are formed again and again. The complex interaction mechanism has also produced complex wind resistant problems.

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