π형 단면을 가지는 교량 거더의 플루터 해석

Flutter Analysis of Bridge Girder with π-Shaped Section

조영래* · 조재영** · 노남균*** · 이학은****

Cho Young Rae · Cho, Jae Young · Roh, Nam Kyun · Lee, Hak Eun

Abstract

교량의 플러터 발생풍속을 예측할 경우에는 주로 주형의 2차원 단면실험을 통하여 추정하고, 전체교량의 3차원 모형실험을 통하여 확인하게 된다. 주형단면의 2차원 단면모형 실험에서는 교량거더의 수직방향과 비틀림 방향의 2 자유도계로 간략화하여 구조물의 거동을 살펴보게 된다. 전산풍공학적 방법에 의하여 구조물의 공기력을 산정하는 방법은 기존에 주로 사용되던 풍동실험을 대치하는 방법으로 개발되고 있으며, 교량의 플러터 발생풍속 예측을 위한 산정기법 역시 다양하다. 본 논문에서는 유사한 형상비를 가지는 π형 단면 거더의 플러터 발생풍속을 비교하였으며, 교량단면의 2차원 단면실험을 통하여 그 결과값을 비교, 검토하였다.

key words : Aerodynamic stability, Complexeigen value, π-Shaped Section

1. INTRODUCTION

It has been reconized that wind responses of long-span bridges mainly include buffeting response du e to wind turbulence and self-excited vibrations, such as flutter, vortex shedding and galloping. The aerodynamic stability of bridge decks is established by carrying out numerous wind tunnel tests using spring-mounted sectional models that reproduce, at small scale, the relevant geometric and structural characteristics of the full scale bridge. Many experiments are required to determine the critical wind speed for the onset of instability, each with slightly different model characteristics, until an acceptable solution is found. The analytical approach has predominantly been conducted in the frequency domain[1].The flutter analysis is generally conducted by complex eigenvalue analysis[2],whereas the buffeting response is typically estimated using a mode-by-mode approach[7,8] that ignores the aerodynamic coupling among modes. More recently, an efficient scheme for coupled multi-mode flutter analysis has been proposed by introducing the unsteady self-excited aerodynamic forces in terms of rational function approximations[3]. For predict the flutter velocities of structures without wind tunnel test, Jeong[4] develop the methodology using computational fluid dynamics.

In this paper, a state-space approach for predicting the flutter response utilizing frequency dependent unsteady aerodynamic forces is presented and buffeting responses of bridge deck with π-shaped section are analyzed using buffeting response spectrum mehtod. The results are compared with the Scanlan's method and the wind tunnel tests.

2. THEORICAL APPROACH

The aerodynamic forces as shown in Fig. 3 are separated into their self-excited and buffeting components. The self-excited forces are caused by interaction between wind motion and the structure. Scanlan[1]

* 정회원 · 고려대학교 사회환경시스템공학과 박사과정 · 공학석사 · E-mail: shalom0728@korea.ac.kr - 발표자

** 정회원 · 고려대학교 사회환경시스템공학과 박사과정

*** 고려대학교 사회환경시스템공학과 석사과정

**** 정회원 · 고려대학교 사회환경시스템공학과 교수

mathematically described the self-excited forces on a bridge deck in terms of the so-called flutter derivatives. The equations of motion in terms of a generalized coordinate vectors $\mathbf{q}$ for a bridge structural system under wind loads can be expressed as

$$\mathbf{M}_s\ddot{\mathbf{q}}(t)+\mathbf{C}_s\dot{\mathbf{q}}(t)+\mathbf{K}_s\mathbf{q}(t)=\mathbf{F}(t) \tag{1}$$

in which

$\mathbf{M_s}$, $\mathbf{C_s}$, $\mathbf{K_s}$ = the structural mass, damping, stiffness matrix, respectively $\mathbf{F(t)}$ = the total loading vector $(\mathbf{F_{se}}+\mathbf{F_b})$; $\mathbf{F_{se}(t)}$, $\mathbf{F_b(t)}$ = self-excited wind load, buffeting wind load, respectively.

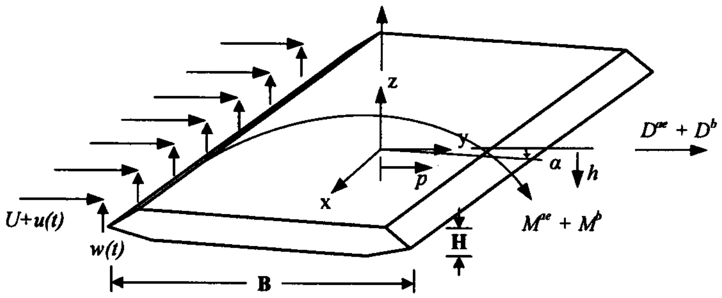


Fig.1. Aerodynamic forces on bridge deck

$\mathbf{D^{se}}$, $\mathbf{L^{se}}$, and $\mathbf{M^{se}}$ are the self-excited drag, lift, and torsional moment per unit span length, respectively in Fig.1. The second order equations can be transformed into first order equations using the state vector and the Eq.1 is expressed in the state-space format as[5,6]

$$\dot{\mathbf{Y}}=\frac{d}{dt}\begin{Bmatrix}\mathbf{q}\\ \dot{\mathbf{q}}\end{Bmatrix}=\begin{Bmatrix}\dot{\mathbf{q}}\\ -\mathbf{M}_s^{-1}\mathbf{C}_s\dot{\mathbf{q}}-\mathbf{M}_s^{-1}\mathbf{K}_s\mathbf{q}+\mathbf{M}_s^{-1}\mathbf{F}\end{Bmatrix}=\begin{Bmatrix}\mathbf{0} & \mathbf{I}\\ -\mathbf{M}_s^{-1}\mathbf{K}_g & -\mathbf{M}_s^{-1}\mathbf{C}_g\end{Bmatrix}\begin{Bmatrix}\mathbf{q}\\ \dot{\mathbf{q}}\end{Bmatrix}+\begin{Bmatrix}\mathbf{0}\\ \mathbf{M}_s^{-1}\mathbf{F}_b\end{Bmatrix}$$

$$\equiv\mathbf{AY}+\mathbf{BF_b} \tag{2}$$

The flutter wind speed is commonly determined by eigenvalue method in the frequency domain, i.e., by iteratively searching for a pair of $\mathbf{k}$ and $\boldsymbol{\omega}$ so that the determinant of the characteristic function of the equations of motion becomes zero. The flutter critical point can be identified by iteratively solving the complex eigenvalues in the state-space of Eq.2 at each wind velocity.

For the autonomous system, the equation of motion in state-space form, Eq.6, becomes

$$\dot{\mathbf{Y}}=\mathbf{AY} \tag{3}$$

Eq.3 can be solved for λ_i for the given system matrix $\mathbf{A}$. For an arbitary i-th, Eq. 3 can be expressed as

$$\lambda_i\begin{Bmatrix}\boldsymbol{\Phi}_i\\ \lambda_i\boldsymbol{\Phi}_i\end{Bmatrix}=\mathbf{A}\begin{Bmatrix}\boldsymbol{\Phi}_i\\ \lambda_i\boldsymbol{\Phi}_i\end{Bmatrix} \tag{4}$$

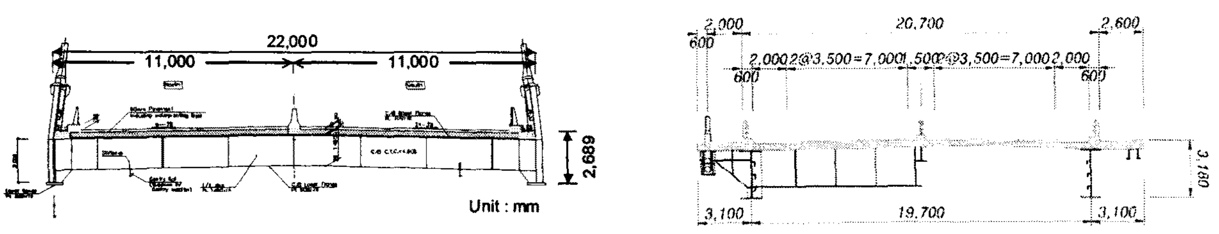
$$\lambda_i=-\xi_i\omega_i+j\omega_{Di}\ ;\ \omega_{Di}=\omega_i\sqrt{1-\xi_i^2}\ ;\ i = 1\text{-}3 \tag{5}$$

where ξ_i, ω_i= the damping ratio and frequency in i-th complex mode, respectively ; j = unit imaginary number ($j = \sqrt{-1}$).

At a given wind velocity, the eigenvalue λ_i and eigenvector ϕ_i can be determined by solving the complex eigenvalue problem. Once the eigenvalues are iteratively predicted, the oscillation frequency ω and reducer k are known at the given wind velocity and the damping and stiffness matrices $\mathbf{C_g}$ and $\mathbf{K_g}$ can then be computed. The flutter wind speed and corresponding flutter frequency can be identified from the eigenvalue solutions at the condition that the total modal damping approaches zero.

3. NNMERICAL EXAMPLE

To verify the accuracy and efficiency of the analytical approach, a simply supported beam with a span 230m was taken as an example and for simplicity and without loss of generality, only the aerodynamic forces acting on the bridge deck were considered. The cross-section of prototype bridge decks are shown in Fig.2. The aspec ratio of case are approximatly 8, respectively.



(a) case 1 **(b) case 2**

Fig.2. Cross-Section of Prototype Bridge Deck

The predicted effective oscillation frequencies and damping ratios of vertical and torsion modes versus wind velocity are shown in Fig.3 It can be seen that with the increase of wind velocity, vertical mode frequency increases gradually while at the same time torsion mode frequency decreases gradually. Correspondingly, the damping ratio of the vertical mode increases, while the damping ratio of the torsion mode remains about constant and decreases at higher wind velocity. Eventually, at the wind velocity of 85 m/s and 92m/s, respectively, the damping ratio of the torsion mode becomes zero.

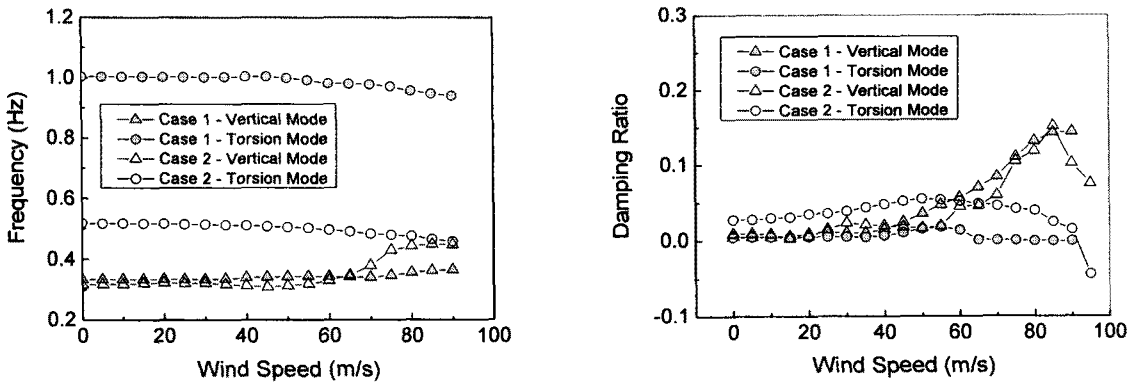


Fig.3. Modal Properties with complex eigenvalue method

This section presents illustrative examples to discuss the effects of damping ratio and to compare the complex eigenvalue approach between the wind tunnel test. The result of the dynamic section model wind tests in smooth flow are summarized in Table 1. From Table 1 one can see that when the damping ratio is increased, the flutter velocity is increase and complex eigenvalue approach agree well with Wind Tunnel Test. The Scanlan's method, on the other hands, is higher than 5%.

Table 2. Comparison of Prediction Mehtod

NO.		Damping Ratio	Presented	Scanlan's Method	Wind Tunnel Test
Case 1	1	0.3%	72 m/s	77 m/s	75 m/s
	2	0.5%	85 m/s	89m/s	84 m/s
	3	1.0%	104 m/s	108 m/s	>90m/s
Case 2		0.3%	92 m/s	95 m/s	>90m/s

4. CONCLUSIONS

Based on the method of the complex eigenvalue approach, numerical bridge flutter stability analyses is performed and compare with results of the wind tunnel test.

1. From a comparison of flutter stability analysis performed in complex eigenvalue method and Scanlan's iterative method(no interaction between the mode), the complex eigenvalue approach is proved to be valid and rational.

2. When the damping ratio is increased, the Flutter Velocity is increase and complex eigenvalue approach agree well with Wind Tunnel Test. The Scanlan's method, on the other hands, is higher than 5%.

3. For bridge girder with π-shaped section of flutter stability between case 1 and case 2, it is obvious that the flutter velocity is affected section geometry, in spite of simiar aspect ratio(b/d $\approx$8).

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