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Enhancing the buffeting response of the Messina Strait Bridge using a multi-unit gyroscopic stabilizer

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SUMMARY
Recent advances in long-span cable-supported bridges have enabled spans exceeding 1,000 m, with proposals targeting up to 5 km. However, current designs struggle to meet aerodynamic stability requirements beyond 2000 m under wind loading, despite various deck configuration solutions. This study investigates the use of multi-unit gyroscopic stabilizers to improve the buffeting response of the Messina Strait Bridge (1992 design). The generalized frequency-domain multi-mode approach is applied to assess the dynamic performance. The stabilizers, integrated within the deck cross-section, demonstrate a consistent positive effect across varying operational conditions. Results also show that improvements in buffeting response are directly linked to the angular velocity of the gyroscopic devices. Overall, findings highlight the potential of gyroscopic stabilization as an effective solution to enhance aerodynamic performance in next-generation ultra-long-span bridges.

Keywords: long-span bridges, buffeting response, gyroscopic stabilization

1. INTRODUCTION

Over the past few decades, the advancement of long-span cable-supported bridge design has progressed significantly. Notable examples include structures with main spans exceeding 1000 meters, such as the Çanakkale Bridge across the Dardanelles Strait, the Stonecutters Bridge in Hong Kong, the Yi Sun-Shin Bridge in South Korea, and the Xihoumen Suspension Bridge in China. Recent design proposals are investigating the feasibility of achieving main span lengths of up to 5 kilometers or more. Current engineering approaches incorporate a variety of cross-sectional configurations, including single-box sections, lattice truss sections, narrow slotted two-box sections and wide slotted two-box sections. Despite these technological advancements, bridge designs may still be insufficient to satisfy the minimum aerodynamic criteria for spans exceeding 2000 meters under wind loading. In the present paper, gyroscopic devices are employed to improve the buffeting response of Messina Strait Bridge (Diana et al., 1995). The generalized frequency-domain multi-mode approach is used to evaluate the buffeting bridge response. Several stabilizing devices are positioned within the internal space of the deck multi-box cross-section (Giaccu and Caracoglia, 2021, 2025). Specifically, the effectiveness of a multi-unit gyroscopic stabilizer is measured as to enhance the dynamic bridge deck performance against buffeting. This confirmed the positive influence of the gyroscopic stabilizer by varying the gyricity. Several operational regimes are systematically analyzed. The positive enhancement is directly dependent on the angular velocity of the gyroscope. Lateral dynamics and drag loads are neglected in this pilot study.

2. BACKGROUND: AERODYNAMICS OF LONG SPAN BRIDGES

The multi-mode analysis method (Scanlan and Jones, 1990; Jain et al., 1998) is briefly summarized below. The bridge deck dynamics is expressed by modal decomposition (vertical and torsional):

$$h(x,t)=\sum_i h_i(x)B\xi_i(t), \qquad \vartheta(x,t)=\sum_i \vartheta_i(x)\xi_i(t) \tag{1}$$

The dynamic behavior of the deck is governed by three equations of motion that include generalized inertia, natural frequency, damping ratio, modal forces and gyroscopic effect Ω (giricity). Loads per unit span (lift and moment) are separated into aeroelastic and buffeting:

$$\begin{gathered} m_v\ddot{h}+c_v\dot{h}+k_v h=L_{ae}(x,t)+L_b(x,t) \\ \left[J_\vartheta+J_\alpha\sum_{j=1}^{2}\delta\left(x-x_{\Omega,j}\right)\right]\ddot{\vartheta}+c_\theta\dot{\vartheta}+k_\theta\vartheta=M_{ae}(x,t)+M_b(x,t)-\Omega\sum_{j=1}^{2}\delta\left(x-x_{\Omega,j}\right)\left(\dot{\alpha}_j\right) \\ J_\alpha\left(\ddot{\alpha}_j\right)+c_\alpha\dot{\alpha}_j+k_\alpha\alpha_j=\Omega\dot{\vartheta}\left(x_{\Omega,j},t\right)\quad j=1,2 \end{gathered} \tag{2}$$

Mean wind direction is orthogonal to the deck. Aeroelasticity is described by Scanlan derivatives:

$$L_{ae}(x,t)=0.5\rho U^2B[KH_1^*\dot{h}(x,t)/U+KH_2^*\dot{\vartheta}(x,t)/U+K^2H_3^*\vartheta(x,t)+K^2H_4^*h(x,t)/U] \tag{3}$$

$$M_{ae}(x,t)=0.5\rho U^2B^2[KA_1^*\dot{h}\ (x,t)/U+KA_2^*\dot{\vartheta}(x,t)/U+K^2A_3^*\vartheta(x,t)+K^2A_4^*h(x,t)/U] \tag{4}$$

Buffeting forces below are generated by turbulent wind fluctuations and are described by quasi-steady aerodynamic coefficients and gust velocity components (*u* lateral, *w* vertical).

$$L_b(x,t)=\frac{\rho U^2B}{2}\left[C_L\left(2\frac{u}{U}\right)+(C_L^{'}+C_D)\frac{u}{U}\right],\quad M_b(x,t)=\frac{\rho U^2B^2}{2}\left[C_M\left(2\frac{u}{U}\right)+(C_M^{'})\frac{w}{U}\right] \tag{5,6}$$

The generalized modal force of deck mode *i* is obtained by integrating lift ($L=L_{ae}+L_b$) and moment ($M=M_{ae}+M_b$) along the span length. If spanwise-uniform Scanlan derivatives are used, this is.

$$Q_i(t)=\int_0^l\left(Lh_iB+M\alpha_i\right)dx \tag{7}$$

3. MULTI-MODE FORMULATION

The multi-mode buffeting analysis uses experimentally obtained flutter derivatives and aerodynamic coefficients of the investigated deck section. The structural response is evaluated through power spectral density functions, allowing computation of displacement statistics and covariance matrices for vertical and torsional deck motions. If the flutter derivatives have no variation along the spanwise sectional coordinate, the multi-mode approach is used to find the modal dynamic equations (with h_i and ϑ_i dimensionless deck mode shape functions of mode i):

$$[\mathbf{E}]\bar{\boldsymbol{\xi}}=\bar{\mathbf{Q}}_{\mathbf{b}} \tag{8}$$

The previous equation is in the $K=\tilde{\omega}B/U$ frequency domain (with $\tilde{\omega}$ generic angular frequency); **E** is the matrix of the dynamic and aeroelastic system, which includes the effects of the gyroscopic devices; $\overline{\mathbf{Q}}_b$ (Fourier transform) is the random vector of generalized buffeting forces from Eqs. (5,6); the generalized coordinate vector is $\overline{\boldsymbol{\xi}}$ (Fourier transform). The previous equation is converted to power spectral density matrix equation (Scanlan and Jones, 1990) that enables to derive cross-power spectral response densities. For example, the cross-power spectral density of vertical deck displacement at sections x_A and x_B is

$$S_{hh}(x_A, x_B, K) = \sum_i \sum_j B^2 h_i(x_A) h_j(x_B) S_{\xi_i \xi_j}(K) \tag{9}$$

Here, i and j are summation indices corresponding to the number of modes considered. The mean-square values of the vertical deck displacements and rotations (variances and co-variances) are:

$$\sigma^2_{hh}(x_A, x_B) = \int_0^\infty S_{hh}(x_A, x_B, K)\,\mathrm{d}K, \qquad \sigma^2_{\vartheta\vartheta}(x_A, x_B) = \int_0^\infty S_{\vartheta\vartheta}(x_A, x_B, K)\,\mathrm{d}K \tag{10}$$

4. MESSINA STRAIT BRIDGE WITH TWO GYROSCOPIC UNITS: PILOT STUDY

The multi-mode buffeting model, equipped with gyroscopic device, is applied to the Messina Strait Bridge with main span length equal to $l = 3300$ m. Two gyroscopic unit stabilizers are installed at deck sections $x_\Omega = l/4$ and $x_\Omega = 3/4l$ on the main deck with variable gyricity Ω – Table 2. The bridge geometry and aerodynamic properties are taken from Diana et al. (1995) and Zasso (1996); they include Scanlan derivatives H_i^* and A_i^* $(i = 1, \dots, 4)$. The structural model (Table 1) is derived from Sepe et al. (2000).

Table 1. Main structural, modal properties of the Messina Bridge deck structural model (from Sepe et al., 2000)

Deck mode i	Frequency [Hz]	Damping ratio ζ_i [%]	Mass/inertia per unit deck length	Generalized mass/inertia of the moving deck and cables
1st vertical ("v1")	0.0615	0.3	54900 [kg/m]	8.86×10^7 [kg]
1st torsional ("t1")	0.0804	0.3	28346000 [kgm]	4.63×10^{10} [kgm^2]

Table 2. Basic properties of each gyroscopic unit, installed at deck cross sections $x_\Omega = l/4$ and $x_\Omega = 3/4l$.

D_Ω [m]	C_Ω [m]	n_Ω [-]	M_Ω [kg]	$J_{\Omega,p}$ [kg×m^2]	$J_{\Omega,11} = J_{\Omega,22}$ [kg×m^2]	k_α [N×m]	c_α [N×m×s]	ζ_α [%]	ω_α [rad/s]	$\mu_{M\Omega}$ [%]	$\mu_{J\Omega}$ [%]
2	0.5	4	1.23×10^4	6.16×10^3	3.08×10^3	192.52	192.52	5	0.25	5.56×10^{-4}	5.32×10^{-7}

The multi-mode analysis employs experimentally obtained Scanlan derivatives (Diana et al, 1995). In this preliminary application (Table 1), the multi-mode analysis is restricted to the first vertical and first torsional deck modes [$i = 1{,}2$ and $j = 1{,}2$ in Eq. (9)]. Representative Scanlan derivatives for the deck cross-section, corresponding to small initial attack angles 0°, are used (Zasso, 1996). The chord-wise admittance function is approximated by Sears function (e.g., Jancauskas and Melbourne, 1986). Buffeting calculations have considered typical sea turbulence exposure at the deck height of 67 m. The modal damping ratios of the two modes is 0.3%.

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5. DISCUSSION AND CONCLUSIONS

Several buffeting analyses are performed, assuming the mean wind speed U orthogonal to the bridge deck between 50 m/s and 70 m/s, below the critical flutter speed for this bridge model (e.g., Sepe et al., 2000). Examples of standard deviations of dynamic vertical displacements and torsional rotations, σ_{hh} and $\sigma_{\vartheta\vartheta}$, are illustrated in Fig. 1; a reduction in buffeting response with increasing gyricity Ω, can be noticed. Although the absolute value predictions may differ from literature results (Diana et al., 1995), the relevance of the calculations must be interpreted in relative terms, before ($\Omega = 0$) and after ($\Omega > 0$) installing the gyroscopic devices.

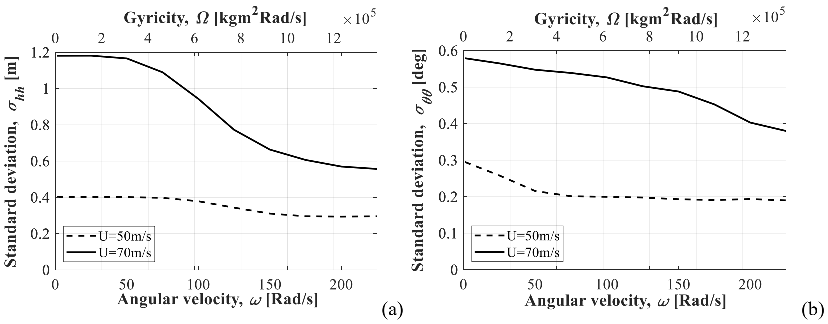

Figure 1. Dynamic buffeting response of the Messina strait bridge at mean wind speed $U = 50, 70$ m/s and cross section $x_\Omega = l/4$ in terms of standard deviations of: (a) σ_{hh} vertical displacement, (b) angular rotations $\sigma_{\vartheta\vartheta}$.

A notable reduction of 50% and 30% respectively for σ_{hh} and $\sigma_{\vartheta\vartheta}$ can be observed for a reference mean velocity U=70m/s. The beneficial effects of the gyroscopic devices increase with the increment of gyroscope's angular velocity ω or giricity Ω. Additional examples and supplementary numerical results will be included in the final presentation.

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