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Unsteady Galloping of Bridge Decks during the Launching Phase

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UNSTEADY GALLOPING OF BRIDGE DECKS DURING THE LAUNCHING PHASE

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*) Either the German or the Italian form of the title may be used.

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To my dear grandpa, Guangzhi Chen

“carving words into stone”
Death’s End (The Three-Body Problem III), by Cixin Liu

Preface

This doctoral thesis was written during the last period of my stay at the Institute of Steel Structures, TU-Braunschweig. I was financially supported by the China Scholarship Council to carry out a doctoral study in Germany. My research began with the fatigue problem of steel structures, but wind engineering gradually attracts me more and I finally decided to work in this area.

Prof. Klaus Thiele, my supervisor, deserves my first and most gratitude, continuously supporting me and this research from every aspect. Moreover, under his supervision, I was given the most freedom to pursue my research interests. I also want to thank Prof. Mathias Clobes, for introducing this research topic to me and continuously encouraging me to carry on with it.

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Braunschweig, July 2021 Cong Chen

Abstract

The present work deals with the unsteady galloping instability, which arises at low reduced flow velocities, for steel-concrete composite bridge decks during the incremental launching phase. In this particular situation, the light weight and bluff shape of the steel box, which is normally first launched, imply a high proneness to the risk of unsteady galloping. The main goal of this thesis is to understand the unsteady galloping with respect to these special cross sections, which have not been investigated in depth before, and to develop an analytical approach for the modeling of unsteady galloping as a basis for design of bridges.

Wind tunnel tests on three sectional models, among which are a generic bridge deck model with typical open cross section and two reference cylinder models, confirmed the high proneness to unsteady galloping instability for the particular situation of bridge launching. Especially, the typical unsteady galloping which arises due to the interaction with Kármán-vortex induced vibration was observed at the 4° mean flow incidence of the bridge deck model, fixing the galloping onset at the Kármán-vortex resonance wind speed up to a quite high Scruton number (the mass-damping parameter). Moreover, the sensitivity of unsteady galloping behaviors to mean flow incidence was highlighted. At the null mean flow incidence of the bridge deck model, the unsteady galloping was initiated in less understandable manner, being the onset velocity clearly higher than the Kármán-vortex resonance one even for a very low Scruton number.

Subsequently, mathematically modeling the unsteady galloping was carried out, with a modified form of Taumra's nonlinear wake oscillator model. Satisfying predictions have been achieved not only for a 2:1 rectangular cylinder, but also for the bridge deck model at its 4° mean flow incidence. In particular, the typical unsteady galloping behavior, that lower than a certain value of Scruton number galloping arises at the Kármán-vortex resonance wind speed, is well captured by the wake oscillator model. Attention was also paid to the so-called physical considerations in the wake oscillator model. Further modifications for the wake oscillator model were consequentially proposed, exhibiting better agreements with the physics of the near-wake of sharp-edged bluff body, maintaining at the same time a good capability for the predictions of unsteady galloping behaviors.

Finally, the wake oscillator model was further extended for continuous structural system, based on coupling multiple wake oscillators to the structural system via finite element method.

A case study, concerning a steel-concrete composite bridge during the critical launching phase, was presented. In particular, by taking into account the aerodynamic contributions of a lattice launching nose, the potentiality of efficiently suppressing the galloping instability through aerodynamic optimization for the launching nose was revealed in the case study. This has promoted consequent wind tunnel tests on the further optimized launching nose, which combined with numerical predictions from the wake oscillator model further confirmed the aforementioned potentiality.

Contents

Notations

Symbols for matrix and vector are extra indicated with bold font

Greek Variables

α .... wind angle of attack or torsional degree of freedom

α_0 .... mean wind angle of attack (for oscillation body)

β, λ .... coefficients in Tamura's nonlinear wake oscillator model

$\boldsymbol{\phi}_i$ .... mode shape vector for structure

$\boldsymbol{\Phi}, \boldsymbol{\Phi}_e$ .... mode shape matrix for structure, and the expanded one

$\boldsymbol{\psi}_s, \boldsymbol{\psi}_{sr}$ ..... displacement vector for a structural system, and its reduced form due to boundary conditions

$\boldsymbol{\psi}_t, \boldsymbol{\psi}_{tr}$ ...... displacement vector for combined system of structure and wake oscillators, and its reduced form due to boundary conditions

$\boldsymbol{\psi}_{tn}$ .... the normalized forms of $\boldsymbol{\psi}_{tr}$, by expanded mode shape matrix $\boldsymbol{\Phi}_e$

$\boldsymbol{\vartheta}, \boldsymbol{\vartheta}_r$ .... displacement vector for wake oscillators, and its reduced form due to boundary conditions

$\boldsymbol{\xi}$ .... vector collected the generalized displacement in mode space

δ_0 .... logarithmic mechanical damping

δ_s .... shear layer thickness

ϵ .... fraction of vorticity in shear layer being transferred to downstream mature vortex

γ .... mode shape factor in VIV theories

μ .... dynamic viscosity of flow

ω .... circular frequency

ω_0 .... circular natural frequency

ϕ .... mode shape function

$\Phi(\tilde{\tau})$ .... *Wagner's function*

ρ .... air density

ρ_r .... correlation coefficient between two points of a distance of r

$\rho_{u,u}$ .... normalized auto-correlation function of $u(t)$

σ_L .... standard deviation of fluctuation lift due to vortex shedding

σ_u .... standard deviation of fluctuation part of longitudinal wind speed

τ .... reduced time, defined through body's natural circular frequency $\tau = \omega_0 t$

τ_{lag} .... reduced time lag

$\tilde{\mu}$ .... tiny number

$\tilde{\tau}$ .... reduced time defined as Ut/b_h

υ .... ratio of V to V_r

υ_s .... ratio of U_S to U

Γ .... circulation of a vortex

φ .... phase angle

φ_{lag} .... phase lag

φ_{Lm} .... phase angle by which motion-induced lift leads body's displacement, defined in a range $-\pi \leq \varphi_{Lm} \leq \pi$

ϑ .... near-wake inclination angle in Tamura's nonlinear wake oscillator model

ϑ_{eff} .... effective rotation angle of near-wake lamina for generating vortex shedding force on oscillation body

ξ_i .... the generalized displacement in mode space (corresponding to its mode shape vector $\boldsymbol{\phi_i}$)

ζ_0 .... mechanical critical damping ratio

Latin variables and Constants

$\widetilde{U}, \widetilde{V}$ .... instantaneous longitudinal and lateral wind speed

$\bar{c}_i, \tilde{c}_i, \bar{k}_i$ ..... diagonal elements for $\bar{\boldsymbol{C}}$, $\tilde{\boldsymbol{C}}$ and $\bar{\boldsymbol{K}}$ matrices

$\bar{r}$ .... $r = \frac{\bar{Y}_s}{V}$

$\bar{Y}$ .... non-dimensional amplitude of Y

$\bar{Y}_s$ .... steady-state non-dimensional amplitude

$\bar{\boldsymbol{I}}_{\boldsymbol{r}}, \bar{\boldsymbol{C}}_{\boldsymbol{r}}, \tilde{\boldsymbol{C}}_{\boldsymbol{r}}, \bar{\boldsymbol{K}}_{\boldsymbol{r}}$ the reduced forms of $\bar{\boldsymbol{I}}$, $\bar{\boldsymbol{C}}$, $\tilde{\boldsymbol{C}}$ and $\bar{\boldsymbol{K}}$, after applying boundary conditions

$\bar{\boldsymbol{I}}, \bar{\boldsymbol{C}}, \tilde{\boldsymbol{C}}, \bar{\boldsymbol{K}}$. mass of inertia, linear damping, nonlinear damping and stiffness matrices for multiple wake oscillators

$\boldsymbol{\hat{A}_r}$,$\boldsymbol{\hat{B}_r}$, $\boldsymbol{\hat{G}_r}$, $\boldsymbol{\hat{H}_r}$ the reduced forms of $\boldsymbol{\hat{A}}$,$\boldsymbol{\hat{B}}$, $\boldsymbol{\hat{G}}$ and $\boldsymbol{\hat{H}}$, after applying boundary conditions

$\boldsymbol{\hat{A}}$,$\boldsymbol{\hat{B}}$, $\boldsymbol{\hat{G}}$, $\boldsymbol{\hat{H}}$. matrices responsible for the coupling between structure and wake oscillators

$\boldsymbol{M_s}$, $\boldsymbol{C_s}$, $\boldsymbol{K_s}$ mass, damping and stiffness matrices for a structural system

$\boldsymbol{M_t}$, $\boldsymbol{C1_t}$, $\boldsymbol{C3_t}$, $\boldsymbol{K_t}$ global mass, linear-damping, nonlinear-damping and stiffness matrices, for combined degrees of freedom of structure and wake oscillators

$\boldsymbol{M}_{sr}$, $\boldsymbol{C}_{sr}$, $\boldsymbol{K}_{sr}$ the reduced forms of $\boldsymbol{M_s}$, $\boldsymbol{C_s}$ and $\boldsymbol{K_s}$, after applying boundary conditions

$\boldsymbol{M}_{tn}$, $\boldsymbol{C1}_{tn}$, $\boldsymbol{C3}_{tn}$, $\boldsymbol{K}_{tn}$ the normalized forms of $\boldsymbol{M}_{tr}$, $\boldsymbol{C1}_{tr}$, $\boldsymbol{C3}_{tr}$ and $\boldsymbol{K}_{tr}$, by expanded mode shape matrix $\boldsymbol{\Phi_e}$

$\boldsymbol{M}_{tr}$, $\boldsymbol{C1}_{tr}$, $\boldsymbol{C3}_{tr}$, $\boldsymbol{K}_{tr}$ the reduced forms of $\boldsymbol{M_t}$, $\boldsymbol{C1_t}$, $\boldsymbol{C3_t}$ and $\boldsymbol{K_t}$, after applying boundary conditions

$\boldsymbol{q_s}$ .... external force vector for a structural system

$\boldsymbol{q_t}$, $\boldsymbol{q}_{tr}$ .... external force vector for combined system of structure and wake oscillators, and its reduced form due to boundary conditions

$\boldsymbol{q}_{QS}$, $\boldsymbol{q}_{QSr}$ .... quasi-steady transverse force vector, and its reduced form due to boundary conditions

$\boldsymbol{q}_{tn}$ .... the normalized forms of $\boldsymbol{q}_{tr}$, by expanded mode shape matrix $\boldsymbol{\Phi_e}$

$\hat{a}_i$, $\hat{b}_i$, $\hat{g}_i$, $\hat{h}_i$ .. elements for $\boldsymbol{\hat{A}}$, $\boldsymbol{\hat{B}}$, $\boldsymbol{\hat{G}}$ and $\boldsymbol{\hat{H}}$ matrices

$\hat{e}_i$ .... coefficent for elements in $\boldsymbol{q}_{QS}$ vector

$\bar{I}_u$, $\bar{I}_v$, $\bar{I}_w$ .... averaged I_u, I_v and I_w, of spatially discrete points

$\bar{L}_u$ .... averaged L_u of spatially discrete points

$\overline{U}$ .... averaged U of spatially discrete points

$\tilde{a}$, $\tilde{b}$, $\tilde{c}$ .... parameters in Corless&Parkinson's model

$\tilde{w}$ .... downwash

a .... combined with b_h to indicate of the position of elastic center, for elastically supported body

A_1 .... galloping factor according to quasi-steady thoery

A_i .... coefficients of polynomials approximating C_{Fy}-α curve (galloping factor A_1 coresponds to the linear slope)

$A_{1,equ}$ .... equivalent galloping factor for a continuous system

b .... width of wind tunnel model or bridge deck (chord length)

b_h .... half chord length

b_{avg} .... averaged value of top and bottom widths of a wind tunnel model

$C(k)$, $F(k)$, $G(k)$ *Theodorsen's circulation function*, as well as its real and imaginary part

c_α .... damping for torsional degree of freedom

C_D, C_L, C_M .. drag, lift and moment coefficient (steady part)

c_g .... width of the strip of turbulence grid

C'_L,c'_L .... standard deviation of lift coefficient fluctuation for the entire prism body and for a unit length of the prism body

C_v .... unsteady lift coefficient due to vortex exciting in Corless&Parkinson's model

c_y .... damping for heaving degree of freedom

c_ϑ .... cofficient related to the damping force for oscillation near-wake lamina, according to unsteady thin airfoil theory

C_{Fy},C_{Fy}^{QS} ..... transverse force coefficient according to quasi-steady theory

$C_{L,un}$ .... unsteady lift due to effective rotation angle of near-wake lamina, in Tamura's nonlinear wake oscillator model

C_{L0},c_{L0} ...... sinusoidal equivalent amplitude of the fluctuation lift coefficient due to vortex shedding for the entire prism body, and for a unit length of the prism body

$C_{lat,0}$ .... RMS value of the fluctuation lift coefficient due to vortex shedding

C_{Lm0} .... amplitude of motion-induced lift coefficient

C_{LmR}, C_{LmI} .. portion of C_{Lm0} in phase with $y(t)$, and in phase with $\dot{y}(t)$

C_{Lm} .... motion-induced lift coefficient

C_{m0} .... potential flow inertia coefficient in Luo&Bearman's model

C_{pb} .... base pressure coefficient of bluff body

C_R .... derived coefficient for F_R

d .... height of wind tunnel model or bridge deck

D, L, M ..... aerodyanmic drag, lift and moment (steady part)

d_g .... mesh size of turbulence grid

d_{ref}, l_{ref} ..... reference height and length for launching nose model

E .... Young's modulus

e .... combined with b_h to indicate of the position of gravity center, for elastically supported body

f .... slope of the unsteady vortex-excited lift coefficient to the near-wake inclination ϑ in Tamura's nonlinear wake oscillator model

F_b .... force reaction due to boundary support

F_L .... restoring force of near-wake lamina

F_R .... lift variation on near-wake lamina, due to its circulation change induced by vortex discharging

F_y .... transverse aerodynamic force

G .... gravity center of near-wake lamina

h .... width of near-wake behind bluff-body

h^* .... non-dimensional form of h, defined h/d

H_i^*, A_i^* ...... flutter derivatives

$H_n(k)$ .... Hänkel's functions

h_{avg} .... $(h_{std}+h_{sk})/2$

h_{sk} .... wake width determined by the distance between minus peaks of skewness of $\widetilde{U}$, being $\widetilde{U}$ transversely measured in the near-wake of bluff body

h_{std} .... wake width determined by peak distance of $\text{std}(\widetilde{U})/U_0$, being $\widetilde{U}$ transversely measured in the near-wake of bluff body

I .... mass moment of inertia at elastic center

i .... $i=\sqrt{-1}$, or used as number counter

I_ϑ .... mass moment of inertia for near-wake lamina

I_u, I_v, I_w ..... turbulence intensities

$I_{\vartheta,a}$ .... the added inertia of moment for oscillation near-wake lamina, according to unsteady thin airfoil theory

I_{xx} .... second moment of area of a cross section

$J_n(k), Y_n(k)$ .. modified Bessel's functions of first and second kind

K .... reduced frequency defined as $b\omega/U$

k .... reduced frequency defined as $b_h\omega/U$

k_α .... stiffness for torsional degree of freedom

k_ϑ .... equivalent rotational stiffness for near-wake lamina

k_y .... stiffness for heaving degree of freedom

l .... half length of near-wake behind bluff-body

l^* .... non-dimensional form of l, defined l/d

l_e .... effective length of sectional wind tunnel model (between two end-plates)

l_F .... vortex formation length

L_u .... longitudinal turbulence integral length

l_V, h_V .... streamwise distance and across-flow distance of vortex pairs

$l_{F,net}$ .... net near-wake length, starting from rear-face of body to the end of near-wake

$l_{FL,O}$ .... distance between pivot point O and F_L being applyied on near-wake lamina

l_{FL} .... length scale for calulating the restoring force F_L on near-wake lamina

l_I .... length scale for calulating I_ϑ of near-wake lamina

$l_{s,i}$ .... spanwise reference length for aerodynamic force calculation at node i of a continuous system)

L_{y1}, L_{y2}, L_{y3} . components of theoretical lift on thin airfoil

m .... mass of body per unit length

m^* .... mass ratio between body and air

M_ϑ .... moment of an oscillation near-wake lamina, according to unsteady thin airfoil theory

M_e .... effective oscillation mass of wind tunnel model

$M_{\alpha 2}$ .... component of theoretical moment on thin airfoil

m_{ij}, c_{ij}, k_{ij} .. elements for $\boldsymbol{M_s}$, $\boldsymbol{C_s}$ and $\boldsymbol{K_s}$ matrices

N .... nodes of a structural system

n .... freqeuncy in Hz

n_0 .... natural frequency in still air

n_m .... frequency at which a wind tunnel model is forced to vibrate

n_o .... oscillation frequency in flowing air

N_r, N_{sr}, N_{wr} .. total amount of degrees of freedom for the combined system of structure and wake oscillators, as well as the portion respectively for structure and for wake oscillators

n_{st} .... Strouhal frequency

n_{vs} .... oscillation frequency of near-wake lamina

O .... pivot point of near-wake lamina

p .... rotational degree of freedom of beam

R .... $R = \bar{Y}^2$

r .... spanwise distance between two points on slender body

Re .... Reynolds number

S_{LL} .... power spectral density of fluctuating lift

S_{uu} .... power spectral density of u

S_{yy} .... power spectral density of y

Sc .... Scruton number defined with d^2

Sc^* .... Scruton number defined with bd

St .... Strouhal number defined with d

t .... physical time

T_u .... integral time length

t_{lag} .... physical time lag

U .... mean wind speed

u, v, w ...... fluctuation part of longitudinal, lateral, and vertical wind speed

u', v', w' ..... standard deviation of u, v and w

U_g .... critical wind speed for across wind galloping, according to quasi-steady theory

U_i .... mean wind speed at a single point

U_r .... critical wind speed for Kármán-vortex induced vibration

U_{rel} .... resultant wind speed due to motion of body

U_S .... mean wind seed at the flow separation point of bluff body

u_V .... relative wind speed of vortex being transported downstream to incoming wind speed U

V .... reduced wind velocity

V_0, V_1, V_2 .... characteristic reduced wind speeds for quasi-steady galloping response ($V_0 = V_g$)

V_g .... reduced form of U_g

V_r .... reduced form of U_r

V_{lb} .... lower bound of V at which φ_{Lm} becomes alwasys positive

x,y,z .... Cartesian coordinate, or degrees of freedom

x_g .... upstream distance of turbulence grid to axis of wind tunnel model

Y .... non-dimensional displacement of body's motion, defined as y/d

$Y_1, \varepsilon_{03}, \varepsilon_{05}$ ... coefficients in Gao&Zhu's model as a function of K

y_0 .... amplitude at which a wind tunnel model is forced to vibrate, or initial displacement for free-decaying motion

y_{rms} .... RMS value of fluctuation part of $y(t)$

Other Symbols

$\circ$ .... Hadamard product

Δ .... small increment or difference

$(\dot{\ })$, $(\ )'$ ...... differentiation with respect to physical time t, and reduced time τ(or $\tilde{\tau}$)

∞ .... infinity

std( ) .... standard deviation of a signal

$^{\top}$ .... transform operation for matrix or vector

Abbreviations

AEVS ...... Alternate Edge Vortex Shedding

CFD .... Computational Fluid Dynamics

HFFB .... High Frequency Force Balance

ILEV .... Impinging Leading Edge Vortices

LEVS .... Leading Edge Vortex Shedding

QS .... Quasi Steady

RMS .... Root Mean Square

TEVS .... Trailing Edge Vortex Shedding

VIV .... Vortex Induced Vibration