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Conceptual design of light bascule bridge

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Abstract. This paper proposed a conceptual design of bascule bridge, which is a new kind of movable bridge with an aim of reducing the weight of superstructure. Compared with the traditional bascule bridge, the light bascule bridge chooses cable-stayed bridge with inclined pylon as its superstructure; therefore, the functions of balance-weight and structure will fuse into one. Otherwise, it adopts moving counterweight to adjust its center of gravity (CG) to open or close the bridge. In order to lighten the superstructure, it uses contact springs to auxiliary retract, and intelligent prestressing system (IPS) to control the main girder's deformation. Simultaneously the vibration control scheme of structure is discussed. Starting from establishing the mechanical model of bridge, this article tries to analyze the conditions that the design parameters of structure and attachments should satisfy to. After the design procedure was presented, an example was also adopted to explain the primary design process of this kind bridge.

Keywords: bridge engineering; bascule bridge; cable-stayed bridge; retractable structure; intelligent prestressing system; special structure; parameter analysis.

1. Introduction

Along with the development of human society, more and more demands of structures have been advanced. A good structure should not only meet the functional requirements, but also embody the regional character of human and culture opinion. Therefore, some special and creative movable bridges were constructed, such as the new Woodrow Wilson Bridge (Cary-Brown *et al*. 2001, Gudelski and Ruddell 2004, Ichniowski 2005, Hansen 2006), Estacio bascule bridge (Astiz *et al* 2006), the new Galata Bridge (Bozdag *et al.* 2006), a moveable pedestrian bridge in Duisburg (Briseghella *et al.* 2003, Wallner and Pircher 2005), and the 17th Street Causeway Bridge in Fort Lauderdale (Phillips and Rodriguez 2003).

Movable bridges are usually divided into three main types: bascule bridges, swing bridges, and lift bridges (Terry 2003). A bascule bridge is a type of movable bridge that is counterbalanced and open by pivoting about a horizontal axis. Some bascule bridges have to have heavy counterweights to achieve proper balance. It is often desired to be counterweight heavy when open, and span heavy when closed, to improve stability of the bridge. Moving counterweight is a possible way to achieve this aim when the superstructure and the deployable counterweight are light. Therefore, a kind of

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special structure is introduced into the light bascule bridge, and some attachments are also designed to lighten the structure and diminish vibrations caused by wind and live load.

This paper focused on the principle of light bascule bridge and the description of each attachment; furthermore, its mechanical properties were studied, and the design procedure was also presented.

2. Concept

The superstructure of conventional bascule bridge usually consists of a cantilever girder with a counterweight, as shown in Fig. 1. The weight of cantilever girder is generally heavier than any other type of girder, and the deployable counterweight is also heavy. To select a lightweight type of girder is provided with an important significance, because the superstructure weight of bascule bridge has a remarkable influence of the whole engineering.

The light bascule bridge chooses cable-stayed bridge with inclined pylon (Shao *et al.* 2005, Tan and Teh 2005, Melnick 2004) as its superstructure, as shown in Fig. 2. The inclined pylon acts as the balance-weight of main girder, as well as the supporting structure of main girder. Supported by some cables in the span, the main girder can be designed to be light, and the inclined pylon can be designed to be light too. So the superstructure of this type of bascule bridge is generally light.

In order to keep the structure opening and closing smoothly, a slide-limited damper is installed between the pylon and the pier. Since CG of superstructure is transformed ceaselessly during the retractable process, and considering not using large-scale power equipments nearby the pivot, the light bascule bridge adopts moving counterweight to adjust its CG to open or close the bridge. The bridge can retract successfully as long as the counterweight gets across the open or close critical

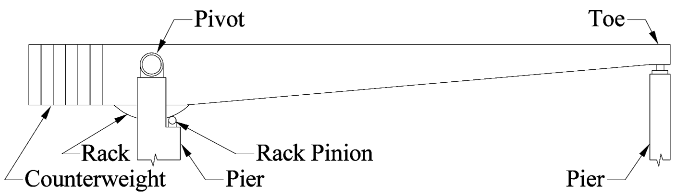

Fig. 1 Superstructure of conventional bascule bridge

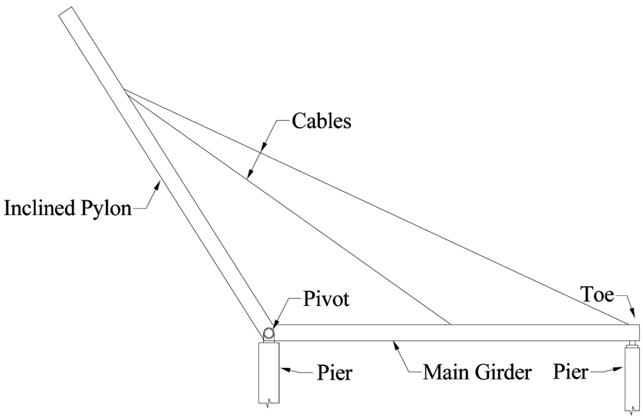

Fig. 2 Superstructure of light bascule bridge

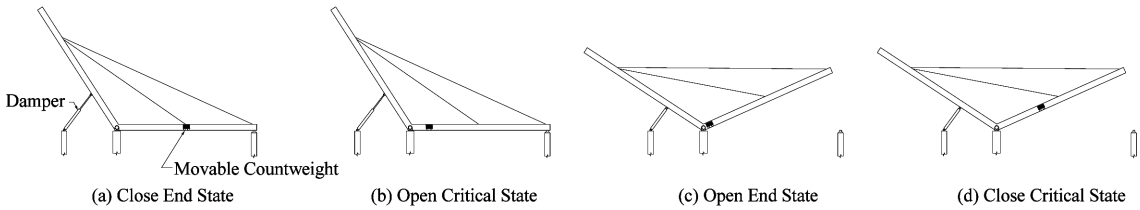

Fig. 3 Retractable process of light bascule bridge

point, as shown in Fig. 3. In the figure, (a)→(b)→(c) is corresponding to the open process, and (c)→(d)→(a) is corresponding to the close process.

The whole or part of counterweight can be designed as a turned mass damper (TMD) to mitigate structure vibration in the normal state. Furthermore, the counterweight can also be designed as a tank in the girder, and achieve open or close aim by transferring liquid between the tank in girder and the tank in pylon.

3. Attachments

3.1 Description of auxiliary springs

In the whole opening or closing process, the superstructure need the maximal moment at the state change, and the needed moment will decrease gradually as soon as the superstructure is start-up. Based on this characteristic of structure, two contact springs are paralleled beside the damper to supply auxiliary moment for the structure at the critical states of retraction, and cushion the structure at the end state of retraction. The key states of springs are shown in Fig. 4.

When the bridge needs to be opened, we should move the counterweight towards the open critical point. Along with CG of bridge is transferred towards the inclined pylon direction, the bridge will be opened under the action of structure weight and tensile spring, and the damper will be pushed in at the same time.

In the opening process, the bridge can be started up successfully if the increased open moment

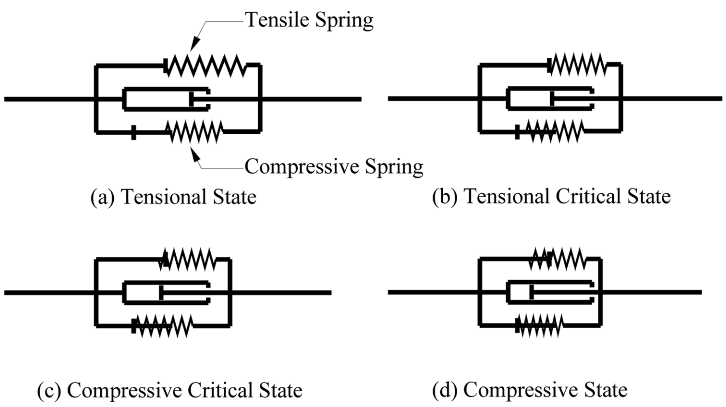

Fig. 4 Key states of springs beside damper

caused by structure weight about the pivot is greater than or equal to the decreasing open moment caused by tensile spring. When the damper is squeezed to contact the compressive spring, the open process can be finished successfully if the increased open moment caused by structure weight about the pivot is greater than or equal to the increased close moment caused by compressive spring. After the bridge is opened completely, the damper will act as a compression strut to keep the structure stable.

When the bridge needs to be closed, we should move the counterweight towards the close critical point. Along with CG of bridge is transferred towards the main girder direction, the bridge will be closed under the action of structure weight and compressive spring, and the damper will be pulled out at the same time.

In the closing process, the bridge can be started up successfully if the increased close moment caused by structure weight about the pivot is greater than or equal to the decreasing close moment caused by compressive spring. When the damper is stretched to contact the tensile spring, the close process can be finished successfully if the increased close moment caused by structure weight about the pivot is greater than or equal to the increased open moment caused by tensile spring. After the bridge is closed completely, the toe of girder will lie on the pier, and the damper will act as a tension bar to stiffen the structure.

3.2 Description of IPS

In the normal state, the main girder is under the actions of dead load, counterweight, cables and live load. However, it is only under the actions of dead load and cables in the open end state. Based on the difference between these two states, the main gird can be designed to be much lighter if the cables can adjust force by themselves according to the conditions of girder. Therefore, the ideas and methods of IPS are introduced into the cables.

IPS is usually composed of sensors, controllers and actuators except the demand of currently prestressing system. The controllers send commands, which based on the information given by the sensors and the states of each actuator, for the actuators to push in or pull out, in order to keep the deflection of main girder in allowed range under the action of external load and IPS.

In order to educe the controllable performance and feasibility of IPS, the author made a demonstration of simple supported bridge with a span of 2 meters in 2004, and the sketch map is shown in Fig. 5. The result shows that IPS beam can bear much heavier live load than the traditional prestressing beam under the same section and the same requirement of deflection.

IPS is an important approach to solve the deflection control problems of structures, which have the high ratio of live load to dead load. There are two ways to achieve intelligent prestressing: one is that the cable is made of intelligent materials such as SMA (Maji and Negret 1998, Janke *et al*

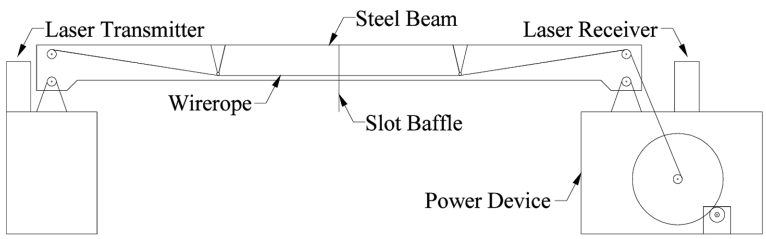

Fig. 5 Model of IPS beam

2005, Sawaguchi *et al.* 2006); the other is that the cable is driven by intelligent anchor (Sobek and Teuffel 2001, Pacheco and Adao 2002, Xu and Lu 2005, Liu *et al.* 2005, Andre *et al.* 2006). Adopting intelligent anchor is more feasible to adjust cable force in cable-stayed bridges.

3.3 Description of slide-limited damper

The design of bridge aims to light structure, but the light structure can be vibrated easily under external excitation (Wallner and Pircher 2005, Bozdag *et al.* 2006); therefore, a slide-limited damper is installed between the pylon and the pier to mitigate vibration.

The slide-limited damper has four functions as follows:

1. Act as a buffer to keep the structure opening and closing smoothly during the state change.
2. Act as a compression strut to keep the structure stable after the bridge finishes open process.
3. Act as a viscous damper to mitigate structural vibration under medium or light load in the normal state.
4. Act as a tension bar to prevent large deformation of the structure under heavy load in the normal state.

4. Analysis

In the opening or closing process, CG of superstructure is transformed ceaselessly; therefore it is necessary to have a study on the bridge's mechanics characteristic.

The mechanics model of bridge is shown in Fig. 6. Where W_t = weight of inclined pylon; W_b = weight of main girder; W_T = weight of counterweight; W_c = closing effect wind; W_o = opening effect wind; M_{sp} = moment caused by spring about pivot; L_b = distance between CG of main girder and pivot; L_t = distance between CG of pylon and pivot; β = angle between pylon and the axes of main girder; a = distance between damper's joint on pylon and pivot; b = distance between damper's joint on pier and pivot.

The principles that the parameters should satisfy are presented in Eq. (1), Eq. (2) and Eq. (3) under the assumption that the rotational impulse of structure is neglected (Xu and Lu 2007).

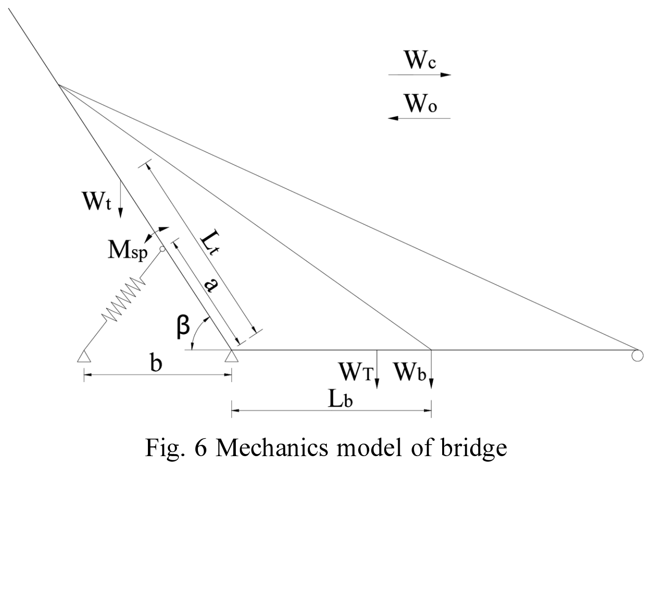

Fig. 6 Mechanics model of bridge

1. Retractable critical equation

$$\begin{cases} W_t \cdot L_t \cos\beta + M_{sp}^0 = W_b \cdot L_b + W_T \cdot L_o + M_{wc}^0 \\ W_t \cdot L_t \cos(\beta - \theta_{ds}) - M_{sp}^{\theta_{ds}} + M_{wo}^{\theta_{ds}} = W_b \cdot L_b \cos\theta_{ds} + W_T \cdot L_c \cos\theta_{ds} \end{cases} \tag{1}$$

2. Sufficient and necessary conditions for open stability

$$\begin{cases} W_t \cdot L_t \cos(\beta - \theta) + M_{sp}^{\theta} \geq W_b \cdot L_b \cos\theta + W_T \cdot L_{oe} \cos\theta + M_{wc}^{\theta} & (0 \leq \theta \leq \theta_s) \\ W_t \cdot L_t \cos(\beta - \theta) - M_{sp}^{\theta} \geq W_b \cdot L_b \cos\theta + W_T \cdot L_{oe} \cos\theta + M_{wc}^{\theta} & (\theta_c \leq \theta \leq \theta_{ds}) \end{cases} \tag{2}$$

3. Sufficient and necessary conditions for close stability

$$\begin{cases} W_t \cdot L_t \cos(\beta - \theta) + M_{sp}^{\theta} + M_{wo}^{\theta} \leq W_b \cdot L_b \cos\theta + W_T \cdot L_{ce} \cos\theta & (0 \leq \theta \leq \theta_s) \\ W_t \cdot L_t \cos(\beta - \theta) - M_{sp}^{\theta} + M_{wo}^{\theta} \leq W_b \cdot L_b \cos\theta + W_T \cdot L_{ce} \cos\theta & (\theta_c \leq \theta \leq \theta_{ds}) \end{cases} \tag{3}$$

Where θ = open angle of bridge; θ_s = open angle of bridge at tensional critical state of spring; θ_c = open angle of bridge at compressive critical state of spring; θ_{ds} = design open angle of bridge; M_{sp}^0 = moment caused by spring about pivot at close state; $M_{sp}^{\theta ds}$ = moment caused by spring about pivot at open state; M_{sp}^{θ} = moment caused by spring about pivot at θ angle; M_{wc}^0 = moment caused by closing effect wind about pivot at close state; $M_{wo}^{\theta ds}$ = moment caused by opening effect wind about pivot at open state; M_{wc}^{θ} = moment caused by closing effect wind about pivot at θ angle; M_{wo}^{θ} = moment caused by opening effect wind about pivot at θ angle; L_o = distance between CG of counterweight and pivot at open critical state; L_c = distance between CG of counterweight and pivot at close critical state; L_{oe} = distance between CG of counterweight and pivot at open end state; L_{ce} = distance between CG of counterweight and pivot at close end state.

M_{sp}^{θ} can be calculated as

$$M_{sp}^{\theta} = \begin{cases} K_s \cdot \left(\sqrt{a^2+b^2-2ab\cos(\beta-\theta)} - \sqrt{a^2+b^2-2ab\cos(\beta-\theta_s)}\right) \cdot \dfrac{ab\sin(\beta-\theta)}{\sqrt{a^2+b^2-2ab\cos(\beta-\theta)}} \\ \quad (0 \leq \theta \leq \theta_s) \\ 0 \quad (\theta_s \leq \theta \leq \theta_c) \\ K_c \cdot \left(\sqrt{a^2+b^2-2ab\cos(\beta-\theta_c)} - \sqrt{a^2+b^2-2ab\cos(\beta-\theta)}\right) \cdot \dfrac{ab\sin(\beta-\theta)}{\sqrt{a^2+b^2-2ab\cos(\beta-\theta)}} \\ \quad (\theta_c \leq \theta \leq \theta_{ds}) \end{cases} \tag{4}$$

Where K_s = tensional spring's stiffness, and K_c = compressive spring's stiffness.

During the retractable process, the damper's stroke can be calculated as

$$\Delta_{\text{dam}} = \sqrt{a^2+b^2-2ab\cos\beta} - \sqrt{a^2+b^2-2ab\cos(\beta-\theta_{ds})} \tag{5}$$

Considering the damper's efficiency, the damper can be perpendicular to pylon during the retractable process. The corresponding open angle is defined as θ_m, then a and b can be related through

$$a = b\cos(\beta - \theta_m), \quad (0 \le \theta_m \le \theta_{ds}) \tag{6}$$

So that Eq. (5) can be rewritten

$$\Delta_{\text{dam}} = b \cdot [\sqrt{\cos^2(\beta - \theta_m) + 1 - 2\cos(\beta - \theta_m)\cos\beta} - \sqrt{\cos^2(\beta - \theta_m) + 1 - 2\cos(\beta - \theta_m)\cos(\beta - \theta_{ds})} \tag{7}$$

And M_{sp}^0 and $M_{sp}^{\theta ds}$ can be expressed by introducing Eq. (6) into Eq. (4) [taking θ = 0 and $_{\text{ds}}$, respectively]

$$M_{sp}^0 = K_s \cdot \left(1 - \sqrt{\frac{1 + \cos^2(\beta - \theta_m) - 2\cos(\beta - \theta_m)\cos(\beta - \theta_s)}{1 + \cos^2(\beta - \theta_m) - 2\cos(\beta - \theta_m)\cos\beta}}\right) \cdot b^2\cos(\beta - \theta_m)\sin\beta \tag{8}$$

$$M_{sp}^{\theta ds} = K_c \cdot \left(\sqrt{\frac{1 + \cos^2(\beta - \theta_m) - 2\cos(\beta - \theta_m)\cos(\beta - \theta_c)}{1 + \cos^2(\beta - \theta_m) - 2\cos(\beta - \theta_m)\cos(\beta - \theta_{ds})}} - 1\right) \cdot b^2\cos(\beta - \theta_m)\sin(\beta - \theta_{ds}) \tag{9}$$

We define moment difference, caused by counterweight about the pivot, between close end state and open critical state as close margin stability

$$M_c = W_T \cdot (L_{ce} - L_o) - M_{wc}^0 - M_{wo}^0 \tag{10}$$

We define moment difference, caused by counterweight about the pivot, between open end state and close critical state as open margin stability

$$M_o = W_T \cdot (L_c - L_{oe})\cos\theta_{ds} - M_{wo}^{\theta_{ds}} - M_{wc}^{\theta_{ds}} \tag{11}$$

The design weight of girder, pylon and counterweight are influenced by the structure's geometry size and the contact springs' mechanical properties as shown in mechanics model; therefore, some conclusions can be drawn clearly without considering wind effect.

Adopt the principle of equal-stability, $M_c = M_o$, then L_o and L_c can be related through

$$L_o = L_{ce} + L_{oe}\cos\theta_{ds} - L_c\cos\theta_{ds} \tag{12}$$

L_o decreased with the increase of L_c, and $L_c > L_o$, obviously.

The weight of counterweight and pylon can be obtained by solving (1)

$$W_T = \frac{W_b L_b \sin\beta\sin\theta_{ds} - [M_{sp}^0\cos(\beta - \theta_{ds}) + M_{sp}^{\theta_{ds}}\cos\beta]}{L_c\cos\beta\cos\theta_{ds} - L_o\cos(\beta - \theta_{ds})} \tag{13}$$

$$W_t = \frac{W_b L_b (L_c - L_o)\cos\theta_{ds} - [M_{sp}^0 L_c\cos\theta_{ds} + M_{sp}^{\theta_{ds}} L_o]}{L_t[L_c\cos\beta\cos\theta_{ds} - L_o\cos(\beta - \theta_{ds})]} \tag{14}$$

In addition, W_t can also be expressed from (1)

$$W_t = \frac{W_b L_b + W_T L_o - M_{sp}^0}{L_t\cos\beta} \tag{15}$$

From the expressions (13) and (15), the main conclusions are presented as follows:
1. The smaller W_b, the smaller W_T and W_t;
2. The smaller L_b, the smaller W_T and W_t;
3. The bigger L_t, the smaller W_t;
4. The smaller β, the smaller W_T and W_t;
5. The bigger L_c, the smaller L_o, W_T and W_t;
6. The bigger M_{sp}^{0} and $M_{sp}^{\theta ds}$, the smaller W_T and W_t;
7. Increase M_{sp}^{0} has more efficiency than $M_{sp}^{\theta ds}$ to decrease W_T and W_t.

5. Design procedure

The primary process for designing the light bascule bridge is presented as follows:
1. Choose β and θ_{ds} based on the shape and function demands of bascule bridge.
2. Design the main girder, the inclined pylon and IPS based on the span and the using load, obtain W_b, W_t, M_{wc}^{θ}, M_{wo}^{θ}, L_b and L_t.
3. Choose W_T, L_{ce}, L_{oe}, L_c and L_o based on the demand of margin stability.
4. Calculate M_{sp}^{0} and $M_{sp}^{\theta ds}$ from the retractable critical equation.
5. Calculate M_{sp}^{θ} bound from the sufficient and necessary conditions.
6. Calculate the critical angle of θ_s and θ_c based on nonnegative M_{sp}^{θ}.
7. Adjust θ_s, θ_c, θ_m, K_s, K_c and b to satisfy M_{sp}^{0} and $M_{sp}^{\theta ds}$ that calculated in step 4, and to make the damper's stroke, Δ_{dam}, in suitable range. If expression M_{sp}^{θ} is in the bound that calculated in step 5, the feasible solution of design is obtained. Otherwise, repeat step 2 to 7 as many times as necessary to obtain the feasible solution of design.
8. Design the slide-limited damper based on the dynamic characteristic of bridge.

In the optimization design of bascule bridge, W_T and L_{ce} should consider the vibration control efficiency of TMD in step 3; furthermore, the function of tensional spring and compressive spring can be achieved by one spring if $K_s = K_c$ in step 7.

5.1 Example

Based on the design procedure, an example without considering wind effect is presented as follows:

Step 1: Design the main girder and the inclined pylon

Based on the span, shape and function demand of bascule bridge, design the main girder and the inclined pylon. Corresponding parameters might as well be assumed: $\beta = 60^{\circ}$, $\theta_{ds} = 30^{\circ}$, span = $2L_b$, $W_t=1.6W_b$, and $L_t = 0.92L_b$.

Step 2: Choose W_T, L_{ce}, L_{oe}, L_c and L_o

Design the counterweight as a TMD to mitigate structure vibration in the normal state. Considering the vibration control efficiency, assume $W_T = 0.3W_b$ and $L_{ce} = L_b$. Considering the margin stability, $L_c = 0.8L_b$ and $L_{oe} = 0$, then $L_o = 0.3L_b$ based on Eq. (12).

Step 3: Calculate M_{sp}^{0} and $M_{sp}^{\theta ds}$

Solve M_{sp}^{0} and $M_{sp}^{\theta ds}$ by introducing the parameters into Eq. (1):

$M_{sp}^{0} = 0.354W_bL_b$; $M_{sp}^{\theta ds} = 0.201W_bL_b$.

Step 4: Calculate M_{sp}^{θ} bound

Solve M_{sp}^{θ} bound by introducing the parameters into Eqs. (2) and (3):
$(0.354\cos\theta - 1.275\sin\theta)W_bL_b \le M_{sp}^{\theta} \le (0.504\cos\theta - 1.275\sin\theta)W_bL_b$, $\theta \in [0^{\circ}, 15.5^{\circ}]$;
$(1.275\sin\theta - 0.504\cos\theta)W_bL_b \le M_{sp}^{\theta} \le (1.275\sin\theta - 0.354\cos\theta)W_bL_b$, $\theta \in [21.6^{\circ}, 30^{\circ}]$.
Where the critical angle of θ_s = arctan(0.354/1.275) = 15.5°;
the critical angle of θ_c = arctan(0.504/1.275) = 21.6°.

Step 5: Choose θ_s, θ_c and calculate θ_m, K_s and K_c

Take $\theta_s = 16^{\circ}$, $\theta_c = 21^{\circ}$, and $K_s = K_c = K$:
Then $\theta_m = 18^{\circ}$ based on Eqs. (8) and (9),
$a = 0.743b$ based on Eq. (6),
$\Delta_{\mathrm{dam}} = 0.544b$ based on Eq. (7),
$Kb^2 = 2.42W_bL_b$ based on Eq. (8).

Step 6: Validate M_{sp}^{θ}

Introduce a, b, K_s, K_c, θ_s, θ_c and β into (4), M_{sp}^{θ} satisfies the bound which solved in step 4 as shown in Fig. 7 (using MATLAB software), so the solution of design is feasible.

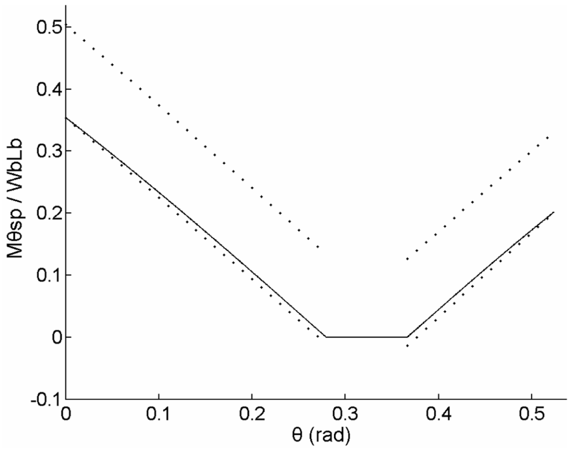

Fig. 7 Auxiliary retractable moment of spring

Where solid line = auxiliary retractable moment of spring, dashed line = feasible bound of auxiliary retractable moment.

Select a suitable damper based on Δ_{dam} to obtain b, and obtain all the other parameters based on the main girder's design.

6. Conclusions

The light bascule bridge is a new kind of movable bridge with an aim of reducing the weight of superstructure. It chooses cable-stayed bridge with inclined pylon as its superstructure, and uses contact springs to auxiliary retract. Moving counterweight is adopted to adjust CG of bridge to open or close the bridge. Simultaneously IPS concept is introduced into superstructure to control deflection of light main girder and the vibration control scheme of structure is also discussed. The principles that the mechanics model parameters should satisfy were presented in the paper and the main conclusions of light bascule bridge were also presented.

The design process of main girder and inclined pylon is not discussed, and the detailing design is not given. However, these problems could be solved if we consider the design conditions. Further experimental studies on the performance of IPS in the bridge are ongoing in Southeast University.

Acknowledgements

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