Study on the Influence of Excitation in Sliding Construction of Long Span Steel Structure

Qinghui Zhou¹*, Chenlong Zhang¹, Long Xiao¹, Xiwang Zhang² and Yidong Xie¹

¹ School of Mechanical-Electrical and Vehicle Engineering, Beijing University of Civil Engineering and Architecture, Beijing Engineering Research Center of Monitoring for Construction Safety, Beijing, 100044, China
² Beijing Mechanism Construction Co., Ltd., Beijing, 100045, China
Email: zhouqinghui@bucea.edu.cn

Abstract. There is a safety risk on sliding construction because of the unstable state of large-span steel structure. The core technology of sliding construction is synchronous control. In this paper, a large-span steel structure sliding construction is taken as an example. The span reaches 202.2 m, which is the first case in China. Based on the theoretical analysis of the sliding process, the mathematical sliding model is established, and the main parameters are analyzed. The displacement and synchronization error under the external exciting force are calculated. The sliding motion, mechanical properties are studied. It also provides measures to improve synchronization performance. The result has proved that the scheme effectively guarantees the construction safety and quality. So it is also a reference for the design and development of the synchronous control.

1. Introduction

Hydraulic synchronous sliding technology is a method to solve the installation of steel structures with complex underground structures or very narrow construction space [1], and has been applied in many domestic projects. The transient working conditions of the steel structure during the sliding process are complex, such as starting, braking, rail jamming, vibration and other working conditions, which will cause the system to vibrate after being subjected to the excitation force, and the stress at each point will continue to change, affecting the structure internally, the rods or parts are subjected to additional force. In addition, there are sudden events encountered in sliding construction, such as wind load, impact load caused by the sudden failure of hydraulic thrusters, etc. The span of the first large span steel structure in China has reached 202.2m, it is in order to ensure the stability of the main truss during the sliding process and effectively control the sliding state, the following main problems must be solved:

1) Establish a sliding unit migration model, analyze the main factors, and provide a theoretical basis for reasonable control of synchronization.
2) Explore the transient motion and dynamic characteristics of sliding construction after being affected to the excitation force.
3) Analyze the parameters that affect the synchronization performance to ensure the stability and safety of the structure during sliding construction.

Due to the large span of the steel structure and heavy weight, the overall sliding construction is
particularly difficult. Aiming at the actual project, this paper conducts a theoretical analysis of the overall slip, establishes a slip unit migration model, analyzes the main parameters of the slip unit asynchronous due to external excitation force, and proposes measures to improve synchronization performance to ensure construction safety and construction quality.

2. Influencing Factors Leading to Out-of-Synchronization in Sliding Construction

2.1. Sliding Unit Offset

When the sliding unit slides on the rails on both sides, the displacement is not synchronized, which results in the deviation of the sliding unit, and the overall deflection of the sliding unit occurs. Assume that $\theta$ is the lateral angle produced when the structure is supported. The arrangement of slide rails and push points is shown in figure 1 and the mutual relationship when the sliding element has a limit deviation is shown in figure 2: $L$ is the span, and $b$ is the width.

![Figure 1. Layout drawing of sliding construction plan.](image1)

![Figure 2. The migration model of the sliding element.](image2)

The mass of the sliding unit of a large component is $m$; $k_1$, $c_1$ are the axial stiffness and damping of the sliding unit along the $Y_1$ direction of the guide rail; $k_2$, $c_2$ are the axial rigidity and damping of the sliding unit along the $Y_2$ direction of the guide rail; $k_\theta$ is the torsional stiffness of the slid unit; $f_1$, $f_2$ are the frictional resistance of the sliding unit; $F_{y1}$, $F_{y2}$ are the traction forces; $\theta$ is the torsion angle of the sliding unit; $a_1$, $a_2$ are the distances from the guide rail to the center of the sliding unit; $y_{s1}$, $y_{s2}$ are the actual displacements of the sliding unit on the guide rail $Y_1$, $Y_2$, respectively; $y_{x1}$, $y_{x2}$ are the theoretical displacements of the pushing point; since $\theta$ is small, $\sin \theta = \theta$ can be assumed. From the geometric relationship in figure 2, we can get:

$$
\begin{bmatrix}
Y \\
\theta
\end{bmatrix} = 
\begin{bmatrix}
\frac{a_2}{a_1 + a_2} & \frac{a_1}{a_1 + a_2} \\
\frac{1}{a_1 + a_2} & \frac{1}{a_1 + a_2}
\end{bmatrix}
\begin{bmatrix}
Y_{s1} \\
Y_{s2}
\end{bmatrix}
\tag{1}
$$

System kinetic energy is:

$$
T = 0.5my^2 + 0.5I\theta^2
\tag{2}
$$

$$
I = J + m(a_1 - a_2)^2
\tag{3}
$$

The potential energy of the system is:
3. The generalized force $Q_j$ is:

$$Q_1 = -c_1(y_{s1} - \dot{y}_{s1}) - c_2(y_{s2} - \dot{y}_{s2}) - f_1 - f_2$$

$$Q_2 = -c_1(y_{s1} - \dot{y}_{s1})a_1 - c_2(y_{s2} - \dot{y}_{s2})a_2 - f_1a_1 - f_2a_2$$

(5)

According to Lagrange's equation:

$$\frac{d}{dt} \left( \frac{\partial \mathcal{L}}{\partial \dot{q}_j} \right) - \frac{\partial \mathcal{L}}{\partial q_j} + \frac{\partial \mathcal{L}}{\partial \dot{q}_j} = Q_j(t)$$

(6)

The equation of motion of the sliding unit is:

$$M\ddot{q} + C\dot{q} + Kq = F$$

(7)

The mass matrix, damping matrix and stiffness matrix are:

$$M = \begin{bmatrix} m & 0 \\ 0 & J + m(a_1 + a_2)^2 \end{bmatrix}$$

(8)

$$C = \begin{bmatrix} -c_1 - c_2 & -c_1a_1 + c_2a_2 \\ -c_1 + c_2a_2 & -c_1a_1^2 - c_2a_2^2 \end{bmatrix}$$

(9)

$$K = \begin{bmatrix} -k_1 - k_2 & -k_1a_1 + k_2a_2 \\ -k_1a_1 + k_2a_2 & -k_1a_1^2 - k_2a_2^2 - k_\theta \end{bmatrix}$$

(10)

The displacement vector $q$ and the external excitation vector $F$ are respectively:

$$q = \begin{bmatrix} \gamma \\ \beta \end{bmatrix}$$

$$F = \begin{bmatrix} F_{y1} + F_{y2} - k_1y_{s1} - k_2y_{s2} - c_1\dot{y}_{s1} - c_2\dot{y}_{s2} - f_1 - f_2 \\ F_{y1}L_1 - F_{y2}L_2 - k_1L_1y_{x1} + k_2L_2y_{x2} - c_1\dot{y}_{s1}L_1 + c_2\dot{y}_{s2}L_2 - f_1L_1 + f_2L_2 \end{bmatrix}$$

(11)

2.2. Model Solving and Analysis

The sliding of large components is an intermittent process, and the sliding unit will frequently be in a start/stop state. The normal slip speed is generally not more than $0.3 m/min$. Considering the round trip, the actual slip speed $v$ is about $2 \times 0.3 m/min$. It is assumed that when the slip starts, it will accelerate to $0.6m/min$ within 0.5 seconds, the inertial acceleration is $0.02 m/s^2$ [2], and the transient response change after the excitation force is analyzed. The large-span steel structure has a span of $201.2 m$, a single beam width of $35 m$, and a weight of about 250 tons per beam. There are 4 jacking points. The rigidity of the steel structure is $3 \times 10^7 N/mm^2$. According to literature [3], the damping ratio should be 0.035. Solve the mathematical model to obtain the change curve of the transient working condition displacement and synchronization error, as shown in figure 3. It can be seen from figure 3(a) that under the action of the traction pulse load, the structure would be displaced along the direction of the external force, and at the same time it would oscillate. The amplitude gradually decrease with time, the error increases with time, and then stabilizes, the structure would be displaced along the direction of the external force. It shows that at the beginning of slippage, the displacement, velocity and acceleration of slippage are all unstable under transient conditions and this unstable condition increases the synchronization error.
3. Influence Parameters of Synchronization Error

3.1. The Effect of Stiffness

The stiffness $K$ of the long-span steel structure affects the transient response of the system, resulting in synchronization errors. Figure 4 is the influence curve of the axial stiffness on the transient response displacement and synchronization error. The increase in axial stiffness would reduce the system amplitude and also shorten the vibration time, as shown in figure 4(a). At the same time, the synchronization error decreases with the increase in axial stiffness, as shown in figure 4(b).

3.2. The Influence of Initial Acceleration on Synchronization Error

In the normal sliding process of the steel structure, in addition to bearing the vertical self-weight load and the reaction force of the support, it also bears the traction force $F_{y1}$, $F_{y2}$, friction force $f_1$, $f_2$ of the
thruster and the internal force generated by the asynchronous displacement. If the traction forces \( F_{y1} \) and \( F_{y2} \) are not uniform, it will cause the deflection caused by the asynchronous displacement during sliding, which would produce a torsion moment on the steel structure. Taking the initial acceleration of the system as a variable and other parameters unchanged, analyze its influence on the synchronization error of the transient response, as shown in figure 5. The displacement increases with the increase of the initial acceleration, the amplitude also become larger, and the time to stabilize become longer; the synchronization error also increase with the increase of the initial acceleration.

![Figure 5](image)

**Figure 5.** The influence of initial acceleration on the transient response displacement and synchronization error.

3.3. The Effect of the Action Form of the Exciting Force on the Synchronization Error

Assuming that the acting forms of the exciting force are triangular, rectangular, and trapezoidal wave, the acting time is all 6S, and the maximum force is the same. As shown in figure 6, the different modes of excitation force affect the displacement and synchronization error. The change shape of the displacement is similar to the action form of the exciting force, but the synchronization error of the rectangular wave is the largest, and the synchronization error of the triangle wave is the smallest. Therefore, the hydraulic jacking force is best loaded in accordance with the shape of the triangle wave.

![Figure 6](image)

**Figure 6.** The effect of the action form of the exciting force on the transient response displacement and synchronization error
4. Measures to Improve Synchronization Performance

4.1. Effective Control of Jacking Traction
In the actual sliding process, in order to reduce the error, when the sliding test starts, the pressure of the hydraulic pusher extension cylinder can be gradually increased, which is 20% and 40% of the required pressure in sequence [4]. Through the self-locking device and mechanical self-locking system set in the hydraulic circuit, when the hydraulic pusher stops working or encounters a power outage, the sliding track can be automatically locked for a long time to ensure the safety of the sliding steel structure [5].

4.2. Reduce Friction Coefficient
Reducing the coefficient of friction can reduce the additional torque caused by uneven traction [6, 7]. Improving the original sliding friction form to rolling friction in the design of the slide rail structure can improve synchronization performance very well.

4.3. Adopt Cumulative Slip to Improve Torsional Stiffness
The cumulative sliding construction method can be used to improve the torsional rigidity to reduce the torsional deformation caused by asynchrony between the rails during the sliding process [8]. It refers to sliding a single stroke for a certain distance, and then connecting the second stroke. After the two strokes form a unit, they slide a distance together, and repeat the operation until the last pound is connected [9].

4.4. Use Cable Structure to Improve System Rigidity
Due to the linear characteristics of the string beam structure, increasing the prestress cannot increase the stiffness of the string beam structure [10] In order to ensure the stability of the structure, cable structures are often used in the design of long-span structures [11]. The cable pretension can improve the force performance of the upper chord member and reduce the bending moment of the upper chord member under load; It can increase the structure's ability to resist sudden external loads, such as wind loads.

5. Conclusion
- Analyzed the working principle of the long-span steel structure synchronous sliding system, and established the system's synchronous control dynamics model.
- Under the action of the exciting force, the structure would shift and oscillate. The amplitude would gradually decrease with time, but the synchronization error would also increase with time.
- The stiffness, initial acceleration and the form of the exciting force of the long-span steel structure would all affect the displacement and synchronization error.
- Controlling the pushing force, reducing the coefficient of friction, adopting cumulative slip, adopting the cable structure and other measures could improve the synchronization performance.

Acknowledgments
This research is supported by “The Fundamental Research Funds for Beijing University of Civil Engineering and Architecture” (X20080).

References
[1] Liu Y, Wu J and Li Y 2004 Synchronous control algorithm in hydraulic synchronous continuous slippage system Chinese Journal of Engineering Machinery (02) 197-200.
[2] He W, Feng W and Gu L 2016 Study on Sliding Construction Calculation and Boundary Conditions Engineering Construction and Design (06) 32-34+37.
[3] GB50011-201 2016 Code for Seismic Design of Buildings Beijing: China Building Industry Press
[4] Gao D 2016 *The Research of New Sliding Construction Technology for Large-Span Steel Structure* Beijing Jiaotong University.

[5] Luo Z 2011 Simultaneously sliding technology and quality control of large-span tube trusses and steel columns *Construction Technology* **40**(S2) 143-146.

[6] Li G L, Han W S, Chen X, et al. 2020 Wear evaluation on slide bearings in expansion joints based on cumulative displacement for long-span suspension bridge under monitored traffic flow *Journal of Performance of Constructed Facilities* **34**(1).

[7] Cui C and Sun W B 2013 FEM analysis of long-span steel structure considering bearings' size effect and friction characteristic *Applied Mechanics and Materials* **351-352** 812-817.

[8] Szydłowski R and Łabuzek 2019 Monitoring and methods of ensuring the safety of long-span post-tensioned slabs Barbara *Proceedings of the Fib Symposium 2019: Concrete - Innovations in Materials, Design and Structures* p 1452-1460.

[9] Zhao J and Liang C 2015 Structural analysis and mechanical behavior research of beam string structures *Architecture Science* **31**(01) 1-6.

[10] Zhang A L, Mu J L, Liu, et al. 2020 Experimental study on static and seismic performance of long-span steel structure in C1 area of Beijing New Airport Terminal Building *Journal of Building Structures* **41**(4) 1-10.

[11] Li Z F, Niu Z R, Ding S H, et al. 2020 Experimental research of mechanical properties of integral joints of continuous steel truss girder in pushing sliding process *Journal of Building Structures* **41**(2) 182-190.