Calculation of Unsteady Aerodynamic Forces by CFD and Their Comparison with Measured Values

by

Hiroshi Sato[1], Jun Murakoshi[2], Koichiro Fumoto[3] and Masao Miyazaki[4]

ABSTRACT

Unsteady aerodynamic forces were calculated for cross sections such as flat plate, box girder and slotted box girder. Seven methods of CFD were applied. The calculated values were compared with theoretical values or measured values from wind tunnel tests. In the case of the flat plate and the box girder, the calculated values agree well with the theoretical or measured values. In the case of the slotted box girder, however, the calculated values did not agree well with the measured values. The methods should be improved for them to be applied for slotted box girders.

KEYWORDS: CFD, Super Long-span Bridges, Unsteady Aerodynamic Forces,

1. INTRODUCTION

Public Works Research Institute has been conducting cooperative research on super long-span bridges with Honshu-Shikoku Bridge Authority, Public Works Research Center, and eight private companies. The research goal is to propose super-long span bridges that have excellent properties in aerodynamic stability and economy. One of our results is the super-long span bridge with the slotted box girder, which has been already presented [1].

Aerodynamic forces on bridge girders are usually measured in wind tunnel. On the other hand, recent progress in computer technology has advanced reliability and applicability of computational fluid dynamics (CFD). Therefore, applicability of CFD to wind resistant design of super long-span bridges was studied as the part of the research.

In the research, unsteady aerodynamic forces were calculated for cross sections such as flat plate, box girder and slotted box girder. Seven methods of CFD were applied. The calculated values were compared with theoretical values or measured values. In this paper described are the cross section of girders, applied CFD methods and the comparison between calculation and measurement.

2. CROSS SECTION OF BRIDGE GIRDER

The cross sections subjected to CFD analysis are shown in Figure-1. It was found that slotted box girder has better flutter characteristics than flat plate or single box girder, and that its characteristics can be improved by some devices like center barrier and guide vane[2]. The slotted box girder used in this research did not have the center barrier or guide vane.

3. CFD ANALYSIS METHODS

The CFD analysis methods in our research are shown in Table-1

The direct method directly calculates an unsteady N-S equation without a turbulence model. We obtained a numerical solution from acoustic, momentum conservation, mass conservation, and state equations. This method ensures tracking of instantaneous values of the turbulent field since it can directly solve the N-S equation without the use of a turbulent model. However, as the number of grid points increases, the time required for calculation sharply rises. The behavior of the vortex below the calculated grid is ignored at the same time. Method 4 was based on this technique[3].

[1] Director, Structures Research Group, Public Works Research Institute, Tsukuba-shi, Ibaraki-ken 305-8516 Japan

[2] Team Leader, Bridge Structures Research Team, ditto

[3] Senior Researcher, Bridge Structures Research Team, ditto

[4] Secretary of Cooperative Research, Sumitomo Heavy Industries Ltd, Shinagawa-ku, Tokyo 141-8686 Japan

When calculation is made according to the Reynolds-Averaged Navier Stokes Equation, turbulence model is required. The k-ε model, the representative model of differentiation method, obtains turbulent stress by solving the transport equation of the modeled turbulent energy k and ε. The k-ε model was applied to the Method 3 and 5. In Method1[4], k-ω SST model[5] was used among double equation models because of Bardina's performance evaluation[6]. In Method 2[7], q-ω model[8] which was based on the k-ε model was used.

Large eddy simulation (LES method) does not use Reynolds' equation. This method takes an in-grid space average of the N-S equation. Smagorinsky's model is frequently used. Method 6 adopted the LES method [9]

The vortex point method introduces the basic solution of a differential equation, instead of solving the differential equation for fluid motion, to formulate an integral equation and divide the boundary into a finite number of elements for boundary integration. The advantage of this method over alternative analysis methods is its small number of unknowns, whose number of dimension is less by one than the other methods. However, the method is invalid unless that the basic solution required to convert the differential equation into an integral equation is already obtained. Method 7 was based on this technique[10]

In FDM, the coordinate system which suits an object boundary well must be used to increase accuracy.(Method1, 3 and 4)[11][4]. The merits of FVM are its easiness to take boundary conditions and to acquire preservation (Method 2 and 5) [12][7]. In FEM, complicated boundary conditions can be treated and accuracy can be increased locally (Method 6).[9]

4. COMPARISON OF CALCULATED FORCES

4.1 Definition of Unsteady Aerodynamic Forces

The calculated unsteady aerodynamic forces were compared with theoretical values and experimental values. The definition of unsteady aerodynamics forces are as follows:

$$L = \pi\rho\left\{B^2\left[L_{ZR}\omega^2 z + L_{ZI}\omega z'\right] + B^3\left[L_{\theta R}\omega^2\theta + L_{\theta I}\omega\theta'\right]\right\} \tag{1}$$

$$M = \pi\rho\left\{B^3\left[M_{ZR}\omega^2 z + M_{ZI}\omega z'\right] + B^4\left[M_{\theta R}\omega^2\theta + M_{\theta I}\omega\theta'\right]\right\} \tag{2}$$

where L: lift; M: aerodynamic moment; ρ: air density; B: girder width; V: velocity; z: vertical displacement; θ: torsional displacement; and ω: circular frequency.

4.2 Flat Plate

Fig.4 compares the calculated and theoretical values of unsteady aerodynamic forces of the flat plate. Although there are some errors in the real part of lift during bending excitation obtained and the imaginary part of lift during torsional excitation, the calculated and theoretical values are almost identical. As for the flat plate, the accuracy of the CFD methods seems relatively high. This accuracy is probably caused by its flatness of the section. Because of its flatness, the effect of viscosity appears only in the upstream and downstream ends of the section. Therefore the difference in calculation methods or in turbulence modeling does not affect much.

4.3 Box Girder

Fig.5 compares the calculated and measured values of unsteady aerodynamic forces of the single box girder section. Although CFD-analyzed and experimental values do not agree as well as they do in the case of the flat plate, an approximate trend can be estimated from the CFD methods. The reasons seem to be as follows: firstly, the handrails at the upstream and downstream ends of the section and the protective fence in the median strip zone were excluded from the present research; secondly, the section of the box girder was very flat.

4.4 Slotted Box Girder

Fig.6 compares the calculated and measured values of unsteady aerodynamic forces of the slotted box girder section. The difference between the CFD-analyzed and wind tunnel experimental values tends to be larger than that of the single box girder.

Among the CFD methods, values calculated according to the Method 6 agrees fairly well with the measured values. Method 6 adopted the LES Method as the turbulence model. The LES Method seems applicable even where flow is strongly unsteady.
As shown in Fig.3, the section of the double box girder forms a very complicated vortex from mutual interference between a vortex discharged from the upstream girder end and a shear layer separated from the front edge of the downstream girder. Therefore, the vortex behavior needs to be simulated accurately. Since vortex behavior is seriously affected by the turbulence model, improvement of the turbulence model seems to be important.

5. CONCLUSIONS

Unsteady aerodynamic forces were calculated for the flat plate, box girder and slotted box girder. Seven methods of CFD were applied. The calculated values were compared with theoretical values or measured values from wind tunnel tests.
It was found that unsteady aerodynamic forces of the flat plate and the flat single box girder can be predicted fairly well by the CFD analysis. The CFD analysis can be applicable to the relatively flat single box section.
On the other hand, satisfactory results were not obtained for the slotted box girder, probably due to the complicated flow in the slot. Improvement of the turbulence model seems to be effective to improve the accuracy of calculation.
This paper is part of the results of the cooperative research conducted by Public Works Research Institute, Honshu-Shikoku Bridge Authority, Public Works Research Center, and eight private companies. We would like to take this opportunity to mention that the CFD analysis for the flat plate, single box girder, and slotted box girder were conducted by Mr. S. Kuroda at Ishikawajima-Harima Heavy Industries Co., Ltd., Mr. H. Kawamoto at Kawasaki Heavy Industries, Ltd., Dr. K. Shimada at Shimizu Corporation, Mr. D. Ichishima at Sumitomo Heavy Industries, Ltd., Mr. S. Shirai at Hitachi Zosen Corporation, Mr. S. Watanabe at Mitsui Engineering & Shipbuilding Co., Ltd., and Mr. S. Sugiyama at Mitsubishi Heavy Industries, Ltd. We would like to acknowledge and thank them for their cooperation.

6. REFERENCES

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Table 1 CFD Approaches

Methods Number	Basic Equation	Turbulence Model	Calculation
1	Reynolds-Averaged Navier Stokes Equation	k-ω	Finite Difference Method
2	Reynolds-Averaged Navier Stokes Equation	q-ω	Finite Volume Method
3	Reynolds-Averaged Navier Stokes Equation	k-ε	Finite Difference Method
4	Navier Stokes Equation	-	Finite Difference Method
5	Reynolds-Averaged Navier Stokes Equation	k-ε	Finite Volume Method
6	Reynolds-Averaged Navier Stokes Equation	Large Eddy Simulation	Finite Element Method
7	Laplace Equation (Vortex points method)	-	Boundary Element Method

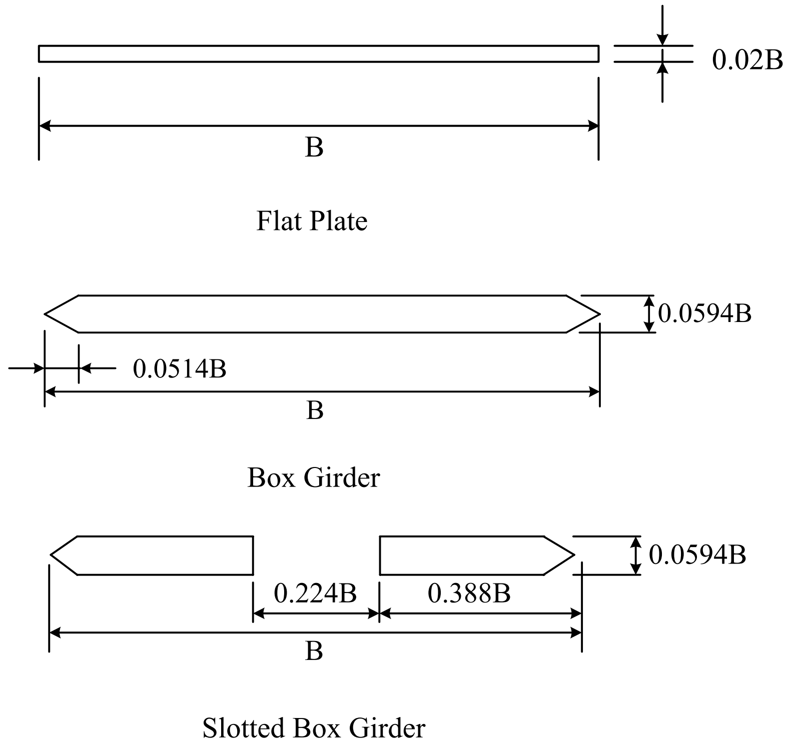

Fig.1 Cross Section

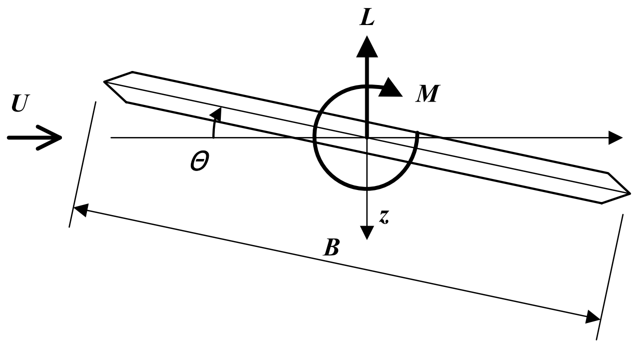

Fig.2 Definition of Forces and Displacement

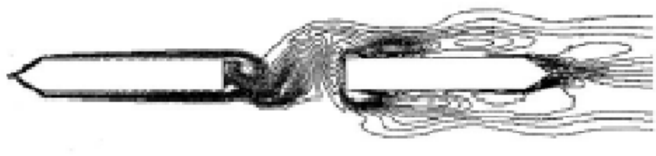

Fig.3 Flow around Slotted Box Girder

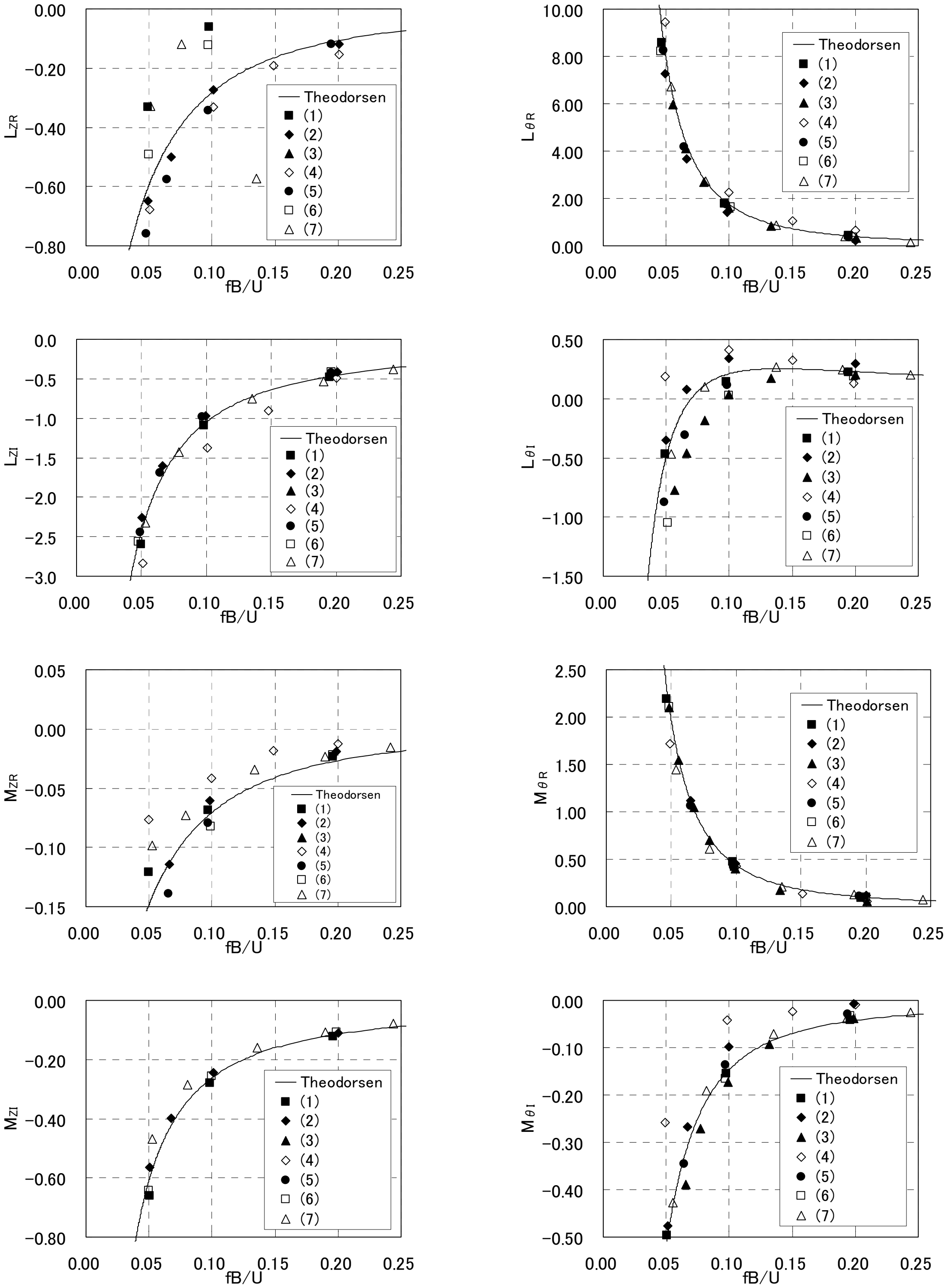

Fig.4 Comparison between Experimental and CFD values for the Unsteady Aerodynamics of a Flat Plate

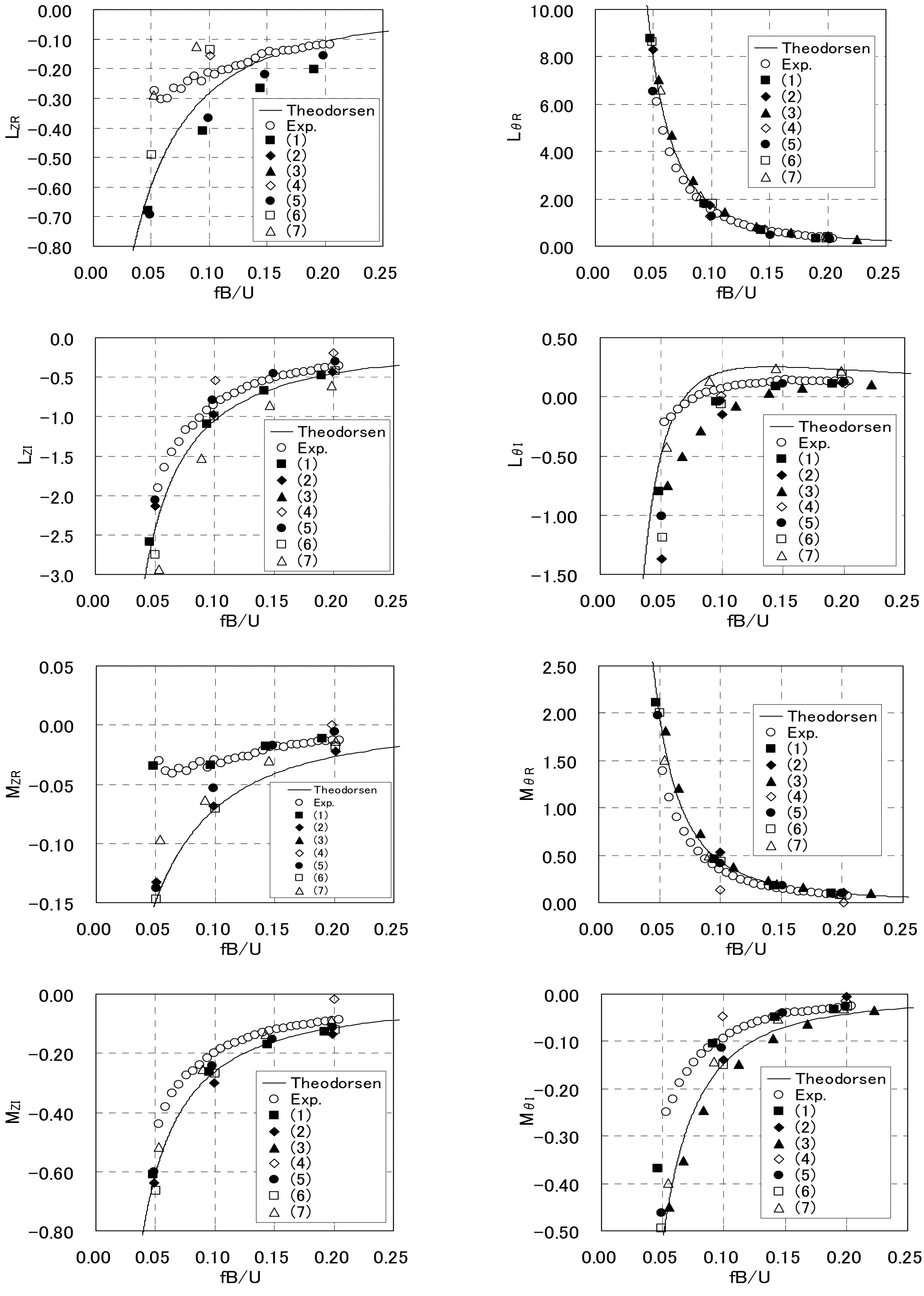

Fig.5 Comparison between Experimental and CFD values for the Aerodynamics of a Single Box Girder

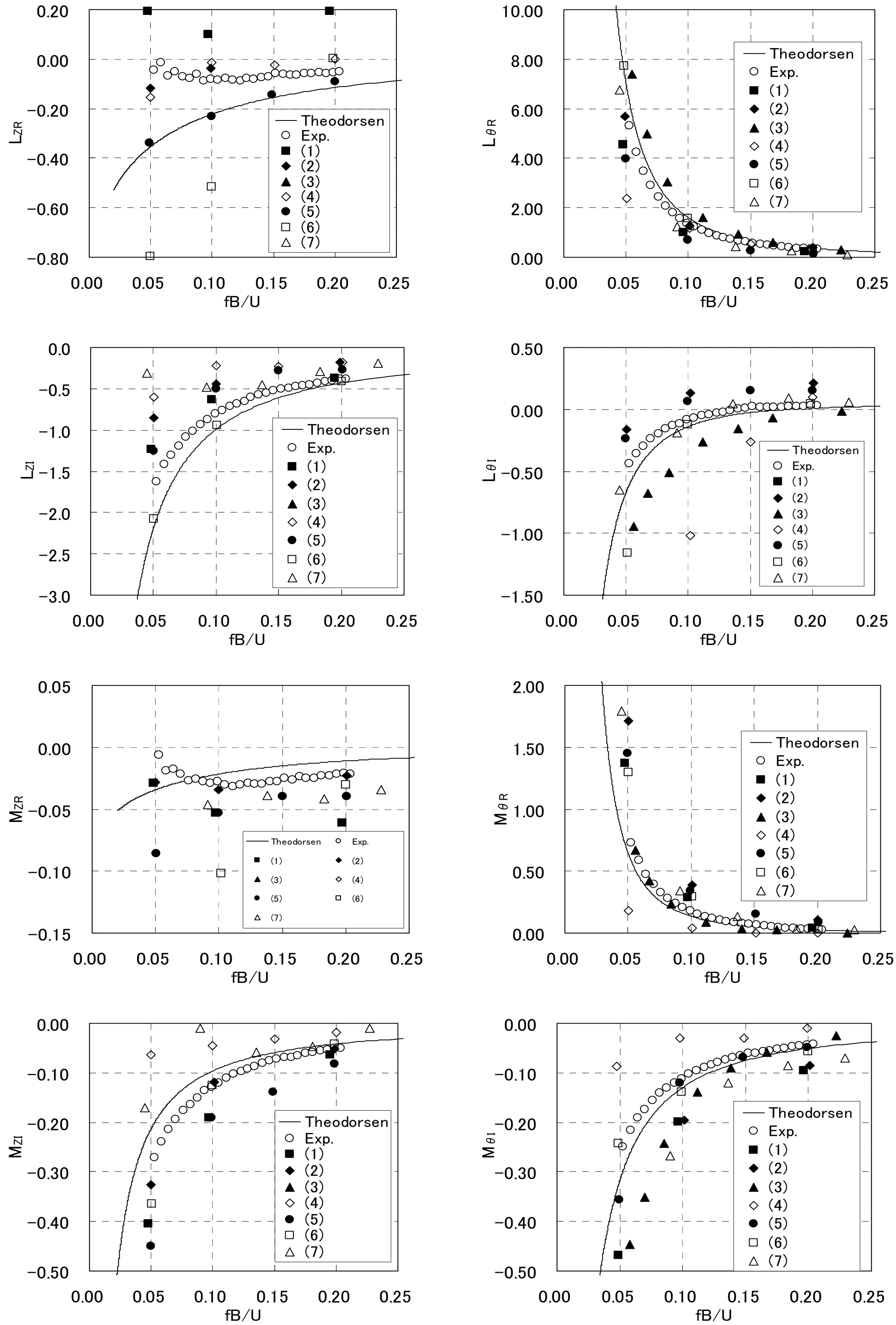

Fig.6 Comparison between Experimental and CFD values for the Unsteady Aerodynamics of a Slotted Box Girder