Wind Engineering Joint Usage/Research Center
FY2014 Research Result Report

Research Field: **Wind Hazard Mitigation/Wind Resistant Design**

Research Period: **FY2014～FY2015**

Research Number:

Research Theme: **Equivalent Analysis on Wind-induced Vibration of Membrane Structures Considering Solid-fluid Interaction**

Representative Researcher: **Prof. Yuanqi Li**

Budget [FY2014]: **350,000 Yen**

*If the research was not continuous, this will be the Final Result Report, so the contents of the report has to be detailed.
*There is no limitation of the number of pages of this report.
*Figures can be included to the report and they can also be colored.
*Submitted reports will be uploaded to the JURC Homepage.

1. Research Aim

This project mainly focuses on realization of numerical estimation on wind-induced vibration of membrane structures considering solid-fluid interaction with equivalent effect of air flow around membrane units in FE analysis.

2. Research Method

The main research contents includes: 1) Experimental investigation on added mass of curved membranes; 2) BLWT Experimental investigation of wind-induced vibration of scaled membrane structures; 3) Equivalent method on wind-induced vibration analysis of membrane structures considering solid-fluid interaction.

With above works, a dynamic FE analysis framework using the proposed modal-dependent added mass model is established to simplify wind-induced vibration analysis of membrane structures considering solid-fluid interaction.

3. Research Results

3.1 Experimental investigation on added mass of curved membranes

1) Experimental objective

The objective of this experiment is to study the effect of surrounding air on the vibration characteristics of curved membrane and verify whether or not the proposed model for added-mass, especially the added-mass coefficient of flat membrane 0.65 can be applied to curved membranes.

2) General introduction

It’s a coupled vibration test of open umbrella membrane under static wind that conducted in a vacuum chamber. The flat membrane was clipped by an inner circle and an outer circle, the diameter of the circle membrane is 30cm (Fig.1). Due to the limitation of the vacuum pump and the chamber’s leakproofness, a complete vacuum could not be achieved. The vibration of membranes was measured in 6 levels of air pressures, i.e., 1.0, 0.8, 0.6, 0.4, 0.2 and 0.05atm. Four laser-displacement sensors were used to measure the vibration displacement (one of the four sensors is specially used to measure the additional circuit error) and a suit of dynamic signal analysis system was used for data acquisition and processing. An isotropic latex membrane, with thickness 0.23mm, was used in the experiment. The incentive method in normal atmosphere condition was to apply small impact load to the membrane surface, while in the other's condition, the incentive was applied by acoustic excitation. All the test cases are listed in Table 1.

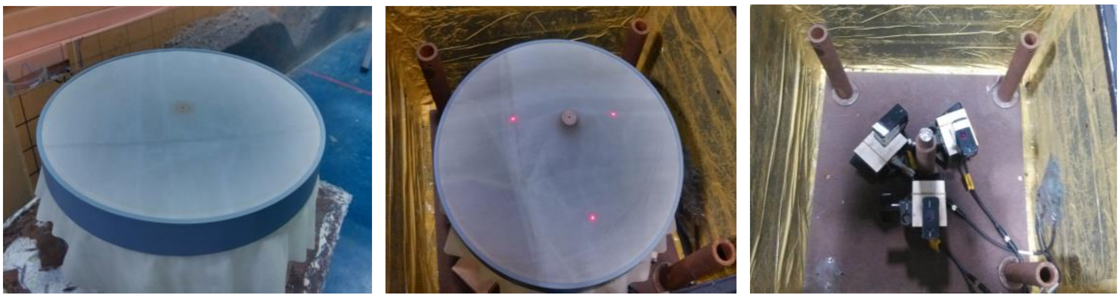


Fig.1 Models in testing

Table 1 The test cases

Air pressure (atm)	Plannar circle membrane			Umbrella membrane					
	σ_1	σ_2	σ_3	σ_1		σ_2		σ_3	
				1/10	1/6	1/10	1/5	1/10	1/5
1	A1	B1	C1	A11	A12	B11	B12	C11	C12
0.8	A2	B2	C2	A21	A22	B21	B22	C21	C22
0.6	A3	B3	C3	A31	A32	B31	B32	C31	C32
0.4	A4	B4	C4	A41	A42	B41	B42	C41	C42
0.2	A5	B5	C5	A51	A52	B51	B52	C51	C52
0.05	A6	B6	C6	A61	A62	B61	B62	C61	C62

*1atm is the standard atmosphere pressure;
*1/10,1/6,1/5 are the rise-span ratios of the umbrella membrane respectively.

3) Experimental program

Firstly, the natural vibration frequency of the planar circle membrane with various prestress in different pressure level can be obtained, then the fundamental frequency of the membrane in vacuum condition and the added-mass coefficient can be obtained by fitting the curve of the relationship between $1/f_t^2$ and ρ with the least square method, as used in Ref.[1]. The initial stress in the membrane can be back calculated by the followed formulation:

$$\sigma = m_s \left(2\pi f_s a / 2.4048\right)^2 / d$$

where σ is the initial stress in membrane of unit width, a is radius of the membrane, d is the membrane thickness, m_s is the membrane mass. According to the calculated prestress, the natural vibration frequency was computed by numerical simulation, then the results were compared with that obtained by the test.

Secondly, the center support was raised to transform the planar membrane to be an umbrella shape membrane, then the natural vibration frequency of the umbrella membrane can be obtained by conducting the coupling vibration test again at various pressure. At last the vacuum frequency and added-mass coefficient can be calculated as the flat membranes in Ref.[1].

Thirdly, keep the initial stress of planar membrane in numerical simulation and raise the center support the same height as in the test, impose added mass to the membrane, then calculate the natural vibration frequency of the umbrella membrane.

4) Main test results

With the same techniques used in Ref.[1], The fundamental frequency of the membrane vibrating in vacuum, as well as the prestress levels in each cases, can be obtained by fitting analysis of the test data, as shown in Table 2. Meanwhile, the fundamental frequency results were compared with the results obtained by FE Analysis in Table 2, and it can be found that they have very good agreement with each other.

Table 2 Fundamental frequency of the membrane vibrating in vacuum

Prestress	Flat circle membrane		Umbrella membrane			
			Rise-span ratio 1/10		Rise-span ratio 1/5(1/6)	
	FE Analysis (Hz)	Fitting result of test (Hz)	FE Analysis(Hz)	Fitting result of test(Hz)	FE Analysis(Hz)	Fitting result of test(Hz)
σ_1=0.41MPa	51.76	51.76	72.6	71.6	77.43(1/6)	76.27(1/6)
σ_2=0.93MPa	77.86	77.83	109.82	105.55	111.88	104.95
σ_3=0.57MPa	60.96	60.86	84.21	83.98	91.07	92.38

Then, the fundamental frequencies in each cases corresponding to 6 levels of air pressures were identified by FDD method, and listed in Table 3.

Table 3 Fundamental frequency based on test results

Case	Fundamental frequency(Hz)	Case	Fundamental frequency(Hz)	Case	Fundamental frequency(Hz)
A10	39.06	B1	55.66	C1	43.95
A20	41.02	B2	58.59	C2	46.88
A30	42.3	B3	61.52	C3	48.83
A40	×	B4	66.41	C4	52.73
A50	×	B5	72.26	C5	56.64
A60	50.78	B6	75.2	C6	58.59
A11	57.62	B11	83.01	C11	69.34
A21	60.55(0.7atm)	B21	86.91	C21	71.29
A31	62.5(0.5atm)	B31	89.84	C31	73.24
A41	×	B41	95.7	C41	76.17
A51	70.31(0.1atm)	B51	100.58	C51	80.08
A61	×	B61	102.59	C61	83.98
A12	60.55	B12	83.01	C12	73.24
A22	63.48	B22	86.91	C22	75.19
A32	65.43	B32	89.84	C32	79.1
A42	67.38	B42	95.7	C42	83.98
A52	70.31	B52	100.58	C52	87.89
A62	75.19	B62	101.56	C62	88.87
* The cases B12-B62 were tested one day after the cases B11-B61, so stress relaxation may occur.					

Based on the fundamental frequencies of the membranes vibrating in each cases corresponding to 6 levels of air pressures, we can obtained the added-mass coefficient with the same techniques used in Ref.[1] for flat membranes, as shown in Table 4. It can be found that, the coefficient, 0.65, which has been established for flat membranes in Ref.[1], seems still reasonable for the curved membranes.

Table 4 Estimated added-mass coefficients

Prestress	Flat circle membrane	Umbrella membrane	
		Rise-span ratio 1/10	Rise-span ratio 1/5(1/6)
σ_1=0.41MPa	0.437	0.6554	0.6898(1/6)
σ_2=0.93MPa	0.56	0.707	0.6816
σ_3=0.57MPa	0.521	0.5677	0.7026

Using the Simplified calculation method proposed in Ref.[1] and [2] for added-mass estimation of the tested curved membranes, the fundamental frequency can be obtained by FE Analysis considering the effect of added-mass, and the results were compared with the results based on tests, as shown in Table 5. A good agreement can also be achieved, which means that the simplified added-mass model can be used for estimating the added mass of curved membranes.

Table 5 Fundamental frequency of membranes vibrating in atmosphere

Prestress	Plannar circle membrane		Umbrella membrane			
			Rise-span ratio 1/10		Rise-span ratio 1/5(1/6)	
	Simplified calculation method(Hz)	Test result (Hz)	Simplified calculation method(Hz)	Test result(Hz)	Simplified calculation method(Hz)	Test result(Hz)
σ_1=0.41MPa	36.38	39.06	58.21	57.62	62.2(1/6)	60.55(1/6)
σ_2=0.93MPa	55.06	55.66	84.7	83.01	89.86	83.01
σ_3=0.57MPa	43.1	43.95	67.65	69.34	73.15	73.24
* The added-mass coefficient α=0.65 is applied in the simplified calculation method.						

3.2 BLWT investigation of wind-induced vibration of scaled membrane structures

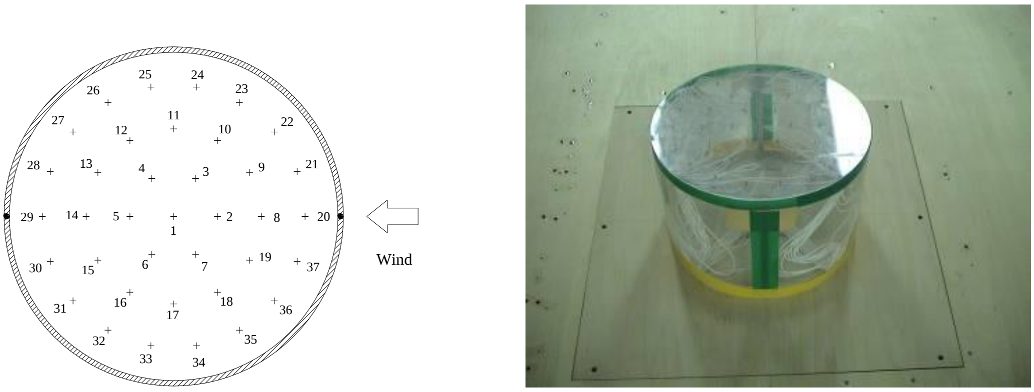
1) Test models

The test model is a circular flat roof. The diameter and the height of the model are 3m and 2m, respectively. The wind tunnel tests were conducted in Wind Engineering Research Center, Tokyo Polytechnic University. The turbulence intensity at the top of the model is 0.21. The expotential index of the wind speed profile is 0.3. Firstly, wind pressure distribution on a circular membrane was obtained by wind tunnel test on rigid model. Wind pressure measuring points were shown in Fig.2. Meanwhile, a corresponding aeroelastic model of the circular membrane was fabricated to get the wind-induced vibration. The scaling parameters were shown in Table 6.

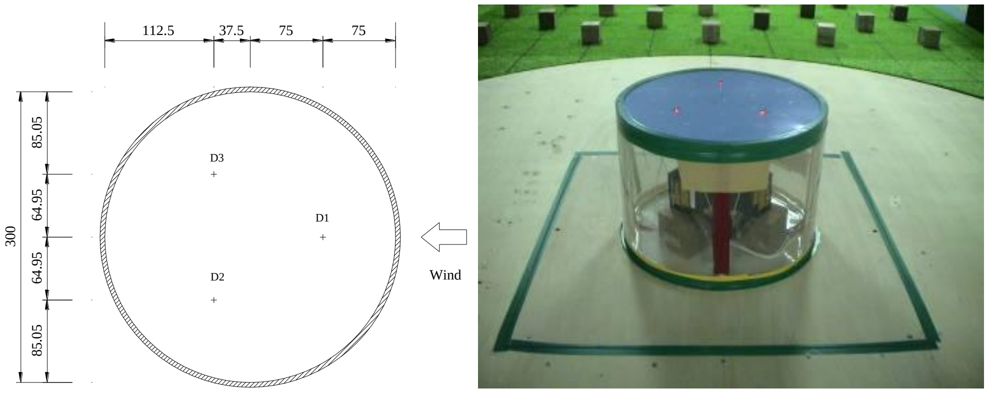
Table 6 Scaling parameters of the aeroelastic model

Parameter	Equation	Scale	Prototype	Model (Required)	Model (Measured)
Length	L	λ_L	3m	0.3m	0.3m
velocity	U	$\lambda_U = \lambda_L / \lambda_t$	33m/s	5m/s	5 m/s
Mass per unit area	M	$\lambda_M = \lambda_L$	1.2kg/m^2	0.12kg/m^2	0.15kg/m^2
Prestress	P	$\lambda_P = \lambda_L^3 / \lambda_t^2$	1kN/m	2.296N/m	2.18N/m
Elastic stiffness	Ed	$\lambda_{Ed} = \lambda_L^3 / \lambda_t^2$	500N/mm	1.148N/mm	0.945N/mm
Damping ratio	ξ	$\lambda_\xi = 1$	-	-	1~2%

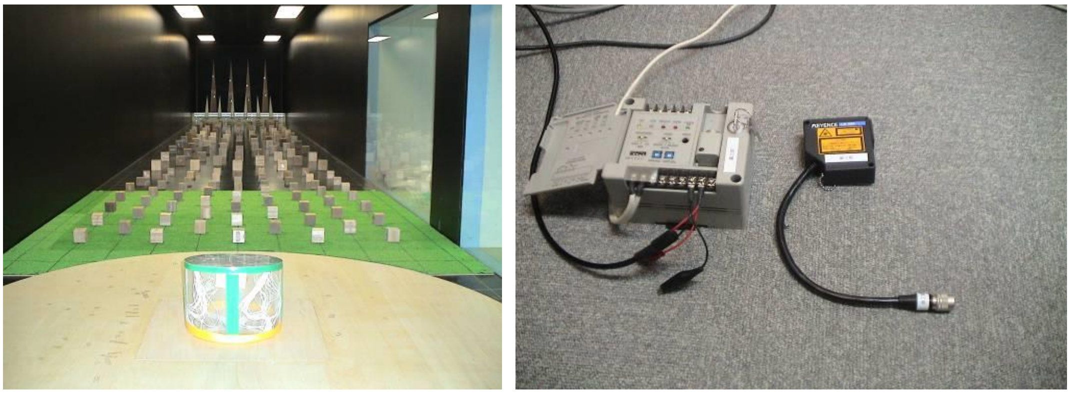
Laser displacement sensors were used to measure the wind induced vibration. The sampling frequency is 781.25Hz. The arrangement of measuring points was shown in Fig.2.



(a) Wind pressure measuring points on rigid model



(b) Displacement measuring points on aeroelastic model



(c) Photos in BLWT of Tokyo Polytechnic University

Fig.2 Wind tunnel tests on circular flat roofs

2) Test results

Considering the distortion of the tube in the pressure data acquisition system to the wind pressure signal, sinusoidal swept technology is used to correct the wind pressure test results. Fig.3 and Fig.4 shows the wind pressure distribution measured from the rigid model test.

In the test, it is difficult to measure the prestress of the membrane directly. Because the natural frequency was affected by the prestress, the prestress could be obtained by the analysis of the natural frequency. For the membrane with prestress level P0, P1 and P2, is 2.18 N/m, 30.93 N/m and 48.73N/m.

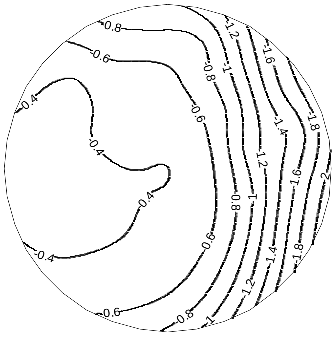


Fig.3 Mean wind pressure coefficients

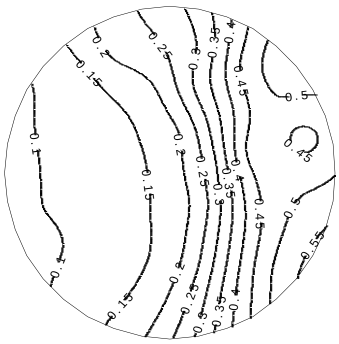
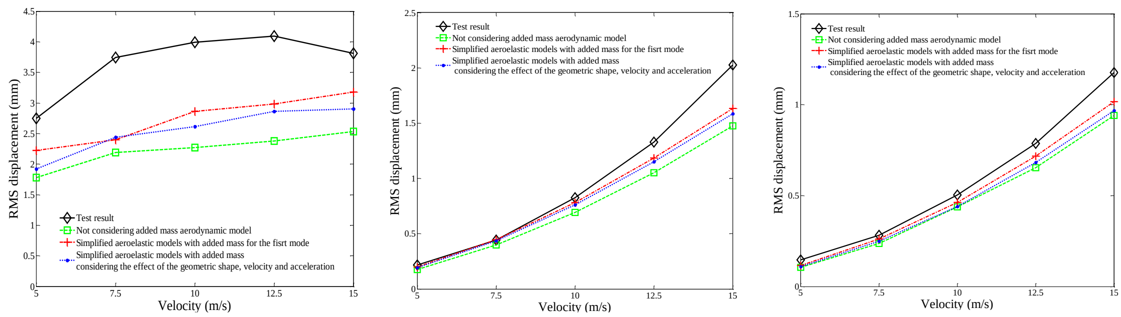


Fig.4 RMS wind pressure coefficients

3.3 Equivalent method on wind-induced vibration analysis of membrane structures considering solid-fluid interaction

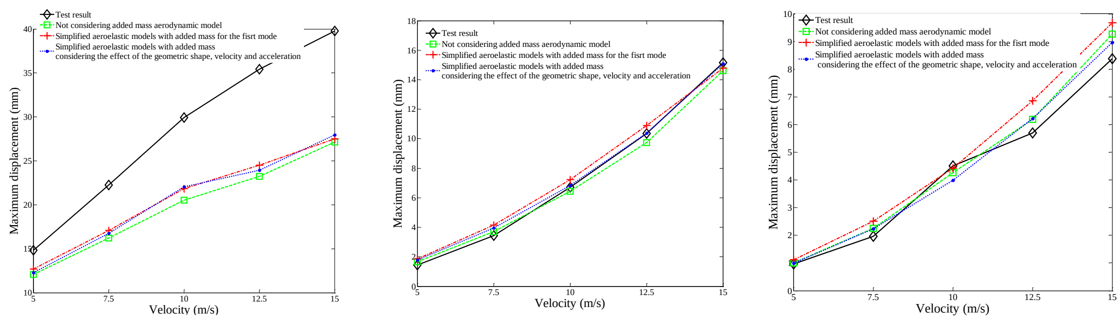
1) Equivalent dynamic analysis considering solid-fluid interaction by the added mass concept

An equivalent dynamic analysis method for wind-induced vibration of membranes considering solid-fluid interaction by the added mass concept is established, and the corotational formulation is used for nonlinear dynamic analysis. On account of different added mass models, two simplified aeroelastic models were discussed, one with added mass for the first mode and the other with added mass considering the effect of the geometric shape, velocity and acceleration. Based on the wind pressure time histories obtained from wind tunnel tests on the rigid model, the wind-induced vibration in time domain was analyzed. The programme is compiled by C++. The elastic modulus of the membrane is 4.3MPa. Fig.5 and Fig.6 compared the test results and the dynamic analysis results on the displacement of measuring point D1 of the membrane with prestress level P0, P1 and P2, respectively.



(a) P0 prestress level (b) P1 prestress level (c)P2 prestress level

Fig.5 RMS displacement at point D1 of the circular membrane



(a) P0 prestress level (b) P1 prestress level (c) P2 prestress level

Fig.6 Maximum displacement at point D1 of the circular membrane

For prestress level P0, the mean displacement and the RMS displacement of the dynamic analysis are lower than that of test results, which is properly due to the plasticity of the membrane when experiencing large deformation. The root mean square displacement and the maximun displacement derived by simplified aeroelastic model considering added mass is closer to the test results than the results derived by aeroelastic model not considering added mass. When the velocity is large, the advantage of considering added mass is more obvious. The root mean square displacement by simplified aeroelastic model considering added mass is much larger than the result derived by aeroelastic model not considering added mass. Therefore, it is not safe if the added mass was not considered in the dynamic analysis of membrane structures.

3.4 Conclusions

Based on the tests and numerical analysis, the following conclusions can be drawn:

1) The simplified added-mass model proposed previously based on the flat membranes can be efficiently used for estimating the added mass of curved membranes.

2) The influence of added mass on wind-induced vibration of a circular membrane was investigated by wind tunnel tests. According to the test results, the added mass has great influence on the wind induced vibration of membranes, which means the solid-fluid interaction has to be considered.

3) The displacement derived by the simplified aeroelastic model considering added mass is closer to the test results than the results derived by aeroelastic model without consideration of added mass. It may be not safe if the added mass was not considered in the dynamic analysis of membrane structures.

4) Two simplified aeroelastic models, one with added mass for the first mode and the other with added mass considering the effect of the geometric shape, velocity and acceleration, were proposed based on the simplified added-mass model, and the efficiency was proved by comparing analysis between test results and corresponding numerical analysis.

4. Published Paper, etc.

1) Zhou Y, Li YQ, Shen ZY, Wand L and Tamura Y, Numerical analysis of added mass for open flat membrane vibrating in still air using the boundary element method, JWEIA, 2014, 131(8): 100–111
2) Yuanqi Li, Yi Zhou, Lei Wang, Zuyan Shen and Yukio Tamura, Experimental and numerical investigation on added mass of membrane structures, Workshop of Wind-induced Vibration of Large-span Spatial Structures, Dec. 15, 2015, Shanghai.
3) Yuanqi Li, Yi Zhou, Lei Wang, Zuyan Shen and Yukio Tamura, Wind-induced vibration of a circular membrane considering added mass effect based on wind tunnel tests, Workshop of Wind-induced Vibration of Large-span Spatial Structures, Dec. 15, 2015, Shanghai.
4) Zhou Y, Li YQ, Shen ZY, Wand L, Yoshida A and Tamura Y, Experimental investigation on the wind pressure distribution on circular flat roofs with different flexibility, submitted to JWEIA.
5) Zhou Y, Li YQ, Shen ZY, Wand L, Yoshida A and Tamura Y, Aeroelastic wind tunnel test on circular flat membrane structures, submitted to JWEIA.

5. Research Organization

1) Representative Researcher

Yuanqi Li	Tongji University, China, Professor

2) Collaborate Researchers

Akihito Yoshida	Tokyo Polytechnic University, Japan, Associate Professor
Yukio Tamura	Tokyo Polytechnic University, Japan, Professor
Akira Katsumura	Wind Engineering Institute Co., Ltd., Japan, Ph.D.
Yi Zhou	Tongji University, China, Ph.D. Candidate

6. Research workshop

Workshop of Joint Usage/Research Center of Wind Engineering, Wind Engineering Research Center, Tokyo Polytechnic University, entitled by *Wind-induced Vibration of Large-span Spatial Structures*, was held in Department of Structural Engineering, Tongji University, Shanghai, China, Dec.15, 2014. The program of the workshop is shown in Table 7 as follows.

Table 7 Program of Workshop on *Wind-induced Vibration of Large-span Spatial Structures*

09:00 - 09:15	Welcome Prof. Yuanqi Li	Tongji University, China
		Chair: Prof. Akihito Yoshida
09:15 - 09:45	**Prof. Shuyang Cao** Tornado-induced wind pressure on a cooling tower	Tongji University China
09:45 – 10:15	**Mr. Huyue Sun**, Ph.D. candidate **Prof. Jihong Ye** 3-D characteristics of separation bubble around large-span flat roofs by PIV technique	Southeast University China
10:15 - 10:30	Tea break	
		Chair: Prof. Jihong Ye
10:30 - 11:00	**Prof. Yuanqi Li** Experimental and numerical investigation on added mass of membrane structures	Tongji University China
11:00 - 11:30	**Mr. Yi Zhou**, Ph.D. candidate **Prof. Yuanqi Li** Wind-induced vibration of a circular membrane considering added mass effect based on wind tunnel tests	Tongji University China
12:00 - 13:15	Lunch	Banmuyuan Restaurant
		Chair: Prof. Yuanqi Li
13:30 - 14:00	**Prof. Akihito Yoshida** Field measurement and system identification of large span structures	Tokyo Polytechnic University Japan
14:00 - 14:30	**Prof. Zhihong Zhang** Field measurement of wind pressure and wind resistance design of Yueqing Stadium	Shanghai Normal University, China
14:30 - 15:00	**Dr. Yanjun Lin** **Mr. Zhaoyang Li**, Ph.D. candidate **Prof. Qilin Zhang** Theoretical and experimental research on wind-induced vibration of membrane and cable-net structures	Shanghai No.7 Construction Co. Ltd. Tongji University, China
15:00 - 15:20	Discussion	
15:20 - 15:30	Final comments and acknowledgements Prof. Akihito Yoshida Prof. Yuanqi Li	Tokyo Polytechnic University Japan Tongji University, China
15:30 - 15:50	Tea break & group photo	
16:00 - 17: 00	Wind tunnel tour in TJU campus TJ-2 & TJ-3, Tornado simulation	Venue: Wind Tunnel Laboratory, Tongji University

References

[1] Li Y.Q., Wang L., Shen Z.Y., Tamura Y., Added mass estimation of flat membranes vibrating in still air, Journal of Wind Engineering & Industrial Aerodynamics, 2011, 99(8), 815-824.

[2] Zhou Y., Li Y.Q., Shen Z.Y., Wand L. and Tamura Y., Numerical analysis of added mass for open flat membrane vibrating in still air using the boundary element method, Journal of Wind Engineering & Industrial Aerodynamics, 2014, 131(8): 100–111.