Wind Engineering Joint Usage/Research Center
FY2015 Research Result Report

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

Research Period: **FY2015～FY2016**

Research Number: 152002

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

Representative Researcher: **Prof. Yuanqi Li**

Budget [FY2015]: **444,000 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 developing and verifying of equivalent method for wind-induced vibration of membrane structures considering solid-fluid interaction with the concept of added mass.

2. Research Method

The main research contents includes: 1) Development of equivalent method for wind-induced vibration of membrane structures with the concept of added mass; 2) BLWT Experimental investigation and verification on wind-induced vibration of membrane structures with a little complex shape; 3) Further verification by filed monitoring data of wind-induced response of a practical project, Yueqing Stadium, in China.

With above works, an equivalent dynamic analysis framework using the proposed modal-dependent added mass model will be established to simplify wind-induced vibration analysis of membrane structures with practical size and shape considering solid-fluid interaction.

3. Research Results

3.1 Development of equivalent method for wind-induced vibration of membrane structures with the concept of added mass

1) Test introduction

A circular flat roof was used as the test model. The wind tunnel tests were conducted in Wind Engineering Research Center, Tokyo Polytechnic University. The detail of wind tunnel tests can be referred to Ref.[1]. Because the natural frequency is affected by the prestress, the prestress can be obtained by analyzing of the natural frequency, as shown in Ref.[2]. The prestress of the membranes is listed in Table 1.

2) Numerical analysis method

An equivalent method for wind-induced vibration of membrane structures with the concept of added mass is established. Firstly, wind pressure based on the measuring points of the rigid model can be decomposed into mean pressure and fluctuating pressure. Secondly, through the interpolation method, the mean pressure on the measuring points can be tranformed to the mean pressure on all the nodes of FE model. Meanwhile, through the interpolation method based on POD modes, the fluctuating pressure on the measuring points can be tranformed to the fluctuating pressure on all the nodes of FE model. Then, through superposition of the mean pressure and the fluctuating pressure, the total pressure can be derived out. Finally, nonlinear dynamic analysis is conducted to derive the displacement response. An equivalent dynamic analysis framework of numerical analysis method is shown in Fig.1.

Table 1 Prestress in the membrane

Prestress level	**Test** ***f*** (Hz)	**Fundamental frequency** f_t （Hz）	**Fundamental frequency** f_s （Hz）	**Prestress** ***F*** (MPa)
P0	6.3	6.08	9.77	0.0145
P1	22.62	22.62	36.64	0.207
P2	28.42	28.42	45.99	0.326

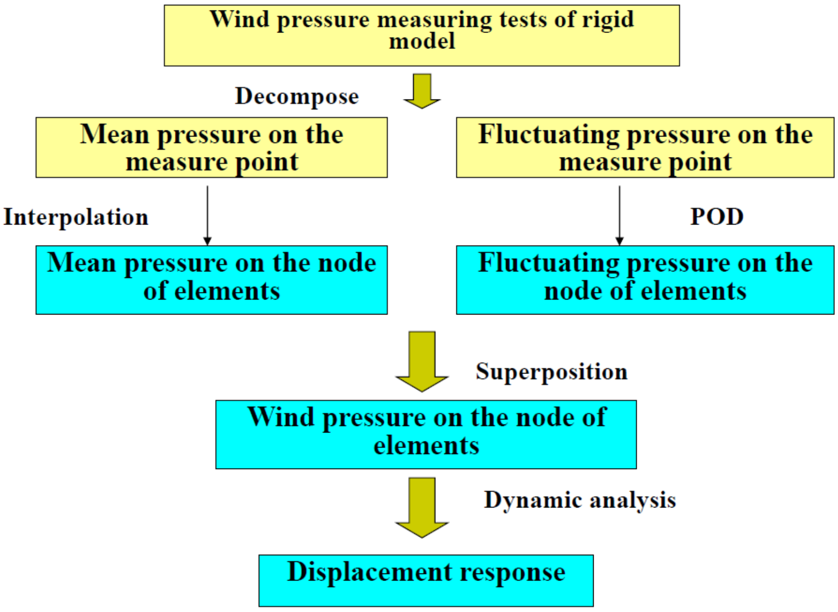


Fig.1 Framework of numerical analysis method of displacement response

When dynamic nonlinear analysis, on account of different added mass models, two simplified aeroelastic models are discussed, one with the added mass considering added mass coefficient 0.65 and the other with the added mass considering the effect of the geometric shape, velocity and accelerationt.

The total programme is compiled by C++. The boundary element method is used to calucate the added mass and the corotational formulation is used for geometric nonliear analysis of membrane.

3) Main numerical analysis results

Table 2 and Table 3 show the results for prestress level P0, especailly the error between the test results and the results of dynamic analysis on the maximum displacement and the RMS displacement. As Table 2 shown, for the maximum displacement, without added mass, the mean error is 26.23%, and the max error is 36.55%; With added mass of an added mass coefficient 0.65, the mean error is 26.53%, and the max error is 38.80%; With added mass considering the effect of geometric and mode shape, the mean error is 26.23%, and the max error is 35.75%. As Table 3 shown, for the RMS displacement,without added mass, the mean error is 57.08%; with added mass of an added mass coefficient 0.65, the mean error is 55.74%; while with added mass considering the effect of geometric and mode shape, the mean error is 56.49%.

Table 2 The error between the test results and the results of dynamic analysis on maximum displacement (Prestress level P0)

Velocity	Without added mass			With added mass					
				First method			Second method		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
5m/s	21.25	29.57	36.55	28.07	29.76	34.85	27.27	34.58	35.33
7.5m/s	24.86	33.07	27.43	29.59	31.01	38.81	30.52	25.77	35.75
10m/s	24.05	30.39	19.27	30.93	21.29	16.92	28.42	23.69	12.67
12.5m/s	22.12	27.02	30.84	30.58	21.78	16.12	31.28	21.52	16.14
15m/s	17.10	24.18	25.74	30.75	22.31	15.16	26.09	24.96	17.89

Table 3 The error between the test results and the results of dynamic analysis on the RMS displacement (Prestress level P0)

Velocity	Without added mass			With added mass					
				First method			Second method		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
5m/s	51.70	62.20	65.32	51.27	53.24	57.77	53.31	57.66	61.72
7.5m/s	55.96	65.32	68.38	58.07	63.71	68.01	57.95	64.11	68.18
10m/s	51.67	62.92	65.46	51.72	58.04	62.26	51.91	57.17	61.21
12.5m/s	43.80	61.82	63.64	46.83	57.13	60.47	47.60	57.26	60.90
15m/s	24.21	55.93	57.93	36.72	53.79	57.12	34.39	55.07	58.89

Table 4 and Table 5 show the results for prestress level P1, especailly the error between the test results and the results of dynamic analysis on the maximum displacement and the RMS displacement. As Table 4 shown, for the maximum displacement, without added mass, the mean error is 13.41%, and the max error is 52.14%, the second max error is 41.69%; with added mass of an added mass coefficient 0.65, the mean error is 11.38%, and the max error is 30.60%, the second max error is 28.04%; With added mass considering the effect of geometric and mode shape, the mean error is 10.25%, and the max error is 30.00%%, the second max error is 23.40%. As Table 5 shown, for the RMS displacement, without added mass, the mean error is 17.84%; with added mass of an added mass coefficient 0.65, the mean error is 9.92%; While with added mass considering the effect of geometric and mode shape, the mean error is 10.69%.

Table 4 The error between the test results and the results of dynamic analysis on maximum displacement (Prestress level P1)

Velocity	Without added mass			With added mass					
				First method			Second method		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
5m/s	14.09	21.32	6.06	28.04	3.59	6.95	22.93	3.10	9.85
7.5m/s	7.24	52.14	0.14	20.18	30.60	1.12	14.84	30.00	3.84
10m/s	3.93	41.69	4.36	7.86	23.72	7.05	1.86	23.40	9.08
12.5m/s	5.92	27.85	3.50	5.44	13.92	2.13	0.36	13.84	2.63
15m/s	3.45	7.48	1.95	2.35	11.97	5.74	0.36	11.90	5.99

Table 5 The error between the test results and the results of dynamic analysis on the RMS displacement (Prestress level P1)

Velocity	Without added mass			With added mass					
				First method			Second method		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
5m/s	15.55	7.34	17.65	13.17	10.47	24.98	4.66	14.00	25.07
7.5m/s	7.42	9.25	15.57	17.44	2.35	1.60	8.42	3.46	14.90
10m/s	1.37	4.83	16.36	1.25	1.62	1.71	0.28	4.16	7.79
12.5m/s	1.97	3.51	5.04	4.12	6.68	8.46	1.08	7.60	10.78
15m/s	3.94	6.02	12.67	3.44	8.24	11.99	7.90	11.63	12.08

Table 6 and Table 7 show the results for prestress level P2, especailly the error between the test results and the results of dynamic analysis on the maximum displacement and the RMS displacement. As Table 6 shown, for the maximum displacement, without added mass, the mean error is 12.70%, and max error is 33.47%; with added mass of an added mass coefficient 0.65, the mean error is 15.46%, and the max error is 31.20%; with added mass considering the effect of geometric and mode shape, the mean error is 11.20%, and max error is 23.64%. As Table 7 shown, for the RMS displacement, without added mass, the mean error is 16.60%; with added mass of an added mass coefficient 0.65, the mean error is 11.01%; While with added mass considering the effect of geometric and mode shape, the mean error is 13.51%.

Table 6 The error between the test results and the results of dynamic analysis on maximum displacement (Prestress level P2)

Velocity	Without added mass			With added mass					
				First method			Second method		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
5m/s	3.03	3.81	18.84	15.00	1.15	28.19	2.62	7.21	20.75
7.5m/s	14.89	19.00	21.71	27.86	21.52	31.20	14.28	14.63	23.64
10m/s	5.67	33.47	13.64	1.77	25.57	10.59	11.53	21.05	4.12
12.5m/s	8.63	4.91	1.28	20.43	3.83	8.94	9.19	2.06	3.61
15m/s	10.71	24.61	6.29	15.53	10.42	9.99	7.00	13.21	13.21

Table 7 The error between the test results and the results of dynamic analysis on the RMS displacement (Prestress level P2)

Velocity	Without added mass			With added mass					
				First method			Second method		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
5m/s	8.60	22.84	23.28	8.94	10.55	8.64	10.77	12.14	10.97
7.5m/s	0.47	9.93	9.29	0.20	27.51	8.16	1.96	25.02	5.23
10m/s	6.09	4.10	14.00	5.62	12.20	3.67	7.96	9.44	0.28
12.5m/s	0.84	12.76	21.83	10.87	3.24	4.26	13.48	0.16	8.26
15m/s	7.24	27.17	29.20	19.50	13.29	12.21	21.89	16.58	16.30

To sum up, considering the added mass in dynamic analysis, it may be excited or restrained the displacement response.For low prestress level, the influence of the added mass on dynamic analysis is limited. While for high prestress level, dynamic analysis considering the added mass can significantly decrease the mean error on the RMS displacement, and decrease the mean error, maximum error on the maximum displacement. Hence, for high prestress level, the influence of the added mass on dynamic analysis is significant.The results of the added mass model considering the effect of geometric and mode shape are better than those considering added mass of an added mass coefficient 0.65.

3.2 Experimental investigation on added mass of curved membranes in wind tunnel

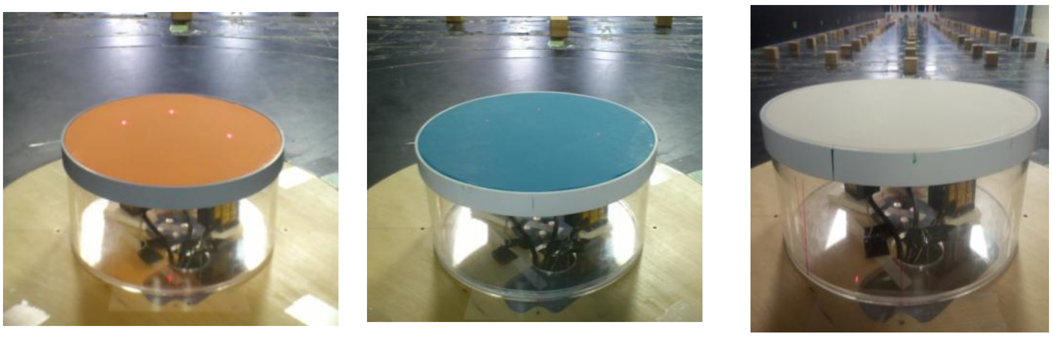
1) Experimental objective

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

2) General introduction

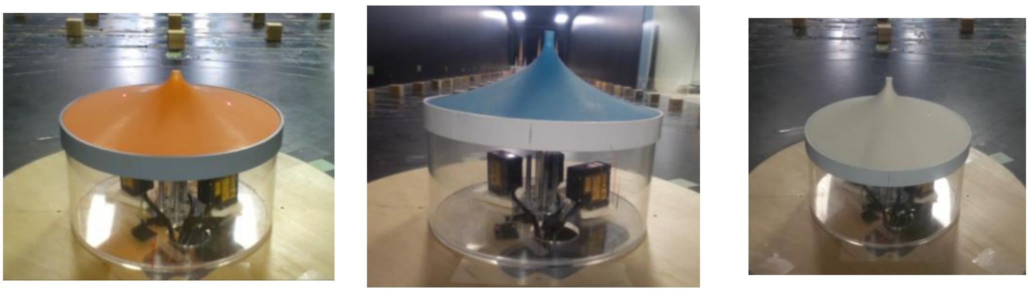
The model is a simple cylindrical building with a dome as roof. The height of circular umbrella membrane will be changed in order to study influence of membrane shape on the vibration. The aeroelastic model use a kind of rubber sheet. The rubber sheet is clipped by a top circle and a bottom circle. the prestress can be imposed uniformly by lifting the inner circle. Three models of circular membrane with different thickness are conducted, then the circular umbrella membrane can be conducted by uplifting the middle support with a height of 70mm, as shown in Fig.2. Two levels of tension stress corresponding to level I and level II are imposed on the circular membrane. Three laser-displacement sensors were used to measure the vibration displacement.

Firstly, the vibration frequency and the aerodynamic damping of curved membrane element with different geometrical shapes and tension level will be investigated in static air. Secondly, though the wind tunnel tests, the structural response, vibration frequency and aerodynamic damping of the curved membrane elements with different geometrical shapes and tension level will be investigated.



Model I Model II Model III

Fig. 2 Aeroelastic model of circular flat membrane



Model I Model II Model III

Fig.3 Aeroelastic model of circular curved membrane

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 exponential index of the wind speed profile is 0.3.

3) Analysis method

The empirical mode decomposition (EMD), a relatively new form of time-series decomposition, has the feature of not assuming a time-series is linear or stationary (like Fourier analysis). Huang et al (1998) introduced the EMD as the first part of a two part process for spectral analysis of non-linear and non-stationary time series. In stage one the time series is adaptively decomposed into a set of intrinsic mode functions (IMFs) and a residual, using the EMD algorithm; In stage two, by a Hilbert transform of the IMFs. This two stage process has become known as the Hilbert Huang Transform (HHT) and is being increasingly used across a range of fields including hydrology and climatology.

4) Experimental results

Table 3 and Table 4 show the results of circular flat membrane and circular curved membrane in still air and in wind tunnel. The vibration frequency of flat membrane and curved membrane in static air and wind tunnel is nearly the same. Hence, the simplified model of added mass is suitable to wind case, especially, the added-mass coefficient of membrane 0.65 can be applied to both the flat membranes and the curved membranes in the wind tunnel. Meanwhile, the numerical analysis results of open membranes in still air can also be suitable to wind cases.

Table 3 Results for circular flat membranes

Tension level	Material thickness (mm)	No wind		Wind velocity					
				5m/s		10m/s		15m/s	
		1st mode	2nd mod	1st mode	2nd mode	1st mode	2nd mod	1st mode	2nd mod
		（Hz）							
I	0.35	20.07	35.80	20.05	34.17	20.68	35.28	22.22	35.39
II	0.35	50.29	72.85	50.28	72.02	49.76	71.44	49.26	70.67
I	0.55	27.79	38.49	28.08	39.16	27.49	39.22	29.05	42.56
II	0.55	35.40	46.42	34.50	48.39	34.04	45.92	34.00	46.52
I	0.85	13.55	19.60	13.50	21.15	13.49	20.98	13.46	20.72
II	0.85	25.13	35.78	25.16	35.71	25.19	35.85	26.21	35..85

Table 4 Results for circular curved membranes

Tension level	Material thickness (mm)	Height (mm)	No wind		Wind velocity					
					5m/s		10m/s		15m/s	
			1st mode	2nd mode	1st mode	2nd mode	1st mode	2nd mode	1st mode	2nd mod
			(Hz)							
I	0.35	70	33.36	50.45	34.94	51.28	34.61	51.65	34.90	51.33
II	0.35		56.86	76.78	57.57	77.39	57.50	77.97	56.90	77.38
I	0.55		43.23	53.36	43.56	53.71	42.96	52.95	42.93	52.55
II	0.55		47.16	59.93	48.59	65.19	47.36	63.14	45.97	61.93
II	0.85		57.76	74.90	58.44	75.22	58.03	75.60	57.54	75.19

3.3 Field measurement of wind pressure of large-span flexible cable-membrane structures under typhoon

1) Experimental objective

It is difficult to identify the dynamic properties of large-span flexible cable-membrane structures under typhoon, because there are few reports about field measurement of wind pressure on such kind of structures. Here, based on the field measurement of wind pressure of Yueqing Stadium under typhoon, the characteristics of wind pressure on the membrane surface is analyzed.

2) Field measurement of wind pressure on membrane surface

Yueqing Stadium locates in Yueqing city, Wenzhou, Zhejiang Province, in the South-East area of China with high probability of typhoon occurrence. The building has an approximate architectural area 20,000 m^2 that can accommodate more than 15,000 people. The plan of this stadium is an ellipse with the longitudinal length 229 meters and the latitudinal length 214 meters. The top level of the highest columns is 42 m. The roof system with a maximum cantilever span of 57m is lunar shaped and covered with PTFE membrane.

Fig.4 Structures of Yueqing Olympic Center

There are totally 124 pressure taps, 248 pressure sensors on the membrane surface. However, when typhoon arrived, there are 50 pressure taps on the upper surface and 44 pressure taps on the lower surface in good condition. Fig.5 gives the wind pressure measuring points on the membrane surface.

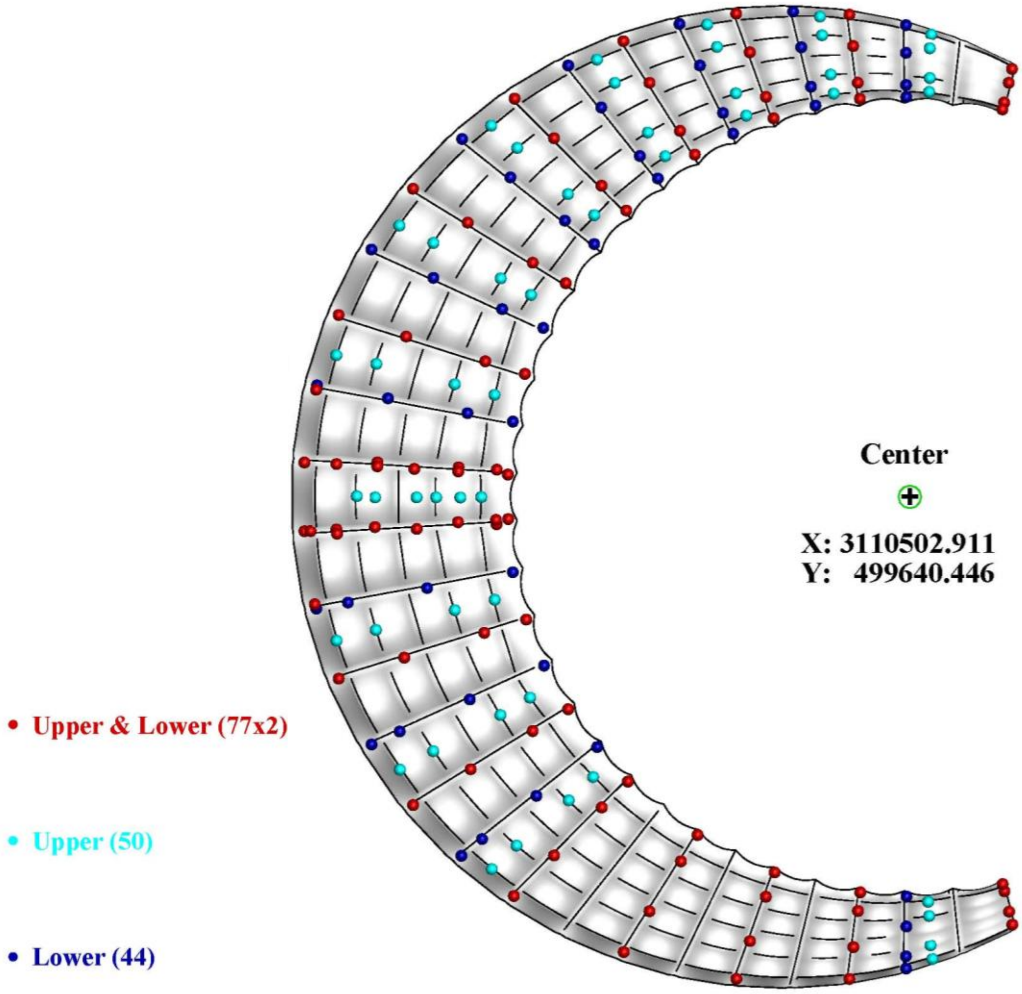


Fig.5 Measuring points on membrane surface

3) Test results and some computational results

Typhoon Fitow, known in the Philippines as Typhoon Quedan, was the strongest typhoon to make landfall in Mainland China during October. It produced the wind gust of 274 km/h in the Shiping Mountains of Zhejiang, setting a record for the province. Equivalent wind load is more than 10 times of the self-weight of roof system. Fig.6 presents the wind pressure of Yueqing Stadium under Typhoon Fitow.

At present, further research by filed monitoring data of wind-induced response of Yueqing Stadium is conducted, and a dynamic analysis considering added mass effect by the proposed added mass model are conducting although the huge computation work is a great challenge to computer and time.

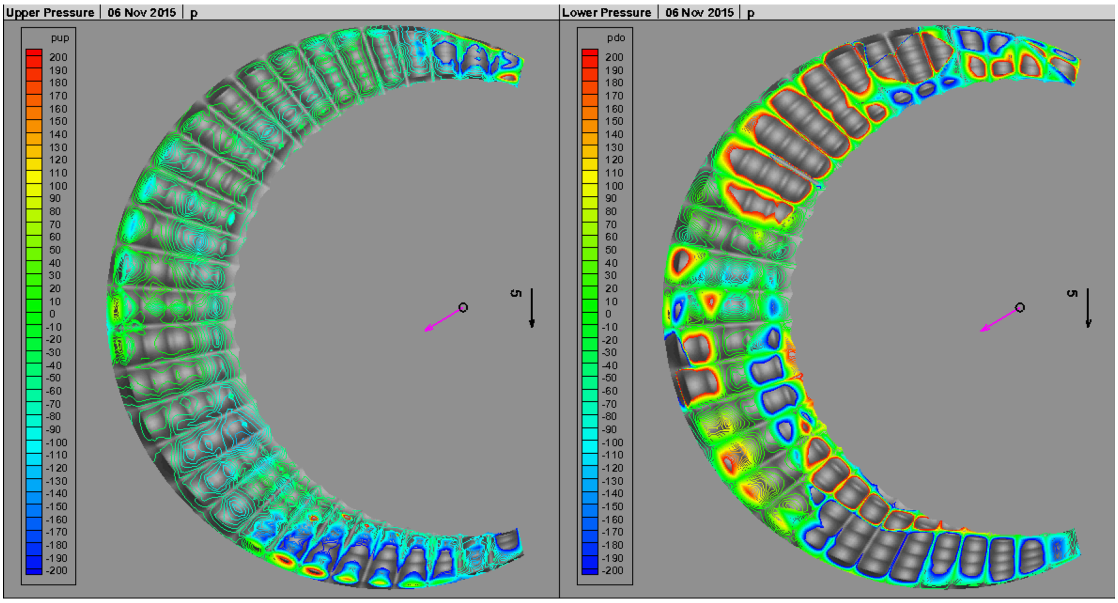


Fig.6 Wind pressure of membrane structure under Typhoon Fitow

3.4 Conclusions

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

1) Considering the added mass in dynamic analysis, it may be excited or restrained displacement response. For high prestress level, the influence of the added mass the dynamic analysis is significant. The results of added mass model considering the effect of geometric and mode shape are better than those considering added mass of an added mass coefficient 0.65.

2) The vibration frequencies of flat membrane and curved membrane in static air and wind tunnel are close to each other. Hence, the proposed simplified model of added mass is suitable to wind cases, especially the added-mass coefficient of membrane 0.65 can be applied to both the flat membranes and the curved membranes in the wind tunnel.

4. Published Paper, etc.

1) Yuanqi Li, Yi Zhou, and Zongya Xu, Added mass estimation of curved membranes vibrating in still air, Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2016, Tokyo 26 - 30 September 2016, Tokyo, Japan.
2) Yuanqi Li, Yi Zhou, Zongya Xu, Lei Wang, and Yukio Tamura, Investigation on added mass of membranes with curved surface, Researches on dynamic characteristics of structures which affect Wind Response, Jan.26, 2016, TPU.
3) 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.
4) 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

Zhihong Zhang	Shanghai Normal University, China, 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, was held on Jan. 26, 2016 in Wind Engineering Research Center, Tokyo Polytechnic University, Japan. The program of the workshop is shown as follows.

東京工芸大学・風工学共同研究拠点 研究集会(2016 年 1 月 26 日)のご案内

1. 高層建築物に作用する風荷重に与える Interference Effect に関する研究

2. Interference Effect on Square Prism based on Aeroelastic Experiments

3. Researches on Dynamic Characteristics of Structures which Affect Wind Responses

東京工芸大学・風工学共同研究拠点の今年度の共同研究テーマとして採択された3つの研究課題に関連する研究集会を1月26日に本学厚木キャンパスにおいて開催します.

本研究集会では, 構造物の動特性が風応答に与える影響や高層建物のInterference Effectに関して, 最新の研究の現状や問題点を把握し, 今後取り組むべき課題を議論いたします. 奮ってご参加いただきたく, ご案内申し上げる次第です.

と き : 2016 年 1 月 26 日 10:00 ～ 11:50

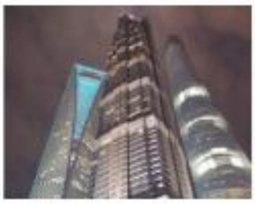
ところ : **東京工芸大学 厚木キャンパス 本館** 4 階 A042 (神奈川県厚木市飯山 1583)

小田急線 本厚木駅 北口 2 番乗り場 または 厚木バスセンター 7 番乗り場

26 系統 東京工芸大学行き(終点下車, 約 20 分)

問合先 : 東京工芸大学 風工学研究拠点事務室 TEL : 046-242-9658(直通)

collaborate@arch.t-kougei.ac.jp



東京工芸大学・風工学共同研究拠点 研究集会

高層建築物に作用する風荷重に与える Interference Effect に関する研究に関する研究集会

10:00 ～ 10:40

趣旨説明 吉田昭仁（東京工芸大学）

1. Effect of Plan Ratio on Wind Interference of High Rise Buildings
Achal Mittal (Indian Institute of Technology, India)
2. Generalization of Interference Effects on Design Wind Loads of Two Tall Buildings
Wonsul Kim (Korea Institute of Ocean Science & Technology, Korea)

Interference Effect on Square Prism based on Aeroelastic Experiments に関する研究集会

10:40 ～ 11:00

趣旨説明 金容徹（東京工芸大学）

1. Investigation on Aerodynamic Behavior of High-rise Buildings under Interference Effects
Yuan-Lung Lo (Tamkang University, Taiwan)

Researches on Dynamic Characteristics of Structures which Affect Wind Responses に関する研究集会

11:00 ～ 11:20

趣旨説明 吉田昭仁（東京工芸大学）

1. Investigation on Added Mass Model for Membranes with Curved Surface
Yuanqi Li (Tongji University, China)

References

[1] Li Y.Q. Equivalent Analysis on Wind-induced Vibration of Membrane Structures Considering Solid-fluid Interaction. Wind Engineering Joint Usage/Research Center. FY2014 Research Result Report.
[2] 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.
[3] 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.