OMA Research of Sky Tower in Wrocław, Poland

Zbigniew Wójcicki[1,*], *Jacek* Grosel[1], *Alexander* Belostotsky[2,3,7], *Pavel* Akimov[2,3,4], *Vladimir* Sidorov[5,6,7]

[1]Civil Engineering Faculty, Wrocław University of Technology, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland
[2]Scientific Research Center "StaDyO"; office 810, ul. 3ya Yamskogo Polya, Moscow, 125040, Russia
[3]National Research Moscow State University of Civil Engineering, Department of Applied Mathematics; 26, Yaroslavskoe Shosse, Moscow, 129337, Russia
[4]Russian Academy of Architecture and Construction Sciences; 24-1, ul. Bolshaya Dmitrovka, Moscow, 107031, Russia
[5]Kielce University of Technology; Al. 1000-lecia Państwa Polskiego 5, 25-541, Kielce, Poland
[6]Moscow State University of Railway Engineering; 9b9 Obrazcova Street, Moscow, 127994, Russia
[7]Perm National Research Polytechnic University; 29 Komsomolsky prospekt, Perm, Perm Krai, 614990, Russia

Abstract. Sky Tower is a skyscraper in Wrocław, Poland. Construction began in December 2007 with the demolition of the 24-story Poltegor structure, until then the tallest building in the city. Sky Tower is the tallest residential building in Poland in the category of height to roof and category of highest floor but is shorter than the Palace of Culture and Science. On the 49th floor is a publicly accessible viewpoint. Operational Modal Analysis (OMA) of Sky Tower was done in 2012 when the tower was almost completed. No excitations with the exception of ambient excitations were used 8 eigenfrequencies and eigenforms were detected.

1 Subject of study

The Sky Tower is a skyscraper in Wrocław, Poland, Figure 1.

The Sky Tower complex consists of 3 connected buildings:

– B1 – 3-storey platform, in which the shopping gallery is located.
– B2 – 50-storey tower, levels from 28 to 48 contain 184 apartments and the remaining levels provide office space.
– B3 – 19-storey "sail" containing 52 apartments on levels from 11 to 18, as well as offices.

The highest tower with spire was originally planned to be 258 m tall (roof height 221 m). The construction of a reinforced concrete structure was completed in September 2011, and its final height is 205.82 m. Total building height is 212 m.

* Corresponding author: zbigniew.wojcicki@pwr.edu.pl

Fig. 1. Sky Tower complex.

2 Measurements

Measurements were made at the end of the construction works. Measurements were carried out using practically all the available measuring equipment. Fifteen seismic accelerometers were connected to two system PULSE cassettes.

Two variants of dynamic research were prepared:

– the first variant included the connection of two system PULSE cassettes and their full synchronization via 2 optical fibre junction stations. However, due to their weight, it proved impossible to carry the suitcases containing the optical fibre stations so high and the availability of lifts was very limited.
– the second variant included connecting two PULSE system cassettes and synchronizing them directly without the optical fibre station using a long LAN cable.

The second variant was finally realized. Signals from fifteen accelerometers mounted in the horizontal direction were recorded. Three DeltaTron 8430 accelerometers were installed on each of the selected floors - three measurements on each level identify the movement of the floor as a rigid plane body.

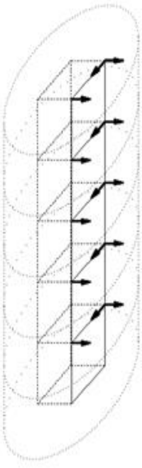

Fig. 2. The placement of accelerometers in the Sky Tower in Wrocław (OMA scheme).

Accelerometers were mounted on the five storeys of the B2 (Figure 2):

– level + 87.04 m (floor 20),
– level + 116.96 m (floor 28),
– level + 139.40 m (floor 34)
– level + 161.84 m (floor 40),
– level + 184.28 m (floor 46).

The schematic location of accelerometers is shown in Figure 2, where the dotted line indicates the outline of the B2 building (tower), the dashed line schematically shows the elevator-stair shaft. The solid line shows the shaft that forms the geometric model in the OMA analysis.

Because the vibration were measured mainly for OMA, the measurements were long – 60 minutes. The distribution and assembly of the equipment took much longer than the measurements itself. Nevertheless, the entire measuring system was mounted, applied to measurements and disassembled during one day.

3 Results

Table 1 summarizes OMA analysis results obtained using the stochastic methods SSI-PC.

Table 1. The results of Operational Modal Analysis (SSI-PC methods).

Mode N^o	Eigenfrequency [Hz]	Damping ratio [%]
1	0,3107	0,6473
2	0,3889	0,6730
3	0,6426	0,8550
4	1,176	1,345
5	1,177	1,119
6	1,261	2,536
7	1,538	1,869
8	1,539	1,860
9	1,615	1,250
10	2,051	1,677

In order to compare the eigenforms and check for their linear dependence on each other, the value of the Modal Assurance Criterion (MAC) was calculated. The results of this analysis are shown in Fig. 3 and in Table 2.

Table 2. Modal Assurance Criterion (MAC) matrix values.

	0.3107 Hz	0.3899 Hz	0.6426 Hz	1.175 Hz	1.177 Hz	1.261 Hz	1.538 Hz	1.539 Hz	1.615 Hz	2.051 Hz
0.3107 Hz	1	0.0001178	0.008871	0.007059	0.007735	0.002152	0.001324	0.002525	0.003118	0.04495
0.3899 Hz	0.0001178	1	0.1898	0.002171	0.0003759	0.02441	0.005253	0.006795	0.002805	0.0002133
0.6426 Hz	0.008871	0.1898	1	0.001516	0.0005745	0.01694	0.009476	0.01161	0.02018	0.006749
1.175 Hz	0.007059	0.002171	0.001516	1	0.9148	0.6632	0.02229	0.01336	0.2172	0.1668
1.177 Hz	0.007735	0.0003759	0.0005745	0.9148	1	0.6292	0.01089	0.0272	0.2451	0.1352
1.261 Hz	0.002152	0.02441	0.01694	0.6632	0.6292	1	0.1436	0.114	0.004757	0.28
1.538 Hz	0.001324	0.005253	0.009476	0.02229	0.01089	0.1436	1	0.9647	0.004005	0.04622
1.539 Hz	0.002525	0.006795	0.01161	0.01336	0.0272	0.114	0.9647	1	0.04324	0.07119
1.615 Hz	0.003118	0.002805	0.02018	0.2172	0.2451	0.004757	0.004005	0.04324	1	0.1537
2.051 Hz	0.04495	0.0002133	0.006749	0.1668	0.1352	0.28	0.04622	0.07119	0.1537	1

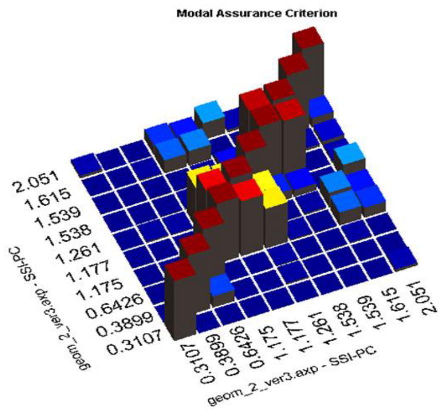

Fig. 3. Modal Assurance Criterion visualise.

Because of the very large value of the MAC (0.9), it was considered that the forms N° 4 and N° 5 are one eigenform of (MAC = 0.91). The result of the comparison of eigenforms N° 7 and N° 8 (MAC = 0.96) were interpreted similarly – compare Table 3.

It should be noted that the above eigenforms have been identified using stochastic methods SSI-PC. The use of identification methods in frequency domain allowed the identification of only one eigenfrequency in the region up to 3 Hz – 1.545 Hz. Deeper analysis showed that the incidence of 1.545 Hz corresponds to the same form that has been detected by the SSI-PC method, i.e. form N° 7 and N° 8, which was previously considered to be one form that corresponds to the frequency (1,538-1,539) Hz.

The final results of the OMA analysis within the scope of the detected eigenfrequencies and the corresponding damping ratios are shown in Table 3.

Table 3. The final results of Operational Modal Analysis.

Mode N°	Mode description	Eigenfrequency [Hz]	Damping ratio [%]
1	1st bending eigenform in the direction of a lesser rigidity (in a direction perpendicular to the plane of the model)	0,3107	0,6473
2	1st bending eigenform in the direction of a greater rigidity (in the plane of the model)	0,3889	0,6730
3	1st torsional eigenform	0,6426	0,8550
4	2nd bending eigenform in the direction of a lesser rigidity (in a direction perpendicular to the plane of the model)	1,177	1,232
5	2nd bending eigenform in the direction of a greater rigidity (in the plane of the model)	1,261	2,536
6	2nd torsional eigenform	1,538	1,865
7	Complex bending-torsional eigenform	1,615	1,250
8	Complex bending-torsional eigenform	2,051	1,677

The eigenforms corresponding to the detected eigenfrequecies are shown in the Fig. 4, Fig. 5 and Fig. 6.

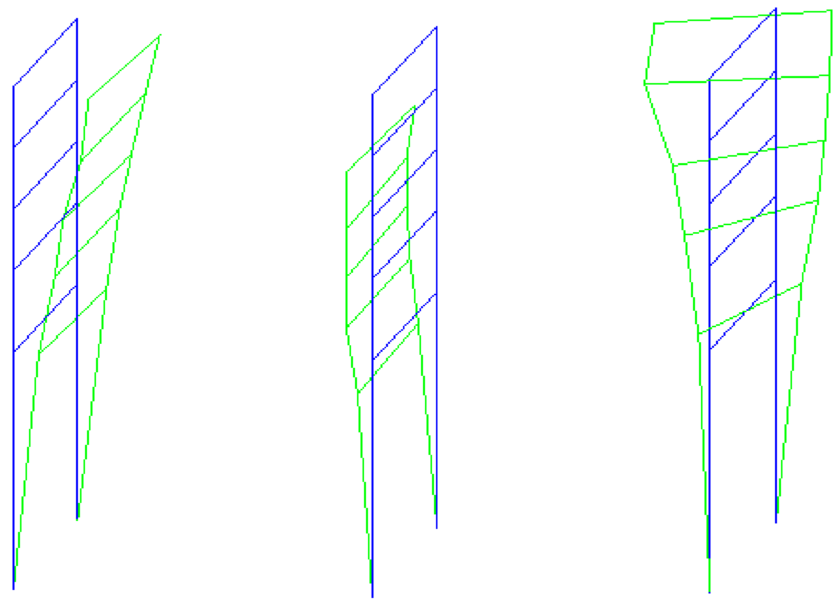

Fig. 4. The first three eigenforms (bending – 0,3107 Hz, bending – 0,3899 Hz, torsional – 0,6426 Hz).

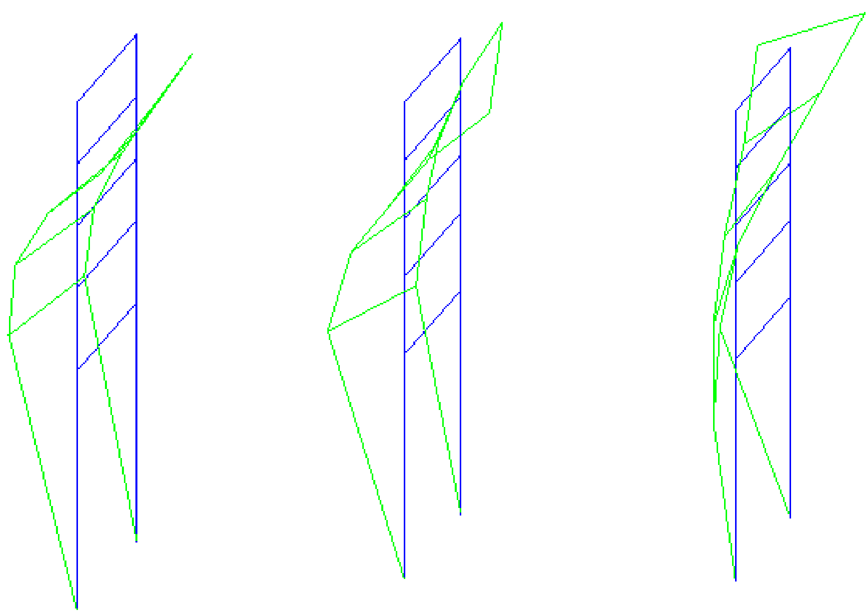

Fig. 5. The next three eigenforms (bending – 1,176 Hz, bending – 1,261 Hz, torsional – 1,538 Hz).

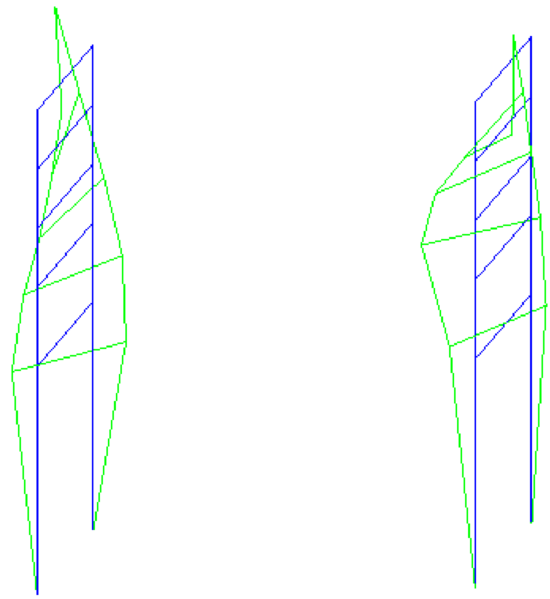

Fig. 6. The last two complex eigenforms (1,615 Hz, 2,051 Hz).

3 Conclusions

Based on the analysis of the results obtained, it is clear that stochastic methods are the more efficient methods of OMA analysis of a tall buildings. Within the analyzed range up to 3 Hz, 8 eigenfrequencies were detected. The use of frequency domain identification methods allowed for the detection of only one eigenfrequency in the range up to 3 Hz, which was consistent with one of eigenfequencies detected by the stochastic method. This confirms the correctness of the operation of the stochastic algorithms, but at the same time demonstrates the essential advantage of using stochastic methods in the detection of relatively low eigenfrequencies of large construction and engineering structures.

According to the authors, OMA modal analysis methods based on stochastic algorithms should be the standard for modal analysis of large structures, especially high and very high buildings.

References

1. R. Brincker, L. Zhang, P. Andersen: Proceedings of IMAC, 625-630 (2000)
2. R. Brincker, C. Ventura, *Introduction to operational modal analysis* (WILEY 2015)
3. Z. Wójcicki, J. Grosel, W. Sawicki, *Experimental dynamic research of civil engineering structures* (in Polish), (DWE 2014)
4. Z. Wójcicki, S. Kostecki, J. Grosel, Procedia Engineering, **153**, 874-881 (2016)
5. J. Grosel, W. Sawicki, J. Marcinowski, Z. Wójcicki, IOMAC'15, 39-45 (2015)