Identification of the Dynamic Properties of the Residential Tower New Orleans

A. J. Bronkhorst, D. Moretti, and C. P. W. Geurts

Abstract This paper describes the application of the Frequency Domain Decomposition (FDD) technique on measured acceleration data on the residential tower *New Orleans* in Rotterdam, the Netherlands. The goal of this study is to determine and analyse multiple natural frequencies and mode shapes of this tower. A measurement campaign was setup on the 158 m high *New Orleans* tower. Accelerations were measured at the 15th, 34th and 44th floor. Modal properties are obtained using the FDD method. A total of 11 modes are identified, of which 7 modes have a clear dominant direction. The first mode, with the lowest natural frequency, is observed in X-direction, which corresponds with the lower bending stiffness of the *New Orleans* tower in this direction compared to the Y-direction. The second mode in X-direction has a higher natural frequency than the second mode in Y-direction. This suggests that the foundation stiffnesses in X-direction are larger than those in Y-direction. The obtained modal properties provide a good basis for further work, in which the properties of an Euler-Bernoulli beam with rotational and translational springs at the base can be determined by matching the measured modal properties.

Keywords High-rise building · Acceleration measurements · Frequency domain decomposition · Natural frequencies · Mode shapes

1 Introduction

Reliable prediction of the dynamic characteristics of high-rise buildings requires accurate estimation of the structural building properties (i.e. stiffness and mass). Accurate estimation of these properties in the design phase is difficult. Bronkhorst and Geurts [1] showed that the predicted natural frequency of several Dutch high-rise buildings deviates significantly from the estimated value. This is attributed to an inaccurate estimation of the building and foundation properties during the design

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phase. It is unclear which properties (i.e. building mass, building stiffness and/or foundation stiffness) are incorrectly estimated and by how much. To determine to what extent the estimated building properties are responsible for the inaccurate estimation of the natural frequency, these properties need to be determined via in-situ measurements. One approach to determine structural properties via measurements is to measure several modes (i.e. natural frequencies and mode shapes) of the building and match these with the modes of a model by tuning its structural properties. In previous measurement studies on Dutch high-rise buildings [1–3], the first three natural frequencies were determined through picking of peaks in the measured output spectra of measurements on one floor. This measurement setup does not allow to obtain information on the mode shapes. According to van den Berg en Steenbergen [2], information on both natural frequencies and mode shapes for more modes is needed for accurate estimation of the building properties. The Frequency Domain Decomposition (FDD) technique is a well-established method, see for example [4–6], to determine natural frequencies and mode shapes from output-only acceleration measurements, also known as Operational Modal Analysis (OMA). This paper describes the application of the FDD technique on measured acceleration data on the *New Orleans* residential tower. The goal of this study is to determine and analyse multiple natural frequencies and mode shapes of this tower. Section 2 describes the measurement setup on the *New Orleans* tower. Section 3 explains the methods used to analyse the data, and to assess the obtained modal properties. The results of this study are presented in Sect. 4. Section 5 gives the conclusions of this study. The obtained modal properties provide the basis for ensuing work, in which the structural properties of an analytical model (i.e. an Euler–Bernoulli beam with rotational and translational spring at the base) are estimated by matching the measured modal properties.

2 Measurement Setup

Measurements were performed on the residential tower *New Orleans* in Rotterdam, shown in Fig. 1a. This building is equipped with a permanent monitoring system. The original reason for setting up this monitoring system was a research project on local wind loads on façade elements, and the influence of pressure equalization on these loads. Details about the setup of the permanent monitoring system can be found in [1, 7, 8].

The permanent monitoring system on the 34th floor was supplemented with additional acceleration sensors (Sundstrand, type QA-700) on the 15th and 44th floor. Figure 1b–d shows the position of the 8 accelerometers of the permanent monitoring setup on the 34th floor, and the additional accelerometers placed on the 15th and 44th floor. The data applied in this study was recorded on 29/03/2020. A total of 129 10-min records were used, which were sampled with 20 Hz. The mean wind velocity ranged between 5 and 16 m/s and the average wind direction varied between 0 and 40°.

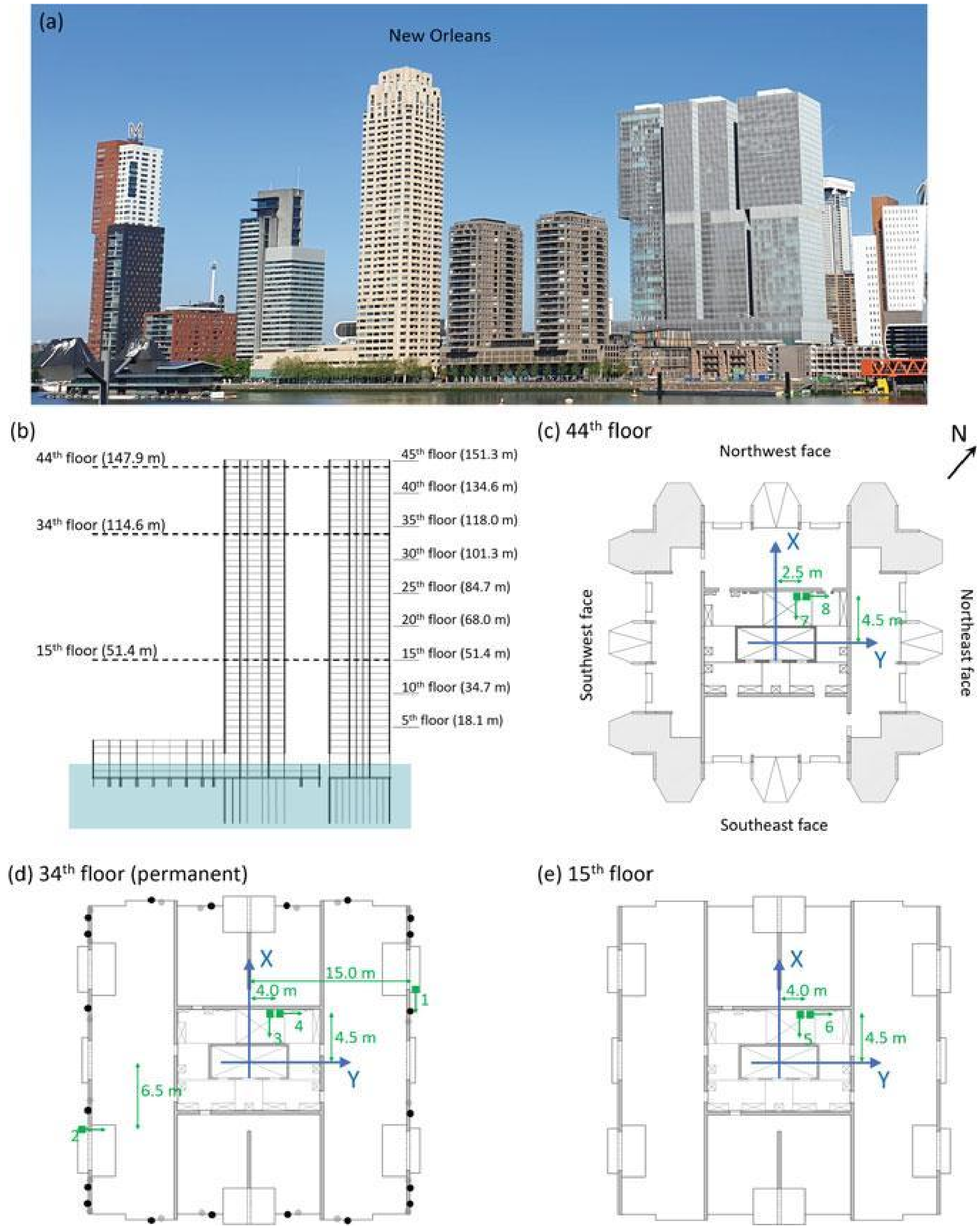

Fig. 1 **a**, **b** Picture and schematic of the New Orleans tower and positions of the acceleration sensors (green squares) on the New Orleans residential tower on **c** the 44th floor, **d** the 34th floor, and **e** the 15th floor. The green arrows indicate the directions of the acceleration sensors

3 Data Analysis

This section describes the methods used to process the measured acceleration data and analyse the obtained mode shapes. The first paragraph explains the processing steps in the Frequency Domain Decomposition, with which the modes of the *New Orleans* are determined. The second paragraph explains the applied scaling procedure for the obtained mode shapes. The last paragraph describes the Modal Assurance Criterion (MAC), which is a technique to assess whether mode shapes are sufficiently well identified to differentiate them from other modes.

3.1 Frequency Domain Decomposition

The Frequency Domain Decomposition (FDD) method was first presented by Brincker et al. [4]. It is a frequency domain technique with which natural frequencies and mode shapes can be estimated from measured acceleration signals on a structure excited by ambient vibrations closely representing white noise.

First the power spectral density matrix G_{yy} of the measured time series is obtained by determining the cross and auto power spectra of all measured signals. The power spectra are computed after detrending the time series by removing the average. Power spectral densities for all measured 10 min time traces were obtained with Welch's averaged, modified periodogram method (cpsd in Matlab R2019a). The applied window size was chosen equal to the number of samples in the measured signal (number of samples in 10 min) and no overlap was applied; zero-padding was used to increase the FFT resolution. Averaging was applied over the 129 power spectra obtained with this procedure.

After obtaining the averaged 8×8 power spectral density matrix G_{yy}, for each frequency instance ω in the spectrum, these matrices were decomposed using the singular value decomposition [4]:

$$G_{yy} = USU^{*\prime} \tag{1}$$

where U is an orthonormal matrix (i.e. $U'U = UU' = I$) containing the singular vectors and S is a diagonal matrix with the singular values at each frequency instance ω. The singular values of S are the ordinates of scalar spectra of single degree of freedom systems. The singular vectors in matrix U can be associated with mode shapes of the tested structure. In particular, in this study the column in U corresponding to the first singular value in S for each frequency that can be identified as a natural frequency (see Fig. 2) is used as mode shape. This may lead to more mode shapes than can be described by the limited set of sensors. Section 3.3 describes how to determine which modes are not sufficiently well described.

3.2 Mode Shape Scaling

The obtained mode shapes φ_i from the matrix U at the identified natural frequencies are scaled using degree of freedom (DOF) scaling; the DOF scaled mode shape is

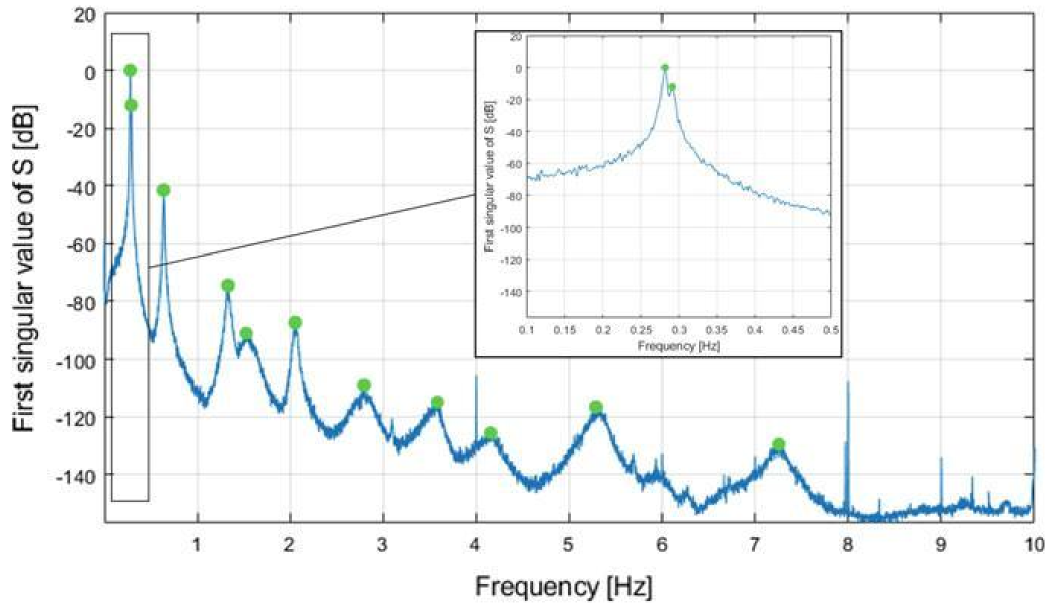

Fig. 2 Dimensionless spectrum of the first singular value of S for each frequency. Indicated in green are the natural frequencies of the New Orleans tower

defined as [9]:

$$\varphi_{i,D} = \frac{\varphi_i}{\varphi_{i,Dn}} \tag{2}$$

where φ_{Dn} is the considered DOF used for scaling; in this study the DOF with the largest component was used.

3.3 Modal Assurance Criterion

To assess whether the obtained modes are orthogonal (i.e. the correlation between the mode shapes is low), the Modal Assurance Criterion (MAC) is applied here. The MAC gives the correlation coefficient between two mode shape vectors, and is defined as [10]:

$$MAC = \frac{\left(\varphi_1^{*\prime}\varphi_2\right)^2}{\left(\varphi_1^{*\prime}\varphi_1\right)\left(\varphi_2^{*\prime}\varphi_2\right)} \tag{3}$$

Normalization is not relevant here and the original mode shapes φ_i can be used. The MAC values of mode shape vectors describing different modes should generally be small; Heylen et al. [10] suggest a value less than 10%. If the MAC is high (larger than 35%), this can mean two things:

- If the modes are at close frequencies, this could indicate the two modes are actually the same mode;
- If the modes are at distant frequencies, this is a strong indication that the number of sensor positions is not sufficient to differentiate sufficiently between the two modes.

4 Results and Discussion

This section discusses the results obtained from the measurements on the *New Orleans* tower. The first paragraph presents the obtained modal frequencies and the DOF-scaled modal displacements, and discusses the orthogonality of the obtained modes. The second paragraph discusses the dominant directions of the obtained mode shapes.

4.1 Orthogonal Modes

Figure 2 shows the dimensionless spectrum of the first singular value of S. The peaks indicated in this graph correspond with the natural frequencies specified in Tables 1 and 2. These tables also specify per mode the dominant direction and the DOF-scaled modal displacements of each sensor. Table 3 gives the MAC values determined for each combination of mode shapes. Table 3 shows that modes 1, 2, 4, 5, 7 and 8 have MAC values which are all smaller than 35%. This indicates the applied measurement setup is sufficient for observability of these modes. It furthermore shows that these modes are orthogonal modes of the *New Orleans* tower.

Table 1 Properties of the modes defined from the singular value spectrum (modes 1–6)

Mode	1	2	3	4	5	6
Dominant direction [–]	X	Y	θ	Y	X	θ
Natural frequency [Hz]	0.282	0.291	0.638	1.332	1.527	2.054
Modal displacement [–]						
Sensor 5 (51.4 m)	−0.30	−0.05	−0.13	0.00	0.89	0.29
Sensor 6 (51.4 m)	−0.02	−0.29	−0.15	−0.90	0.05	0.50
Sensor 1 (114.6 m)	−0.71	−0.10	−1.00	−0.02	−0.23	−1.00
Sensor 2 (114.6 m)	−0.03	−0.78	0.43	0.19	0.02	0.45
Sensor 3 (114.6 m)	−0.67	−0.11	−0.28	0.00	−0.06	−0.24
Sensor 4 (114.6 m)	−0.03	−0.76	−0.30	0.06	−0.02	−0.21
Sensor 7 (147.9 m)	−1.00	−0.12	−0.23	−0.04	−1.00	−0.25
Sensor 8 (147.9 m)	−0.09	−1.00	−0.38	1.00	−0.11	−0.61

Table 2 Properties of the modes defined from the singular value spectrum (modes 7–11)

Mode	7	8	9	10	11
Dominant direction [–]	Y		Y		
Natural frequency [Hz]	2.771	3.560	4.155	5.300	7.250
Modal displacement [–]					
Sensor 5 (51.4 m)	0.02	0.33	0.03	0.08	-0.16
Sensor 6 (51.4 m)	−0.73	0.22	0.18	−0.03	−0.06
Sensor 1 (114.6 m)	−0.11	−1.00	−0.12	−1.00	−1.00
Sensor 2 (114.6 m)	0.83	0.11	1.00	0.15	0.20
Sensor 3 (114.6 m)	−0.06	−0.80	−0.08	−0.58	−0.51
Sensor 4 (114.6 m)	0.99	−0.38	0.95	−0.29	−0.13
Sensor 7 (147.9 m)	0.01	0.41	−0.06	0.16	0.16
Sensor 8 (147.9 m)	−1.00	0.39	0.35	0.14	0.11

Table 3 Modal assurance criterion (MAC) values for the modes of Tables 1 and 2

Mode	1	2	3	4	5	6	7	8	9	10	11
1	1.00										
2	0.04	1.00									
3	0.44	0.06	1.00								
4	0.00	0.20	0.01	1.00							
5	0.24	0.01	0.06	0.00	1.00						
6	0.27	0.03	0.69	0.24	0.19	1.00					
7	0.00	0.00	0.09	0.00	0.00	0.04	1.00				
8	0.11	0.00	0.32	0.01	0.00	0.30	0.06	1.00			
9	0.00	0.73	0.01	0.05	0.00	0.02	0.26	0.00	1.00		
10	0.27	0.00	0.63	0.01	0.01	0.43	0.00	0.88	0.00	1.00	
11	0.30	0.00	0.68	0.02	0.00	0.39	0.00	0.74	0.02	0.94	1.00

Colour legend: 0–0.25; 0.25–0.5; 0.5–0.75; 0.75–1

Mode 3, 6, 9, 10 and 11 have more than 35% correlation with some lower modes (e.g. mode 3 with mode 1). According to Heylen et al. [10], this is a strong indication that the sensor setup violates the base assumption of observability for these modes. This means the applied setup is not sufficient to properly distinguish the mode shapes of these modes from the mode shapes of lower modes. It is noted that when mode 3 is not considered, mode 6 does meet the 35% correlation criterion. Measurements at additional floor levels with a minimum of 3 sensors on each floor are needed to meet the observability criterion for these modes. The best floor levels should be based on the expected mode shapes of these higher modes (i.e. mode 3, 6 and 8–11). The analytical model that will be fitted on the obtained modal properties in ensuing work could be used to determine the floor levels at which additional measurements should be performed to properly assess the higher modes.

Although the setup is not enough to properly distinguish the mode shapes of mode 3 and mode 6, it is sufficient to determine that these modes are (dominant) torsional modes. The next paragraph provides more information about the dominant direction of the measured modes.

4.2 Dominant Direction

The dominant direction is determined from the DOF-scaled modal displacements specified in Tables 1 and 2. The modal displacements obtained for the sensors that are oriented in the direction opposite to the dominant direction are indicated in light grey. For example, the modal displacements of mode 1 for the sensors in X-direction are clearly larger than for the sensors in Y-direction. For a number of modes (mode 1, 2, 3, 4, 5, 7 and 9) a clear dominant direction (translational or torsional) of the mode shape is found. For these modes, relatively small modal displacements are observed in the non-dominant direction.

Table 2 shows that for modes 8, 10 and 11 no clear dominant direction can be determined from the modal displacements. The modes appear to consist of a combination of torsion and translation in X-direction. This could have implications when fitting a model on these measured mode shapes. The modes with a clear dominant direction can be fitted with a simpler model (only considering the dominant direction), while the modes with combined directions require a more complex model that considers all directions (both translations and rotation).

The dominant direction of the torsional modes can be established by considering the position of the sensor with respect to the neutral axis of the building. Because the torsional movement of the tower is very small, the angular modal displacements can be determined by dividing the modal displacement with the distance between the sensor and the building axes (see Fig. 1). Table 4 gives the DOF-scaled angular modal displacements per sensor for mode 3 and 6. For mode 3, the modal displacements are similar for each set of sensors per floor, with an average value of -0.36 for the 15th floor (51.4 m), −0.71 for the 34th floor (114.6 m), and −0.98 for the 44th floor (147.9 m). Figure 3 shows that mode 3 gradually increases in angular modal displacement with height. The variability in angular modal displacements between different sensors at the same floor is small compared to those observed for mode 6. This shows mode 3 is a well-defined torsional mode around the neutral axis of the *New Orleans* tower. The larger variability observed for mode 6 indicates this mode shape is not as well-defined as mode 3, but the main contribution is torsional.

Table 4 The DOF-scaled angular modal displacements for mode 3 and mode 6

Mode	1	6
Sensor 5 (51.4 m)	−0.34	0.48
Sensor 6 (51.4 m)	−0.38	0.83
Sensor 1 (114.6 m)	−0.71	−0.44
Sensor 2 (114.6 m)	−0.70	−0.46
Sensor 3 (114.6 m)	−0.73	−0.39
Sensor 4 (114.6 m)	−0.71	−0.31
Sensor 7 (147.9 m)	−0.96	−0.66
Sensor 8 (147.9 m)	−1.00	−1.00

Figure 3 shows the DOF-scaled mode shapes of mode 1–7. The top row of graphs shows the modes with the main contribution in X-direction, the middle row the modes mainly in Y-direction, and the bottom row the modes in torsional direction. The first mode with the lowest natural frequency of 0.282 Hz is observed in X-direction. This corresponds with the lower bending stiffness of the *New Orleans* tower in this direction compared to the Y-direction. The second mode in X-direction (mode 5) has, however, a higher natural frequency than the second mode in Y-direction (mode 4). Because the mass of the building is the same for both directions, the foundation stiffness (rotational and/or translational) appears to be responsible for this difference in natural frequencies.

The obtained natural frequencies and mode shapes provide a good first basis for a study on the identification of the structural properties of an analytical beam model of the *New Orleans* tower. The mode shapes determined for mode 1 to mode 7 indicate that the *New Orleans* tower can be well-represented by an Euler-Bernoulli beam with rotational and translational springs at the base.

5 Conclusion

This paper described a study on the application of the Frequency Domain Decomposition (FDD) technique on acceleration data measured on the *New Orleans* residential tower. A total of 11 modes were identified. Application of the Modal Assurance Criterion showed that 6 of the identified modes (i.e. mode 1, 2, 4, 5, 7 and 8) meet the requirement for orthogonality. For these modes the applied measurement setup is sufficient for observability. The other modes (mode 3, 6, 9, 10 and 11) do not meet the MAC requirements to properly distinguish them from lower modes. Measurements at additional floor levels are needed to meet the observability criterion for these modes.

For a number of modes (mode 1, 2, 3, 4, 5, 7 and 9) a clear dominant direction (translational or rotational) of the mode shape is observed. For these modes, relatively small modal displacements are found in the non-dominant direction. For the other

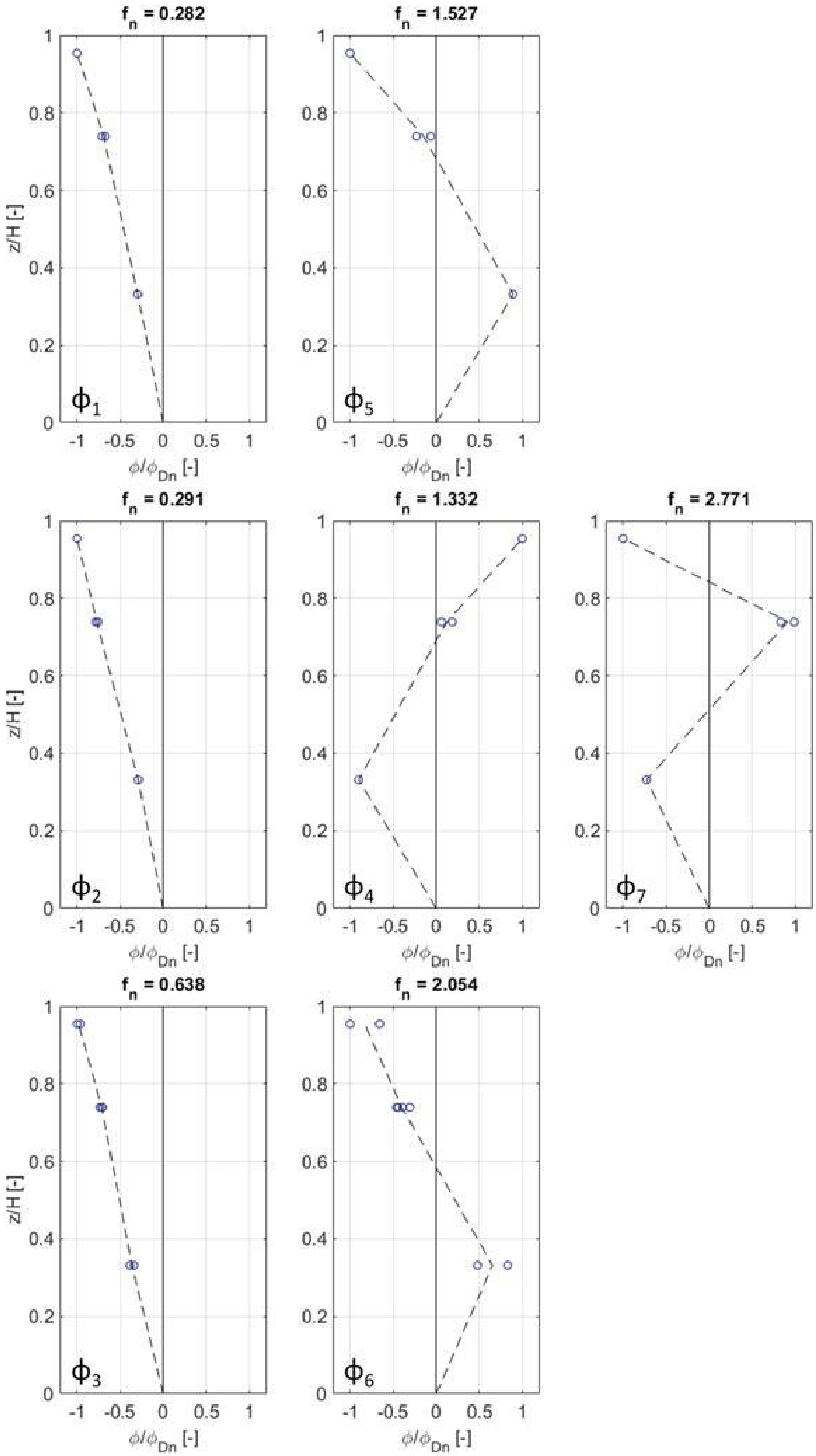

Fig. 3 DOF-scaled mode shapes of mode 1–7: (top row) mode 1 and 5 with dominant X-direction, (middle row) mode 2, 4 and 7 with dominant Y-direction, (bottom row) mode 3 and 6 with dominant torsional direction

modes (mode 6, 8, 10 and 11), the mode shapes do not have a clear dominant direction, but consist of a combination of directions. This could have implications for the required model setup to estimate the structural properties of the *New Orleans* tower.

The obtained modal properties obtained in this study provide a good first basis for the estimation of the structural properties (i.e. building mass, building stiffness and foundation stiffness) of the *New Orleans* tower by fitting an Euler–Bernoulli beam with rotational and translational springs at the base.

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