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MODAL ANALYSIS OF TALL SLENDER STRUCTURES USING SOFTWARE GMAST

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Abstract: *The paper is concerned with a verification of modal properties of tall slender structures computed by recently developed software GMAST. Software GMAST determines eigen-frequencies, eigen-modes and corresponding modal quantities of stacks, towers, guyed masts and similar civil engineering structures using slope-deflection method. A numerical model is based on an idealization of the structure as a continuous 2D beam with continuously distributed parameters on elastic supports. Shaft of structure is divided into sections which could be considered as prismatic i.e. with constant unit mass, bending stiffness and static axial force. The effect of guy ropes is introduced in a form of elastic supports with a frequency dependent stiffness. The applicability of the software in praxis is presented on an example of existing structures, for which the numerically and experimentally identified modal properties are compared.*

Keywords: ***modal analysis, tall slender structures, guyed masts, towers, software.***

1. Introduction

Tall slender structures are commonly used in the telecommunication industry to carry broadcasting antennas, microwave link dishes, telephone arrays as well as various meteorological monitoring aerials at substantial heights. They are represented either by self-supporting or cantilever structure i.e. tower or structure which is additionally held up by guys i.e. guyed mast. Towers and guyed masts are predominantly loaded by wind and in some areas also by atmospheric ice. Due to their slenderness, flexibility and low structural damping they are usually very sensitive to the dynamic component of the wind, see e.g. Simiu and Scanlan (1996). Several collapses in the past for instance the failure of 648m high mast in Konstantynow (Poland, 1991) or a presence of vibration absorber could serve as a sufficient proof of the wind significance for this type of the structures. The towers excited by the wind gusts vibrate predominantly in one or in combination of a few lowest natural modes, see e.g. Stottrup (2009). The corresponding natural frequencies are well separated and thus the simplified analysis of dynamic response can be performed. On the other hand the guyed masts are characterised by clusters of natural frequencies, see e.g. Madugula (2002). The response to the turbulent wind is more complex and governed by many natural modes. In contrary to towers the natural modes and frequencies are dependent on character of the loading and are noticeably different for deformed and undeformed structure. The guy ropes creating the supports of the shaft behave strongly non-linear. Their stiffness is influenced by direction and magnitude of the static as well as dynamic component of the wind, see e.g. the book Fischer & Pirner (1987). The response spectrum analysis recommended by the code EN 1993-3-1 (1993) for evaluation of dynamic response of the tall structures requires the knowledge of the modal properties. In the last decades many authors proposed different models and methods for evaluating of the natural modes and frequencies and analysis of the dynamic response, see e.g. Gerstoft & Davenport (1986), Nielsen (1995). In this paper the model presented in the book Kolousek et.al. (1983) and used in recently developed software GMAST (Hračov & Pospíšil (2012)) has been analyzed. The accuracy of the model from the point of view of modal properties has been verified for several cases of real experimentally tested structures.

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2. Modal analysis of existing structures using software GMAST

A numerical model applied in software GMAST is based on an idealization of the structure as a continuous 2D beam with continuously distributed parameters on elastic supports, see Náprstek (1972) or Kolousek et.al. (1983). Shaft of structure is divided into sections which could be considered as prismatic i.e. with constant unit mass, bending stiffness and static axial force. Cabins, platforms, wireless and TV antennas and other important equipment are modelled as concentrated masses placed into the nodes between prismatic sections. The effect of guy ropes is introduced in a form of elastic supports with a frequency dependent stiffness. The influence of initial shaft displacements on tension forces in guy ropes is implemented into the program. Only planar displacements are assumed. The change of the structural geometry and other effects associated with initial displacements are neglected. The modal properties are determined using slope-deflection method, see Kolousek et.al. (1967). The determinant of the complex dynamic stiffness matrix of the structure is calculated for a set of user defined excitation frequencies. Consequently, the zeros of a characteristics polynomial identify eigen-frequencies of the structure. The typical form of graphical user interface (GUI) of software GMAST is presented in Figures 1 and 2 . In particular Figure 1 shows the input of the data about the shaft, ropes and check of the geometry. The input of parameters for eigen-solution and the results in a form of the determinant of the dynamic stiffness matrix as a function of frequency, the shape of the selected eigen-mode and the modal dynamic component in guy ropes are shown in Figure 2.

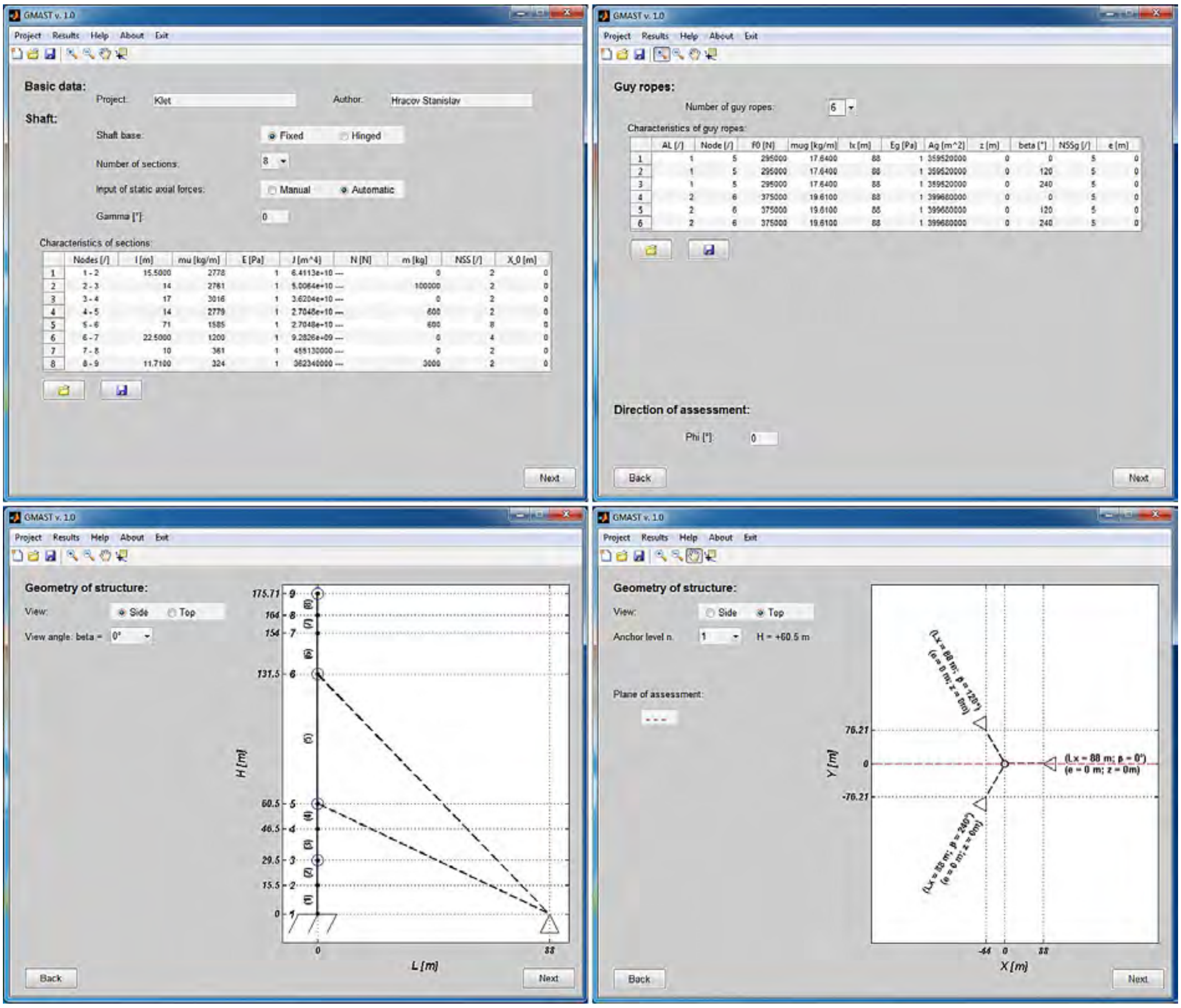

Fig. 1: GUI of software GMAST - Panels of input data (top) and Panels of geometry check (bottom)

Four different structures have been analysed in order to obtain modal properties and compare them with the experimentally measured counterparts. The comparison has been performed in particular for 313 m and 161 m tall guyed steel lattice masts with triangular cross section, 175 m tall guyed steel tubular mast and 185 m tall tower built from reinforced concrete lower part followed by variable cross-section steel cylinders. The top of the all structures creates a laminate or steel extension carrying TV antennas. A general view of the analyzed tower and guyed masts are presented in Figure 3. The basic geometrical characteristics of structures are summarized in Table 1.

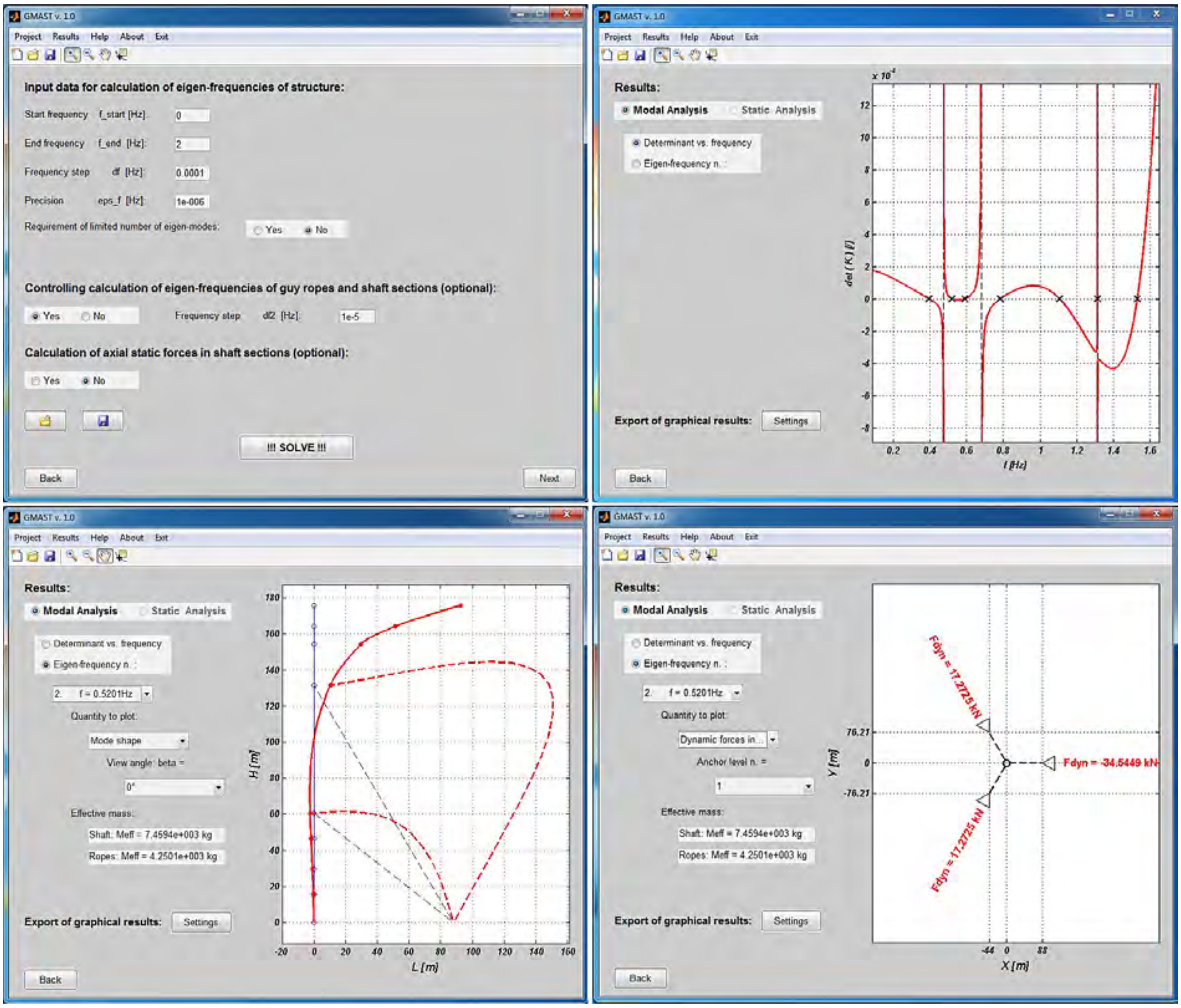

Fig. 2: GUI of software GMAST - Panels with input of computational parameters and with typical results

Fig. 3: View of TV mast Klet', TV mast Javořice, TV mast Krašov and TV tower Hošťálkovice

Tab. 1: Basic characteristics of analyzed tall slender structures

Name	Klet'	Javořice	Hošťálkovice	Krašov
Type [/]	guyed tubular mast	guyed lattice mast	tower	guyed lattice mast
Height [m]	175	161	185	313
Guy levels [/]	2	3	-	5
Guy directions [/]	3	3	-	3

3. Experimental modal analysis of existing structures

The dynamic measurements on existing structures consisted in determining the resonant frequencies (eigen-frequencies) of the structures based on the analysis of the vibration due to the wind load. The resonant frequencies and energy participation of respective eigen-modes on total response were determined from the power spectral density of measured accelerations. The response was measured using six accelerometers ENDEVCO connected to the amplifiers and located at different heights. The sensors were connected wirelessly via antenna and routed to the Wi-Fi module. The module finally transmitted the data to the measuring computer. The sampling frequency was chosen to 500 Hz, which is highly sufficient for analysis of this type of structures. Therefore the undesirable effects caused by incorrectly chosen sampling did not occur. All time histories were in the range from 120 to 300 s taking into account the requirement of stationarity. In Figures 4 and 5 the power spectral densities of accelerations of typical records for guyed mast TV Klet' and tower TV Hošťálkovice are for different elevations presented. On each elevation two identical orthogonal directions X and Y were recorder. The spectral peaks i.e. eigen-frequencies are pointed out and labelled with corresponding values.

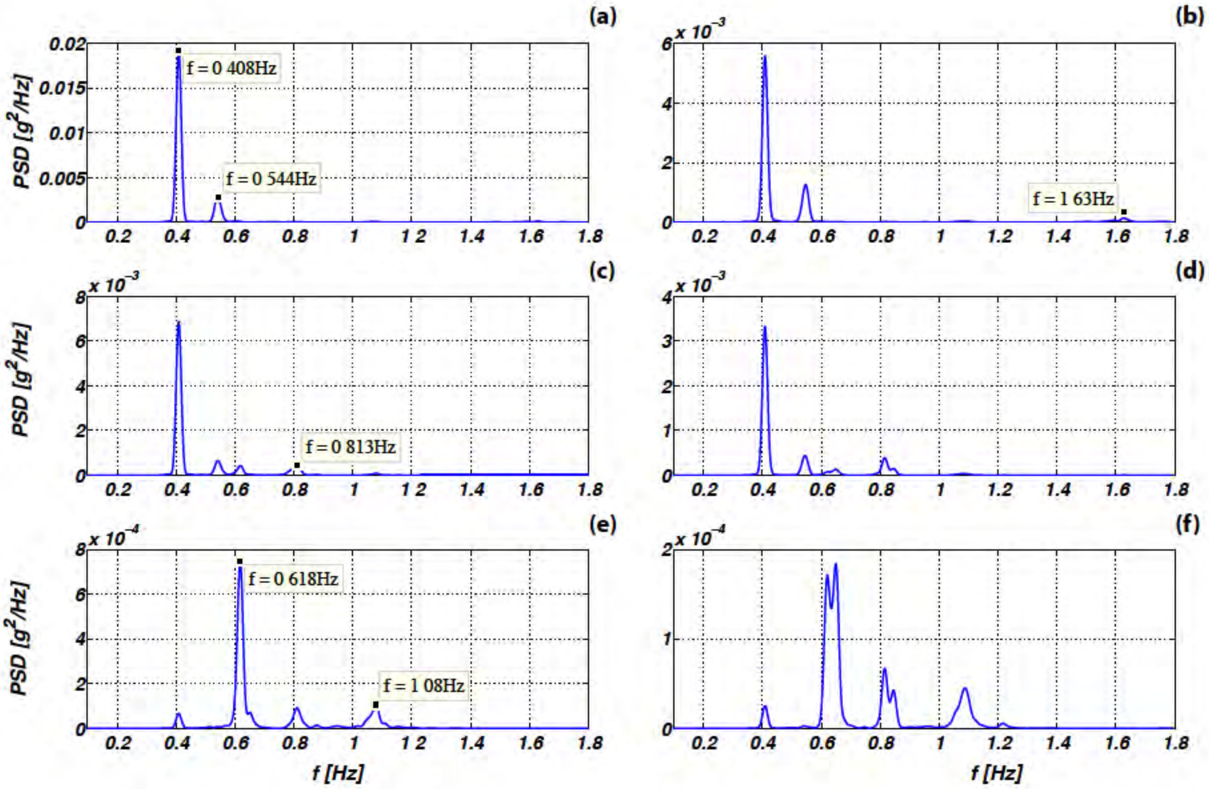

Fig. 4: Power spectral densities of accelerations - Klet'
(a), (b) - height: +150 m, direction: X, Y; (c), (d) - height: +127,2 m, direction: X, Y;
(e), (f) - height: +57,5 m, direction: X, Y.

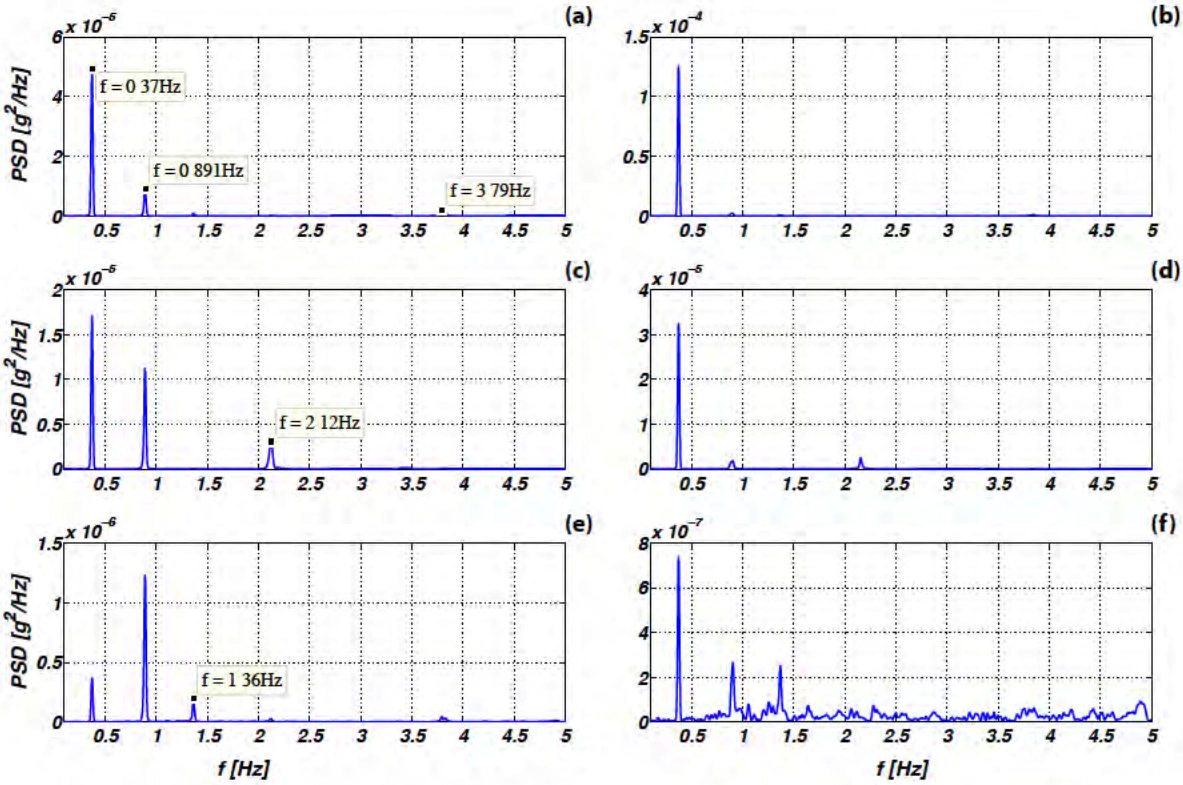

Fig. 5: Power spectral densities of accelerations - Hošťálkovice
(a), (b) - height: +132 m, direction: X, Y; (c), (d) - height: +108 m, direction: X, Y;
(e), (f) - height: +62 m, direction: X, Y.

4. Analysis of the results

To determine the accuracy of numerical eigen-solution using software GMAST the relative error between experimental and theoretical eigen-frequencies was investigated in a form:

$$\Delta f_j = \frac{f_{\mathrm{GMAST},j} - f_{exp,j}}{f_{\mathrm{GMAST},j}} \cdot 100 \qquad [\%]. \tag{1}$$

The calculated errors using Eq. 1 together with determined natural frequencies are given for all analyzed structures in Tables 2 and 3.

Tab. 2: Calculated and measured natural frequencies and relative errors Δf - Klet' and Hošťálkovice

Structure	Klet'			Hošťálkovice		
n.	$f_n[Hz]$		Δf	$f_n[Hz]$		Δf
[/]	GMAST	Measur.	[%]	GMAST	Measur.	[%]
1	0,396	0,408	-3,03	0,368	0,370	-0,54
2	0,520	0,544	-4,62	0,915	0,891	2,62
3	0,590	0,618	-4,24	1,394	1,360	2,44
4	0,783	0,813	-3,83	2,165	2,120	2,08
5	1,106	1,08	0,24	3,883	3,790	2,40
6	1,312	-	-	5,975	-	-
7	1,530	1,630	6,54	8,412	-	-

Tab. 3: Calculated and measured natural frequencies and relative errors Δf - Javořice and Krašov

Structure	Javořice			Krašov		
n.	$f_n[Hz]$		Δf	$f_n[Hz]$		Δf
[/]	GMAST	Measur.	[%]	GMAST	Measur.	[%]
1	0,427	0,446	-4,45	0,170	0,16	5,88
2	0,513	0,526	-2,53	0,207	0,21	-1,45
3	0,567	0,565	0,35	0,259	0,26	-0,39
4	0,703	0,709	-0,85	0,333	0,34	-2,10
5	0,792	0,872	-10,10	0,394	0,39	1,02
6	1,333	1,278	4,12	0,514	0,48	6,61
7	1,353	1,394	-3,03	0,534	0,54	-1,12

The low relative errors show on good agreement between the numerical and experimental results. For all cases of four structures the error is below 7 % with one exception equal to 10%. This acceptable accuracy reveals that the computational model of software GMAST can be recommended for modal analysis of tall slender structures and used for subsequent assessment of their dynamic behaviour.

5. Conclusions

The analysis of the numerical model used in software GMAST has been carried out in order to determine the accuracy of computed modal properties of tall slender structures. The applied numerical model is based on an idealization of the structure as a continuous two dimensional beam with continuously distributed parameters on elastic supports. The elastic supports with frequency dependent stiffness represent the effect of supporting guy ropes. The model has been analyzed in cases of four different existing structures theoretically as well as experimentally.

The comparison between theoretically and experimentally obtained results of three guyed masts and one tower has shown good agreement and acceptable accuracy. The comparison reveals that the model used in software GMAST is entitled to use for modal analysis of tall slender structures and to assess their dynamic behaviour. The future work will be focused on the investigation of the initial displacement influence on changes of modal properties and subsequently on the dynamic response of structures. Also the module for the calculation of torsional natural modes will be implemented into the software GMAST in order to enable the assessment of the coupled bending-torsion vibration.

Acknowledgments

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