# In Situ Measurements for the Structural Assessment of Existing Tall Industrial Chimneys

**I. Vlad**
*Technical University of Civil Engineering Bucharest, Romania*

**M. Vlad**
*University of Bucharest, Faculty of Physics, Romania*

**SUMMARY:**
The analysis and design of tall cantilever chimneys to resist earthquakes or wind-induced vibrations requires knowledge of the mode shapes and natural frequencies of vibrations. The same information is needed for the evaluation of seismic vulnerability of very flexible structures, such as high-rise chimneys, aspect which represents a challenging aspect in earthquake engineering. The present paper is mainly devoted to experimental programs within which the response to ambient vibrations of the most representative chimneys, from the point of view of their heights, was recorded. The dynamic investigations performed on real chimneys showed that information gathered from ambient vibration measurements provide reliable and efficient data of real interest for a clear understanding of the behavior of the investigated chimneys. Based on the obtained results, a formula for the direct determination of the natural eigenperiod of vibration of tall reinforced concrete chimneys is considered.

*Keywords: chimney, seismic vulnerability, ambient vibrations, diagnosis, eigenperiod*

## 1. INTRODUCTION

In the last 60 years, among various engineering structures, chimneys have been an important application in the Romanian construction industry. Over 200 such industrial chimneys, with heights ranging between 60 and 350 m, are nowadays in operation. The paper is focused on the dynamic instrumental investigation of existing reinforced concrete industrial chimneys.

An industrial chimney is an essential part of any factory. Reinforced concrete chimneys are used to help to disperse combustion by-products, such as nitrogen oxides, sulphur dioxide, carbon monoxide and other particulate matter produced during the combustion of fossil fuels and other industrial processes. The basic purpose to build a chimney in a factory is to protect the health of people in the immediate vicinity and to increase the height at which pollutants are discharged to help proper dispersion without affecting the air quality in general. The benefits of industrial chimneys are widely known.

The long term behaviour of reinforced concrete chimneys in Romania has been influenced by a great number of factors, among the most important being: the seismicity of the Romanian territory, corrosion of RC shell, as a result of condensation of the high acidic flue gases which escape into the annular space between the brick masonry liner and the chimney, the level of knowledge at the time of design, the design and completion quality etc. For heights exceeding 100 m, RC chimneys were favoured, because their inherent stiffness for earthquake and wind resistance. These structures were found to be vulnerable to damage during strong earthquakes, despite the fact that none of them collapsed, experiencing, in turn, extensive cracking along the casting joints. The behaviour of RC industrial chimneys in Romania has been, and still is, largely influenced by the thermal and chemical impact of the exhaust gases, influencing their normal operation and increasing the seismic risk in case of future strong earthquakes. In conclusion, the main causes for the inadequate behaviour under thermal and chemical action were the use of poor quality materials for heat insulation and corrosion protection, the abusive operation with exhaust gas temperatures exceeding the design ones, the absence of maintenance actions, to which can be added certain inaccurate assumptions concerning the stiffness of the structure during the various stages of concrete ageing and, consequently an underestimation of the stresses which resulted from temperature variations. The above causes induced damage such as vertical cracks in the RC shell, the size of which impedes operation under normal conditions, the deterioration of heat insulation and of anti-acid bricks and the initiation of chemical-sulphate attack in the structure of concrete.

As a consequence, design companies (such as the Institute for Studies and Power Engineering - ISPE), academic and individual experts have performed extensive technical assessments in order to establish the actual behaviour of the most important RC chimneys and, in some cases, have initiated retrofit projects for the improvement of the thermal and corrosion protection.

The authors of the paper were involved in many such technical assessments, from which ten examples will be considered. It must be specified that the paper is focussed mainly on the full scale dynamic investigations of the eigencharacteristics of such structures.

## 2. OBJECTIVES OF THE INSTRUMENTAL INVESTIGATIONS

The technical assessment of engineering structures involving RC chimneys, influenced by the operating regime and by the successive strong seismic motions, is stipulated in the in-force technical and legal legislation. By their specific, the assessment operations for the seismic level of protection of chimneys, for the establishment of the rehabilitation technical solutions and of the intervention works require from the teams involved, together with the experience to approach such works, an excellent training in structural dynamics and earthquake engineering, especially since the university education does not contain a particular tuition in this field. This is motivated by the fact that the engineer is faced, each time, with extremely different issues, unconventional, being forced to accurately interpret phenomena related to the conception, design, implementation, maintenance and conservation of these engineering structures and, not eventually, their behavior to wind and seismic actions. Moreover, the ultimate goal of a chimney technical assessment lies in identifying and locating the occurred in-time modifications of the elastic and inertial characteristics, in view of developing a unitary concept of rehabilitation (possibly by capital repair), in order to remedy the existing situation, and thus to ensure seismic protection to future strong earthquakes, according to the legislation in force. Given the destination and the importance of industrial chimneys, which are basic components in thermal power plants, as well as the permanent natural ambient vibration and technological processes, combined with the plant traffic, instrumental investigations were carried out. Imposing these requirements in the assessment process, a number of helpful technical information and valuable instrumental data was obtained, e.g. the overall dynamic characteristics and the damaged areas of chimneys caused by strong earthquakes. The dynamic instrumental results that were made available to the designer have contributed to the initiation and choice of technical solutions and, finally, to rehabilitation proposals, in order to ensure appropriate performance parameters, according to the in-force requirements, and in the conditions of reasonable costs.

*The main objectives of the instrumental investigations* carried out were related to the following aspects:

- characterization of chimneys in order to define their dynamic identity and integrity;
- establishing of modal dynamic characteristics from ambient vibration tests (eigenperiods, eigenshapes and damping);
- identification, location, quantification and explanation of existing damage areas, as a result of instrumental measurements;
- identification of possible elastic and/or inelastic discontinuities induced by cumulative damage processes;
- pointing out the vulnerable potential zones to future seismic actions;
- providing useful and accurate information in order to verify the correctness of the methodology used to define the adopted structural model of analysis for the RC chimneys, including the soil-structure interaction effects.

The elucidation on the basis of instrumental investigations of some of the above mentioned aspects has contributed, along with other considerations (the nature and quality of materials, numerical analysis), to the estimation of the actual level of seismic protection of the examined chimneys, using the regulation and technical requirements in-force (Vlad and Vlad, 1998).

## 3. SELECTED CHIMNEY CONFIGURATIONS

Six different chimney heights, corresponding to ten industrial chimneys located in particular seismic areas, were selected for this paper. These heights are: 80 m, 106 m, 120 m, 160 m, 200 m, 250 m, and cover the practical range for existing RC industrial chimneys built in Romania. In Fig.3.1 a schematic drawing showing the ten investigated chimneys is presented, and in Fig. 3.2 general views of some of them.

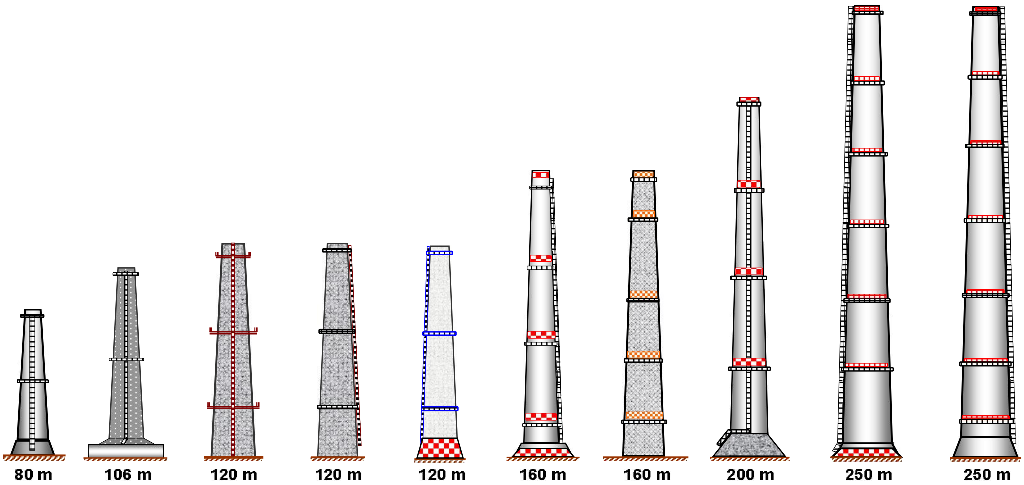



**Figure 3.1.** Schematics of the configuration of the chimneys.

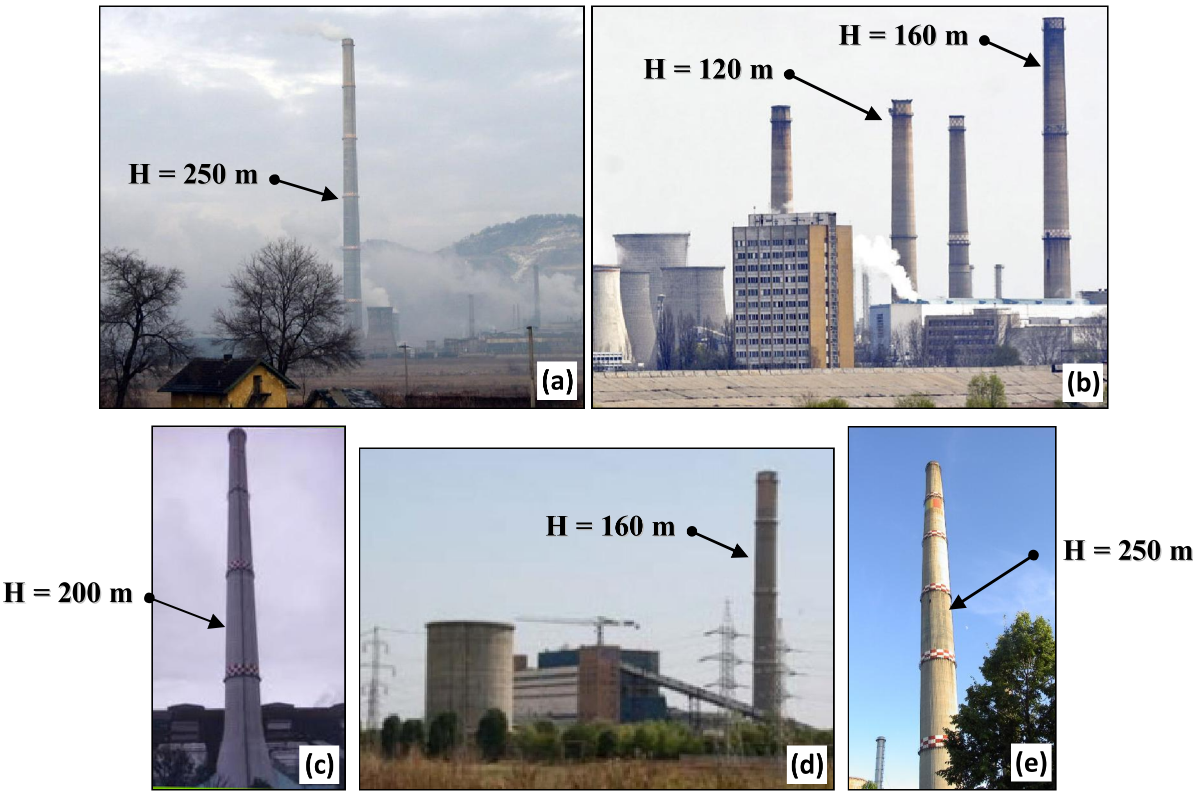



**Figure 3.2.** General view of some of the taller chimneys.

## 4. SOME ASPECTS RELATED TO INSTRUMENTAL INVESTIGATIONS

The main concern of the present paper is the dynamic testing of full-scale structures from the point of view of knowledge needed for earthquake-resistant design. The structural models of analysis used in the design process of buildings and engineering structures are "*idealizations*" conceived to represent the response of real structures to loads generated by strong earthquakes. The most sophisticated and brilliant structural analysis methods are easily defeated by poor, inaccurate, or inappropriate data. Professor Mete A. Sozen, in a summary of a talk about the importance of the structural analysis entitled "*A Way of Thinking*", has stated: "*Today, ready access to versatile and powerful software enables the structural engineer to do more and think less*".

In order to develop a better understanding of the earthquake motions of buildings and engineering structures it is desirable to have experimental measurements of the actual motions and of stresses and strains which occur during strong earthquakes. Information of this kind is difficult to obtain, as in most locations earthquakes are infrequent and strong motions occur at large time intervals.

System identification using *ambient vibration measurement*s presents a challenge requiring the use of special identification techniques, which can deal with very small magnitudes of ambient vibration contaminated by noise without the knowledge of input forces.

The structural models of analysis of buildings and engineering structures can be verified by conducting full scale ambient and forced vibration experiments. Both of these can be used to identify the dynamic characteristics of a structural system, i.e. eigenfrequencies of vibration, damping ratio and mode shapes.

The beginning of the ambient and forced vibration tests of structures originates in 1936 and is due to the U.S. Coast and Geodetic Survey for determining the fundamental periods of vibration for some high-rise buildings, and 1937 for determining the fundamental periods of vibration of some bridges. A procedure for obtaining information on the physical properties of the buildings and engineering structures was to perform dynamic measurements while the structure was excited into motion by a shaking machine installed in the structure and which exerted dynamic forces upon it. The *forced vibration tests* required large forces to produce useful (larger) response amplitudes of full-scale structures. The vibration exciter (the shaker) was usually located on the top of the building. This led to more prominent excitation of the modes of vibration that had large amplitudes at the higher levels of the structures. The paths of waves propagating through the structure are different from those in case of earthquake ground shaking, ambient noise, or wind excitation, and cautious interpretation of the results is required to take such differences into account (Ivanović et al., 2000), (Luco, 1987).

The *ambient vibration tests* describe the *linear* behaviour of buildings and engineering structures, since the amplitudes of vibration are small. When a structure is behaving linearly, the maximum response will depend on the fundamental eigenperiod of vibration and on the magnitude of the actual damping. An advantage of the ambient vibration over the forced vibration instrumental investigations is that usually only light equipment and smaller number of operators are required. An excellent literature review on the subject of ambient vibration testing which illustrates the state-of-the-art in the application of the ambient vibration method was written and published in 2000 in the ISET Journal of Earthquake Technology (Ivanović et al., 2000). The authors showed that the use of ambient vibration tests essentially started in 1970. Of 87 example papers quoted, 77% describe the use of ambient vibration measurements to test buildings, dams, nuclear power plants, chimneys etc. and the remaining 23% describe the ambient vibration tests on bridges.

For each industrial chimney the instrumental data acquisition was performed *in situ*, at full scale. The measurements were performed under high fidelity conditions using Kinemetrics equipment. The number of measuring points was established at the intermediate bridges along the height of the chimney stacks on a horizontal radial direction, as shown in Fig. 4.1. The vibration sources considered in each case were: ambient vibrations combined with traffic, and the in-plant operation of equipment in the vicinity of the chimney stacks. Some elements related to this complex type of excitation will be in brief presented. As it is known, the Earth surface is in a permanent low state of vibration, known as *ambient vibration* (the microseismic background at any given site on the Earth is comprised of energy generated from multiple simultaneous sources). Ground at a particular site is continuously in a state of low amplitude motion due to various natural and cultural disturbing factors. Ambient vibrations have a random nature and cover a relatively wide band of frequencies. The Earth motions are induced in buildings and engineering structures, within a process of low intensity steady state vibrations. The recordings made in the field have shown that these vibrations are of almost stationary nature. Chimneys involved in vibration behave like “dynamic filters”, amplifying the spectral components with frequencies in the immediate vicinity of their own eigenfrequencies, and attenuating those spectral components whose frequencies are outside the domain of existence of the eigenfrequencies of vibration of these structures. Generally, chimneys are considered as the most “*unitary*” engineering structures which don’t have in their framing elements without “*structural role*” that could change their response during an earthquake. Given the high degree of flexibility, granted by the initial design of these engineering structures, within the energetic process generated by ambient vibrations, chimneys are fully driven in motion. Consequently, the analysis of the recorded vibrations allows, with some degree of certainty, to identify the fundamental eigenvalues and, in some cases, some of the higher order. Instrumental data were pre-processed before being used as input in the structural identification procedure. Velocities, simultaneously recorded, were processed both in *time* and *frequency domains*, and by means of Fourier amplitude spectra the frequency content of motions were determined. The instrumental results were obtained after processing the recorded signals, using representative samples from the amplitudes point of view. The Fourier amplitude spectra of velocities put to evidence the *frequency content* of the recorded motions, as well as the appropriate amplifications of dominant frequencies. By processing the recorded signals were identified eigenfrequencies (relative spectral peaks) corresponding to the first two to five eigenmodes of vibration.

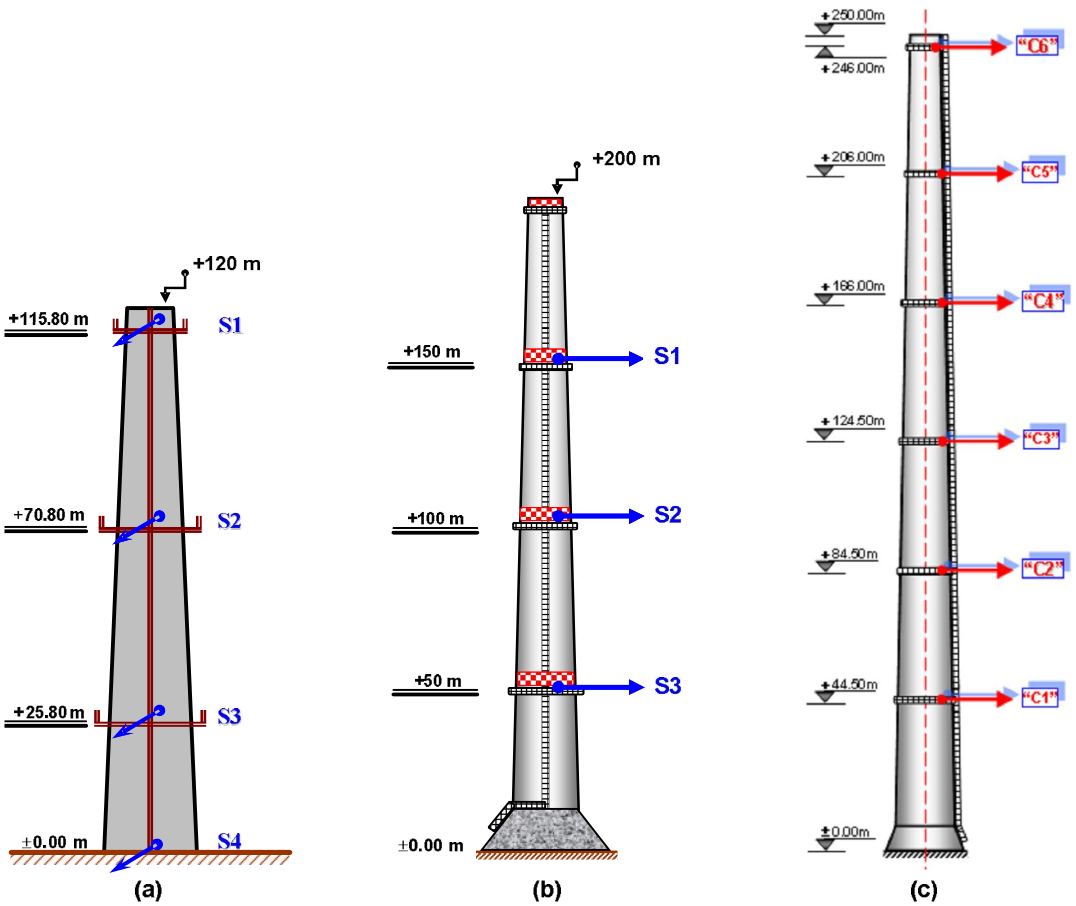


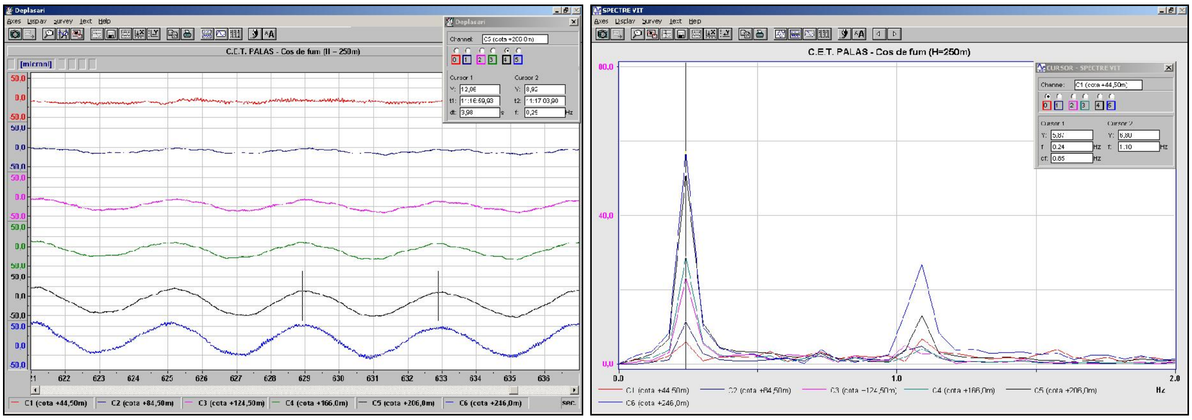

**Figure 4.1.** Location of sensors in different configurations.

## 5. SAMPLES OF SOME OF THE OBTAINED RESULTS

To illustrate the obtained results, three of the investigated chimney stacks were selected: an industrial chimney of 120 m, one of 200 m and one of 250 m height. The main reasons for which this selection was made were: height (250 m), strengthening (200 m) and change in operation conditions (120 m).

### 5.1. "Palas – Constanta" thermal power plant chimney (H = 250 m)

The first case study refers to the instrumental investigations carried out in view of identifying the eigencharacteristics of a 250 m high reinforced concrete chimney stack (Fig. 3.2, e), erected by using sliding forms (Vlad and Vlad, 1989). The number of measuring points depended on the complexity of the experiment that allowed the arrangement of six seismometers at the intermediate bridges along the height of the chimney stack, on a horizontal radial direction, as shown in Fig. 4.1,c. The vibration sources that were considered were: microseisms combined with traffic and the in-plant operation of the equipment in the vicinity of the chimney stack. The time domain representations (velocities and displacements) were performed in view of getting an overall image of the spatial motion of the ensemble "*industrial chimney – foundation*". Typical time domain representations and the corresponding amplitude Fourier spectra are shown in Fig. 5.1.




(a) (b)

**Figure 5.1**. Ambient vibration testing. (a) time domain [μm]; (b) amplitude Fourier spectra (filter: 0÷2 Hz).

Long time intervals of time were recorded, thus contributing to a higher resolution of the results. After processing and interpreting the data obtained by instrumental investigations, the values of the eigen-frequencies/eigenperiods of vibration corresponding to the first five eigenmodes of vibration were obtained. These measured values are summarized in Table 6.1. Fig. 5.2 illustrates the first three natural modes of vibration of the high reinforced concrete chimney, identified by means of instrumental data.

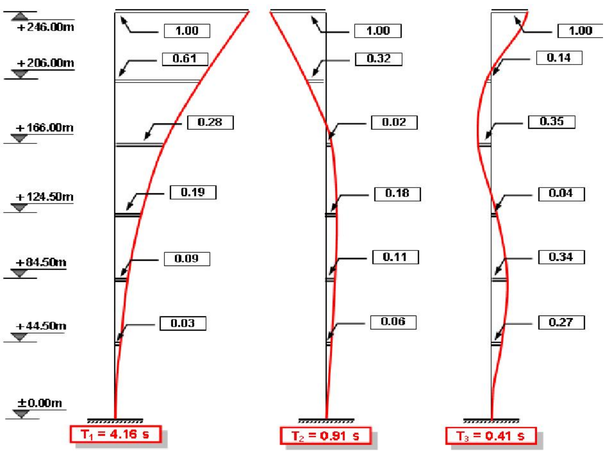



**Figure 5.2.** Eigenmodes of vibration for the 250 m industrial chimney.

Considering the spectral composition of the Vrancea earthquakes (characterized by intermediate focal depths), to which the amplification of the dominant components correspond to periods in the range 1÷1.6 s, the chimney stack in discussion presents a *relatively reduced degree of vulnerability*, taking into account the value of the fundamental eigenperiod of vibration ($T_1 = 4.16$ s). To this tall chimney stack, the ratios between the first three eigenperiods of vibration instrumentally obtained correspond to the theoretical established values in the technical literature ($T_2 \approx 0.25\ T_1$; $T_3 \approx 0.10\ T_1$).

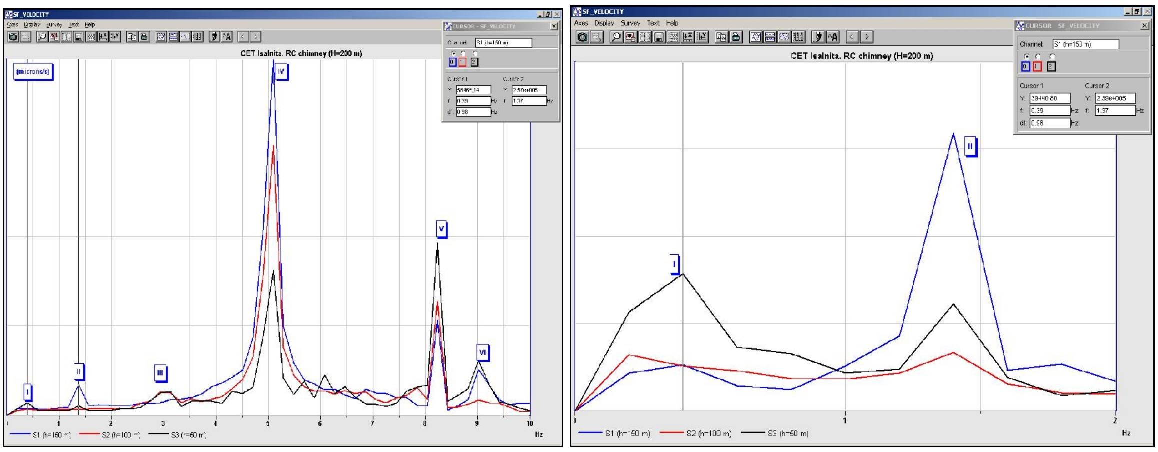
On the basis of auto-correlation functions of the recorded signals, it turned out that the values of the fraction of critical damping obtained on the basis of specific processing pertain to the interval 6…8.3%. Considering the eigenvalues and the eigenshapes of vibration instrumentally obtained one can state that, in the actual technical state, the structural system of the chimney doesn't present "*inertial and elastic discontinuities*". The instrumental investigations allowed us to assign to the chimney stack a well-defined "*dynamic identity*", as the dynamic eigencharacteristics corresponding to its eigenmodes of vibration pertain to an expected range of results (Vlad and Vlad, 2011).

### 5.2. "Isalnita – Craiova" thermal power plant chimney (H = 200 m)

The chimney was designed in the period 1964-1965 and was completed in 1967 (Fig. 3.2,c). As a result it has undergone the March 4, 1977 ($M_{G\text{-}R}$=7.2), August 30/31, 1986 ($M_{G\text{-}R}$=7.0), May 30, 1990 ($M_{G\text{-}R}$=6.7) and May 31, 1990 ($M_{G\text{-}R}$=6.1) Vrancea strong earthquakes. Some details about this industrial chimney are given, as follows: as it was previously mentioned its height is 200 m; the thickness of the tower wall varies from 50 cm (at +33 m) up to 18 cm (+200 m) and the thickness of the truncated frustum of cone is 40 cm; the foundation, laying on marl rock at about -10 m, has a circular – ring shaped outline (inner radius: 12 m and outer radius: 19.20 m); the thermal insulation is of kieselguhr and the corrosion protection is of antacid brick insulation type; the reinforcement of the chimney was made with longitudinal and circular smooth steel bars, positioned only on a single surface, the outer one. The number of measuring points depended on the access on the chimney and the number of available sensors at the time, which allowed us the arrangement of only three sensors at the intermediate bridges levels at 150 m, 100 m and 50 m, on a horizontal radial direction, as shown in Fig. 4.1, b. The following typical types of analysis have been carried out:

- numerical integration in time domain, obtaining in this manner from the basic signal (velocities) the vibration displacements;
- Fast Fourier Transform (FFT) of the real signal, both for velocities and displacements;
- auto-correlation functions (cross-correlation of an input signal with itself), by means of which it is possible to detect an inherent periodicity in the signal itself and to determine the damping ratio.

Some of the data acquisition results are shown in Fig. 5.3 (in Fig. 5.3,b the recorded signal was filtered in the range 0÷2 Hz).




(a) (b)

**Figure 5.3.** Amplitude Fourier spectra representations; velocities [μm/s].

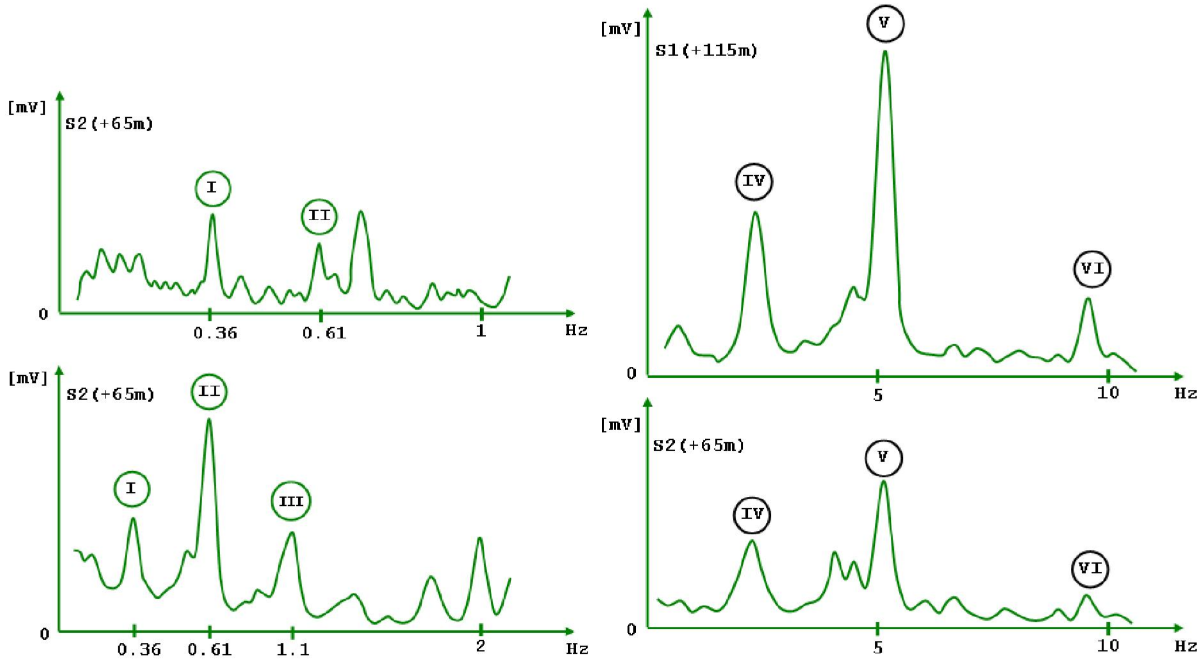
### 5.3. “Bucharest – South” thermal power plant chimney (120 m)

This thermal power plant chimney, with a height of 120 m, was designed in the period 1963-1965 as a “single wall” chimney, the space between the reinforced concrete shell and the inner masonry tube (exhaust) not being accessible.

The constitutive parts of this engineering structure have the following characteristics: the base of the stack that connects the foundation and the bearing shaft develops between -5.0 m and +4.80 m, and consists of a 60 cm thick tapered concrete wall; the bearing trunk of truncated cone shape, which extends from +4.80 m to +120.0 m, has the outer diameters ranging between 12 m (bottom) and 7.40 m (top) with thicknesses from 62 to 18 cm; the exhaust tube, located inside the chimney, consisted of antacid ceramic bricks varying from 25…$12^5$ cm, the last section (at the top of the chimney) being made of artificial basalt; the space between the outer wall and the masonry inner lining was filled with multi-cellular expanded glass coating (5…8 cm thick); the reinforcement of the chimney was made with longitudinal and circular smooth steel bars.

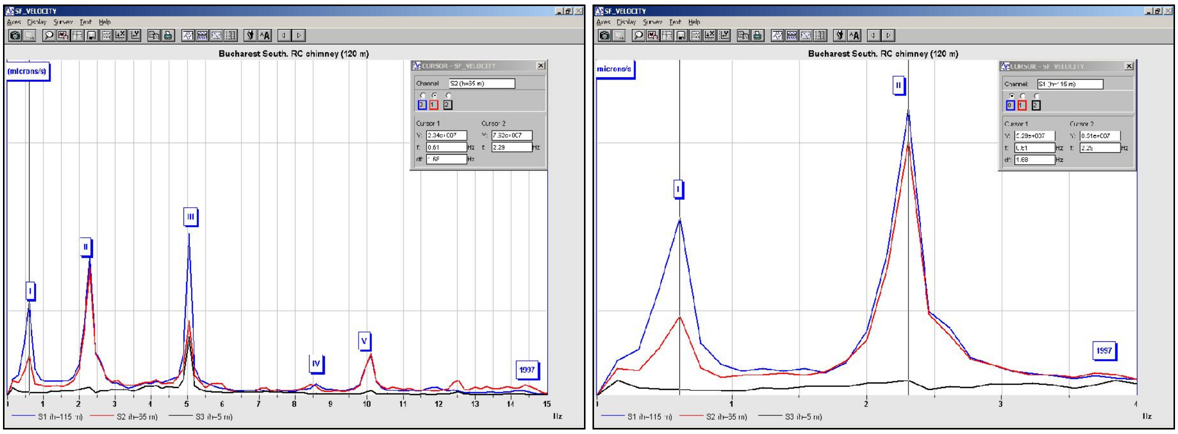
Since 1979, cracks in the chimney concrete exterior shell, both on vertical and horizontal directions, have been reported (especially in areas located between +70 m and + 105 m). The process of degradation which continued over time can be mainly blamed on the plant operation conditions. From the moment of putting into service (in 1965) and until 1977, the associated boilers worked with flue gas. Since 1977 they started operating with oil: until 1982 with light fuel oil with maximum 1% sulfur, later with viscous oil with increased content of sulfur (>5%) and high combustion temperature. This fact has substantially contributed to the weakening of the chimney, not only in what concerns the inner thermal and antacid coating, but also in what concerns the exterior reinforced concrete shell. Thus, in the period 1991-1992, the rehabilitation of the chimney has been completed.

The Technical University of Civil Engineering Bucharest, together with the Building Research Institute – INCERC Bucharest, was involved in a program of instrumental dynamic investigations, at full scale, in 1987 and in 1997, before and after the capital repairs. In Fig. 5.4 and 5.5 are presented, by comparison, the results obtained, and in Table 6.1 one can see the shortening of the fundamental eigenperiod of vibration for this 120 m industrial chimney.




(a) (b)

**Figure 5.4.** Amplitude Fourier spectra representations (1987).




(a) (b)

**Figure 5.5.** Amplitude Fourier spectra representations (1997).

## 6. FINAL REMARKS

Table 6.1 shows the eigenperiods that were obtained by instrumental investigations for the selected 10 chimneys.

**Table 6.1.** Values of the eigenperiods of vibration established by dynamic investigations

| Chimney height (m) | $T_1$ (s) | $T_2$ (s) | $T_3$ (s) | $T_4$ (s) | $T_5$ (s) |
|---|---|---|---|---|---|
| 250 (newly built) | 3.33 | 0.89 | - | - | - |
| 250 | 4.16 | 0.91 | 0.41 | 0.33 | 0.20 |
| 200 | 2.94 | 0.71 | 0.33 | 0.20 | 0.12 |
| 160 | 2.70 | 0.60 | 0.30 | - | - |
| 160 | 3.13 | 0.71 | 0.32 | - | - |
| 120 | 2.72 | 0.48 | - | - | - |
| 120 (1987) | 2.78 | 1.64 | 0.91 | 0.45 | 0.19 |
| 120 (1997) | 1.64 | 0.45 | 0.19 | 0.12 | 0.10 |
| 106 | 1.82 | 0.42 | - | - | - |
| 80 | 1.34 | 0.30 | - | - | - |

As damping for chimneys vary greatly from code to code and is very different from reality, instrumental investigations for each industrial chimney are necessary in order to find its actual value. The critical damping had values ranging from 2.4 to 4.5% for the fundamental eigenmode of vibration, and from 0.5 to 2.2% for the second eigenmode of vibration, in most cases.

An empirical formula for obtaining the fundamental eigenperiod of vibration for undamaged RC chimneys is $T_1 = 1.7 \cdot H/100$ (where H is the chimney height in meters). In Fig. 5.6 a chart showing a comparison between the computed and the instrumentally obtained fundamental eigenperiod of vibration is presented.

Evaluation of seismic vulnerability of industrial chimneys in a seismic country as Romania is a challenging problem in earthquake engineering. They are often considered as parts of vital facilities and thus they must be fully functional after very strong ground motions. A literature review has indicated few failures of tall reinforced concrete chimneys from earthquake excitation. After more than 25 years of operation, the action of internal and external factors had as result a certain state of damage. Consequently, seismic assessments for the actual performance capacity of the existing chimneys were necessary, in order to estimate the necessary upgrading works. Nowadays, fewer and fewer new chimneys are being constructed and more attention is being paid to extending the lives of the existing ones. The most expensive components of an unplanned chimney repair is usually the cost of lost production from the units served. Therefore, the owner pays to carry out regular inspections, so that unplanned shutdowns for a repair can be avoided. Inspection can be visual, involving access to the external and internal surfaces of the chimneys. Sometimes internal access is not possible. That's why, within a technical assessment of a reinforced concrete chimney, dynamic investigations using vibration techniques should be mandatory. The immediate result of such an investigation is obtaining the values of the chimney eigencharacteristics and the identification of regions with cracks in the concrete shells.

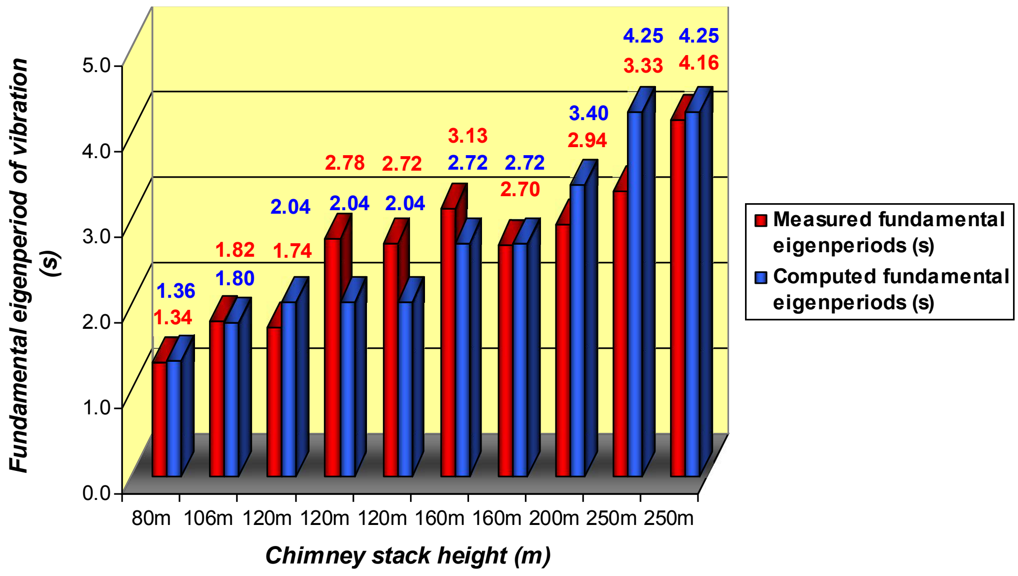



**Figure 5.6.** Graphic comparison between measured and computed fundamental eigenperiods of vibration.

The main author of the present paper has conducted such dynamic experiments for chimneys ranging from 80 m to 250 m. The results that were obtained were given to the designer in order to incorporate them in structural models of analysis, thus being able to establish the most appropriate and economic solutions of interventions. In two of the above presented case studies, a chimney of 200 m and one of 120 m heights were saved from demolition, being strengthened, after performing such dynamic investigations. Following different periods of operation and incidence of strong earthquakes in seismic regions, the owners of industrial chimneys must perform technical assessments. The fastest and cost effective evaluation is that of checking the "*dynamic identity*" of such engineering structures. That means to obtain the eigencharacteristics of a chimney and to identify the possible damaged areas. As it is well known, the eigencharacteristics of a dynamic system are functions of its mass and its stiffness. During the period of operation of a chimney, natural phenomena as cross-wind vibrations and earthquakes, as well as artificial phenomena as chemical effects, thermal effects, and difficult operation conditions, a decrease of the overall stiffness and a change in damping are possible. The immediate effects are the lengthening of the periods of vibration and the increase of damping, subsequently meaning structural damage. By periodically obtaining such information about the evolution of these eigencharacteristics it is possible to monitor the behaviour of such engineering structures and their state of damage.

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