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EXPERIMENTAL DETERMINATION OF NATURAL VIBRATION FREQUENCIES OF SUPPORT STRUCTURES FOR LARGE INDUSTRIAL EQUIPMENT

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SUMMARY

Using results from several microtremor measurements and of acceleration records obtained in an earthquake on steel support structures for large industrial boilers different System Identifications (SI) procedures are used to identify the natural vibration frequencies of the structure-equipment system.

The results of applying "blind" identification using different SI techniques and models are compared among themselves and to the vibration frequencies of the systems as obtained from dynamic structural analysis procedures used in engineering practice.

The comparisons of the SI results show that there is very large dispersion in the natural vibration frequencies obtained from the different SI techniques and models, and therefore it is concluded that the reliability of such procedures in predicting the actual values of this parameter is very low. Furthermore, in general, the frequencies identified from the microtremor measurements correspond to the analytically determined frequencies for the situation where the heavy hanging masses in the structure are not active in the dynamic response. In general, the SI procedures fail to identify the true frequencies of the system under earthquake excitation (large amplitude).

The results for the SI using actual earthquake records show a similar behavior, but the dispersion of the results is somewhat lower. The correlation to the parameters obtained from the analytical models is highly dependent on the modeling assumptions. A major source of uncertainty is the mass distribution, in height and in plan, that is used in the models.

The observed results lead to the following observations: a. The microtremor measurements are not really appropriate to estimate the actual vibration frequencies of this type of structures; b. When using earthquake induced response the number of signals to consider can not be too small (sample size for statistics); c. Most of the SI techniques are not really appropriate for this type of system, they are more likely to work on systems for which a reliable prediction of the expected frequencies can be made "a priori".

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INTRODUCTION

In general the structures that support large industrial equipment like steam boilers, electrostatic precipitators, etc. have irregular distributions of mass and stiffness both in plan and over the height. In addition, they may include special support devices to handle deformations induced by temperature effects and/or operational conditions. The aim of the research reported here is to evaluate the quality of the different methods of SI and models used in the analysis of two different types of these structures. To that purpose a comparison is made of results obtained from different methods of SI, using microtremor measurements data and also actual earthquake response data measured in one of these structures that had previously been instrumented.

STRUCTURAL SYSTEMS

Description of Structural System – Nueva Renca Heat Recovery Steam Generator

The Nueva Renca heat recovery steam generator (HRSG) supporting structure is an integral part of the equipment itself. In the transverse direction (perpendicular to the gas flow), twelve heavy steel moment frames made up of two columns and two beams with bolted connections provide the necessary lateral support. In the longitudinal direction the lateral support is provided by the boiler casing, which is welded to the inside flange of the two columns of the transverse frames. The heavy internal parts of the boiler (heat exchangers and piping) are hanging from the top beam of the frames. Figure 1 shows an overall view of the structure (Vogt [1]).

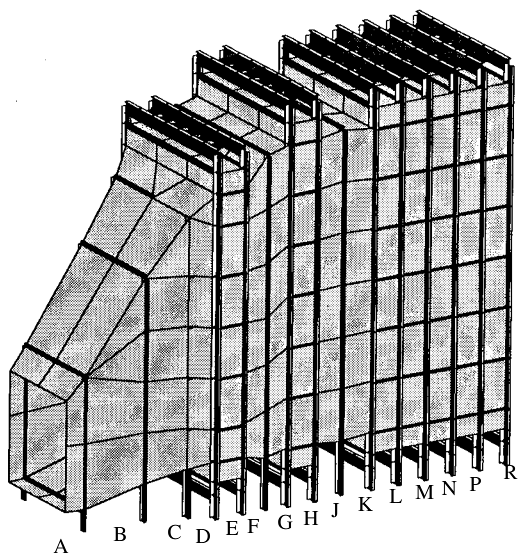


Figure 1. General view of the HRSG casing and steel support structure.

The columns of the different frames are bolted down to base plates, that provide sliding supports to accommodate for thermally induced displacements during operation. For overall lateral stability only one of the frames is fixed to the ground in the longitudinal direction and has one of its legs on a sliding support in the transverse direction.

On top of the beams of the transverse frames three heavy pressure vessels are located. The support structures for the drums are directly attached to the top girder of the HRSG frames.

The total weight of the structure including internal parts, drums, and platforms under operating conditions is 3000 ton. The overall dimensions of the HRSG structure are: 27 m in height, 12.7 m wide, and 26 m in length approximately. The main columns and beams are made of special structural shapes, that for the columns go from W18 x 40 to W36 x 201, and for the beams they go from W16 x 67 to W40 x 397. In Valdivia [2] a much more detailed description of the support structure can be found.

A complete three-dimensional model was created for the structural elements including the casing and the internal parts of the boiler. The model considers standard beam-column elements for the major beams and columns and shell type finite elements for the modeling of the casing.

For the dynamic analysis the mass of the internal parts was considered as attached to the column on one side for the transverse direction and divided uniformly between both columns of the frame for the longitudinal direction. The mass of the drums was added to the top beam at the vessels support location. Over the height, the mass of the modules (internal parts) was attached at the locations of the seismic stoppers at the top, bottom, and sides of the frames. In the vertical direction, the module was attached at the double channels steel shapes that span between frames. These are the actual support members for the modules. Drums were attached on the top transverse beams where they are supported. Figure 2 shows a three-dimensional view of the model of the steel support structure.

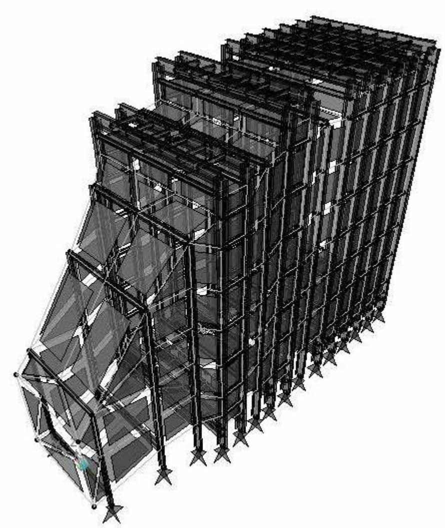


Figure 2. 3D view of steel support structure. Nueva Renca HRSG.

Description of Structural System – Ventanas II Boiler

In this case the steel support structure is approximately 64 m in height, and has 21 levels. The structure is made up of steel frames, with bracing throughout the height. The plan dimensions are approximately 16.5 meters by 21.5 meters. At the top of the structure a rigid diaphragm is made up of steel girders and in plan diagonal elements.

The large weight of the internal parts of the boiler are hanging from these girders. Restraint against lateral movement of the heavy hanging mass is provided through the use of rods (levels 15.062 m, 30.988 m, and 45.009 m) and seismic stoppers (level 15.062 m), that are designed to provide energy dissipation through nonlinear behavior. The mass of the internal parts of the boiler is considered to be attached to the structure at the top girders for vertical motions, and to the lateral resisting frames through the rods and stoppers at the corresponding levels for horizontal motions. The total weight of the structure has been estimated at 5756 ton, of which 4351 ton correspond to the hanging internal parts of the boiler. The columns are fixed in their base. The main columns, beams, and diagonals are made of special structural shapes, that for the columns go from W14 x 43 to W14 x 665, in the beams they go from W10 x 33 to W24 x 103, and in the diagonals they go from W8 x 24 to W14 x 211. In Valdivia [2] a much more detailed description of the support structure can be found.

A complete three-dimensional model was built using the program SAP2000. This model includes the standard structural elements (beams, columns, and diagonals, connecting rods) and also nonlinear elements (stoppers). In this way a no-linear analysis of the structure could be carried out. The model considers "frame type" elements for the columns, beams, diagonals, and connecting rods. For the stoppers a special element, "plastic type", was defined, with a bilinear constitutive (forces – deformation) relation. This served to represent the behavior of this element during the earthquake of the 3 of March of 1985. The characteristics of this elasto-plastic constitutive relation to model the behavior of stoppers were taken from the work developed by Hormazábal [3]. Figure 3 shows a three dimensional view of the model of steel support structure.

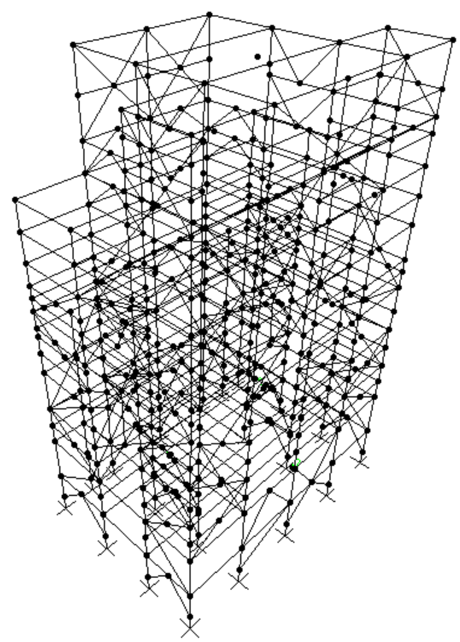


Figure 3. 3D view of the model of steel support structure. Ventanas II Boiler.

EXPERIMENTAL DATA

Microtremor Measurements

The microtremors measurements were carried out in both boilers (Nueva Renca HRSG and the conventional Ventanas II Boiler), during a maintenance period of the equipments and they included different locations in the structure.

HRSG - Nueva Renca Combined Cycle Power Plant.

Two different configurations of the recording instruments were used. In the first one, the instruments were located at the top platform (at the 27 m level) at three different transverse frames location (the two extremes frames and the frame with fixed base supports). On the other, the instruments are located at three different heights along the fixed base frame column (base plate of the column, bottom flange of bottom girder level, and top flange of top girder level).

Using these two configurations several data sets were obtained. The time series are sampled at 100 Hz and have a duration of about 20 seconds (2048 samples). From all the data sets obtained, some were disregarded due to problems observed in the measurements (signal overflows). The instruments used are velocity sensors, made by VTC Corporation, Japan, (VTC [5]).

Typical results obtained are shown in Figure 4 in the form of time histories for the signals (velocities). For the representations in the frequency domain the range of frequencies shown has been restricted to 0 – 25 Hz, since no relevant information is expected in the very high frequencies range. On the other hand, the frequency response function of the instruments used is flat up to 25 Hz, thus the information outside this range can be disregarded.

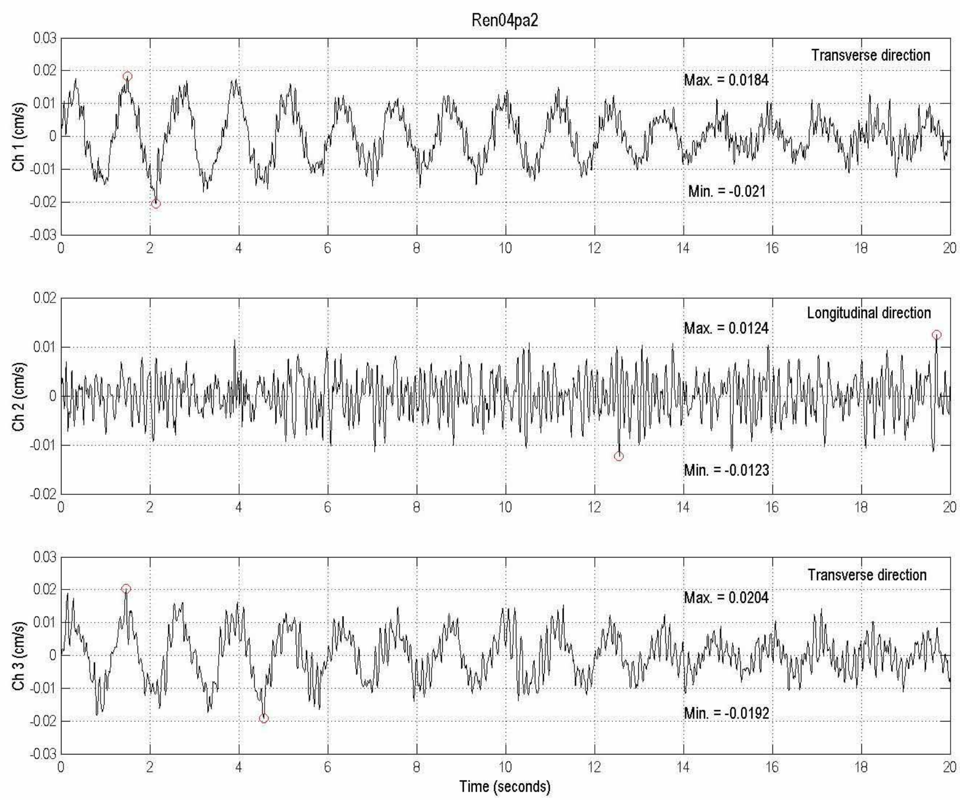


Figure 4. Sample of time history of microtremor at top platform level.

Boiler - Ventanas II Thermoelectrical Power Plant

Similar work had been carried out before for this support structure (Hormazábal [3]). Microtremor measurements were carried out at different locations in the structure. They included simultaneous measurements at different levels, and also at different locations in plan.

For the measurement of the microtremors three velocity sensors were used, (Kinemetrics, Model Ranger SS-1), jointly with a system of data acquisition, (IOTECH, Model Daqbook 200). This system registers the history of velocity of the three sensors in parallel (the time is common) and it stores them in digital form for later processing (Hormazábal [3]). In this case also two types of configuration of measurements were made. One configuration consisted of arranging the three sensors in three different positions in plan at platform level +48,3 m. In the other configuration the sensors are located in different platforms (levels), always keeping one of them in the platform of the level +48,3 m.

In all the measurements 200 samples per second were taken (time step of sampling is 0.005 s) and a antialias filter was applied (100 Hz., upper limit of the registered frequencies). Only in the one of the measurements the time step of sampling was varied to 100 samples per second. In addition, a notch type filter was used in order to eliminate the noise around the frequency of 50 Hz. An example of the recorded time series is shown in Figure 5.

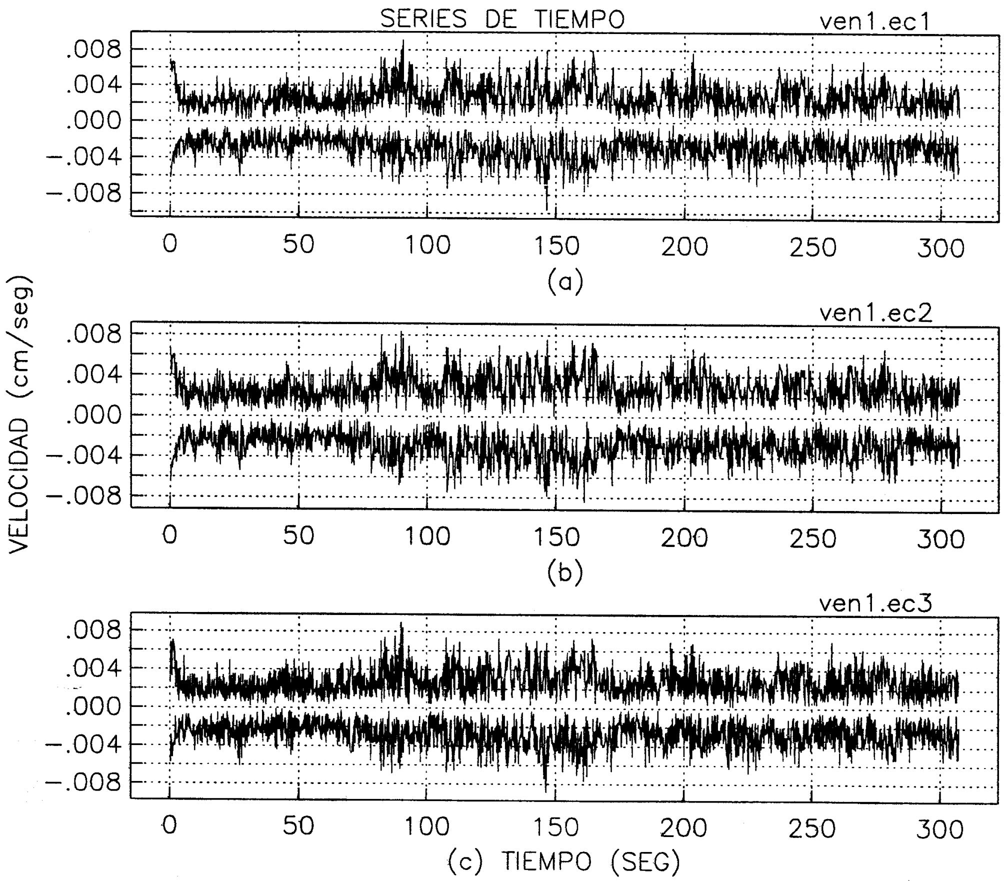


Figure 5. Sample of time history of microtremor at top platform level. measured in the Ventanas II Boiler. From Hormazábal [3].

Actual earthquake record

The large earthquake that occurred in Central Chile in 1985 was recorded at the Ventanas II Boiler steel support structure, both at the base and at the top level of the structure using SMA-1 type accelerometers (by Kinemetrics). The records obtained at that time were digitized and are shown in Figures 6 and 7.

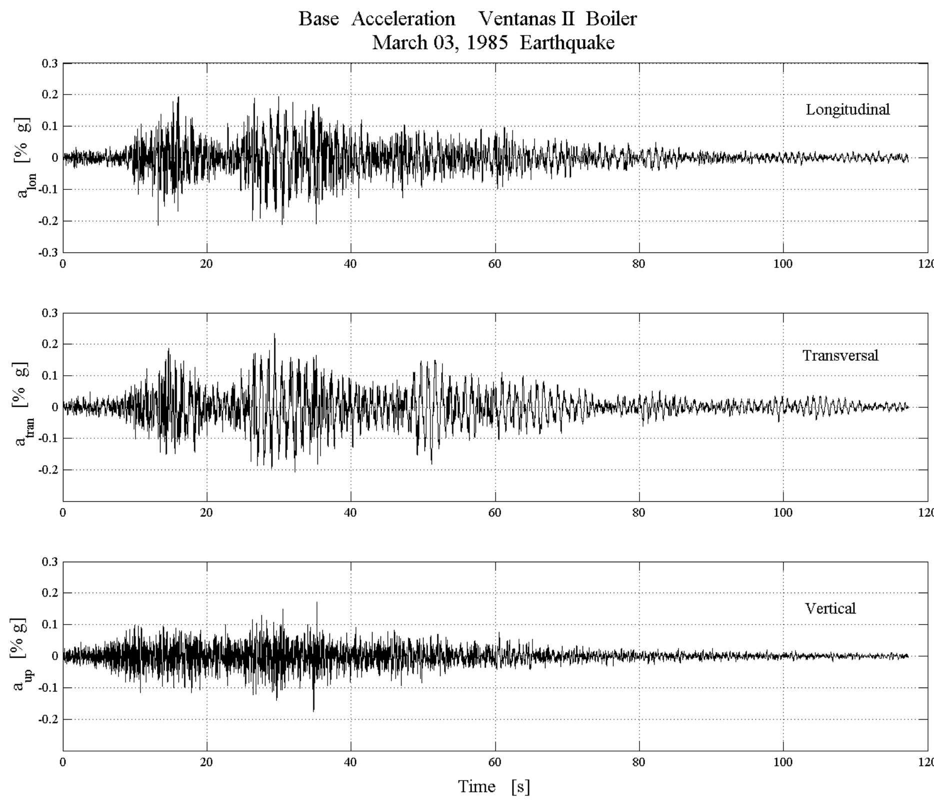


Figure 6. Record obtained by the SMA-1 located at the base of Ventanas II Boiler.

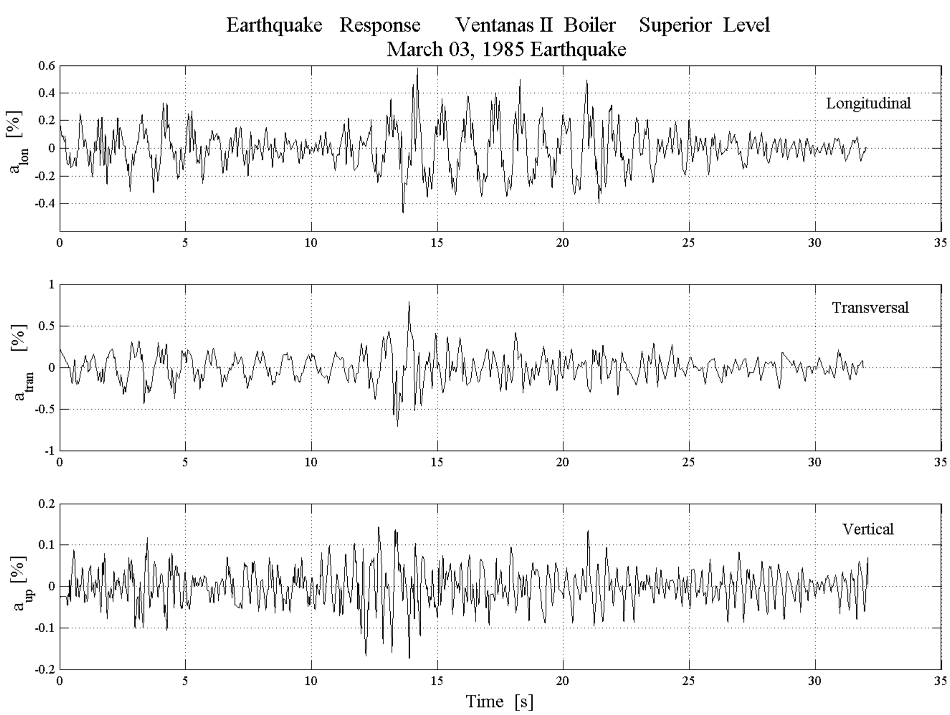


Figure 7. Record obtained by the SMA-1 located at top of Ventanas II Boiler.

Because the recording instruments are analogic it was necessary to correct the records. This was done using a procedure that works in the frequency domain and is described in detail in Valdivia [5].

SYSTEM IDENTIFICATION PROCEDURES

From the measurements described in the previous section a process of identification of the dynamic properties of the structures was carried out. In this study, the typical tools of identification of dynamic systems, available in the Toolbox of Dynamic Systems Identification of Matlab (MathWorks [6]) and other routines specially prepared for this effect were used (also based in Matlab).

Identification of the system by inspection

This procedure was based on the inspection of the Fourier Amplitude Spectra and the Empirical Transfer Function of each measured signal.

For each one of the microtremor measurements of the Nueva Renca HRSG and for the record of the earthquake of 03.03.1985 of the Ventanas II Boiler, the Fourier Amplitude Spectra (FAS) and the Empirical Transfer Function (ETFE) were calculated. Figures 8 to 11 show an example of each of different type of results obtained (FAS and ETFE).

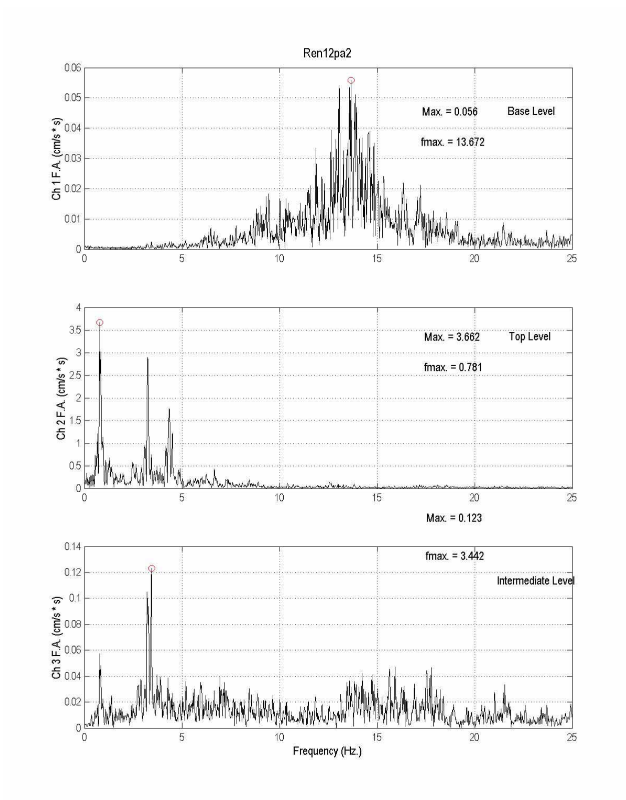


Figure 8. FAS of microtremor measurements over the height. Nueva Renca HRSG.

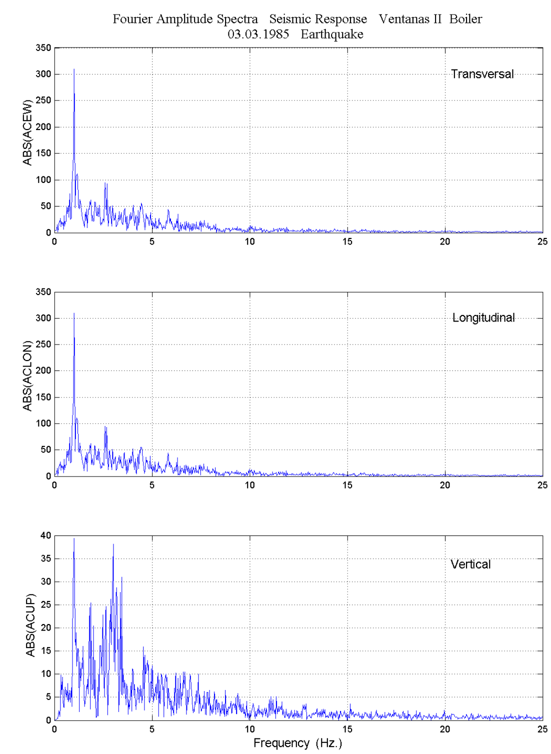


Figure 9. FAS of the record of seismic response of the Ventanas II Boiler.

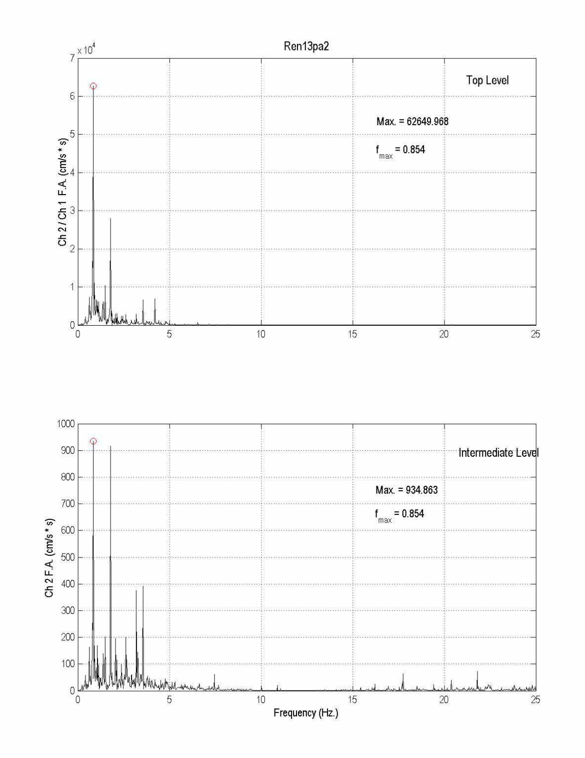


Figure 10. ETFE obtained from microtremor measurements. Nueva Renca HRSG.

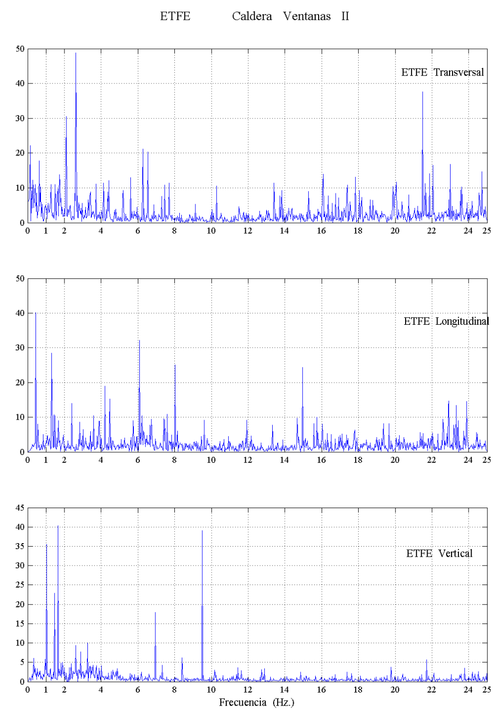


Figure 11. ETFE obtained from the record of seismic response of the Ventanas II Boiler.

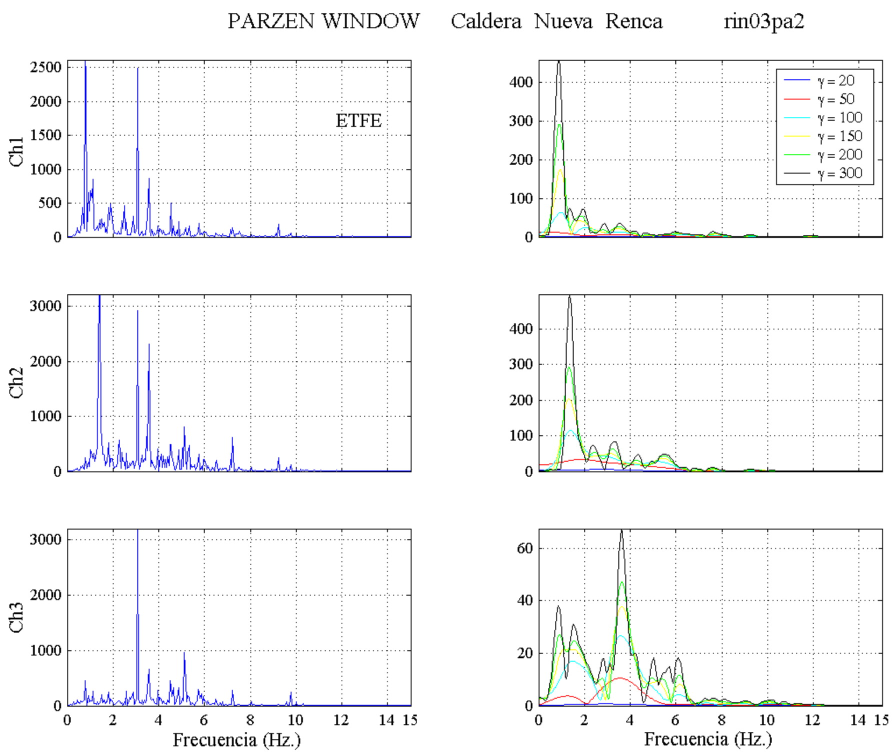
The identification of the system dynamic parameters is carried out by inspection, based on the Fourier Amplitude Spectra and the Empirical Transfer Function described previously. A complete set of plots with all the results obtained can be found in Valdivia [2].

Methods of System Identification

The identification techniques are used to obtain the dynamic properties of the systems from records of their dynamic behavior (seismic or microtremors). Although there are numerous techniques of system identification (parametric and nonparametric) in this study only some of them were used.

Two parametric methods were used: AutoRegressive and Exogenous Models (ARX - ARMAX) and Eigensystem Realization Algorithm with Data Correlation (ERA-DC). And two nonparametric methods were used too: Method of Transfer Functions using the Average Weight of M realizations of N observations and Method of Transfer Functions using Parzen Windows.

Figures 12 and 13 show the results obtained with the Parzen Windows Method for one of the microtremor signals (Nueva Renca HRSG) and one of the records of earthquake response (Ventanas II Boiler). A complete set of plots with all the results obtained can be found in Valdivia [2].



.**Figure 12. Example of the Transfer Function obtained for the Nueva Renca HRSG.**

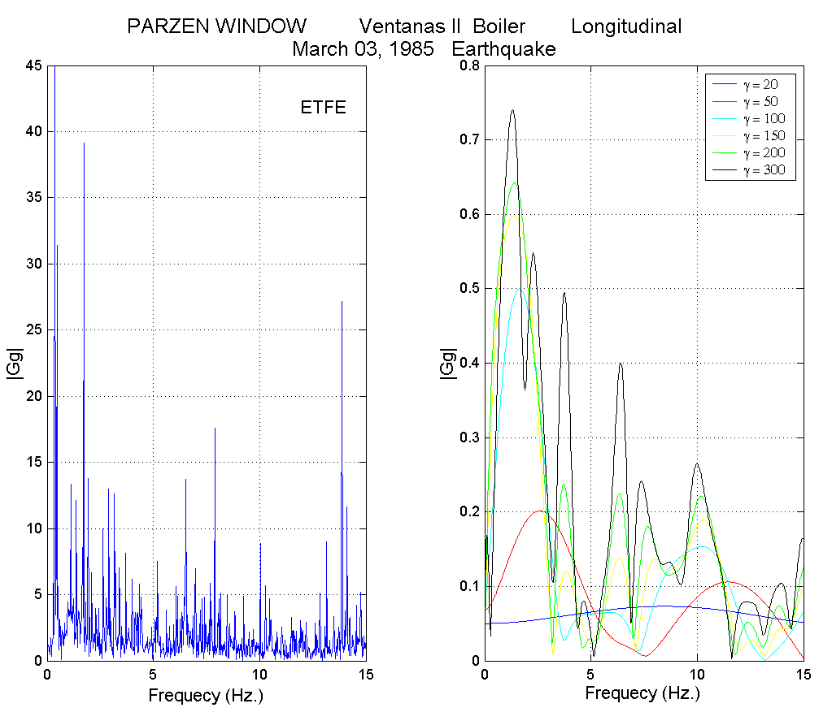


Figure 13. Example of the Transfer Function obtained for the Ventanas II Boiler.

Figures 14 and 15 show the results obtained with the Average Weight of M realizations of N observations Method for one of the microtremor signals (Nueva Renca HRSG) and one of records of earthquake response (Ventanas II Boiler).

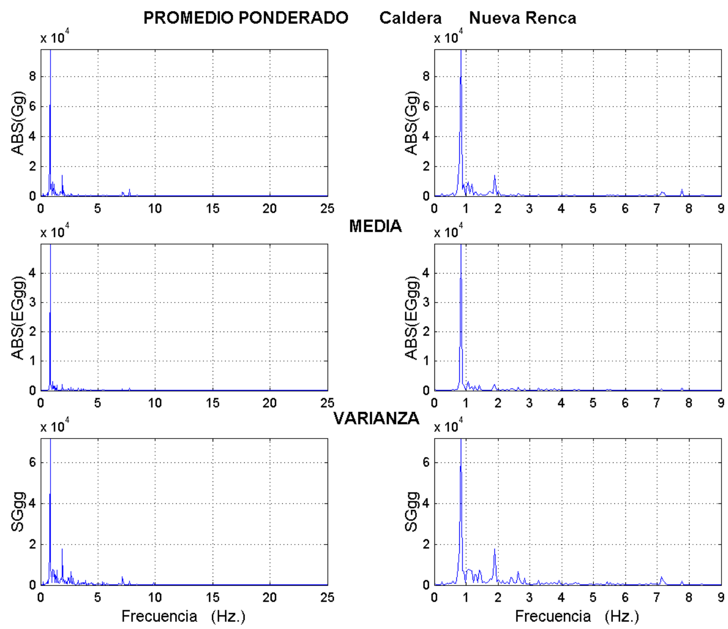


Figure 14. Transfer Function obtained with the Average Weight of M realizations of N observations Method for the Nueva Renca HRSG.

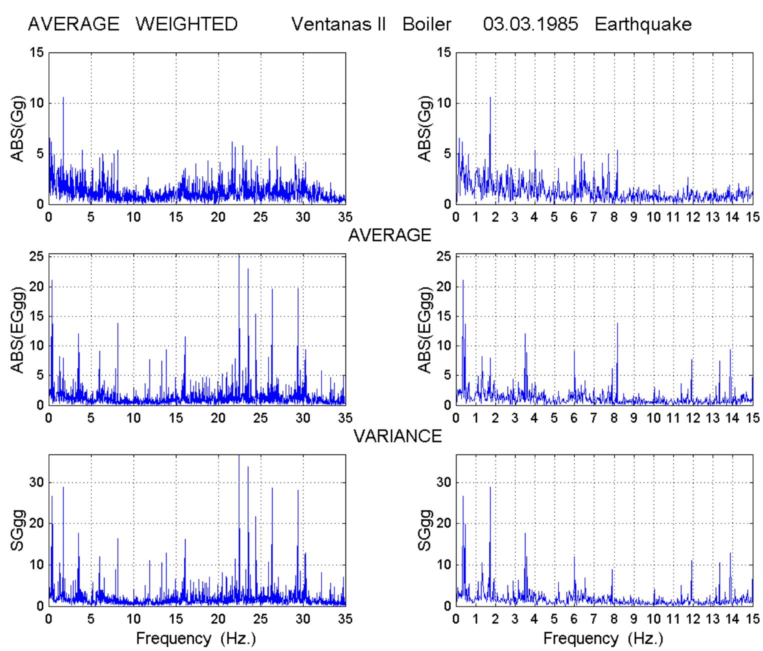


Figure 15. Transfer Function obtained with the Average Weight of M realizations of N observations Method for the Ventanas II Boiler.

Figures 16 and 17 show the results obtained with the AutoRegressive and Exogenous Models for one of the microtremor signals (Nueva Renca HRSG) and one of the records of earthquake response (Ventanas II Boiler).

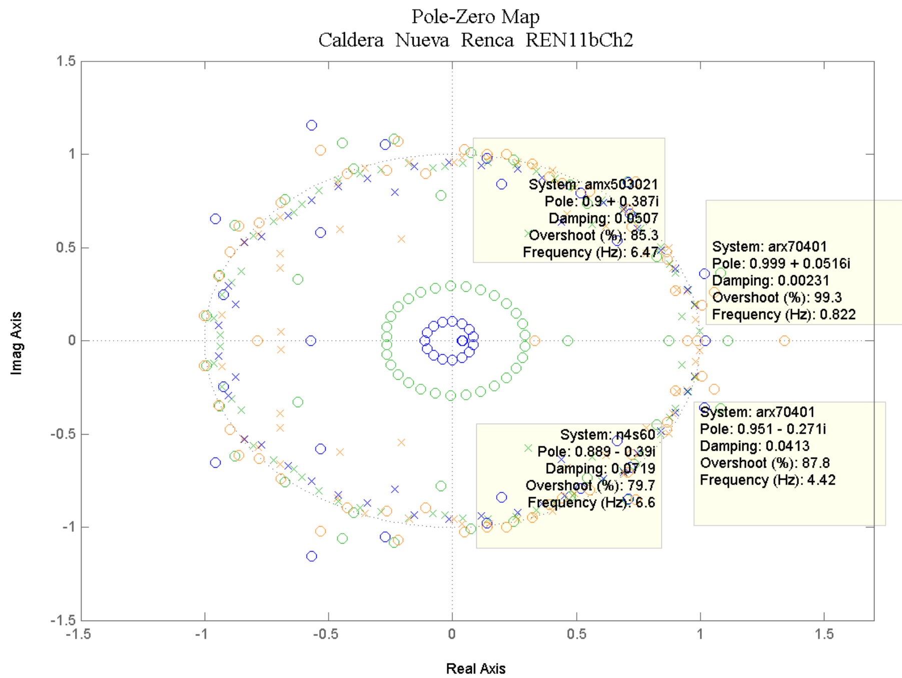


Figure 16. Map of estimated Poles and Zeros in one of the microtremor measurements recorded in the Nueva Renca HRSG.

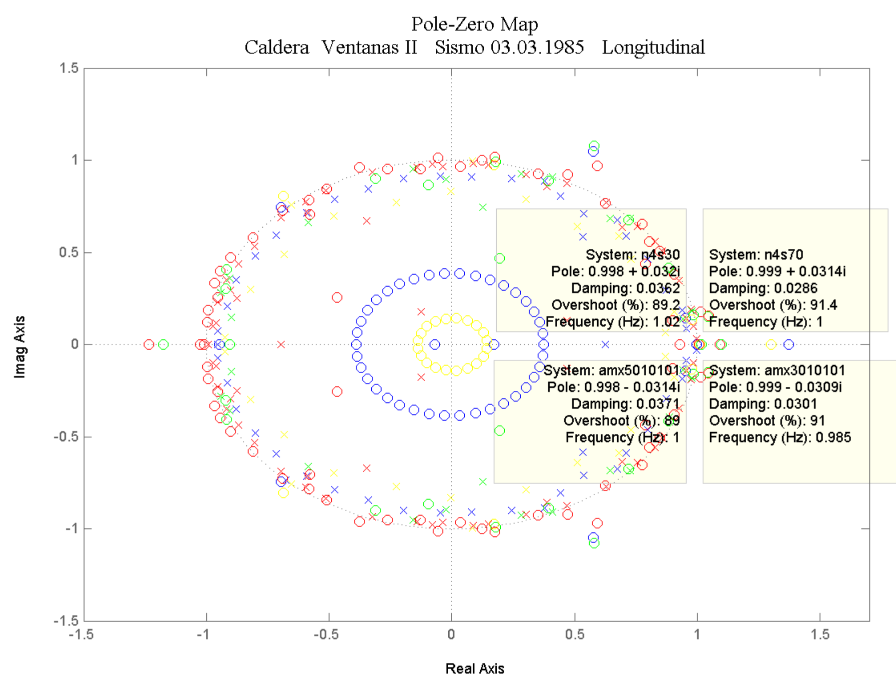


Figure 17. Map of estimated Poles and Zeros in one of the earthquake responses recorded (Longitudinal direction) in the Ventanas II Boiler.

DISCUSSION OF RESULTS OBTAINED

To each of the microtremor measurements of the Nueva Renca HRSG and to the three records of the seismic response of the Ventanas II Boiler all the different SI methods already mentioned were applied. A complete set of plots with all the results obtained can be found in Valdivia [2]. In Table 1 the results obtained for the steel support structure of the Nueva Renca HRSG are shown. Models #1 and #2 correspond to those without considering the masses of the internal components of the boiler, considering the bases of the columns as pinned in the first case (free to rotate) and fixed (built in) in the second. Models #3 and #4 consider the masses of the internal components and the bases of the columns as pinned and fixed respectively. The frequency values of the analytical models included in Table 1 correspond to the modes that show a relevant value of the modal mass associated to lateral vibration of the structure in anyone of the two directions of analysis.

Table 1. Identified and Analytical Frequencies for the Nueva Renca HRSG. In Hz.

SI Methods					Analytical Model			
ETFE	Parzen Windows	Weighted Aver.	ARX / ARMAX	ERA / DC	#1	#2	#3	#4
0.83-0.85	0.85-0.92	0.83	0.83-0.89	0.83-0.90	0.69	0.73	0.60	0.63
1.39	1.20-1.40	1.5-1.9	1.40-1.47	1.30-1.40	1.39	1.67	1.12	1.59
4.35-4.40	4.50-4.79		4.30-4.73	4.50-4.70	2.77	3.51	3.61	2.60
	6.30-6.90	6.5-6.8	6.30-6.90	6.30-6.90	5.86	6.36	3.85	3.65

In general, the frequency values identified are consistently repeated for each one of the identification methods used, and they even match the values obtained directly from the ETFE. In three out of the four identification methods four frequency ranges (0.83 - 0.89, 1.3 - 1.4, 4.3 - 4.7, and 6.3 - 6.9 Hz.) are observed. In the case of the Weighted Average Method the frequency range 4.3 - 4.7 Hz was not observed and in the case of the ETFE method the frequency range 6.3 - 6.9 Hz could not be identified. When comparing the values of the frequencies identified (with all the identification methods used) with the frequency values obtained from the analysis (different models) a great difference among them is found. Only in the cases of model #1 and # 2, the second and fourth relevant frequencies (respectively) match with one of the frequency ranges identified from the measured data.

In Table 2 the results obtained for the steel support structure of the Ventanas II Boiler are shown. Model #1 corresponds to that without considering the mass of the internal components of the boiler. Model #2 considers the mass of the internal components. The frequency of the analytical models included in Table 2, correspond to the modes that show a relevant value of the modal mass associated to lateral vibration of the structure in anyone of the two directions of analysis. Table 2 does not include the identification using the ETFE, since only three signals are available and the results do not contribute relevant information, as predominant frequencies are not observed.

Table 2. Identified and Analytical Frequencies for the Ventanas II Boiler. In Hz.

SI Methods				Analytical Model	
Parzen Windows	Weighted Aver.	ARX / ARMAX	ERA / DC	#1	#2
0.40	0.40			1.365	0.282
1.00		0.99-1.05	0.90-0.95	3.009	0.429
1.20-1.40	1.70			3.269	0.461
3.40-3.80			6.32-6.87	3.785	0.591

In addition, the frequency values identified from the microtremor measurements done in a previous study are: 1.28 - 1.33, 1.367, 1.41, 1.67 and 1.69 Hz. (Hormazábal [3]).

When comparing the frequency values identified from actual seismic response and the ones identified from the microtremor measurements smaller frequency values are observed in the first case. From the results obtained with the different analytical models it is clear that the effect of including the mass of the internal components is quite pronounced in the smaller frequency values. When comparing the frequency values identified with all the identification methods used (actual seismic response) with the analytical frequency values (model # 2), it is observed that the first analytical frequency (0.282 Hz.) it was not detected with the identification, only the following frequencies (0.429 and 0.461 Hz.) can be associated with the first frequency identified with the two nonparametric methods used (0.40 Hz). In the case of model # 1, that has the first calculated frequency at 1.365 Hz. it is within the frequency ranges identified from the microtremor measurements, being very near to one of them.

If the quality of the results identified using the experimental data in both structure -equipment systems is compared it is possible to notice the great difference that it males to have an adequate number of recorded signals. This is clear since in the case of the Nueva Renca HRSG the identified frequency ranges consistently appear for all the identification methods used, unlike what happens in the results obtained for the Ventanas II Boiler. In this case it is not possible to detect the presence of such frequency ranges in all the identification methods.

It is important to emphasize that during the process of identification of frequencies it is very important ”to know” in advance the ranges within which the frequency values that are sought will be found. This is required in both the parametric and the nonparametric identification methods (except in the case of the Weighted Average Method) in order to be able to choose adequate values for the parameters that control the identification process. Normally the criteria used are based on the expected mode shapes or frequencies for each structure or system. This is feasible when the structure being studied has a reasonably well known behavior and, as a consequence, their dynamic characteristics can be “predicted”. In the case of the type of structures that are being studied this assumption is not fulfilled. In fact, this is one of the reasons that prompted this research effort. Therefore, it was necessary to use the values of the dynamic properties calculated analytically as the basis for the selection of the parameters of the identification methods and later for comparison of the results obtained from the experimental procedure.

CONCLUSIONS

Based on the experience of applying the different identification methods to many data sets it is possible to be establish that results obtained (identified frequencies) depend strongly on the initial selection of the many parameters that these methods have. Normally, the selection of these parameters is done having a fair notion of the dynamic properties of the system being studied. This is common in typical structures for which it is expected to obtain certain mode shapes, whose natural frequencies and the level of modal damping ratio are at least approximately known a priori . As it has been previously explained in this work, one of the special characteristics of the studied equipment is the great complexity that they have, and therefore, the dynamic properties of the system (mode shapes, natural frequencies, and modal damping ratios) are not known a priori and hence they can not help in the selection of the necessary parameters used in the identification methods. This has been verified in the steel support structures for the two boilers studied.

Among the different identification methods used, the Weighted Averages Method is the one that presents the most independent results of the “a priori” frequency values expected. In the case of both boilers it was possible to confirm that the frequencies identified from the microtremor measurements correspond to the system that only considers the steel support structure, without including the mass of the internal components. In the case of the Ventanas II Boiler it was not possible to obtain a good identification, since the data sets are few and the length of the digitized record of the seismic response is so short that it did not allow to divide it in parts. This, in spite of the fact that the data corresponds to an actual seismic response that has a vibration amplitude that has excited the mass of the internal components of the equipment.

Based on the experience accumulated during the development of this work, consisting of the use of the different identification methods, it is possible to conclude that when using a combination of the different types of identification methods a more reliable process of System Identification can be achieved than that obtained with any individual method. The combination of identification methods that appears as the most effective consists of starting by applying the identification methods of the Non-Parametric type (Weighted Averages Method) followed by applying some of the Parametric identification methods (ERA - DC).

Also, it became clear that if a large number of experimental measurements (data sets) is not available, it is very difficult to obtain reliable results using the different system identification methods, even when the combination of them, as recommended in the previous paragraph, is used.

ACKNOWLEDGMENTS

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