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# Full-Scale Dynamic Testing of ENEL Power Plant Structures

Essais dynamiques des structures des centrales électriques - ENEL

Dynamische Versuche an den ENEL Grosskraftwerkbauwerke

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## SUMMARY
The ENEL Power Plants' major steel or concrete structures have been the object of dynamic investigations. This paper gives a short overview of some of these investigations undertaken to verify the design and construction qualities.

## RESUME
Le comportement des plus importantes structures des centrales électriques de l'ENEL a été examine au moyen d'essais et relevés dynamiques effectues. Le present article donne un aperçu de ces investigations entreprises dans le but de verifier la qualité du projet et de la construction.

## ZUSAMMENFASSUNG
Das Verhalten der wichtigsten Strukturen der ENEL Grosskraftwerken ist mit dynamischen Verfahren experimentell untersucht worden. Dieser Artikel gibt einen Überblick über die zus Qualitätssicherung vorgenommenen Prüfungen.

## 1. INTRODUCTION

In structural design, the assessment of safety is performed in three different steps:

- calculation of the "response" S of the mathematical model of the structure to the applied actions;
- calculation of the "resistance" R, provided by the geometrical dimensions of the structural system, the mechanical properties of the materials, the restraint conditions,etc.;
- comparison between the quantities R and S: the structure is "safe" if $R - S > 0$.

Each quantity involved in the above calculations has to be estimated in the design stage: the extrapolation of the data acquired from past experiences to future actions, materials and constructions involves a number of uncertainties which require an adequate margin between R and S.
The basic formulations of safety analyses are the following:

- starting from the upper and lower p - fractiles of the random variables R and S, the ratio $R_k/S_k$ is computed providing the characteristic safety factor ("Level 1" methods);
- the performance function $Z = R - S$ is defined allowing to express the limit state condition as $Z = 0$; then the distance between the average $\mu_z$ of the probability density function of the random variable Z and the $Z = 0$ point is expressed through $s_z$, the standard deviation of Z : $\mu_z = \beta s_z$. The reliability index $\beta = \mu_z / s_z$ is adopted as a measure of the safety ("level 2" methods);
- with reference to the inequality $S > R$, which expresses the failure, considering S and R as random variables, the probability of failure is given by:

$$P_{fail} = \text{Prob}\,[S > R] = \iint_{[S>R]} p_{R,S}(S,R)\,dS \cdot dR$$

  where $p_{R,S}(S,R)$ is the joint probability density function of the random variables S and R. ("Level 3" methods).

For structures prevailingly exposed to randomly fluctuating environmental actions, the largest uncertainties concern precisely the modelling of the external actions (wind, waves, earthquakes etc.). The monitoring of these structures after their construction yields directly the action effects without any knowledge of the applied actions and the technological quantities, depending on the structural system geometry and the actual material characteristics.
The structural survey allows hence to answer two different questions:

- the improvement of the statistical distribution of environmental actions and of their correlative probabilistic models;
- the assessment of the integrity of a structure during its lifetime with special concern for progressive damaging phenomena.

In the present paper, some typical full-scale investigations are briefly described, as examples of the increasing interest in structural dynamic investigations. Some of these investigations have already been performed by ISMES, on behalf of ENEL, at the Torvaldaliga Nord Power Plant (four thermoelectric groups of 660 Mw each), and some others are planned by ENEL to be conducted at the Termini Imerese and at the S.Filippo del Mela Power Plants (both consisting of two Thermoelectric groups of 320 Mw each).
In all cases, initial dynamic testing provides first of all a set of useful reference data for allowing future evaluations of the structural integrity. Repeating the dynamic testing of the structure during its lifetime and measuring

the response quantities as before, an eventual deviation between subsequent corresponding outputs will indicate structural deteriorations.
In some cases, a further aim of the measurements is the improved knowledge of the environmental actions. In this respect, the recently performed testing must be considered as preliminary investigations and further efforts will be made by ENEL to gain more information.

## 2. GENERAL ASPECTS OF THE EXPERIMENTAL PROGRAMS

Three classes of quantities are involved in the structural problems:

a) input quantities describing external actions;

b) technological quantities depending on the structural system geometry and the material characteristics;

c) output quantities representing the action effects.

In the design stage, the quantities (a) and (b) are given and the quantities (c) are calculated by means of the structural mechanics methods.
During the acceptance tests of the constructions, the response is measured to given loadings, applied to a well identified structure. The comparison between the calculated and measured response gives the required information on the conformity of the as-built construction with respect to the idealized structure.
The system identification technique applied to civil structures requires the knowledge both of (a) and (c) quantities. It is then possible to identify the characteristic parameters of (b) and to recognize if some changes of them are still running: these goals can be attained more directly in the frequency domain through the application of the powerful modal and transfer analyses techniques.
Moreover, having measured the output quantities (c) and knowing the technological quantities (b), an evaluation can be made of the external actions (a).

## 3. OUTLINE OF THE EXPERIMENTAL TECHNIQUES

It is well known from the theory of linear systems, that the dynamic characteristics of a structural system can be inferred if its response (output) to some given excitation (input) is measured. In forced vibration tests, this excitation is provided artificially by means of one or more structural vibrators, of the electro-mechanical or hydraulic type, placed at the appropriate points on the structure to be tested. In general, these vibrators are used for generating a sinusoïdally varying force of adjustable amplitude and controlled slowly sweeping frequency between the limits of a consistent frequency range.
In some cases it is possible to take advantage of the natural excitation provided by ambient wind, wave or traffic forces; without requiring the installation of structural vibrators, ambient vibration surveys can yield valuable data on the actual performance of as-built structures under the true environmental conditions. Yet, forced harmonic vibration tests will usually produce more complete and more accurate information about the dynamic structural parameters, mainly because of the precise control of the excitation characteristics possible with this method.
The structural response to the applied excitation is measured by means of various transducers: accelerometers, seismometers, displacement or strain-gauges mounted on the tested structure at appropriate locations.
For the simultaneous recording of the transducer signals, use is made of a computerized data acquisition and processing system, developed by ISMES and the hardware of which is located in a Mobile Laboratory. Data from the various installed transducers are fed to signal conditioners which drive, after on-line analog-to-digital conversion, into the computer memory. During the acquisition process, single channels may be observed in real time on an oscilloscope and, at the end of it, pre-processing of the test data can be undertaken directly on site to obtain preliminary information in the form of response curves or transfer functions plots. All the collected data are finally driven into a multichannel tape recorder and may thus be subsequentely played back to a

computer for the more thorough analysis to be made at the Central ISMES Laboratories.

## 4. FULL-SCALE INVESTIGATIONS

### 4.1 Turbogenerator foundation

A steam turbogenerator concrete foundation (50.60 x 16.00 m in plant and 12 m in height) was subjected to forced harmonic vibrations by means of a mechanical vibrator covering an overall frequency range from 1 to 50 Hz (the frequency corresponding to the rotational speed of the machine). The structural response was measured using 40 seismometers located at appropriate points of the structure; the analysis of the response allowed to identify the 8 lowest natural frequencies, modal shapes and corresponding damping ratios: these frequencies appeared to be sufficiently low indicating thus satisfactory design and construction qualities. Further amplification peaks,without clearly defined corresponding vibration shapes, were noticed at higher frequencies, because of the limited number of measurement positions: the vibration behaviour at higher frequencies is the most significant for this structure subjected to the steady-state operating forces caused by inevitable unbalanced masses of the rotor: in order to check the satisfactory serviceability of the machine-foundation system, the actual vibration levels must hence be investigated by direct measurements during operating conditions.

### 4.2. Machine Hall

The Torvaldaliga Nord Power Plant machine hall overall structure was also subjected to forced harmonic vibrations. This industrial building, 276x62 m large and 34 m high,is composed by 17 steel portal frames laterally connected by longitudinal beams and braced with diagonal trusses; a thermal expansion joint provides a structural disconnection between two nearly symmetric halves of the complete machine hall.
The aim of this investigation was in fact to make an evaluation of construction quality through the determination of its dynamic characteristics, although the machine hall structural service is prevailingly static. The tests, executed during the licensing process, allowed to evaluate the quality of the connections through the measured damping ratios associated with the fundamental vibration modes. The vibration tests were executed symmetrically on the two halves of the building; the construction quality could thus be appreciated by comparing the corresponding responses of the two half structures; this was expecially interesting considering that the two parts of the machine hall were constructed by two different contractors.

### 4.3. Multiflue chimney

Finally, the Torvaldaliga Nord Power Plant multiflue chimney was analyzed under dynamic excitation of artificially produced harmonic forces and high natural wind forces excitation as well. This chimney is composed of an outer slightly tapered concrete shell 243 m high and four inside steel flue liners; each liner is divided into five elements hinged one to another and supported individually by steel platforms.
The chimney's dynamic characteristics were first investigated through analysis of the structure response to harmonic varying forces applied to the tip in two orthogonal directions. The first three natural vibration modes of this cantilever-type structure were thus identified in two orthogonal vertical planes (natural frequencies, modal shapes and related damping ratios). Due to the eccentricity of the excitation force, the characteristic of the fundamental torsional vibration mode could also be determined.
These modal parameters showed to be in satisfactory agreement with the ones computed in the design stage. Moreover,making reference to a lumped masses stick-model, the actual rocking impedance of the overall foundation (raft, piles and participating soil) was evaluated: this by computing the ratio of the measured foundation raft rocking to the actual total dynamic moment acting upon

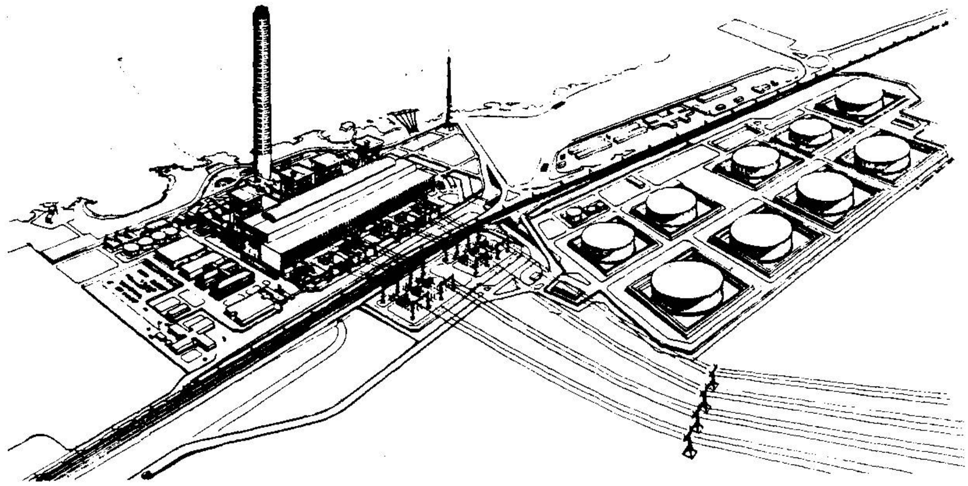
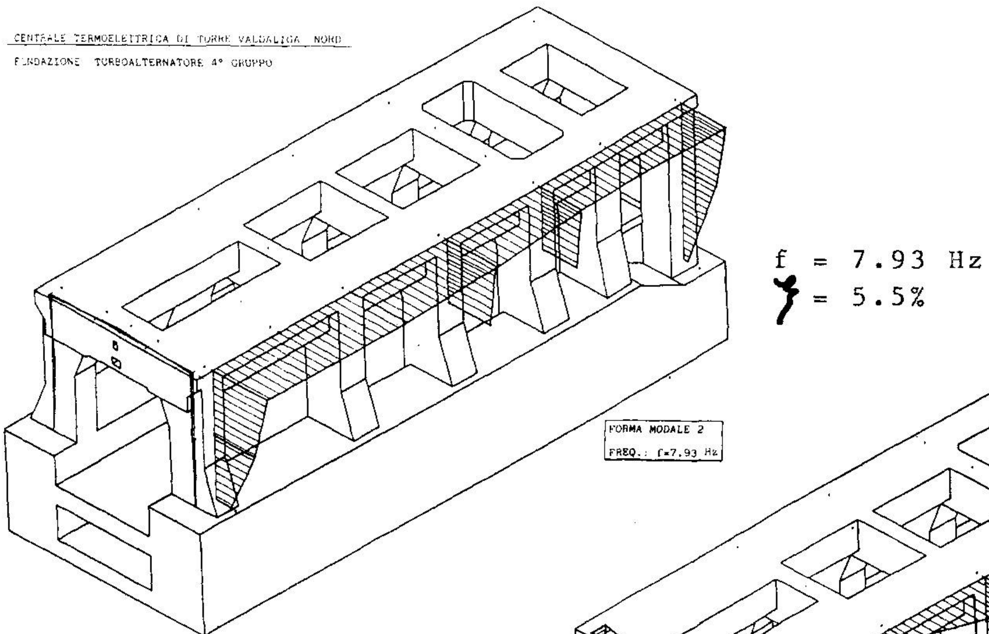


Fig.1 TORVALDALIGA NORD POWER PLANT



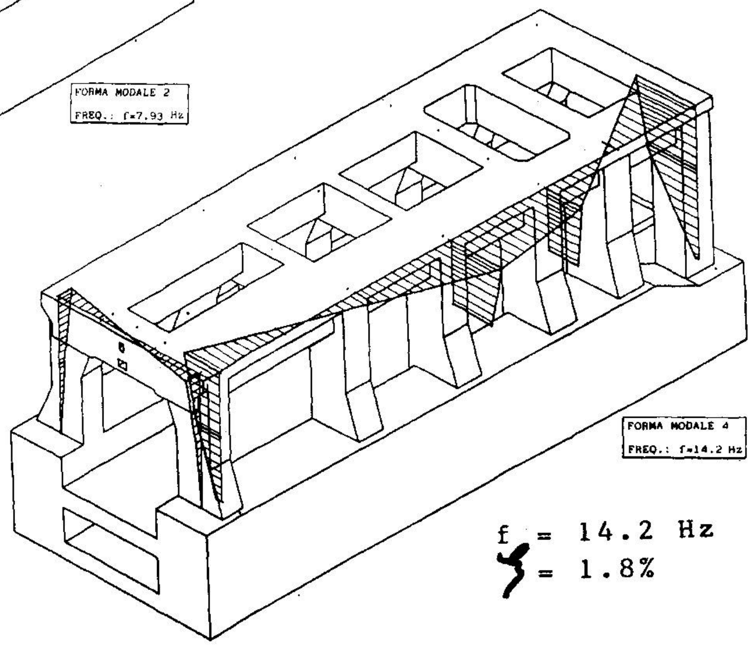




Fig.2
Turboalternator foundation
2nd and 4th vibration modes

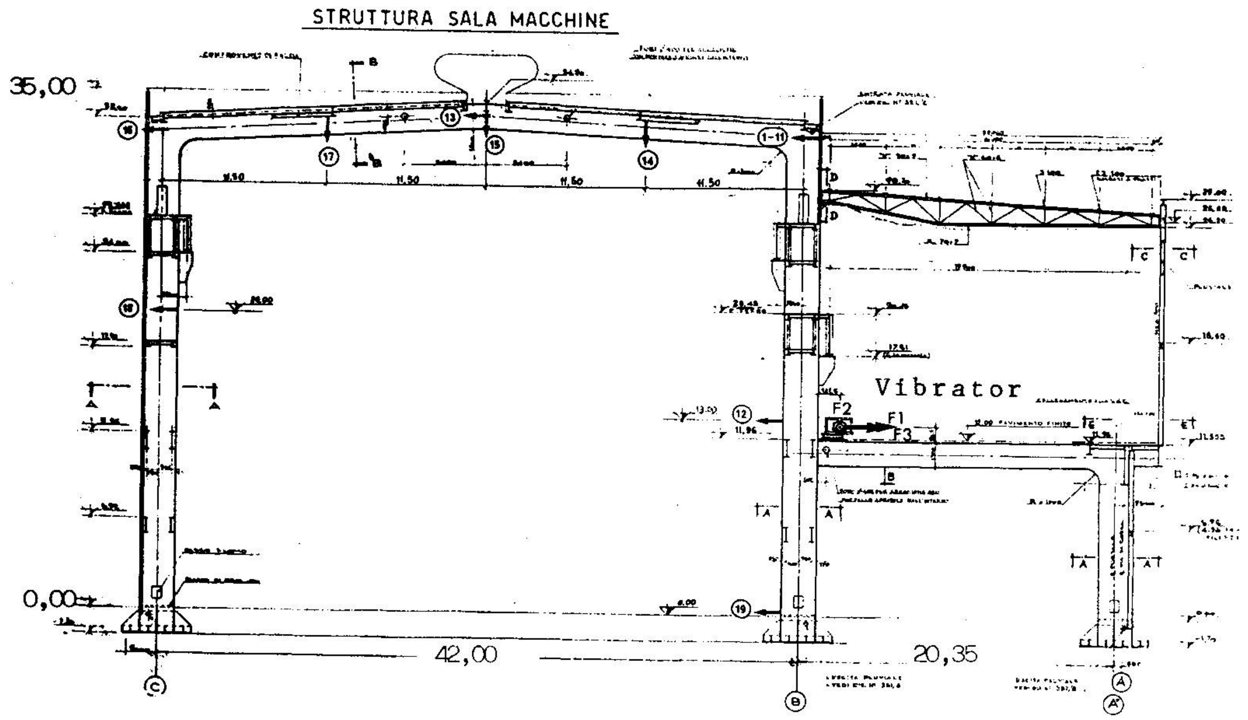



Fig.3 Torvaldaliga Nord Machine Hall structure

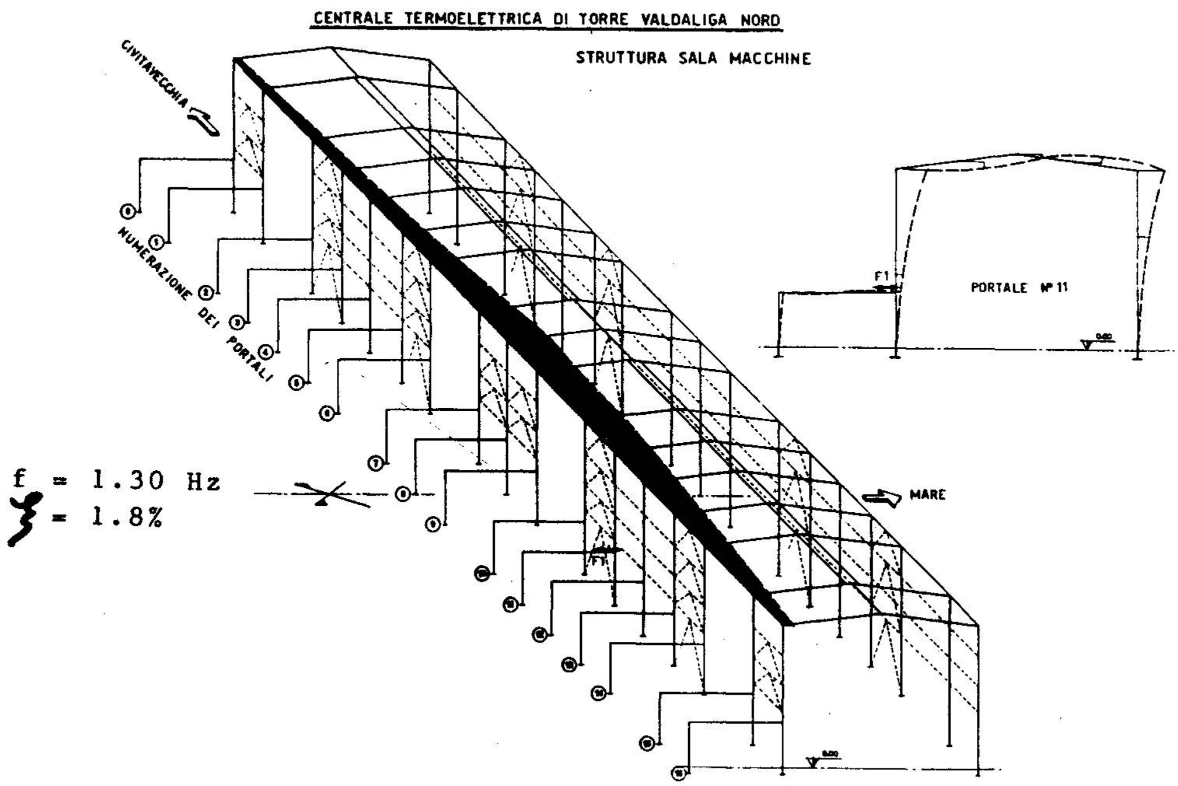



Fig.4 First lateral vibration mode

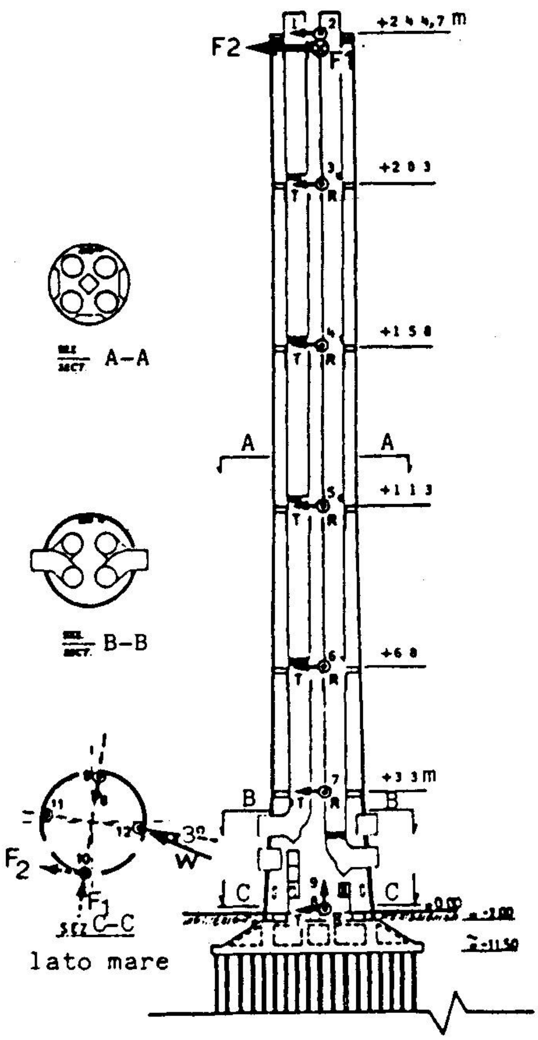



Fig.5 Torvaldaliga Nord multiflue chimney

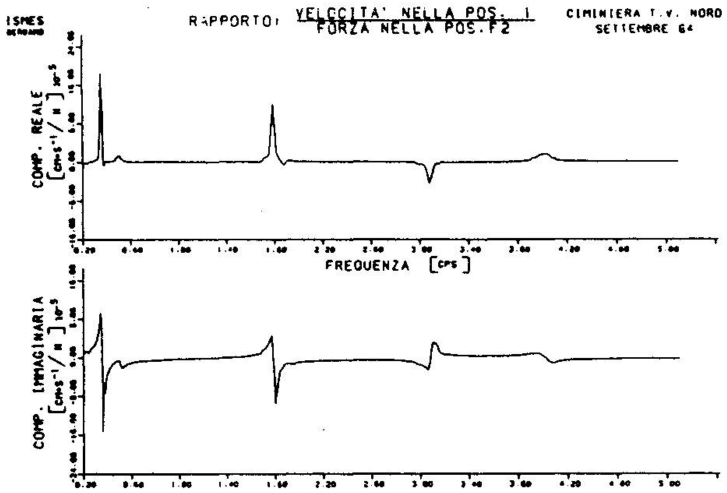



Fig.6 Tip velocity response transfer function

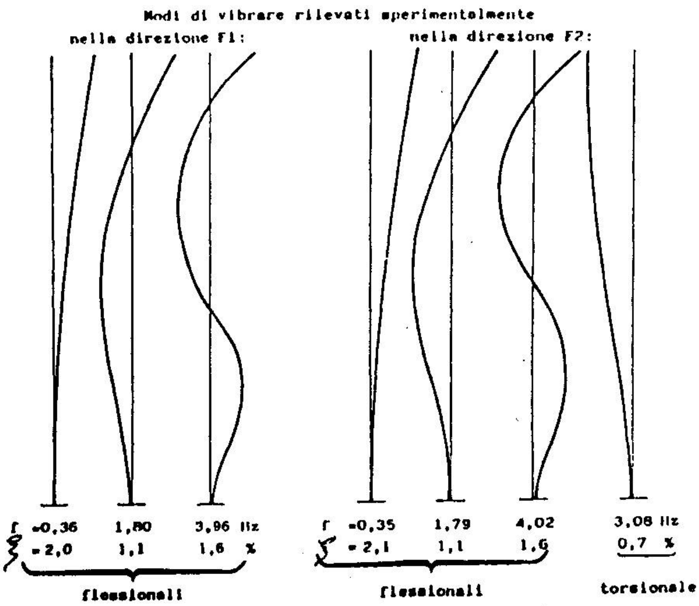



Fig.7 Experimental modal shapes, frequencies and damping ratios

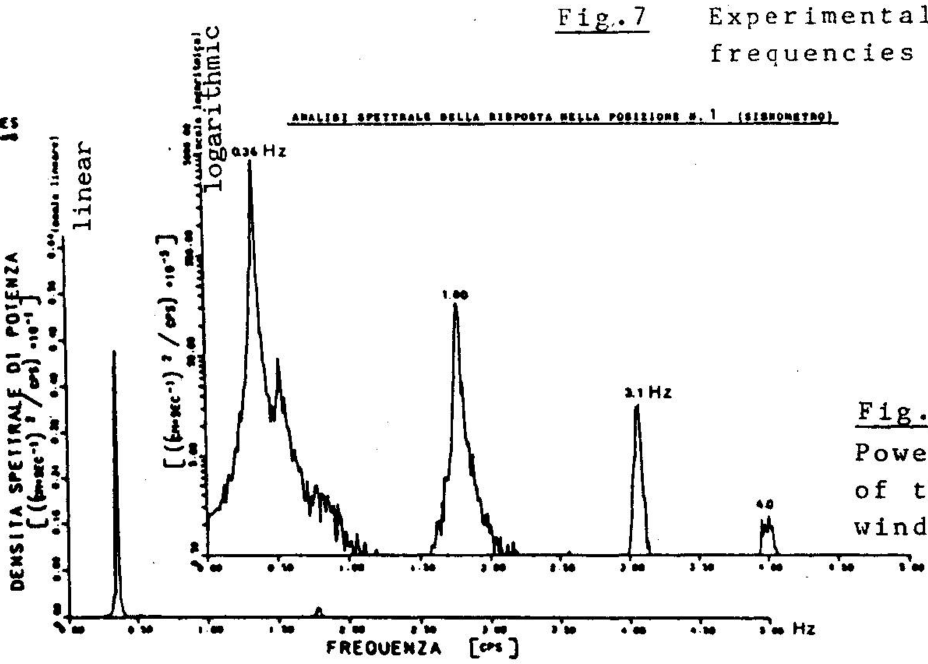



Fig.8 Power spectral density of the chimney's tip wind induced vibrations

it. The obtained resulting stiffness, although somewhat larger, appeared to be of the same magnitude as the value computed through the usual design assumptions.
The spectral analysis of the chimney's response to strong environmental wind excitation (with an average wind speed of about 21 m/s) showed evident peaks at the same frequencies found previously. The chimney's response to the wind resulted, almost entirely, in being due to the fundamental vibration mode: the fundamental torsional mode appeared to be, although very slightly, excited too. The vibration response intensity was found to be of the same order of magnitude as well in the along-wind direction as in the cross-wind one.

### 4.4. Cooling water intake

To provide the cooling water of the machines, in Torvaldaliga Nord Power Plant the sea water is drawn by means of a subsea concrete channel starting with an intake 300 m off from the coast and 16 m under the sea-level.
In view of evaluating the waves actions on the intake, 26 pressure transducers were set up on the walls and under the foundation slab of the structure, as well as wavemeters and anemometers for the measurement of the high waves and wind speed and direction. The main aim of these experiments was the investigation of the local actions of the waves, a physical phenomenon at present time not representable in a mathematical form, owing to the particular geometry of the intake. The need of full-scale tests came from the difficulties of reproduction of local actions on a reduced scale physical model: the greatest difficulties derive from the scale-effect of the water-air interface (shock action of the waves). From the full-scale measurements, information is expected, moreover, about sub-pressure variations, caused by the waves, on the foundation soil; this phenomenon could hardly be reproduced on a reduced-scale physical model, because of its strong dependence on the nature and stratigraphy of the foundation soil.

### 4.5. Coal/oil-ships jetties

In both S.Filippo del Mela and Termini Imerese Power Plants, an off-shore jetty is at present time under construction: the S.Filippo del Mela jetty, designed for the dock of up to 120.000 WT coal-ships, is located in open sea, in non constant sounding depth, up to 33 m, and is composed of ø 1500 and ø 1800 concrete piles and an overcapping concrete plane frame; the Termini Imerese jetty, designed for the dock of up to 50.000 WT oil-tanker, is located in open sea, in about 14 m sounding depth and is composed of ø 1422 steel piles and an overcapping steel frame.The design live loads are mainly the waves actions (design wave height 9 m), the bollard pull and the tacking ship impact (design tacking speed 0.15 m/s).
Dynamic in situ investigation tests are foreseen as well on insulated elements (piles) as on the overall construction, by means of artificially forced excitation: through the former, by measuring the displacement and the rocking of the pile at tip section and at ground-sea interface section, the translational and rotational stiffnesses and damping ratios of the infixed part of the pile are expected; through the latter, a complete dynamic characterization is expected, which will allow a comparison with the design forecast (first modal frequencies in the range from 0.5 up to 1.6 Hz) and a collection of some reference dynamic parameters for future checks especially after an eventual severe loading such as sea-storm or ship collision.

## 5. REMARKS

The disposal of a numerical reference model of the tested structure allows to deduce more complete and more significant information from the experimental data. This, not necessarily very refined reference model, must allow:

- a rational interpretation of the response of the tested structure;
- the evaluation, by applying the system identification techniques, of the main technological parameters;

- a sensitivity analysis of possible variations of these parameters with the aim of making a rational interpretation of observed eventual deviations in time of the periodically repeated dynamic investigations results.

The full-scale dynamic testing or monitoring of large constructions gives information about the actual but overall structural behaviour; if necessary this overall structural behaviour assessment can be integrated by local testings of the actual material properties or conditions.
The past monitoring experiences have revealed that nowadays the structural response measuring instruments are much more reliable than the external action measuring instruments: there appeared, in particular, the need of gust anemometers to obtain the dynamic wind speed characteristics and pressure-transducers to obtain directly the dynamic wind actions. Concerning the dynamic measurement of wave actions, the pressure transducers have also a fundamental role, as indicated by the on-going technological progress of these instruments.

## 6. CONCLUSIONS

In the last three decades,major advances have been made in structural design and construction technology. In particular, design procedures were fundamentally improved by the introduction of the probabilistic concept of safety. Making use of continously refined computational techniques of static and dynamic structural analyses it is thus nowadays possible to design large civil or industrial engineering structures according to more precise specifications, in order to meet in particular definite serviceability requirements. Nevertheless, uncertainties remain in what concerns the actual engineering performance of the as-built structure, under the true environmental conditions, due to constitutive material properties, construction quality, foundation behaviour, numerical modelling idealization, etc.
There is, thus, a strong need for a postconstruction verification of the design assumptions and execution criteria in order to finally check the actual serviceability, safety and thus the quality of the construction. In this respect,the recent development of dynamic testing and analysis techniques has provided an efficient means for getting the required valid information.

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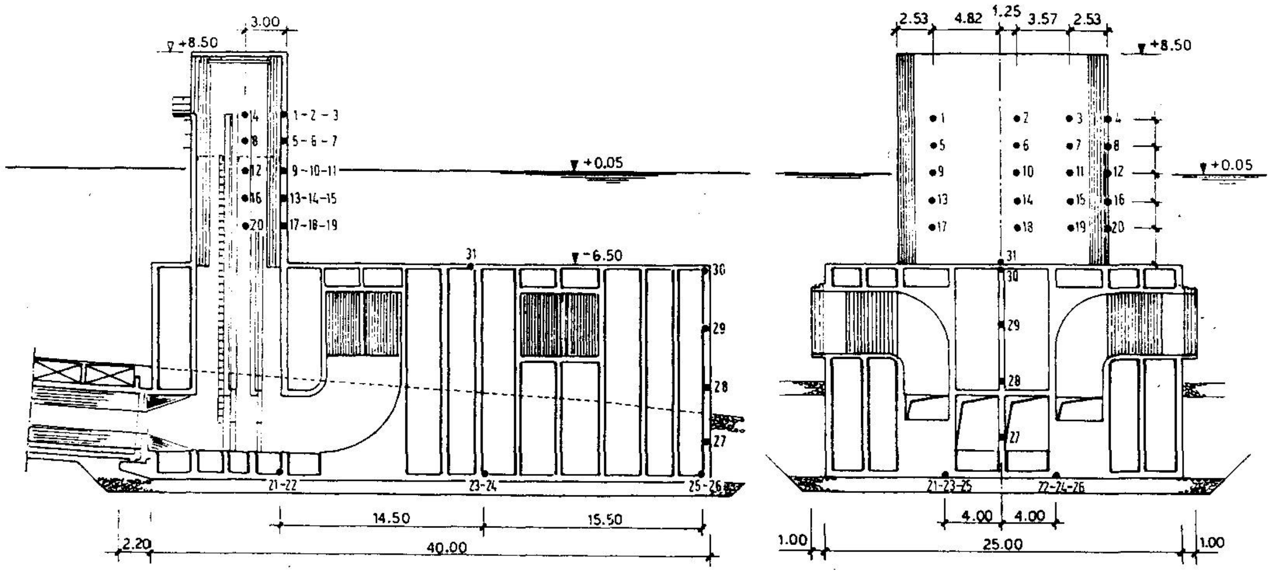


Fig.9 Torvaldaliga Nord cooling water intake (lateral and front view).