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In-Situ Dynamic Tests on Ancient Monuments

Essais Dynamiques In-Situ pour des Structures Monumentales

Dynamische In-Situ Prüfungen an Denkmalsbauten

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SUMMARY
In-situ dynamic tests can be performed from time to time on structures of particular interest, with the purpose of ascertaining their dynamic response. Then the variations observed in the dynamic characteristics from one test to the next may by taken as an index that something has changed in the structure itself. Lastly, attempts can be made to diagnose the cause and type of modifications undergone by the structure. The paper relates three initial experiences pertaining to the Brunelleschi Dome, the remains of the temple of «Ares the Avenger» in the Augustean Forum in Rome and the Arnolfo Tower in the Palazzo Vecchio in Florence.

RESUME
Pour des structures d'intérêt particulier il est possible d'exécuter de temps en temps des essais in situ pour la détermination de leur comportement dynamique. D'éventuelles variations de caractéristiques dynamiques observées d'un essai à l'autre que quelque chose changé dans la structure examinée. Enfin il est possible de déterminer les types de modifications arrivées dans la structure et leurs causes. Le rapport décrit trois expériences sur la Coupole de Brunelleschi à Florence, sur les restes du Temple de Mars Ultor à Rome et sur la Tour d'Arnolfo à Palazzo Vecchio à Florence.

ZUSAMMENFASSUNG
An Bauten von besonderem Interesse ist es möglich, in entsprechenden Zeitabständen Prüfungen am Ort durchzuführen, um das dynamische Verhalten zu bestimmen. Aus den beobachteten Veränderungen der dynamischen Eigenschaften zwischen den Prüfungen ist es möglich, Hinweise auf Veränderungen zu erhalten. Schliesslich kann durch eine Diagnose der eingetretenen Veränderungen versucht werden, deren Ursache zu bestimmen. Der Bericht beschreibt drei Erfahrungsbeispiele: die Kuppel der Brunelleschi in Florenz, die Reste des Tempels des Mars Ultrix im Forum Augustus und den Turm des Arnulf im Palazzo Vecchio in Florenz.

FOREWORD

In the last 20 years ENEL - through its R & D Dept. and in particular through CRIS, in co-operation with ISMES - has developped, and largely applied, experimental and numerical techniques aiming at the dynamic characterization of the big structures pertaining to ENEL installations (dams, chimneys, cooling towers). This characterization was deemed necessary in view of a seismic safety assessment.
The positive experience gained in this industrial framework has prompted attempts in order to transfer these same techniques and know-how to the study, and more specifically to the seismic risk assessment, of monumental structures.
These attempts originated, in recent years, a certain number of in-situ surveys as well as interpretations of results by means of mathematical models. The methodology used in these endeavours is of a general type; it can be broken up into different phases (or types of activity), which we intend to describe in the first paragraphs of the present paper.
In the last-but-one paragraph we illustrate the actual experiences so far carried out, referring to the Arnolfo Tower and to the Brunelleschi Dome in Florence, on one hand; to the remains of the temple of "Mars Ultor" in the Augustean Forum in Rome, on the other hand.

1. DESCRIPTION OF IN-SITU TESTS

According to the type of monument and its environmental situation, the planning of an in-situ test campaign can be oriented either toward a "natural excitation", i.e. taking advantage of environmental dynamic "noise" (wind, traffic, etc.), or toward artificial excitation by means of shakers imparting a sine or a random force to the structure.
In case natural excitation is chosen, since this is usually of slight intensity, it is advisable to install not only the usual contact instruments (seismometers, accelerometers), but also laser interferometric instruments (e.g. "LADIR") which can operate at a distance (up to 200-300 m) with a high sensitivity (down to 0.1 μm). The latter are very convenient for those monuments where it is not possible, or advisable, to get direct access or to execute rigid fixings for "traditional" electro-mechanical instruments.
In case artificial excitation is chosen, it remains to decide whether to install mechanical-type vibrodynes (rotating masses), which can provide only sine excitation, or a different type of exciter (hydraulic or electro-mechanical actuators), which, if driven by a suitable control unit, can provide either sine-wave or non-sinusoidal forces; in the limit this latter type of exciter can impart fully random excitation with a pre-established power spectrum.
The choice between the two possibilities can be taken considering the opportunity of exciting the different modes separately (one by one) or simultaneously. In the former case a sine wave sweep is used; the interpretation of results is easier, but the duration of the test is greater.
In both cases the excitation level is somehow controllable so as

to respond to the necessities of the particular test in hand.
The excitation units have to be placed on the structure or on its foundations so as to excite all interesting "natural vibration modes". This can entail the necessity of moving the exciters (if it is only one) or of installing more than one exciter (multipoint excitation); in fact, an excitation applied in a point of a nodal line of a mode cannot excite that particular mode. As one can see, it is advisable to get a preliminary knowledge (as accurate as possible) of the modal shapes; this can be achieved by means of mathematical models (see further on).
It is good to keep in mind that usually only the first few modes (e.g. 3 to 6) of the structure are of interest.
In a like manner, turning now our attention to the sensors intended to measure the structural response to the excitation, those have to be distributed in such numbers and positions as to pick up the maximum amplitudes of the sought-after modes, i.e. along the antinodal lines of the particular mode of interest. In every point one can choose to place one, two or three-directional sensors according to whether only some particular components of motion, or the whole vectorial information, are desired. As to the nature of the physical quantity being measured, seismometers and accelerometers pick up respectively the local velocities and the accelerations of the movement, and they need to be rigidly joined to the point of the structure whose motion is investigated; the laser interferometer is able to measure the displacement component along the sighting line, and - as already stated - the measurement takes place without material contact and up to distances of 200 ÷ 300 m. It requires, however, a rigid base for the laser emitter.
All the data collected during the test are to be acquired and stored on magnetic support, if possible already in digital form for later processing.
More detailed considerations about the mini- or micro-computer to be used, to the connecting cables, to amplifiers, analog-to-digital converters, signal conditioning etc. can be found in the vast specialized literature concerning data acquisition systems.
The off-line data processing include: computation of transfer functions (excitation vs. response), Fourier Analysis (FFT), coherence analysis, cross-correlations etc. - many of these procedures convert the responses from the time-domain (where they are acquired) to the so-called frequency domain; afterward these frequency responses can be treated with well-known techniques in order to separate from the total response the responses of the single modes. This separation can be controlled (validated) a posteriori; if need be, the modal responses thus identified can be compared with the homologous modal responses as derived from a mathematical model of the structure. From the processing of experimental data - and only in this way - it is also possible to derive the damping factors of each individual mode.
It is to be noted that - in the present stat of the art - all these procedures are based on the hypothesis of linearity of the system: this has to be taken into account, above all as far as the damping factors are concerned: in fact, the damping degree that can be derived from the low-intensity excitation tests may differ quite considerably from the damping degree at high levels of excitation, such as occur e.g. during a strong earthquake.

2. DESCRIPTION OF THE MATHEMATICAL MODELS

The mathematical models that can be used in order to simulate the dynamic behaviour of a monumental structure can span the gamut from the simpler (plane models with 1-D beam elements) to the more complex ones (3-D, F.E. models) through all the intermediate steps (2-D models, in a plane or with a rotational symmetry), according to the geometrical features of the structure to be modeled and to the degree of accuracy which is reasonable to adopt in relation to the available informations.

Obviously, to more complex models there correspond greater computational times and costs, so that also economical considerations, or the degree of urgency of the study, can affect the choice.

Whatever the final choice, hence apart from the degree of sophistication of the numerical model, one can detect at least four different uses of these models (often referring to different phases of a same study):

- A preliminary use in order to plan the in-situ tests, namely to identify the more suitable positions for the sensors and the excitation units; to determine the probable frequency range of the sought-after modes; to estimate the more suitable excitation level, so as to assure both an admissible level for the structural effects induced by the excitation (against the strength of the structural parts) and a sufficient amplitude of the response signals (against the instruments sensitivity).
- A joint utilization of the mathematical model and the test results so as to get a mutual validation. We intend by this that a comparison with the mathematical model can indicate whether the data collected during the tests are reliable and consistent; on the other hand, a comparison between modal shapes and frequencies obtained by the two approaches can give the mathematical model a credibility that nothing guarantees "a priori". Besides, such a comparison allows an "a posteriori" calibration of the numerical value of some physical constants which often are not known with sufficient accuracy for the structure as a whole (e.g. the Young moduli of the materials). This calibration entails a "identification" process which can be made more or less sophisticated according to circumstances.
- use of the mathematical model "backward" in time ("hindcasting") in order to estimate, through additional hypotheses if need be, what has been the structure behaviour, in its pristine state or under various stages of deterioration, under dynamic excitations which happened in the past.
- A like use of the mathematical model, but "forward" in time ("forecasting") in order to assess, again with the help of additional hypotheses where needed, what will be the structure behaviour in its present state, or after alternative interventions, under dynamic excitations which can foreseeably happen in the future. Of course this last use entails the problem of defining an accelerogram, or at least a power spectrum of the earthquake, that should be significant and credible for the monument site.

3. INFORMATIZATION OF TEST RESULTS AND OF NUMERICAL ASSESSMENTS

For monumental structures of a certain importance it appears feasible - as well as desirable - to create, on a suitable informatic support (HW/SW) a structural data-base as complete and continuously updated as possible.
In it one should include not only the knowledge about the "state" of the monument (historical and architectural informations, present configuration, interventions etc.), but also all the numerical data concerning the results obtained successively from in-situ tests, from "continuous" monitoring, from the mathematical-numerical models with their main conclusions.
This data-base would provide a precious lore of historical-technical documentation permanently available to those people and organizations that are responsible toward the safety and preservation of the monument. It would also be of great help to obtain without delay diagnostic interpretations (if feasible) after exceptional events; besides, it could be used to get a preliminary evaluation of the effects of any proposed alteration or reinforcement.
Such an "informatization" would indeed make easier the systematic use of dynamic tests (i.e. their regular and scheduled repetition in time) in order to reveal, through any alteration of the vibrational "signature" of the monument, the tendencies toward structural degradation, or progressive evolution, if any. The diagnostic use of in-situ dynamic tests could further be enhanced by repeating the tests after the site has undergone some exceptional event (e.g. a strong earthquake) that, albeit without apparent damage, may induce some suspicion about possible detrimental effects on the structural qualities of the monument.

4. DESCRIPTION OF SOME TESTS AND ANALYSES CARRIED OUT IN THE PAST

The studies carried out so far with the above-illustrated methodology - albeit not completely followed in each particular case - concern three important monumental complexes, two of them situated in Florence and one in Rome:
- The Arnolfo Tower of the Palazzo della Signoria (Palazzo Vecchio) in Florence.
- The Brunelleschi Dome, part of the Cathedral of Santa Maria del Fiore, in Florence.
- The remains of the Temple of Mars Ultor in the Augustean Forum in Rome.

In the following we propose to illustrate briefly the activities carried out, as well as the main results obtained, for each one of the three monuments.

4.1 The Arnolfo Tower

This well-known monument is part of the Palazzo della Signoria (Palazzo Vecchio) in Florence.
It is a stone-masonry tower, built-in into the structure of the palace, from which it stems at a height of 38.5 m. The

free-standing height of the Tower is about 43 m.
The cross-section is rectangular, with sides of 6.00 m and 8.00 m.
The structural scheme is that of a hollow rectangular cylinder, with wall thickness of about 1.50 m.
The structure presents a slight overhanging (1 m) with respect to the façade of the Palace. It was built around 1300 on a design by Arnolfo di Cambio, whence its name.
The in-situ tests were carried out by means of a rotating-vector vibrodyne installed in the so-called "Albergaccio del Savonarola", a small jail situated at an elevation just below the lookout walkway around the Tower.
The response acquisition was effected through 29 seismometers of the type GEOTECH TELEDYNE S13, positioned all along the height of the Tower and in correspondence of the two orthogonal axes of the cross-section. On the side facing Piazza della Signoria the number of measurement points was increased by using two velocity transducers of the laser-interferometric type, installed in the square on the side opposite to the Tower. This allowed to detect the response at some points in which it would have been impossible to locate inertial-type transducers. A cable network for a total length of some 5000 m connected the vibrodyne and all the transducers to a recording station from which the excitation and the data acquisition was controlled.
Environmental circumstances during the tests were particularly favorable, inasmuch as it was also possible to record the Tower response to a series of strong wind gusts.
This will allow, after data analysis on the recorded signals, an interesting comparison between the two types of excitation.
On this monument so far no attempt was made to set up a numerical model with which to interpret the results; however, such a model (e.g. F.E. one) would not appear particularly difficult and it is intended to work on it in due time.
The frequency of the first mode has been preliminarly identified at 0.49 Hz.

4.2 The Brunelleschi dome

For this structure - so well known that we deem superflous to give even a brief description - we carried out, so far, many numerical analyses with increasingly sophisticated F.E. models, under different hypotheses of static loads and of uncracked or cracked state. Also, numerical determinations of modal shapes and corresponding frequencies were carried out, again for the uncracked and cracked structure.
Finally, a preliminary attempt was made to detect and record naturally-induced vibrations, due either to vehicular traffic nearby or to wind gusts.

4.2.1 Dynamical analyses by F.E.M.

The F.E. mesh discretizes one fourth of the Dome (with the Skylight reduced to a rigid body having the right mass but not the real geometry), of the underlying Drum and of the Pillars. It is not attempted to represent the structural interactions with the three Chapels (North, East, i.e. on the back side, South), nor with the main Nave (West side of the Dome) see Fig. 1.

This one-fourth model can represent the whole Dome symmetric or antisymmetric dynamic behaviour thanks to suitable symmetry or antisymmetry conditions on the mutually orthogonal vertical planes (geometric symmetry planes) that bound the model. In this way the two halves of pillars included in the model have been made geometrically symmetrical, which does not correspond with the actual situation [unless the ¼ model is assumed to represent the back (East) ¼ of the Dome].
These are limitative assumptions, which it will not be impossible to eliminate in further developments, provided one accepts the obvious implication of a larger mesh, entailing a much greater computational onus.
Under the above assumptions we determined the first six modal shapes (and relevant frequencies) both for the uncracked dome and for the dome with cracks representing - albeit with considerable simplifications - the present situation. In each case two modes are of the symmetrical type, two are anti-symmetrical and two are torsional ones.
The results are synthetically shown, as far as theoretical frequencies are concerned, in the following table:

		UNCRACKED DOME	CRACKED DOME
MATHEMATICAL MODEL C.R.I.S.	SYMMETRICAL MODES	2.14 4.08	1.86 1.95
	ANTI-SYMMETRICAL MODES	1.03 3.03	0.89 2.25
	TORSIONAL MODES	1.65 2.70	1.60 2.16

As for modal shapes, it has been deemed that the most suitable form of graphic representation is a software-generated animation film; this has in fact been produced with satisfactory results.
The above-presented frequency table shows that, for some modal shapes, a direct pairing is possible between the vibrational modes of the uncracked Dome and those of the cracked structure: obviously in this latter case the frequencies are appreciably decreased, this being interpreted as a quantitative index of the degradation of the "modal stiffness" brought about by the cracking. In fact, the modal stiffness of similar modal shapes are roughly proportional to the square of the respective frequencies, so that the expression:

$$\frac{f_0^2 - f^2}{f_0^2} = 1 - \left(\frac{f}{f_0}\right)^2,$$

where f = frequency of a mode of the cracked structure, f_0 = frequency of the like mode of the uncracked structure, can be taken as an index of the loss of strength resources due to the cracking.
For other modal shapes, however, it is not possible to establish a direct pairing between "sound" and "cracked" model, because the

cracks alter in a deep way not only the partial and global stiffnesses, but also the very geometry (or better the topological internal connections) of the structure, so that the introduction of new internal degrees of freedom brings about some completely "new" modal shapes.
It is also to be remarked that the above computational frequencies - even apart from the error introduced by neglecting the constraints provided by the Chapels and the Nave - have to be regarded as a relative, and not an absolute, succession of values, inasmuch the mechanical properties assumed in the computations are purely hypothetical (they are: $E = 5000$ MPa, $\nu = 0.1$, $\rho = 1800$ Kg m^{-3} etc).
Moreover, it has to be stressed that in the present state of the art the mathematical model cannot yield any information about the level of energy dissipation, in other words about the "damping factors" associated with the different modal shapes.
All that the mathematical model can yield with good reliability (apart from the approximations introduced by the adopted discretization, i.e. the fourfold symmetry and the absence of Chapels and Nave) are the modal shapes.
The next steps of the dynamic investigation of the Dome can be foreseen as follows:

- Increased sophistication of the mathematical model, including in it the Chapels (a fourfold symmetry may be preserved by admitting that the constraint introduced by the Nave is rougly similar to that posed by a Chapel, and by neglecting the different cross-section of West pillars with reference to the East ones). With this refined mathematical model one should compute again the modal shapes and relevant frequencies.
- Validation and calibration of the mathematical model including the cracks, through in-situ determination of some eigenfrequencies and of the corresponding modal shapes. The in-situ tests would also yield directly, as already stated, the damping factor of each mode.
- At last, as a conclusive and crowning step of all the investigation, computation - via the validated and calibrated mathematical model - of the structural response to one or more "design earthquake", obviously either in the present, cracked, conditions or under various hypotheses of reinforcement. This last phase on one hand will allow to get insights on the seismic safety conditions of the Dome as well as on the effectiveness of different proposals for intervention, but on the other hand it will pose delicate, complex problems in order to define one or more earthquakes that can be considered as credible, significant and consistent with the site seismo-tectonic and seismographic profile.

4.2.2 In-situ dynamic surveys: a first attempt

On the Brunelleschi Dome one has carried out - apart from the sporadic measurements of traffic-induced vibrations made many years ago and not well documented - a simple survey of wind-induced vibrations over two out of the eight "sails" (curved panels) forming up the structure. The input (wind gusts) has been of moderate intensity. The response was measured by 8 seismometers placed on the two "sails" at three different levels, spanning the elevations from the "serraglio" (the summit ring on which the

Skylight rests) to the boundary between the masonry Dome and the underlying stone Drum.
In order to detect the vertical component (if any) of the displacements at the elevation of the "serraglio" also two vertical-component seismometers were installed, one for every monitored sail. The transducer signals were recorded on magnetic tape as acquired; the recording covers a time span of about 36 hours.
During selected intervals of time the signals were fed also to a spectrum analyzer; this allowed us to reveal both the frequencies preferentially excited by wind gusts and the phase and amplitude relationships (transfer functions) between the different points being surveyed.
The selectively predominant frequency turned up to be 1.86 Hz for the North "sail" and 1.77 Hz for the East "sail": this difference points out to structural asymmetries that it will be necessary to investigate in depth.
A fuller analysis of the recorded data is pending; we hope that the results will yield indications toward a preliminary calibration of the mathematical model, so that the latter can be used to plan, if necessary, the operational procedures to follow for an effective forced-vibration test.

4.3 Remains of the "Mars Ultor" Temple in the Augustean Forum in Rome

This monument is reduced nowadays to three Corynthian columns (in Carrara marble), 17 m high, connected among themselves as well as to a back wall (in "peperino", a tufaceous conglomerate) by a summit horizontal structure. The whole is tied to a transversal wall, to which a flat lesena similar to the three columns is attached (see Fig. 2).

4.3.1 Dynamic numerical (F.E.) analysis

These remains have been discretized by a F.E. mathematical model made up by 1434 elements (of the isoparametric, 2nd order tupe) adding up to about 29000 degrees of freedom (of which about 1600 blocked by boundary constraints) (see Fig. 3).
The physical properties of the different materials and the structural constraints were assumed on the basis of some trial computations so as to obtain, from the mathematical model, a frequency response sufficiently like the one that was recorded during the in-situ dynamic tests (see § 4.3.2).
After this rough "calibration" of the numerical model we carried out a numerical simulation of the dynamic excitation of the first mode as carried out in the field.
The comparison between the amplitude level of the vibrations (computed vs. measured values) turned out to be quite good, thus confirming that the "calibrated" mathematical model is adequate to represent this geometrically and physically complex structure.
It will now be possible to obtain numerically an answer to several questions concerning the monument, first of all e.g. to evaluate the effectiveness of possible interventions aiming at achieving a better seismic safety of these archeologically important remains.

4.3.2 In-situ dynamic surveys

The in-situ tests were carried out taking avail both of natural-excitation sources (wind gusts, vehicular traffic in the nearby urban streets) and of an artificial-excitation device (vibrodyne) with a controllable sine-wave output (amplitude and frequency of the imparted force, which was in fact a rotating vector, could be varied in a controlled way). The movements of the several points under observation were measured by the laser-interferometric, contactless system (LADIR) already mentioned under § 4.1. Besides, the movements of some more easily accessible points (especially along the foundations) were monitored with electro-mechanical seismometers of the classic type (see Fig. 4 and 5).
By effecting a sine sweep (with the vibrodyne) or by analyzing the response spectra (with the natural excitation) it has been possible to detect the first mode of vibration, at a frequency of about 2 Hz and with a damping factor of the order of 2% of the critical damping. In the low-intensity input range that was covered by the tests, the structural behaviour is very nearly linear (see Fig. 6).
The low frequency of the first mode, as well as the corresponding modal shape, induce to expect a pronounced deformability of the foundation layers (this is confirmed by the fact that in the calibration of the mathematical model it has been necessary to assign a very low value to the Young modulus of the thin foundation layer represented in the mesh).
The informations thus collected, anyway, have been very useful in order to carry out the calibration of the mathematical model already related under § 4.3.1.
It is good to keep in mind that the campaign of in-situ surveys cannot be considered exhaustive, inasmuch only the first mode has been clearly identified.
If these investigations will have a sequel, it will be therefore necessary to repeat, and enlarge in scope, the in-situ surveys.
It can be added that the mobile equipments developed for excitation, measurements and data processing - already exhaustively tested in the many surveys carried out on the big industrial structures of different ENEL installations - worked in a fully satisfactory way and without any noteworthy difficulty also in this new context.

5. CONCLUSIONS

Although the experiences so far carried out have been partial ones with a demonstrative character, one can already state that the methodologies developed until now, and systematically used for industrial structures, can be used with full confidence and put to good avail also for monumental structures. They can undoubtedly lead to a better knowledge of the dynamic behaviour of such structures, thus opening the way to a quantitative evaluation of their seismic safety with technical-scientific tools that reflect the current "state of the art".
Sooner or later it will be inevitable, we think, to pass from episodic, demonstrative applications to a systematic use of those tools. If and when this decision will be reached - which obviously

entails both a strategic view and the availability of adequate financial funding - an inestimable wealth of knowledge will be within reach. We allude to that vast body of specific, detailed data, informatically organized for the best efficiency of use, that will ensure in a way hitherto impossible the protection of the ingent treasure of architectural/archeologic monuments existing in our Country and exposed to the seismic risk which is so widespread in our territory.
Such a knowledge will have to be considered not as a closed body, gained "una tantum" for each monument, but on the contrary as a peculiar type of "monitoring", to be repeated with a quasi-regular time schedule, albeit at intervals which are by no means short (e.g. some years for those structures which suffer no particular problems). In this way the dynamic "dossier" of each structure can be viewed as an objective documentation undergoing a "continous" evolution and updating, which should follow and accompany the monument in every phase, alteration or transformation of its existence.

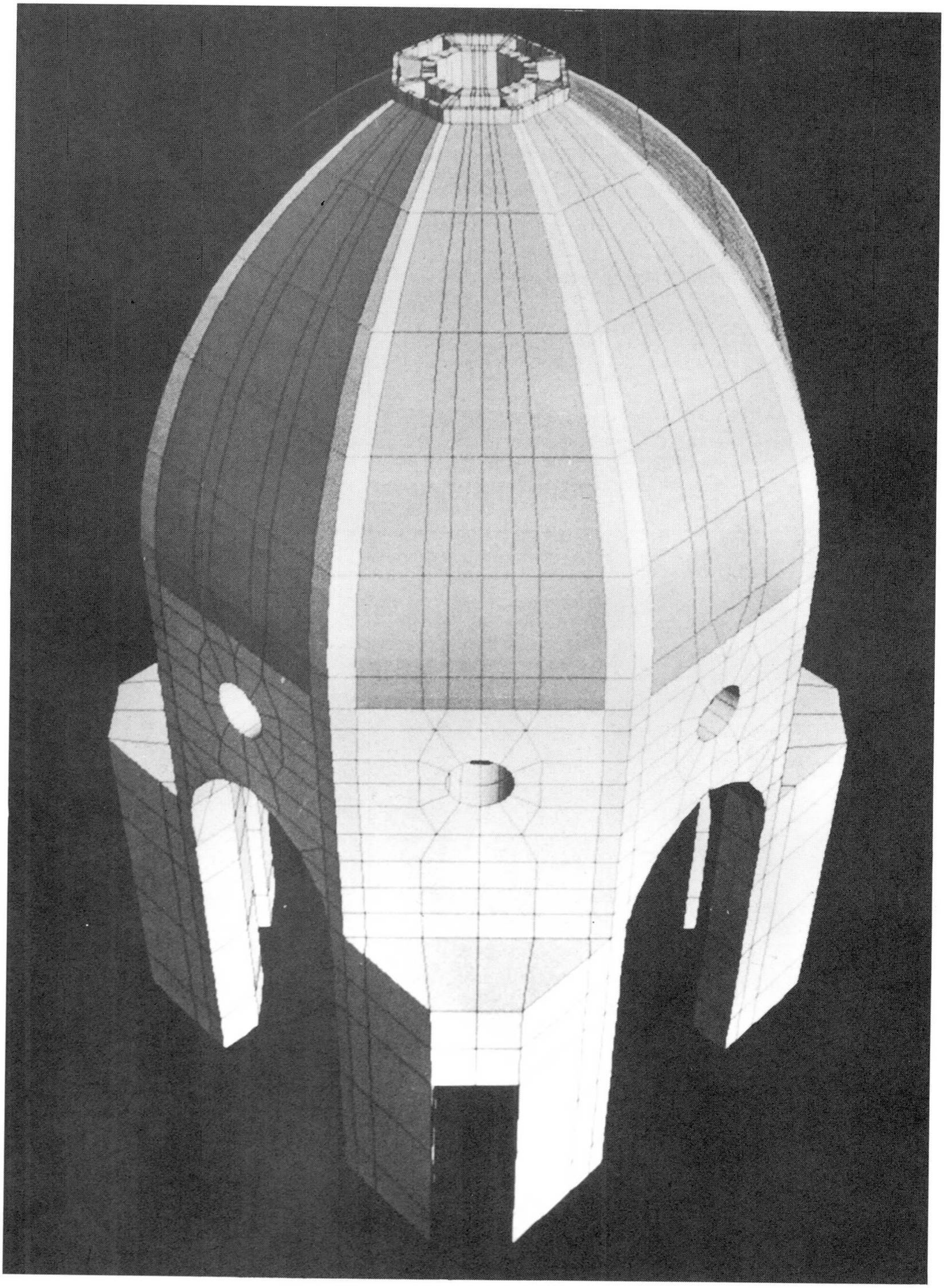

Fig. 1 - 3D F.E. mesh used for dynamical analyses of Brunelleschi Dome.

Fig. 2 - Panoramic view of remains of the "Mars Ultor" Temple in the Augustean Forum in Rome.

Fig. 3 - 3 D F.E. mesh used for numerical simulation of dynamic behaviour for the remains of the Mars Ultor Temple.

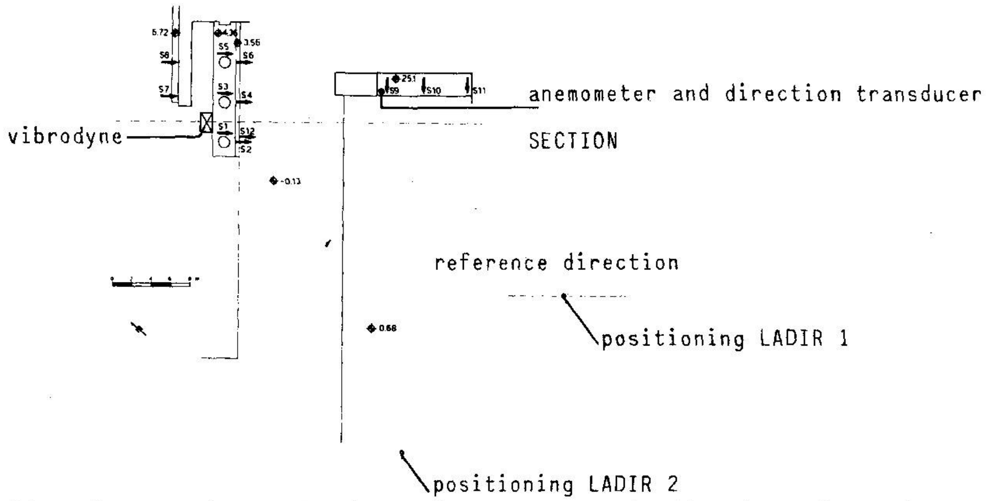

Fig. 4 - Horizontal view of sensors and vibrodyne locations.

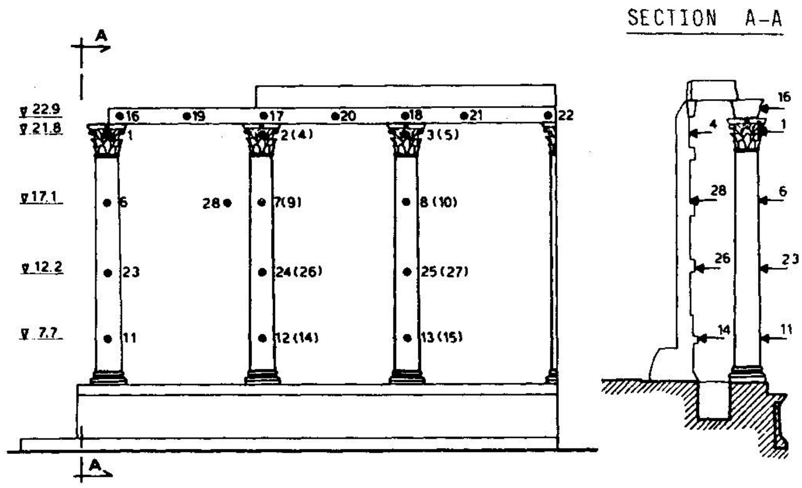

Fig. 5 - Vertical view of sensors and vibrodyne locations.

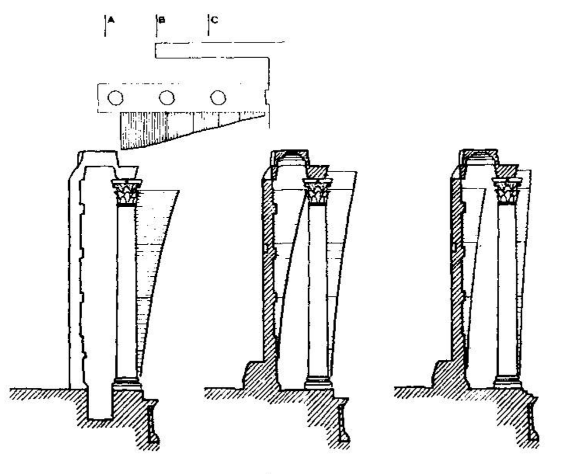

Fig. 6 - Graphic representation of measurement data: first mode.