Seismic Analysis of the Large 70-Meter Antenna, Part II: General Dynamic Response and a Seismic Safety Check

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An extensive dynamic analysis for the new JPL 70-meter antenna structure is presented. Analytical procedures are based on the normal mode decomposition, which include damping and special forcing functions. The dynamic response can be obtained for any arbitrarily selected point on the structure.

A new computer program for computing the time-dependent, resultant structural displacement, summing the effects of all participating modes, was developed also. Program compatibility with natural frequency analysis output was verified. The program was applied to the JPL 70-meter antenna structure and the dynamic response for several specially selected points was computed.

Seismic analysis of structures, a special application of the general dynamic analysis, is based also on the normal modal decomposition. Strength specification of the antenna, with respect to the earthquake excitation, is done by using the common response spectra. The results indicated basically a safe design under an assumed 5% or more damping coefficient. However, for the antenna located at Goldstone, with more active seismic environment, this study strongly recommends an experimental program that determines the true damping coefficient for a more reliable safety check.

I. Introduction

The development of a general dynamic analysis for an RF antenna which leads to a better understanding of the full range of pointing error sources is important from the point of view of evaluating the antenna performance and preparing it for higher frequency operation. Normal modal decomposition is suitable for an antenna structure represented by a finite element model with multi-thousand degrees of freedom. The theoretical background of such an approach is given in Refs. 1, 2, 3, 4. The primary purpose of this study was to get the time history of the dynamic response of the antenna subject to different forcing functions. Another important task was related to the upgrading and rehabilitation of the present JPL 64-/70-meter antenna to ensure that the antenna structure design satisfies the local earthquake safety criteria. Because seismic analysis is also based on normal modal decomposition, the dynamic analysis was treated more generally and expanded to give the general dynamic response.

The seismicity map of the world shown in Fig. 1 illustrates the strong epicenter locations as obtained from different U.S.A. and foreign seismological stations. In particular, the West Mediterranean area is of interest to the JPL antenna located in Madrid (Spain). Southeastern Australia is important for the antenna located in Canberra, and the southwestern U.S.A. for the antenna located at Goldstone, California. Fig. 1 together with a previous study[1] have indicated that the seismicity of the overseas JPL stations in Spain and Australia do not pose serious problems. However, the Goldstone antenna is subjected occasionally to substantial seismic activity and hence, requires a careful consideration of earthquake-induced loads.

The method of seismic analysis based on normal modal analysis was presented earlier in Ref. 5. However, for most engineering design safety purposes the simplified approach based on the design response spectra is usually adequate. The approach describes the structure earthquake characteristics in a statistical manner, encompassing a number of earthquake motions appropriately selected to the given excitation magnitude and the distance of object from the center of earthquake. The specification of the structure strength can be evaluated on a statistical basis.

II. Governing Equations

The dynamic equations of motion for a multi-degree of freedom system subjected to a ground forcing function can be summarized from Part I of the study (Ref. 5) as:

$$[M]\ \{\ddot{y}\} + [C]\ \{\dot{y}\} + [K]\ \{y\} = -[M]\ \{a\} \tag{1}$$

where $[M]$, $[C]$, $[K]$ are mass, damping and stiffness matrices, respectively, $\{y\}$ is the displacement vector relative to the ground displacement of modal mass and $\{a\}$ is the horizontal component of ground acceleration.

Equation (1) represents a system of N linear differential equations of second order which are transformed into a set of N uncoupled equations in normal coordinates, $\{z\}$. The mode equation is written as:

$$\ddot{z}_r + 2\,\xi_r\,\omega_r\,\dot{z}_r + \omega_r^2\,z_r = \alpha_r\,a(t) \tag{2}$$

where ω_r, ξ_r are the natural circular frequency and damping ratio, respectively and α_r is the rth modal participation factor, which determines to what extent each mode participates in the final response. The solution of Eq. (2) is given by:

$$z_r = \frac{\alpha_r}{\omega_r} \int_0^t a(\tau) \exp\left[-\xi_r\,\omega_r\,(t-\tau)\right] \sin \omega_r (t-\tau)\, d\tau \tag{3}$$

where τ is the time variable for Duhamel integral.

The resultant relative nodal displacements, after determining z_r are computed by:

$$\{y\} = \sum_{r=1}^{N} \{y_{or}\}\ \{z_r\} = [y_o]\ \{z\} \tag{4}$$

where y_{or} is the rth eigenvector and N is the number of modes. Any numerical integration of Eq. (3) can be employed. When it is desirable to know more precisely what the actual structure dynamic response will be, the complete dynamic analysis of the structure is performed. This requires the knowledge of the natural frequencies ω, the eigenvectors and the weighting or participation factors. The participation factors are obtained from the antenna eigenvalue analysis program.

A simplified approximate approach, adequate for common design purposes can be performed too where the upper bound of the response spectra is estimated. Such approximate analysis, based on ground-motion response spectra is an attractive alternative which avoids a major computation task of numerical integration of the coupled Eq. (1) or their transformation to a system of normal (modal) coordinates. Various earthquake motion responses for a single degree-of-freedom system, represented by Eq. (2), have been evaluated (Ref. 2) and are used in the form of design response spectra, as shown in Fig. 2.

III. Antenna Finite-Element Model

The 70-m antenna-structure components are shown in Fig. 3. For an economical processing on the UNIVAC 1100/81 computer, only half of the structure was modeled. The Y-Z plane is a plane of symmetry and the Z-axis is the focal axis as in Fig. 4. The X-axis is the axis of the reflector elevation rotation. The finite element model of only half of the structure contains about 2000 nodes, 7000 finite element members and 6000 degrees of freedom (Ref. 6). The JPL IDEAS structure

[1] "Antenna (210 ft) Facilities in Southeast Australia and Southern Europe," JPL Preliminary Engineering Report, Vol. 3 and 4 (internal document), JPL Contract No. 951281 with Holms and Narver, Inc., Jet Propulsion Laboratory, Pasadena, Calif., August 1965.

analysis computer program was used for performing the eigenvalue analysis. In order to obtain a good convergence between the multi-thousand degree of freedom finite element model of the antenna and its condensed representation to suit the dynamic analysis, two methods were applied: the inverse power (Stodola Method) and the Subspace-Iteration method.

Although the natural frequency (eigenvalue) analysis of the antenna structure does not require the presence of any external loading, the approach employed in this study was to make use of two antenna loading decompositions. These two loading decompositions were made possible in general to include the arbitrarily oriented acceleration vector in a 3-D space.

To illustrate the two loading deflection decompositions further, Figs. 5(a) and 5(b) give a general geometrically symmetrical antenna structure with asymmetric loading. By resolving the loading (forces or moments) as shown in Fig. 5(a) into two decompositions, the loading in decomposition 2 is antisymmetrical (equal but directionally opposite forces). In each loading decomposition pattern, only half the antenna structure is modeled and different boundary conditions are applied in each case which affect the stiffness matrix $[K]$ and may generate different eigenvalues (frequencies). Generally, in order to obtain the whole antenna response, superposition of the two decompositions of the half-antenna models is necessary. Ten modes for each of the two decompositions were obtained as in Table 1 together with participation factors. In our study only loading decomposition 2 was chosen since it resulted in larger participation factors relative to decomposition 1.

It is also chosen because it closely represents a no-external-load situation when the antenna is at zenith position and under gravity loading. Furthermore, a complete eigenvector analysis was made at decomposition 2, and the results are listed in Table 2 for five selected points on the antenna as shown in Fig. 4.

IV. Design Response Spectra

The specification of the strength of 64-meter antenna located at Goldstone, with respect to the appropriate earthquake loading, has been based on the site design response spectra, as shown in Fig. 2. In fact, the same method was proposed by Prof. G. W. Housner of Caltech in 1959, recommended by U.S. Atomic Commission in 1963, and was employed in checking the 64-m antenna in 1964. The new 70-m antenna structure is characterized by twenty, closely spaced, natural frequencies, which are computed from structure programs and listed in Table 1. For design convenience, three different damping ratios (2, 5 and 10%) were selected and the response spectra for each mode were obtained and plotted in Fig. 6. The dotted band in Fig. 6 indicates the safety margin given by Prof. Housner circa 1960 for the 64-m antenna which ranges between 0.25 g and 0.35 g.

Figure 6 indicates also that viscous damping coefficients play an important role in determining the structure safety. Prior seismic analysis work has not provided the true damping coefficients of the antenna because of air resistance or bearing friction. If the coefficient was to be greater than 5%, then the safety margin previously used circa 1960 is suitable. If the damping coefficient obtained from a future experiment is to be less than 5%, then the safety margin should be increased for a safer design.

V. Results of General Dynamic Analysis

Five points, A, B, C, D and E, for the whole antenna structure were selected as representative from the dynamic point of view shown in Fig. 4. A FORTRAN program TRANSIENT was developed to perform the operations represented by Eq. (4), which give the time-dependent resultant nodal displacements, compounded from all participating modes. The values of natural frequencies, eigenvectors and participation factors were taken from the JPL IDEAS eigenvalue analysis program. These are listed in Tables 1 and 2. With the El Centro (1940) earthquake excitation (shown in Fig. 7) as a sample forcing input, the results of five time-dependent responses, each for a particular point on the antenna structure, are presented in Figs. 8, through 12, respectively. The 5% damping ratio was taken as a computational parameter.

The maximum displacements were determined at five antenna points for illustration. The comparison of the five peak displacements is shown in Fig. 13. Point A (top of the apex) has the largest displacements (11 cm) due to the more flexible quadripod supports compared to the back-up reflector structure. Point B, at the rim of the reflector, has a maximum displacement of 2 cm. Point C (bottom of the reflector, dish) and Point D (elevation drive gear) have similar maximum displacements (8 mm and 7 mm, respectively). Point E (at the bottom of the alidade) experiences the smallest peak displacements of 2 mm. The results show that the level of the maximum displacements is not excessive.

VI. Summary

A new dynamic technique for computing the time-dependent multi-mode resultant displacement of a large structure was developed. This new tool, which includes damping and special forcing functions, is important in solving many engineering problems, such as those dealing with structure dynamics under nonsteady wind loading, control system design and pointing error analyses. The seismic analysis of the antenna structure was performed as a special application of this general dynamic technique and shows, according to the obliging seismic criteria, basically a safe design.

In the past it was recommended that the 64-m antenna structure be designed to withstand an equivalent, constant, lateral acceleration of 25% G for good earthquake resistance. Those early seismic analyses were based on rough estimates of the fundamental mode frequency. With the first 20 natural frequencies obtained from this mathematical model for the 70-m antenna, more extensive dynamic studies can be performed in general and on seismic responses in particular. Our seismic study results suggest an experimental program that determines the true damping coefficients for a more reliable safety check.

References

1. Clough, R. W., and Penzien, L., *Dynamics of Structures*, New York, McGraw-Hill, 1975.
2. Wiegel, R. L., *Earthquake Engineering*, New York, Prentice-Hall, 1970.
3. Zienkiewicz, O. C., *The Finite Element Method in Engineering Science*, New York, McGraw-Hill, 1977.
4. Levy, S., and Wilkinson, J. P. D., *The Component Element Method in Dynamics with Application to Earthquake and Vehicle Engineering*, New York, McGraw-Hill, 1976.
5. Kiedron, K., and Chian, C. T., Seismic Analysis of the Large 70-Meter Antenna, Part I: Earthquake Response Spectra Versus Full Transient Analysis, *TDA Progress Report 42-81*, pp. 31–42, Jet Propulsion Laboratory, Pasadena, Calif., March 1985.
6. Levy, R., and Strain, D., "Design Optimization of 70M Antenna with Reflective Symmetry," Proc. of 21st Annual Meeting Society of Engineering Science, Inc., Virginia Polytechnic Institute and State University, Blacksburg, VA, Oct. 15-17, 1984.

Table 1. Antenna dynamic characteristics

Mode No.	Circular Frequency (ω), Radian/s	Frequency (f), Hz	Participation Factors (α)
	Decomposition 1		
1	9.99	1.59	−0.056
2	16.64	2.65	0.156
3	17.20	2.74	1.213
4	21.15	3.37	−1.410
5	21.29	3.39	1.379
6	22.73	3.62	1.059
7	23.52	3.74	−0.153
8	24.40	3.88	0.281
9	25.37	4.04	0.885
10	26.16	4.16	−0.154
	Decomposition 2		
1	7.89	1.26	2.703
2	8.61	1.37	−1.518
3	10.13	1.61	3.280
4	13.39	2.13	−3.732
5	16.68	2.65	0.333
6	18.13	2.88	3.287
7	18.43	2.93	−0.443
8	18.70	2.98	−0.340
9	19.13	3.04	2.301
10	19.60	3.12	0.033

Table 2. Values of eigenvectors for decomposition 2

Mode No.	Node Identification				
	A	*B*	*C*	*D*	*E*
1	0.693	0.103	0.066	0.058	0.012
2	0.598	−0.020	−0.015	−0.013	−0.003
3	0.460	−0.068	0.018	0.014	−0.004
4	0.395	−0.236	−0.108	−0.082	−0.002
5	0.067	−0.187	0.006	−0.011	0.013
6	−0.096	−0.023	0.023	0.017	0.005
7	−0.104	0.030	−0.005	−0.003	−0.003
8	−0.014	0.043	−0.009	0.000	0.001
9	0.108	−0.117	0.053	0.036	0.013
10	0.071	0.010	0.000	0.000	−0.001

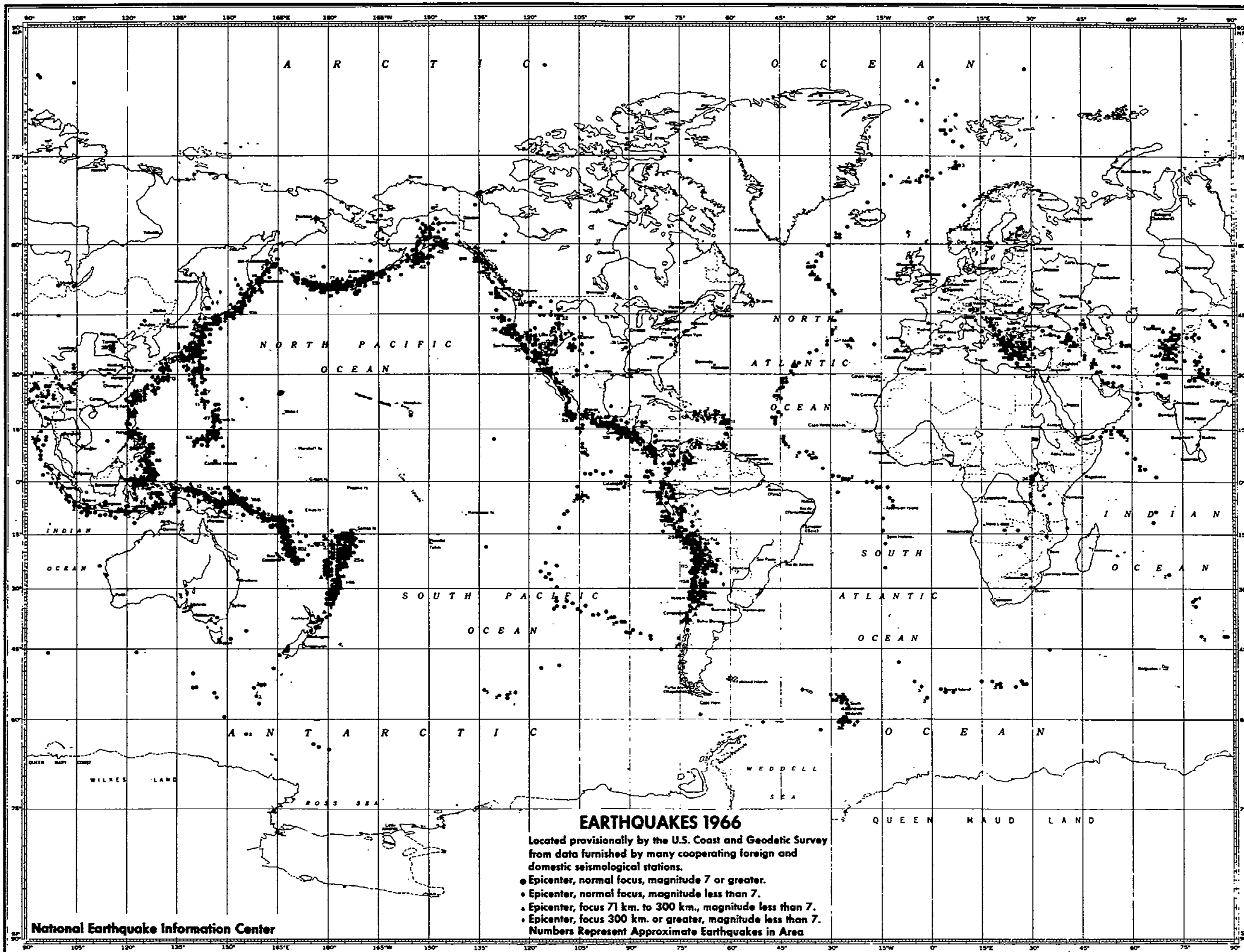

Fig. 1. Seismicity map of the world (from Ref. 2, p. 23)

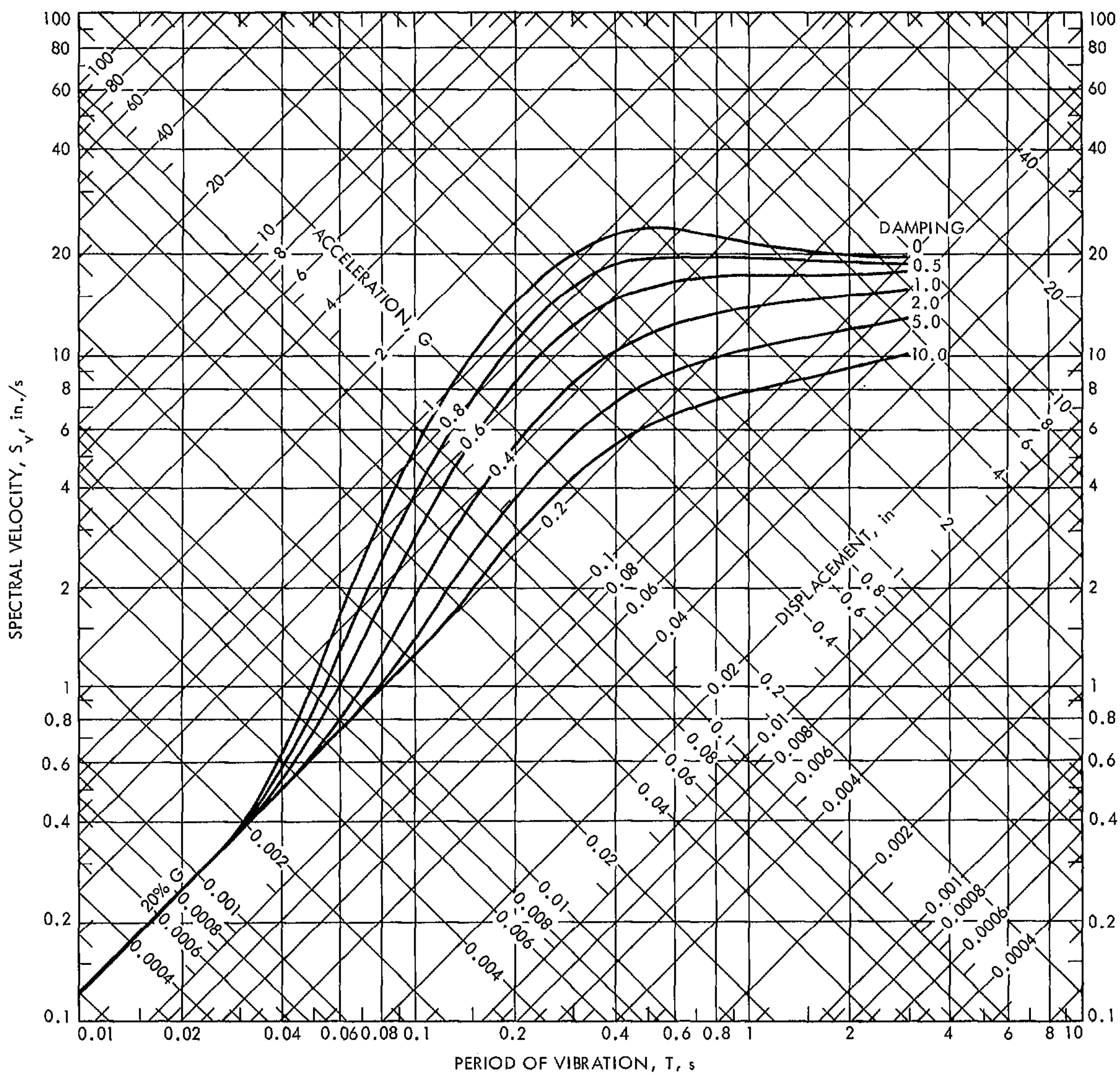

Fig. 2. Design response spectra

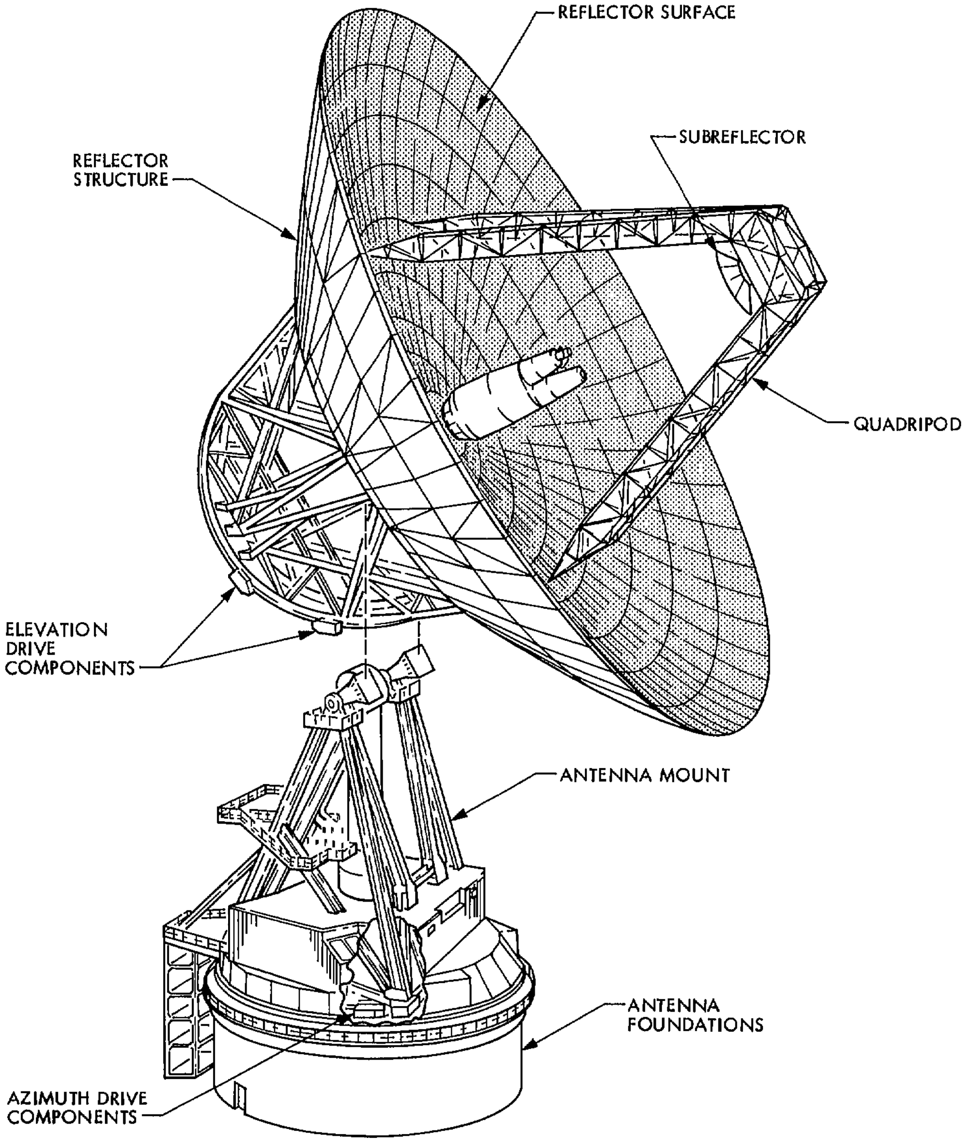

Fig. 3. Antenna components

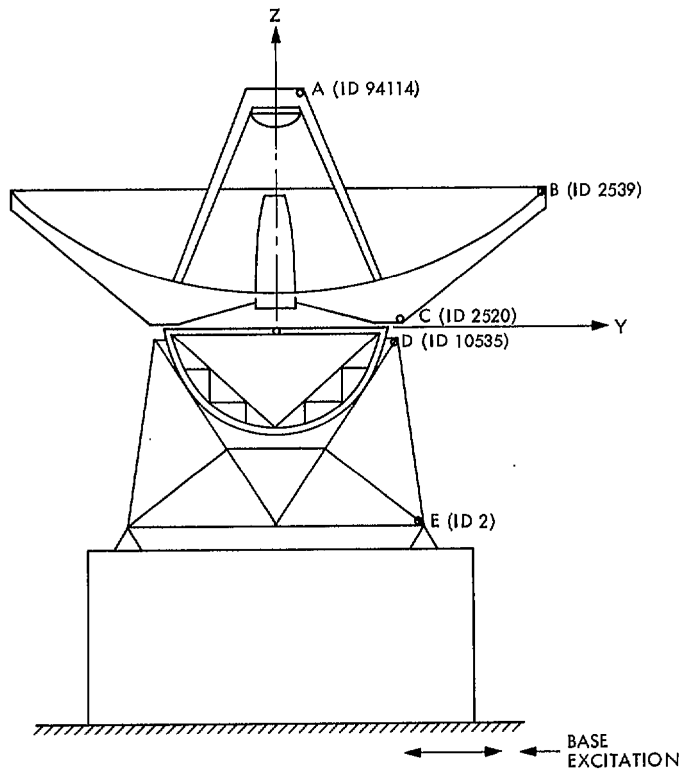

Fig. 4. Locations of selected dynamic response points

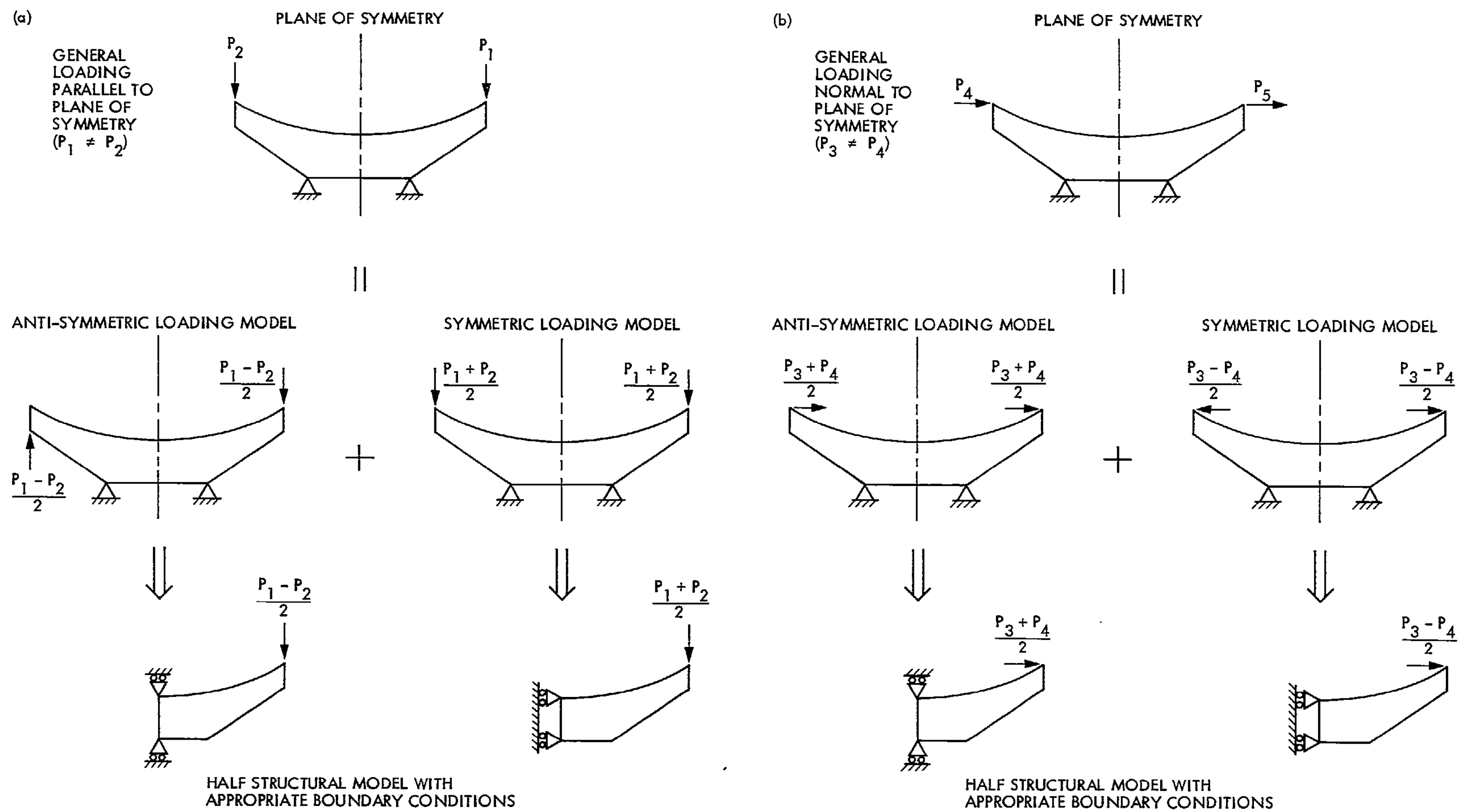

Fig. 5. Load decomposition on a symmetric antenna

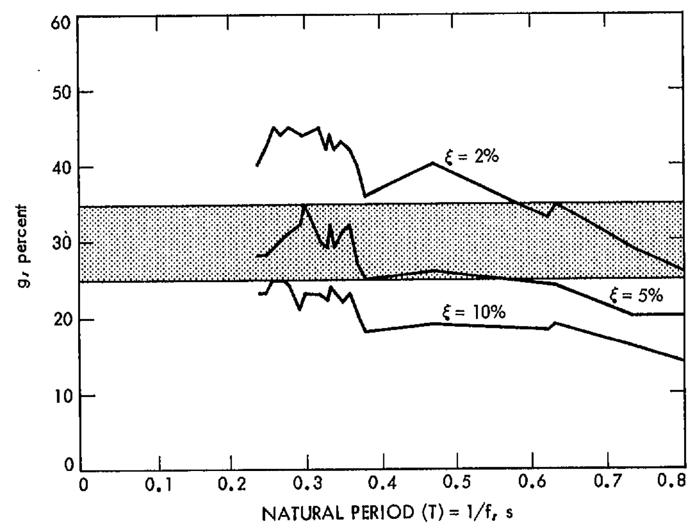

Fig. 6. Antenna response spectra

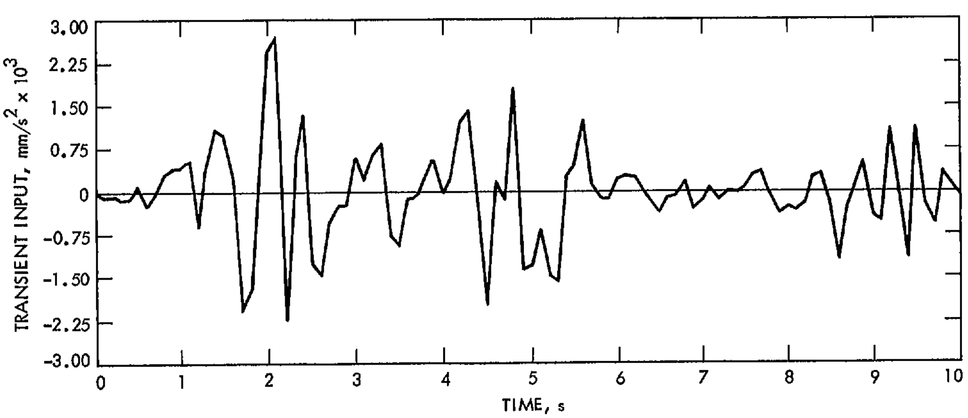

Fig. 7. Dynamic El Centro input

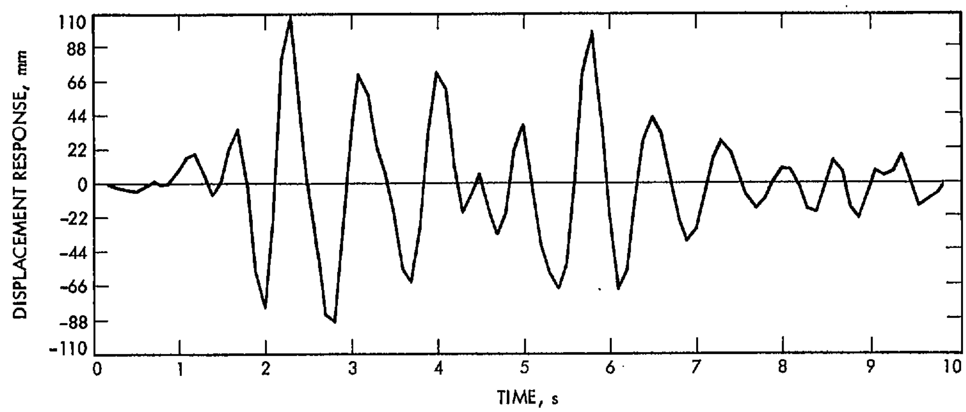

Fig. 8. Dynamic response for point *A*

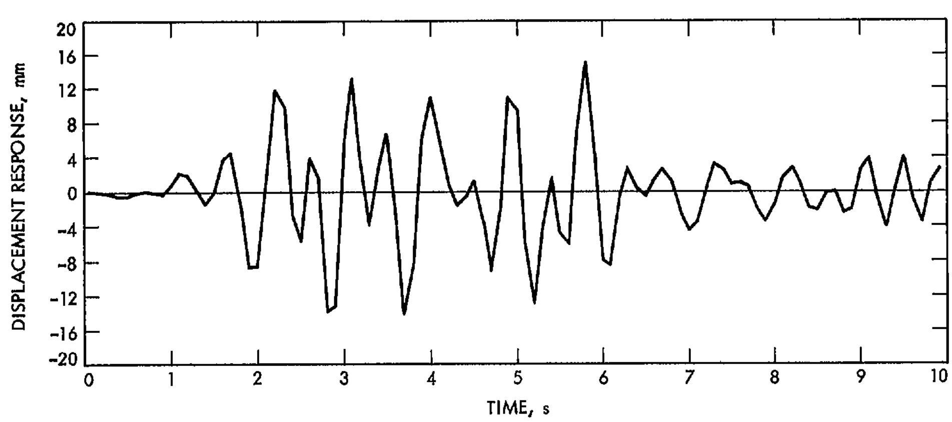

Fig. 9. Dynamic response for point *B*

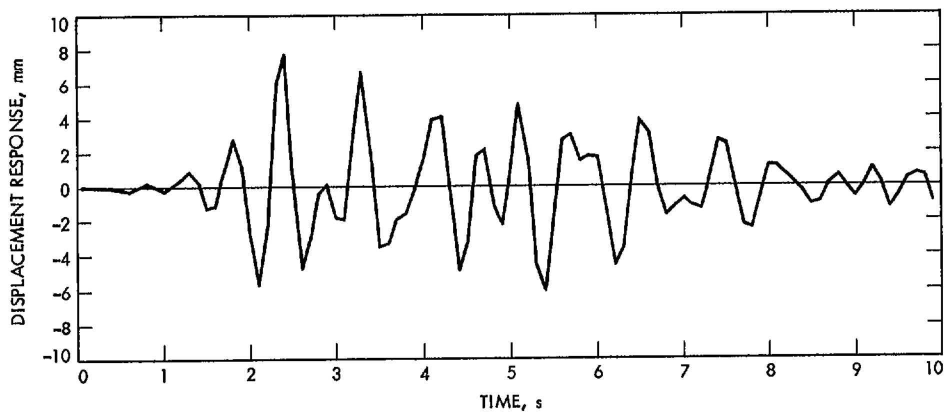

Fig. 10. Dynamic response for point *C*

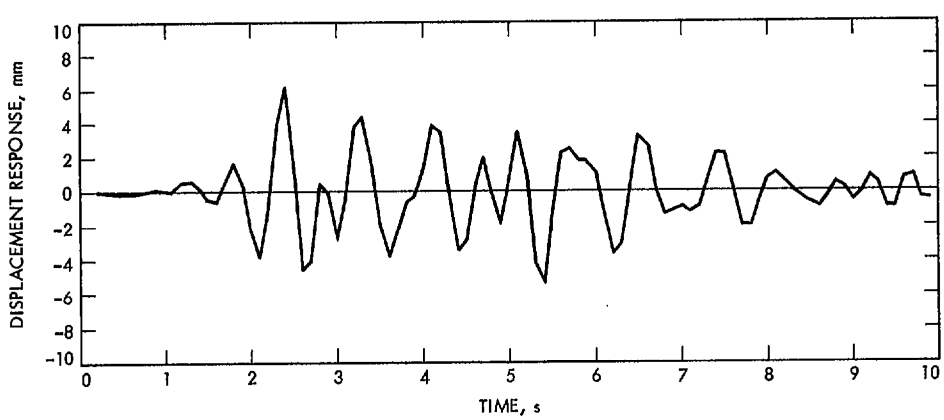

Fig. 11. Dynamic response for point *D*

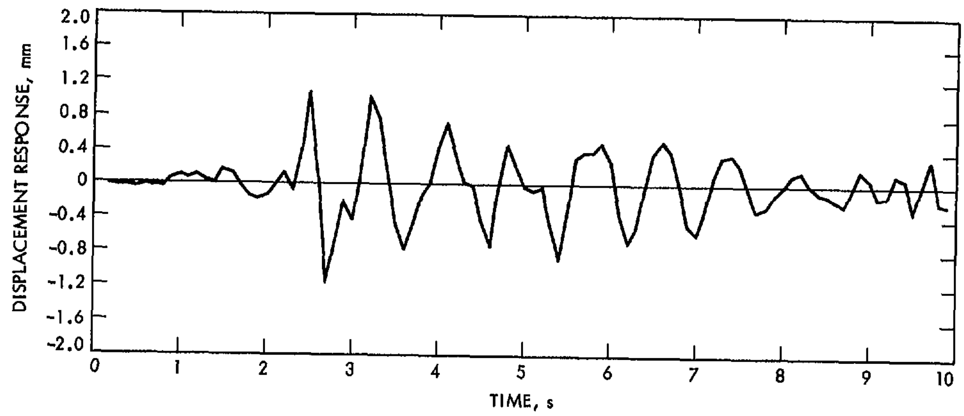

Fig. 12. Dynamic response for point *E*

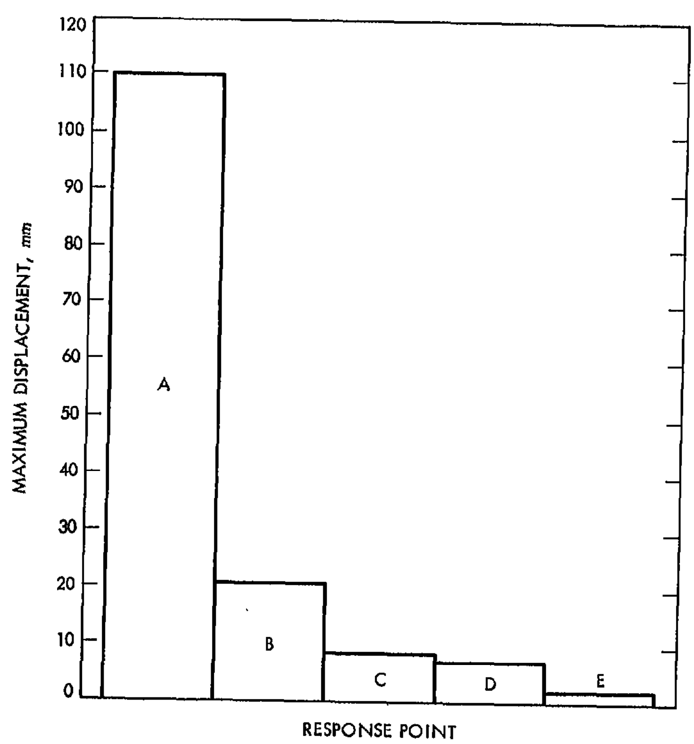

Fig. 13. Maximum displacements at the five selected antenna points