SEISMIC RESPONSE ANALYSIS OF A REACTOR COOLANT PUMP

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SUMMARY

The Westinghouse Type 93A reactor coolant pump (RCP) is analyzed for seismic response. Simply described, the RCP is a vertical, single-stage, centrifugal pump designed to move 90,000 gpm (568 m^3/sec) of water and driven by a 6000 hp motor for use in the PWR primary system.

The RCP assembly is generally axisymmetric and is modeled using 3-dimensional finite elements to represent its parts. These finite elements are of the types normally found in general purpose computer programs such as ANSYS or NASTRAN. The structural frame and the rotating shaft are the principal branches of the model. Each consists of a series of pipe elements complemented by mass elements. Orthogonal sets of linear spring elements connect the branches at the bearings and possibly at each labyrinth. Fluid elements are added to include the interaction between the shaft and the pump case through the intervening water mass. To complete the model, stiffness matrix elements representing the support structure and the neighboring loop piping are attached. It is impractical to idealize faithfully each geometric irregularity. Several adjacent sections are combined into one suitable element with total stiffness and mass equivalence. The number of elements in the model is thus minimized. Shear deflection of the pipe elements is considered; mass and mass inertia are lumped at nodal points, as needed, to compensate for the actual material distribution. The RCP model contains 82 nodes, 155 elements and 160 master dynamic degrees of freedom.

The seismic analysis is performed by the spectrum method in ANSYS, with seismic velocity as the input excitation parameter. In each computer run, the model is excited with a set of three orthogonal spectra: SSE-X, SSE-Y and SSE-Z. The first and third spectra are exactly the same in magnitude and are horizontal with a given orientation. SSE-Y is vertical at 2/3 the magnitude of the horizontal spectrum. Additional sets of horizontal excitation on another orientation can be included in the same run. For each load excitation, the modal displacement, forces and stresses are computed at each node. Then a post-run subroutine calculates the square root of the sum of the squares (RSS) for each quantity. The vector sum of one horizontal RSS and the vertical RSS are recorded as the final values: SSE X-Y and SSE Y-Z. To determine which orientation of the horizontal spectra was the worst stress case, six 15-degree positions were run for the softest and stiffest support matrices. The 0-degree and 30-degree orientations appeared to give high stresses with the model on the stiffest support. Absolute displacements were reviewed for selected nodes along the model branches. For clearance evaluation, the relative displacements at bearing and labyrinths were computed for comparison with actual gaps. Finally, the accelerations of nodes previously chosen were listed in the printout.

The in-depth analysis in this work, believed to have no published precedent, has found the RCP adequate to withstand the imposed seismic loading. All component stresses were within the applicable faulted criteria and the relative movements between closely-mated parts fell inside their nominal clearance limits.

1. Introduction

Current nuclear steam supply systems (NSSS) are designed to remove the heat of fission by circulating coolant in closed loops from the reactor. For water reactors, this prime function is designated to the reactor coolant pump (RCP). Literally considered the heart of the power plant, the RCP is essential to the NSSS operation. There is one pump in each loop and it pushes the primary water from the reactor to the steam generator and back to the reactor. The basic loop is composed of the hot leg, the steam generator, the cross-over leg, the RCP and the cold leg. Both hot and cold legs are welded to the reactor vessel and large gate valves may be installed in them for isolating the loop.

In the normal reactor coolant loop analysis (RCLA), the RCP is modeled simply with two masses much like a dumbbell although it is sometimes advisable to model separately the rotating assembly of the pump. This is generally consistent with the purpose of the loop analysis and in line with keeping the problem size within the computer program capacity while obviously minimizing the cost of the analysis. Clearly, the RCLA precludes the possibility of evaluating the detailed parts of the pump. To analyze the RCP itself, therefore, it would be necessary to employ a detailed model of the pump in a simplified representation of the loop.

This paper deals with assessing the effects of a given seismic excitation on the parts of the RCP and its overall structural integrity by the response spectrum method.

2. The Reactor Coolant Pump

The reactor coolant pump under analysis is the Westinghouse Type 93A RCP. It is a vertical, single-stage centrifugal pump designed to move 90,000 gpm (568 m^3/sec) with a head of 280 ft. (85.3 m) and consists of three general areas: the pump proper, the seals and the motor. A cut-away view of the RCP is shown in Figure 1.

The pump proper is essentially the hydraulic parts and these are the impeller, turning vane/diffuser assembly, diffuser adapter, pump case and the pump shaft. The pump case, or casing as it is usually called, is permanently welded to the loop piping at the suction and discharge nozzles. Attached to the bottom of the pump shaft is the impeller. The reactor coolant flows from the suction nozzle, through the diffuser adapter and into the eye of the impeller. As the fluid travels the passages between the impeller vanes, a velocity head is imparted to it. At exit from the impeller, the coolant is directed to the diffuser part of the turning vane/diffuser assembly where the velocity head is converted to pressure head. The coolant then goes to the turning vane which gradually guides the flow into a radial discharge.

In addition to the hydraulic parts, there is a thermal barrier-heat exchanger (TBHX) directly above the impeller and is interposed between the hot coolant and the pump radial bearing. During normal operation, the TBHX shields the pump bearing and the seal area overhead. This is achieved by high pressure injection water that is introduced into the bearing cavity. The injection water splits into two flow paths. The upward flow goes past the radial bearing and into the seal area while the remainder flows down through the TBHX cooling coils and past the thermal barrier labyrinth onto the top of the impeller where it acts as a buffer to prevent the reactor coolant from entering the bearing cavity. If a loss of injection water occurs, the TBHX would function as a heat exchanger to cool the reactor coolant before it enters the bearing cavity and seal area.

Above the pump bearing is located in series three mechanical seals which break down the high injection pressure to 3 psi (0.211 kg/cm^2). The No. 1 seal is the principal seal of the pump and is of the controlled leakage, film-riding type face seal. The leakage path is maintained by a wedge of water 4.5 mils (0.114 mm) thick at the interface of the seal ring and seal runner. The No. 2 seal is a rubbing-type face seal with a shrunk graphitar insert as the seal-ring and a plated stainless steel runner. This seal directs the leakage from the No. 1 seal into the volume control tank which is kept at 50 psi (3.515 kg/cm^2). The No. 3 seal is also a rubbing-type face seal similar to the No. 2 seal except that the seal ring secondary is a bellows. This seal directs the No. 2 seal leakage to the waste disposal drain tank. The No. 3 seal leakage of 100 cc/hr goes to the sump or evaporates into the containment.

The RCP is driven by a drip-proof, vertical, solid shaft, air-cooled, squirrel-cage, induction motor. It is equipped with an oil-lubricated, double-acting Kingsbury thrust bearing, two oil-submerged pivoted-pad radial guide bearings and a flywheel with an anti-rotation device. Water-type heat exchangers are used to cool the lubricating oil. The stator and rotor are of standard construction with thermalastic epoxy impregnation. The motor sits on a support stand that is bolted to the main flange closure of the casing. A spool piece connects the pump shaft to the motor shaft. This scheme conveniently allows the servicing of the seals without removal of the motor.

3. The RCP Dynamics Model

Before the RCP modeling can be achieved, it is necessary to decide which computer program would be used for the analysis. Its finite element library would then be studied for choice in the idealization. In the present case, the ANSYS program [1] was chosen for familiarity and convenience.

The mathematical representation of the RCP was developed from the detail drawings together with the general assembly drawing. Since most component parts of the pump are axisymmetric, the cylinder or pipe finite element was selected as the principal element of the model. When irregular segments or slices of the pump parts are combined to be represented by a single pipe element, it is likely that the mass center location and inertias of the model and those of the actual parts will be different. It would then be necessary to compensate the masses and inertias at the nodal ends of the model element so as to maintain equivalence. At Westinghouse, this computation is facilitated by the PHYTRI program [2]. The mass element is usually employed to model all concentrated masses. It is also used to represent those compensating masses which are introduced, as previously explained, to preserve the rigid body mass and inertia distributions.

Another finite element in the model is the linear spring element. It is used to represent the bearing film stiffnesses, the brackets of the sidearm oil cooler and the base plate of the upper oil pot. The suction piping or cross-over leg and discharge piping or cold leg are lumped together in the model by a 6 x 6 stiffness matrix element. The casing foot and the support structure of the pump are also represented by another single stiffness matrix type element. To account for the interaction effects of fluid around the shaft, the fluid element is used. The annular fluid is found in the casing, in the seal housing and in the motor upper oil part. Figure 2 shows the pipe elements laid side by side with the pump section they represent. The structural frame and rotating assembly are the principal branches of the model which is put together and presented for clarity in a diagram in Figure 3. There are 155 active elements, 82 nodes, and 160 dynamic degrees of freedom in the RCP model.

4. Analytical Considerations

Data for the RCP analysis supplied from the equipment specification were (a) the piping stiffness, (b) the support stiffness and (c) the seismic response spectra.

Instead of the usual piping geometry, the suction and discharge piping stiffness were lumped into one 6 x 6 matrix based on the RCLA coordinate system. Because of the relative position on the pump in the loop, it was necessary to transform the given piping stiffness matrix to the local coordinate system of the pump.

Seven cases of support stiffness were stipulated in the RCP specification. To avoid analyzing completely all cases of support, a way of eliminating the non-controlling cases was determined. The main diagonals of the matrices were listed in order and a comparison of the terms was made. The matrix showing the stiffest support was found and then transformed also to the RCP coordinate system.

The horizontal and vertical seismic response spectra are shown in Figure 4 and represent the safe shutdown earthquake (SSE) values for design. These two spectra originated from different elevations in the containment. In practice, the vertical spectrum is taken as 2/3 of the corresponding horizontal spectrum at the particular level. In accordance with the ANSYS input instructions, 20 points of each spectrum for frequencies from 1 Hz to 40 Hz, inclusive, were chosen and formatted as seismic velocity loads on the model. Two orthogonal sets in the horizontal direction and one set in the vertical direction comprised the full excitation. At this point, the question as to which direction to apply the horizontal loads for maximum stress arose. Therefore, six orthogonal pairs of horizontal excitation were applied to the RCP model separately at 15^0 intervals. The preliminary stress evaluation showed that the motor stand was the highly stressed part at Node 12 in Figure 3 when the X-horizontal shock was directed at 0^0; i.e.: along the discharge nozzle piping. However, it was also found that the motor stand was highly stressed at Node 14 when the X-horizontal shock was in the 30^0 direction. Thus, the complete seismic run was composed of 5 loadsteps to cover both 0^0 and 30^0 cases; viz.: X-horizontal shock at 0^0, Y-vertical shock, Z-horizontal shock at 90^0, X-horizontal shock at 30^0 and Z-horizontal shock at 120^0.

An important consideration is the number of dynamic degrees of freedom (DDOF) to be used in the analysis. The present RCP model has a total of 82 x 6 = 492 master displacements. For the spectrum analysis, it is always recommended that the DDOF's be reduced for the sake of economy. Since the ANSYS program has a limit of 172 DDOF's, 160 master displacements were first chosen. An examination of the result showed natural frequencies as high as 20,000 Hz and as low as 1.8 Hz. In view of the wide frequency range, ANSYS flashed a warning on the possibility of eigenvalue error. The highest/lowest frequency ratio is limited to 3000. A systematic elimination of the high frequencies without changing the model was instituted. With 150 DDOF's the maximum frequency was 1655 Hz, which was acceptable. It was noted that only 138 frequencies appeared showing that 150 DDOF's were more than sufficient. As a side study, it was found that as low as 44 DDOF's for the RCP model could be used without materially affecting frequencies of the pump below 40 Hz. However, the computed stress values become unreliable.

The choice of spring constants is not critical. These constants are related to film stiffness and range from 10^7 lbs/in at the motor bearings to 25 x 10^4 lbs/in at the pump bearing. After the first trial, the relative modal displacements are monitored and the spring constants are adjusted to prevent violation of the designed clearances between closely-mated parts.

5. Results and Conclusion

The ANSYS first calculates the modal displacements for each node and then performs the stress pass. The forces and moments are printed out with the nodal stresses. In order to determine the total effects of the seismic loads, a POST 8 [3] subroutine is utilized at Westinghouse. It takes the square root of the sum of the squares (RSS) of the modal displacements, forces and moments for a specified combination of horizontal and vertical loads or deflections. In this analysis, the bigger of the horizontal (X or Z) response is added vectorially to the vertical (Y) response. This stipulation arises entirely from the equipment criteria.

Accordingly, the results are tabulated for various parts of the pump. The RSS displacements are shown in the Table I, which is self-explanatory. It is important to check the clearances in the bearings. The relative lateral displacements between two adjacent nodes are calculated by POST 8 for each mode and the RSS values are compared with the actual gaps. These comparisons are listed in Table II. The RSS of all the nodal forces and moments are found and used to calculate the element stress at the node. The fidelity of the element representing the part dictates the accuracy of the stress. Nevertheless, it can be said that the stresses in Table III are quite correct. This aspect could easily be clarified by using the real section for computing the stress. Table IV is a special stress calculation of the bolting rings in the RCP. The high bolt stress in the lower motor bracket is still reasonably well within the ASME Code III [4] allowable. The RSS nodal accelerations for the RCP are tabulated in Table V. These values may be used to recheck the seismic forces acting on any part of the pump and the resulting stress.

The foregoing analysis confirms the structural adequacy of the Westinghouse Type 93A RCP in withstanding the effects of the particular SSE.

References

[1] DeSalvo, G.J., Swanson, J.A., ANSYS User's Manual, Swanson Analysis System, Inc., Elizabeth, Pennsylvania (October 1972)

[2] Geiger, T.L., "PHYTRI - Mathematical Modeling for Physical Characteristics in Triaxial Vibration," Westinghouse Electro-Mechanical Division, Cheswick, Pennsylvania (1971)

[3] Reed, A.E., "POST 8 - Computational Subroutine in Post ANSYS," Westinghouse Electro-Mechanical Division, Cheswick, Pennsylvania (1973)

[4] ASME Boiler and Pressure Vessel Code, Section III: Subsections NA and NB, American Society of Mechanical Engineers, New York, New York (July 1974)

TABLE I DISPLACEMENT RESPONSE OF RCP

Location	Model Node	RSS Displacement (Inch)	
		Horizontal	Vertical
Top of Motor	1	0.6953	0.0071
Bottom of Motor	10	0.3267	0.0067
Main Flange	15	0.2250	0.0062
Suction Nozzle	20	0.0907	0.0061
Flywheel	53	0.7075	0.0424
Rotor Core	61	0.4803	0.0429
Motor Shaft @ Flange	65	0.3317	0.0431
Pump Shaft @ Coupling	68	0.2948	0.0432
Pump Shaft @ Seal	72	0.2378	0.0434
Pump Shaft @ Bearing	74	0.1690	0.0434
Pump Shaft @ TBHX	76	0.1381	0.0434
Impeller	78	0.0911	0.0434

TABLE II RELATIVE DISPLACEMENT OF RCP

Location	Model Nodes	RSS Relative Displacement (Mils)	Clearance (Mils)
Motor Upper Radial Brg.	21-56	4.40	5
Motor Upper Thrust Brg.	21-51	24.68	25
Motor Core Centerline	6-61	7.79	125
Motor Lower Radial Brg.	9-64	4.91	5
Shaft Seal	24-71	28.11	100
Pump Bearing	26-74	12.13	15
TBHX Labyrinth	79-76	11.71	30
Impeller Labyrinth	31-78	33.34	50

TABLE III MAXIMUM SSE STRESSES IN THE RCP

Part	Model Node	Stress (psi)
Motor Frame	8	5,197
Motor Stand, Upper	12	25,379
Motor Stand, Lower	14	17,668
Main Flange	25	1,730
Casing Mouth	16	1,228
TV/Diffuser	16	2,308
Thrust Brg. Support	22	2,367
Motor Shaft	56	4,396
Pump Shaft	72	2,889

TABLE IV SSE STRESSES IN THE RCP BOLTS

Bolt Location	Model Node	Stress Intensity (psi)
Thrust Runner Plate	21	10,560
Upper Motor Bracket	5	36,880
Lower Motor Bracket	8	85,220
Upper Motor Stand	11	34,110
Lower Motor Stand	14	50,630
Main Flange	15	3,860

TABLE V ACCELERATION RESPONSE OF RCP

	Model Node	RMS Acceleration (G's)	
		Horizontal	Vertical
Motor Frame	1	2.240	0.115
	3	1.778	0.115
	6	1.339	0.097
	8	1.262	0.088
	14	1.262	0.059
	15	1.253	0.057
	20	1.105	0.055
Casing Internals	23	1.288	0.057
	25	1.239	0.057
	26	1.204	0.057
	28	1.138	0.056
	31	1.118	0.056
	45	1.219	0.057
	46	1.231	0.056
	48	1.186	0.056
Motor Shaft	53	2.545	1.290
	56	2.063	1.287
	59	1.617	1.230
	61	1.379	1.303
	63	1.303	1.305
	65	1.449	1.311
Spool Piece	66	1.517	1.312
	67	1.668	1.313
Pump Shaft	69	1.869	1.314
	71	2.010	1.317
	73	1.775	1.319
	74	1.534	1.320
	76	1.337	1.321
	78	1.051	1.322

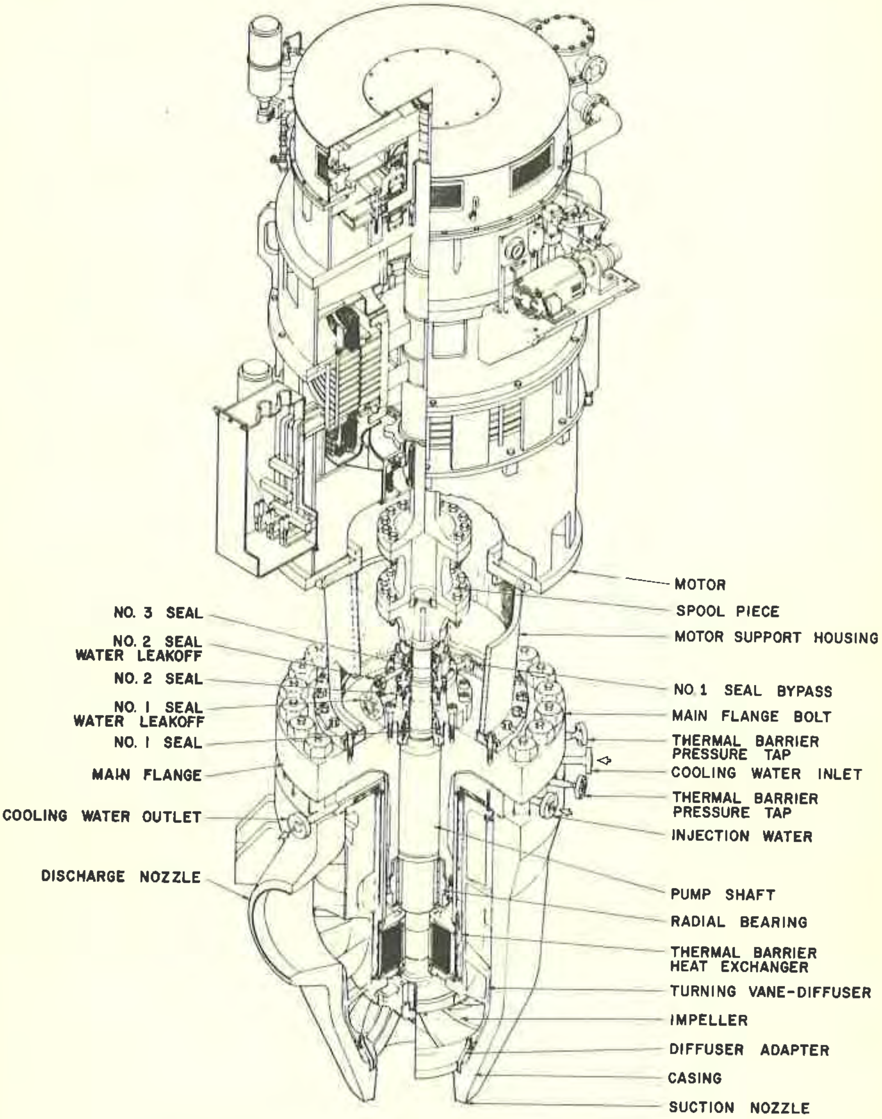

FIGURE 1 REACTOR COOLANT PUMP CUTAWAY VIEW

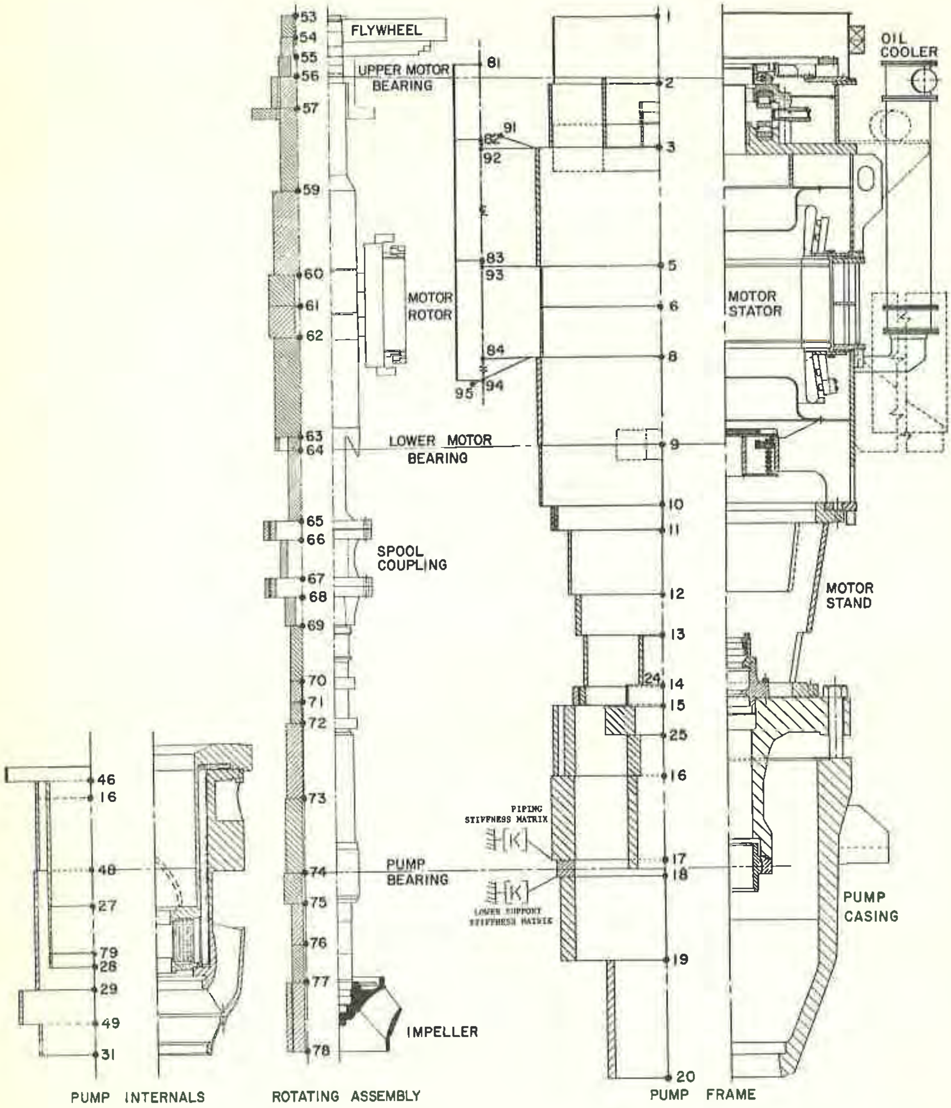

FIGURE 2 MODEL OF A REACTOR COOLANT PUMP

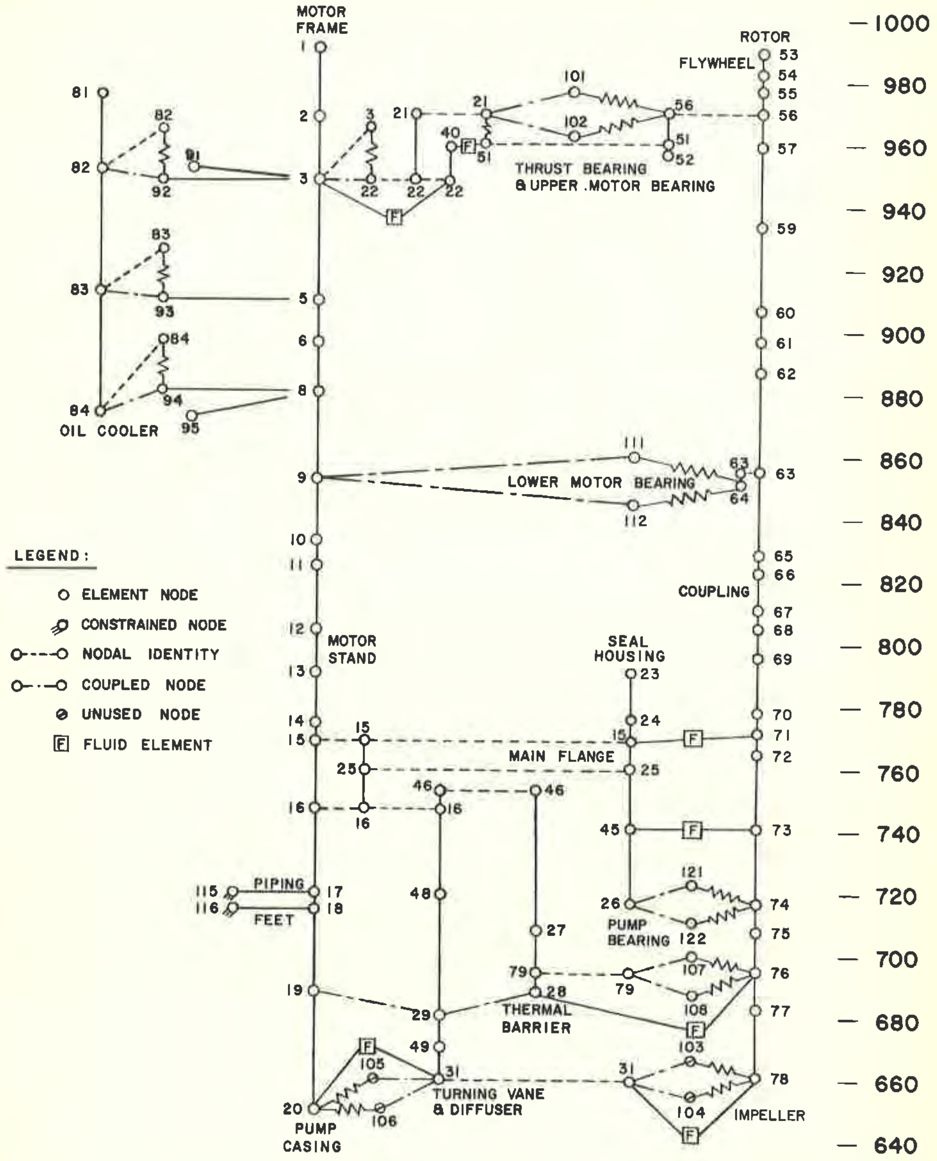

FIGURE 3 DIAGRAM OF THE RCP SEISMIC MODEL

FIGURE 4
SSE SEISMIC RESPONSE SPECTRA