STRUCTURAL ANALYSIS OF THE SUPPORT SYSTEM FOR A LARGE COMPRESSOR DRIVEN BY A SYNCHRONOUS ELECTRIC MOTOR

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Summary

For economic reasons, the steam drive for a large compressor was replaced by a large synchronous electric motor. Due to the resulting large increase in mass and because the unit was mounted on a steel frame approximately 18 feet above ground level, it was deemed necessary to determine if a steady state or transient vibration problem existed. There was a definite possibility that a resonant or near resonant condition could be encountered. The ensuing analysis, which led to some structural changes as the analysis proceeded, did not reveal any major steady state vibration problems. However, the analysis did indicate that the system would go through several natural frequencies of the support structure during start-up and shutdown. This led to the development of special start-up and shutdown procedures to minimize the possibility of exciting any of the major structural modes. A coast-down could result in significant support structure and/or equipment damage, especially under certain circumstances. In any event, dynamic field tests verified the major analytical results. The unit has now been operating for over three years without any major vibration problems.

Introduction

Due to the increased cost of generating steam from natural gas or oil, it was necessary to replace the existing steam drive for a large compressor with a large synchronous electric motor. To achieve the desired compressor speed, a gear system (increaser) was also required. The particular synchronous motor was rated at 2,500 hp at 1200 rpm. The motor/exciter, couplings, gear box and compressor weighed about 43,600 lbs (21.8 tons). See Tables A-1 and A-2 in Appendix A for additional data.

The existing steam-driven compressor was mounted on a steel frame/platform about 18 ft above concrete footers. To prevent extended process downtime, it was necessary to have the electric motor and gear drive mounted at the same level. This posed some potential dynamic problems due to the large increase in mass. Start-up, shutdown, coast down and steady state operation had to be investigated to determine if any resonant or near resonant conditions existed between the various operating speeds and the support structure. We basically did not want any major structural natural frequency (mode) near the operating speeds of the system. We would have preferred to have the major structural natural frequencies above the highest operating speed of any component in the system; i.e., the motor, gear drive and compressor.

It is important to realize that this was a rush analysis. In fact the drawings were being revised and the replacement support structure was under fabrication during the final stages of the analysis.

Discussion of the Model

Two basic models were developed. Model A consisted of the support frame, motor, increaser, compressor and the piping. The second model, B, consisted of all of model A except the inlet and outlet piping. These basic models are shown in Figures 1 thru 5 and the Appendix.

Figure 1: Basic Model With Piping (Model A)

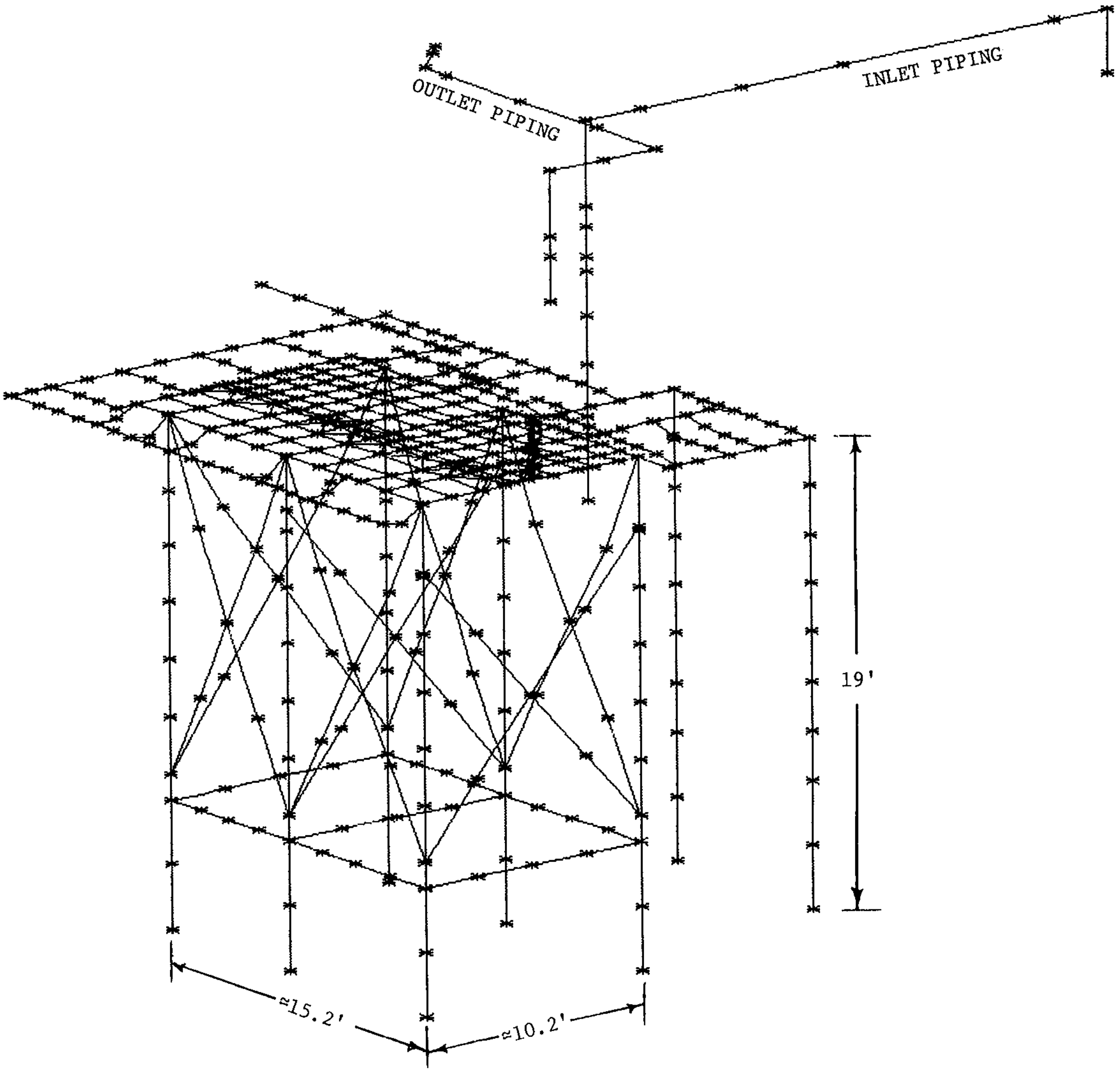


Figure 2: Basic Model Without Piping (Models B and C)

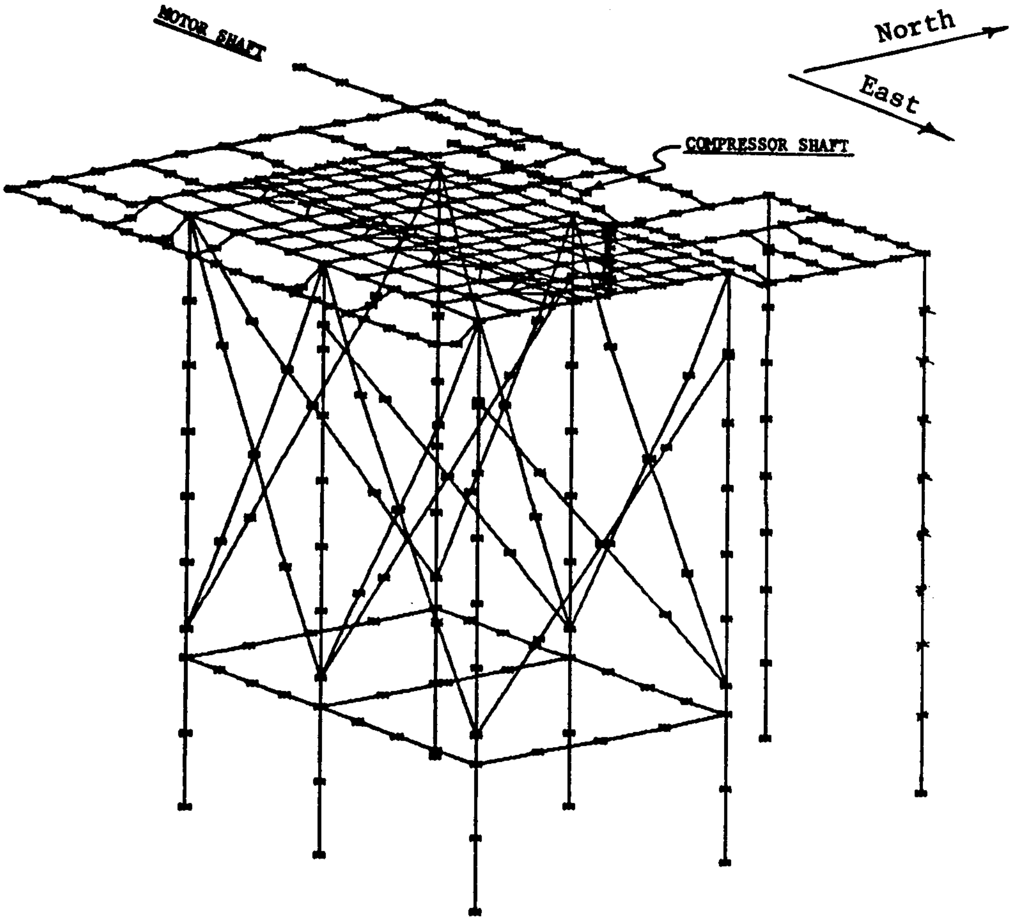


Figure 3: Concrete Portion of the Support Structure

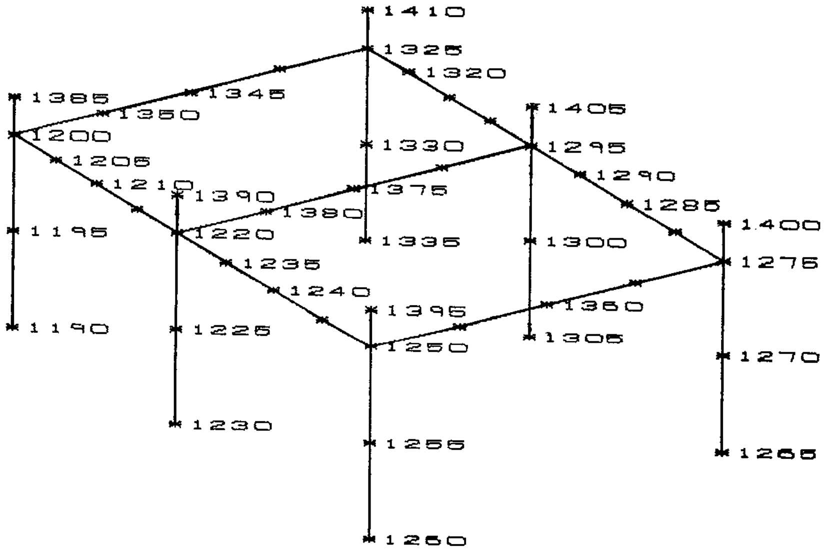


Figure 4: Special View of the Sole Plate, Piping and Shafting

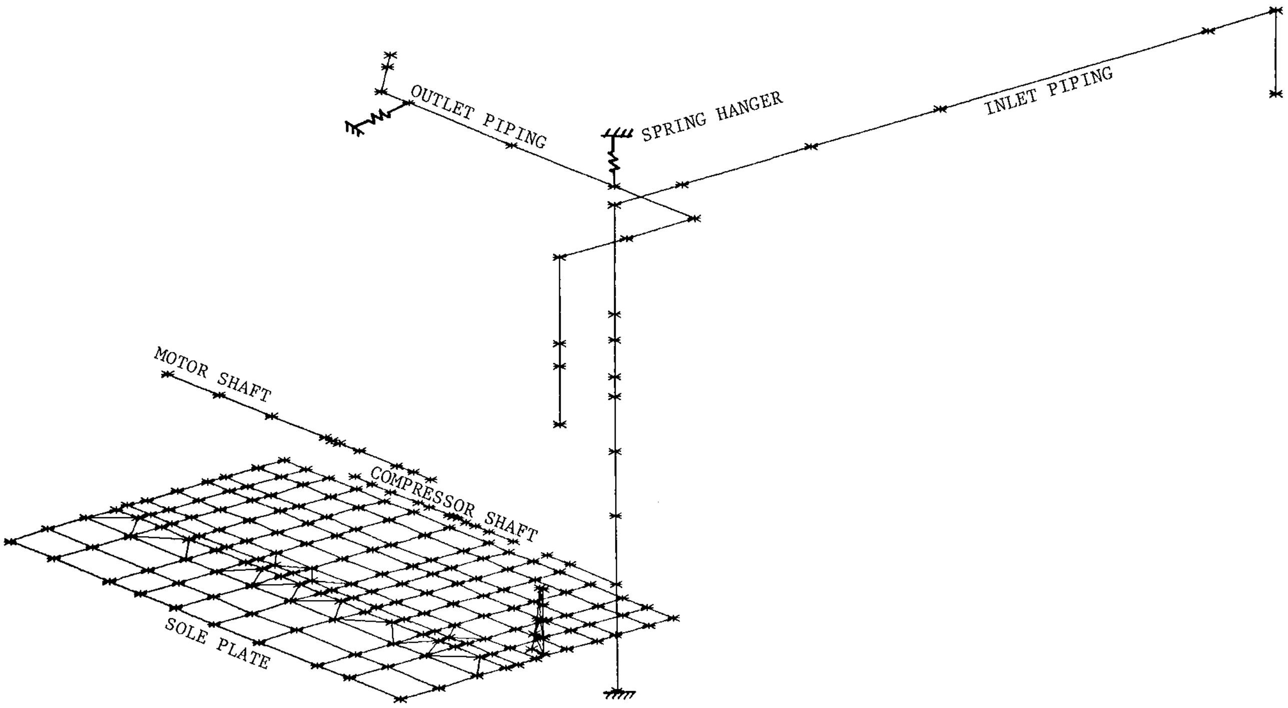
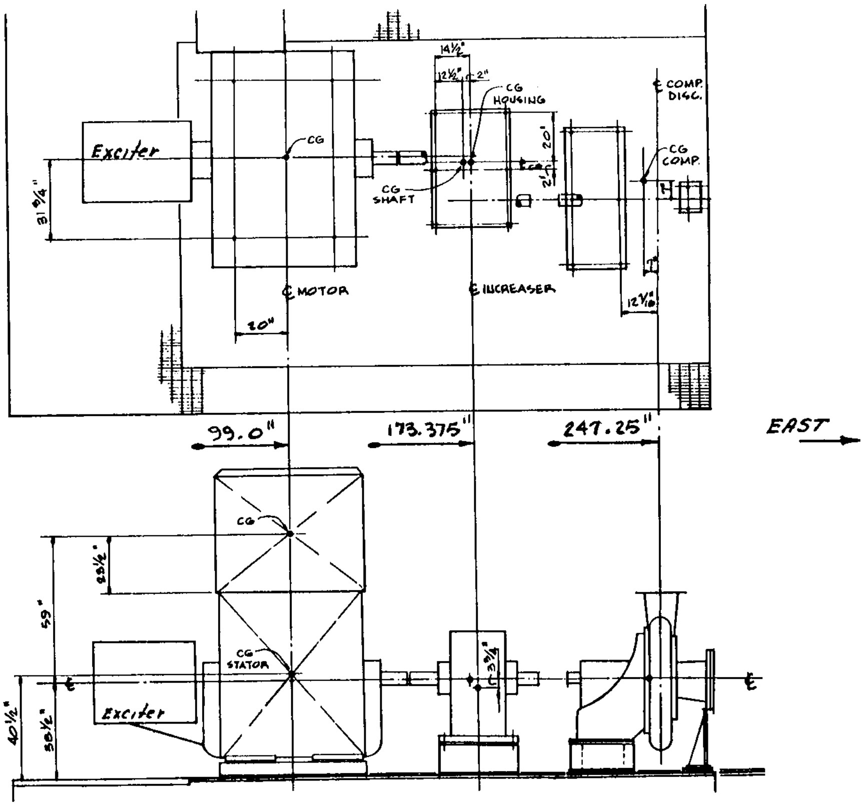


Figure 5: Basic Layout of the Motor, Increaser, Compressor and Shafting



The number of grid points and primary elements used in each model are shown in Table I.

Table I: Grid Point and Element Summary Table

Model ID	CQUAD2/CTRIA2/CBAR	Grid Points
A	865	468
B	838	440

Both models also contained CONM2 elements, CELAS2 elements and a large number of MPC equations.

Static Analysis

The structure was statically analyzed both to determine its adequacy and to uncover any problems with the model. The static analysis consisted of nine subcases as listed below.

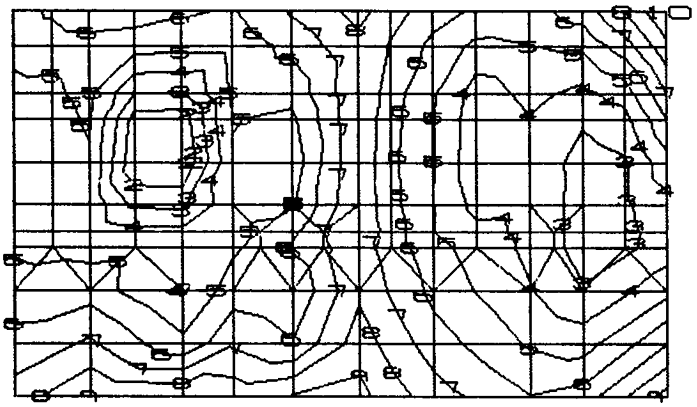
Table II: Static Loads Used in Analyses of Models A and B

Load SID	Load Description	Magnitude (lbf)	Applicable Subcase
1	Gravity		1
2	Gravity plus maximum motor torque		2
3	Maximum motor torque	10,500	3
4	Maximum torque on motor and increaser	10,500 18,800	4
5	Maximum torque on motor, increaser and compressor	2,950 10,500 18,800	5
6	Pull out torque on motor and increaser	1,570 2,810	6
7	Maximum motor torque reversed	-10,500	7
8	Maximum torque on motor and increaser reversed	-10,500 -18,800	8
9	Compressor freeze	2,950 18,800	9

Results from the Static Analysis

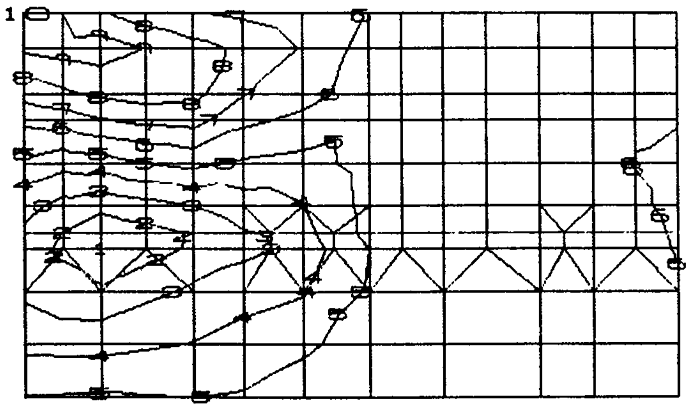
The static analysis did not reveal any major problems. The worst situation by far involved the deflection of the structure due to gravity (dead weight). Even in this situation the deflections were not excessive. Some typical deflection contour plots of the sole plate are shown in Figures 6 and 7.

Figure 6: Sole Plate Displacement Contour Plot for Gravity Loading (δ_Z)



SYMBOL	Z-Displacement
1	-7.818777E-03
2	-7.167690E-03
3	-6.516602E-03
4	-5.865514E-03
5	-5.214427E-03
6	-4.563339E-03
7	-3.912251E-03
8	-3.261166E-03
9	-2.610080E-03
10	-1.959000E-03

Figure 7: Sole Plate Displacement Contour Plots for Subcase 3 (Maximum Motor Torque)



SYMBOL	Z-Displacement
1	-3.331339E-04
2	-2.645201E-04
3	-1.959065E-04
4	-1.272928E-04
5	-5.867924E-05
6	9.934360E-06
7	7.854796E-05
8	1.471616E-04
9	2.157752E-04
10	2.843887E-04

The only item of some concern was the non-symmetrical distribution of the reactions at the footers. Such a non-symmetric load distribution could result in some unusual dynamic responses and mode shapes.

An unexpected situation was encountered in the shafting under the action of only gravity loading. Bending stress levels of 3,434 psi and 2,740 psi were predicted in the compressor shaft. However, these were fictitious stresses since they were a result of differential deflections that would be removed by proper shimming of the motor, increaser, and compressor bases. Thus, for all intents and purposes, the stress levels in the shafts under gravity loading would be zero.

Dynamic Analysis

The dynamic analysis only involved determination of the structural natural frequencies via Rigid Format 3. Again two basic models were used; one with the piping (model A) and one without the piping (model B). A special run of model B was used to investigate the maximum possible effect of the fill dirt around the concrete footer and first level cross beams as shown in Figure 3. This special analysis was designated as Model C.

The applicable forcing frequencies are listed in Table III.

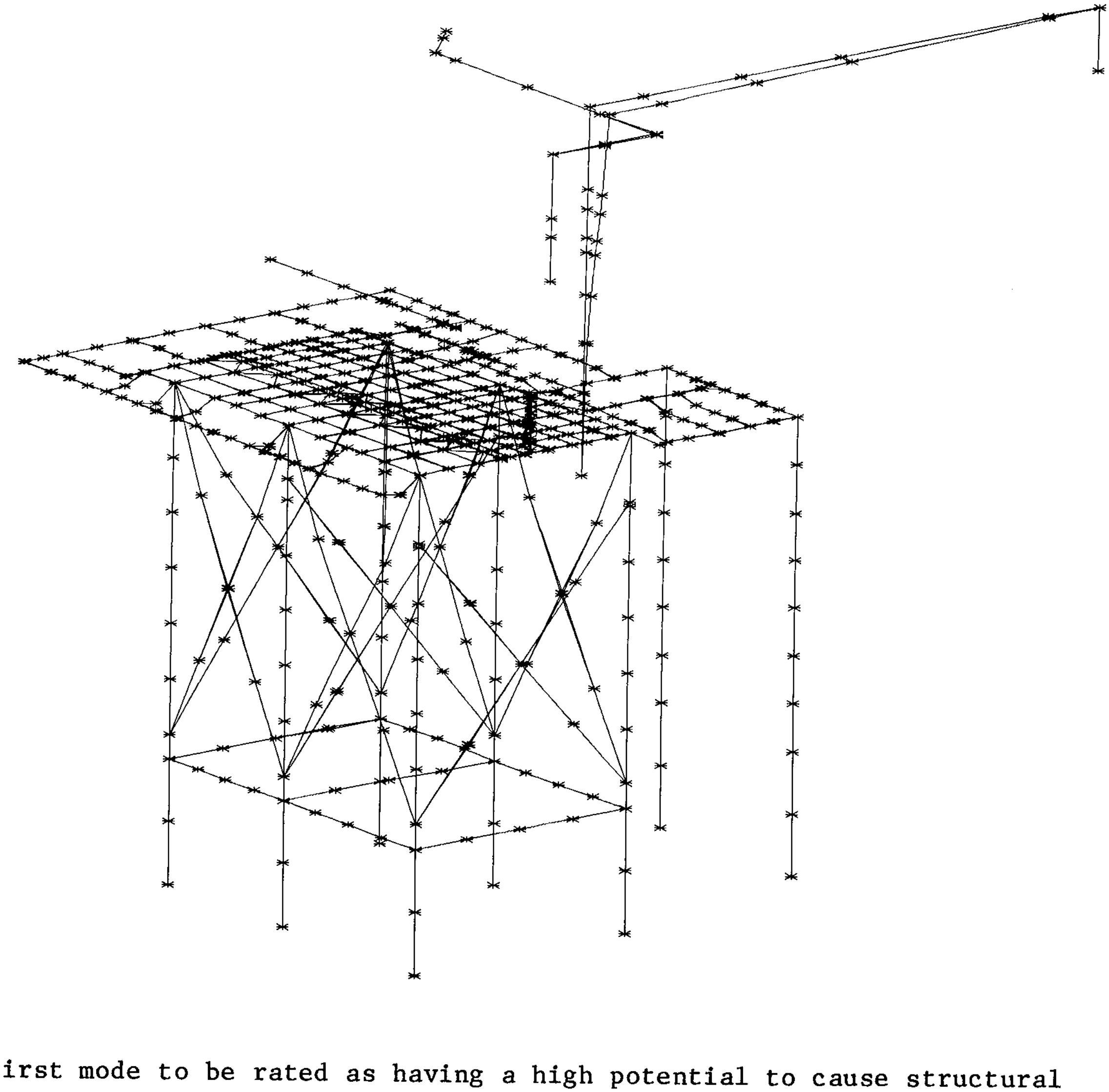
Table III: Major Forcing Frequencies

Source	RPM	CPS(Hz)	Comments
Electric Motor	0-1200	0-20	2500 HP, Synchronous Motor
Gear Output & Compressor	0-5027	0-83.78	4.189:1 gear ratio
Line Frequency	7200	120	
Comp. Speed times Number of vanes	0-50,270	0-837.8	No. of vanes is 10, also called the cut-off frequency

Both the Inverse Power and FEER eigenvalue extraction routines were used. In reviewing the various modes; the modal frequency, the percentage of the structure participating in the mode and the location of the maximum modal displacement were used to evaluate the damage potential involved in exciting a given mode. In the tabular listing of the modal results, the column labeled "Mode Evaluation (Damage Potential)" is indicative of the probability of encountering support structure and/or equipment damage if the particular mode is excited in a resonant or near resonant condition. In the case of the support structure and piping system, damage is indicative of encountering dynamic plus static stress levels exceeding 90% of the yield strength of the material. Equipment damage would be characterized by excessive shaft bending, fatigue cracks developing in the housing of a component, bearing damage and/or the development of rotational interferences due to component deformations. An example of the later situation would involve the compressor blades rubbing the housing. The preceding discussion applies to the data in Tables IV through VIII. In the associated figures, an arrow (↝) indicates the area where damage would most likely occur if the particular mode was excited.

For model A, 80 eigenvalues were extracted. The modal results are summarized in Table IV. The lowest natural frequency at 7.24 cps involved a piping mode. As shown in Table IV, the next three modes were also piping modes. Surprisingly, there were no major structural modes below 20 cps. In fact, the next 21 modes (20 to 44 cps) only involved minor structural members such as the X-bracing, the grating supports and outlet piping. Thus none of the first 25 modes (7.24 thru 44 cps) were deemed to have a high potential for causing structural and/or equipment damage. Two of the piping modes were relatively close to the motor speed. However, the location of the piping relative to the motor would require excellent transmissibility and a rather large motor imbalance to excite either of these modes. If such excitation did occur, it would be relatively simple to supply damping or otherwise alter the pipe's natural frequency. A typical piping mode is shown in Figure 8.

Figure 8: <u>First Inlet Piping Mode (7.24 cps)</u>



The first mode to be rated as having a high potential to cause structural and/or equipment damage was mode 26 (44.37 cps). A mode having an even greater potential for causing damage is shown in Figure 9 (mode 29). This 47.46 cps mode is so classified because of the large modal displacement being experienced by all of the major support columns. Some sole plate and shaft motion is also present.

Figure 9: Mode 29 (47.46 cps): Major Mode Involving Most of the Structure Plus the Piping and Includes Some Shaft Bending (High Damage Potential)

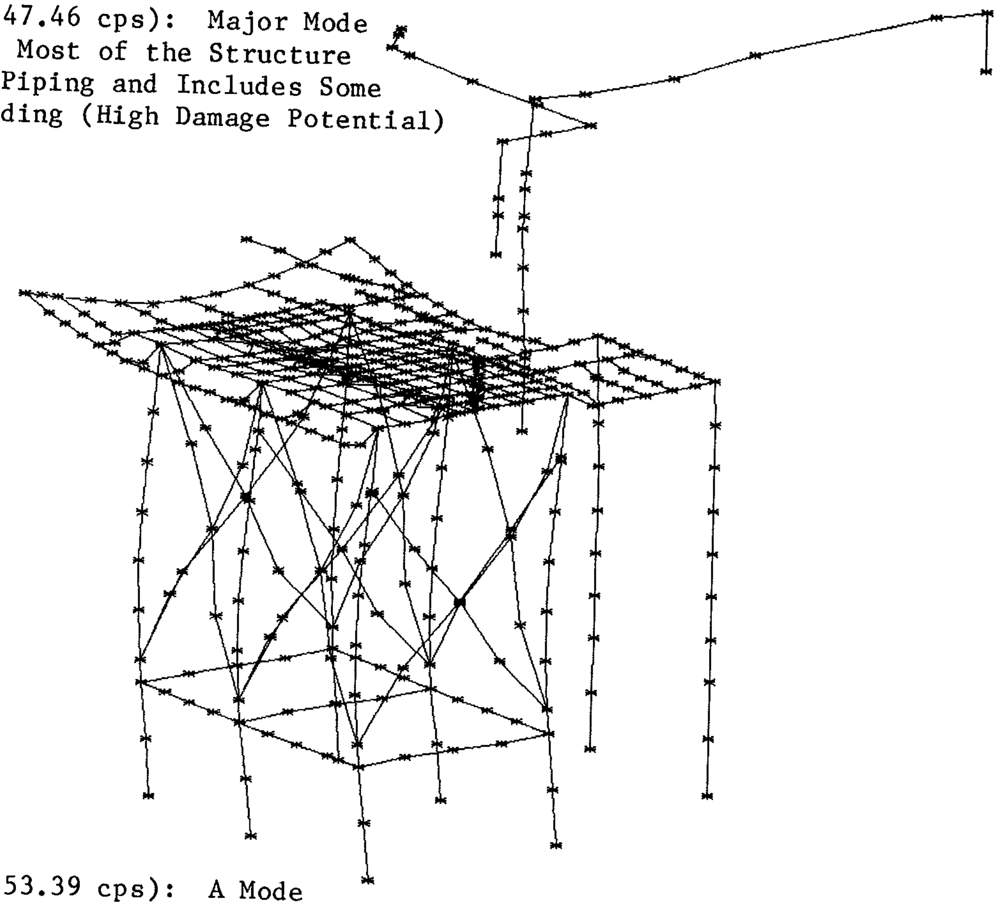
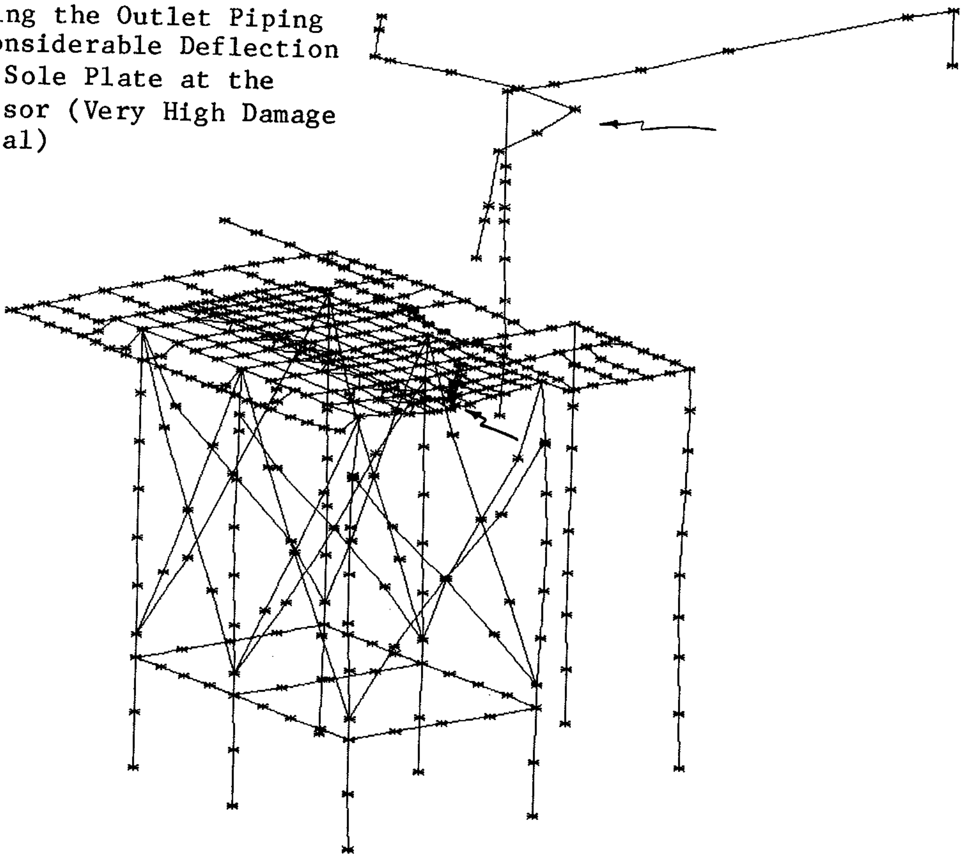


Figure 10: Mode 33 (53.39 cps): A Mode Involving the Outlet Piping With Considerable Deflection of the Sole Plate at the Compressor (Very High Damage Potential)



Mode 33 as shown in Figure 10 also has a high potential to cause damage. As shown in the deformed plot, large displacements are being encountered at the compressor which is also causing quite large outlet pipe deflections. This mode also results in severe deflection of the compressor shaft. Needless to say, if this mode was excited in a resonant or near resonant fashion, a compressor failure would be encountered. In addition the outlet pipe line would probably rupture.

As shown in Table IV, the next 23 modes (55.49 cps - 65.11 cps) were all deemed to have a minor damage potential. Mode number 57 with a frequency of 67.66 cps is classified as having a high damage potential. It is a major structural mode involving all major support columns, sole plate motion under the motor and some inlet pipe motion. The plot of this mode is shown in Figure 11. If this mode was excited, major support structure failures would be encountered.

Figure 11: Mode 57 (67.66 cps): A Major Structural Mode Involving All Major Columns, Sole Plate Motion Under the Motor and Some Inlet Pipe Motion (High Damage Potential)

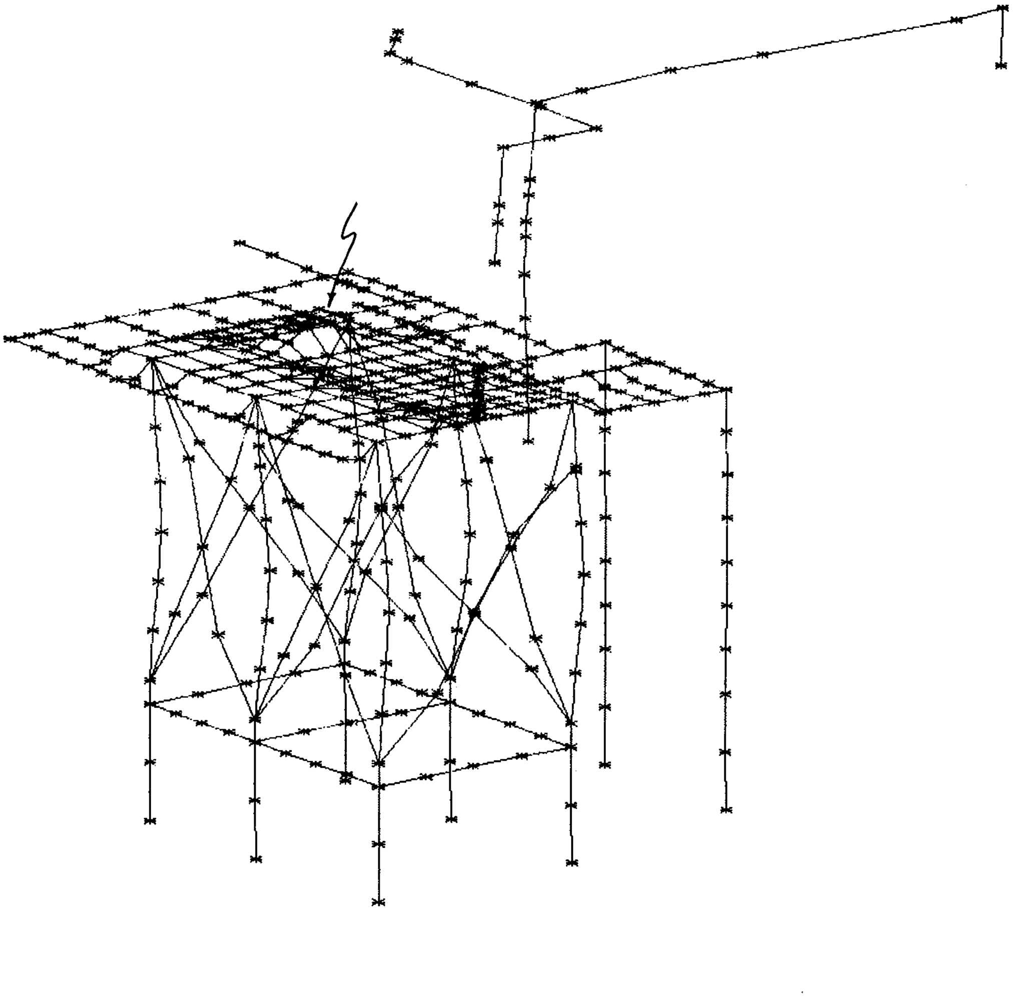


Table IV: Modal Results from Model A Which Includes the Piping (0-90 cps)

Mode Number	Natural Frequency (cps, Hz)	Description of Mode	Mode Evaluation* (Damage Potential)	Applicable Figure	Nearest Steady State Forcing Frequency
1	7.24	1st major inlet piping mode	Moderate	Figure 8	20.00
2	18.07	1st outlet piping mode	Moderate		20.00
3	18.44	2nd inlet piping mode	Moderate		20.00
4	19.73		Minor		20.00
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
25	43.99		Minor		20.00
26	44.37	A mode involving most of the support structure and piping	High		20.00
27	45.99	South west grating mode	Minor		20.00
28	46.45	West grating mode	Minor		20.00
29	47.46	Major mode involving most of structure plus piping. Some motor shaft bending.	High	Figure 9	83.78
30	47.86		Minor		83.78
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
32	51.82		Minor		83.78
33	53.39	Mode involving outlet piping with considerable deflection of sole plate at the compressor	Very High	Figure 10	83.78
34	55.49		Minor		83.78
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
56	65.11		Minor		83.78
57	67.66	A structural mode involving all major columns, sole plate motion under the motor and some inlet pipe motion	High	Figure 11	83.78
58	68.00	A mode involving sole plate motion directly under the motor	Moderate		83.78
59	68.26		Minor		83.78
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
76	81.47		Minor		83.78
77	82.83	A rather mild mode involving motion of some Columns as well as sole plate motion between the increaser and compressor. Normalized at point on north grating.	Minor +		83.78
78	84.07	A rather mild mode with some sole plate motion	Minor +		83.78
79	84.99	Minor support member mode	Minor		83.78
80	86.83	Minor support member mode	Minor		83.78

*Mode Evaluation (Damage Potential) is indicative of the probability of encountering support structure and/or equipment damage if the particular mode is excited in a resonant or near-resonant condition.

As indicated in Table IV, modes 77 and 78 are rather mild but they do involve some major portions of the structure. The peak motions in these cases involve the north grating. If these modes were excited for a long period of time, some problems could be encountered. Since their frequencies, 82.83 and 84.07 cps, are rather close to the operating speed of 83.78 cps such long time excitations are possible. This situation should be monitored during start-ups and shutdowns. If these modes had involved the motions of major structural members as in the case of modes 33 or 57, then a major structural change would have been required.

The next series of modes involve natural frequencies in the range of the line frequency (120 cps). They are also shown in Table V. All the modes below 120 cps were classified as minor. There is a mode just above 120 cps which has a high damage potential. This is mode 2A-12 with a frequency of 120.76 cps. It is shown in Figure 12. This major structural mode involves motion of the lateral concrete beams as well as the rest of the structure. Needless to say, this frequency is too close to the 120 cps forcing frequency. Fortunately, the fill dirt around the concrete beams and the concrete portions of the columns should serve to shift the frequency of this mode upward, out of range, since the lateral concrete beams would not be allowed to deflect as shown in Figure 12. This essentially eliminated this mode.

Modes 2A-14 (124.21 cps) and 2A-20 (128.72 cps) are rated as having moderate and high damage potentials. However, they are sufficiently above the 120 cps range to not be of any great concern.

Figure 12: Mode 2A-12 (120.76 cps): A Major Structural Mode Involving Columns, Grating and Portions of the Sole Plate (High Damage Potential)

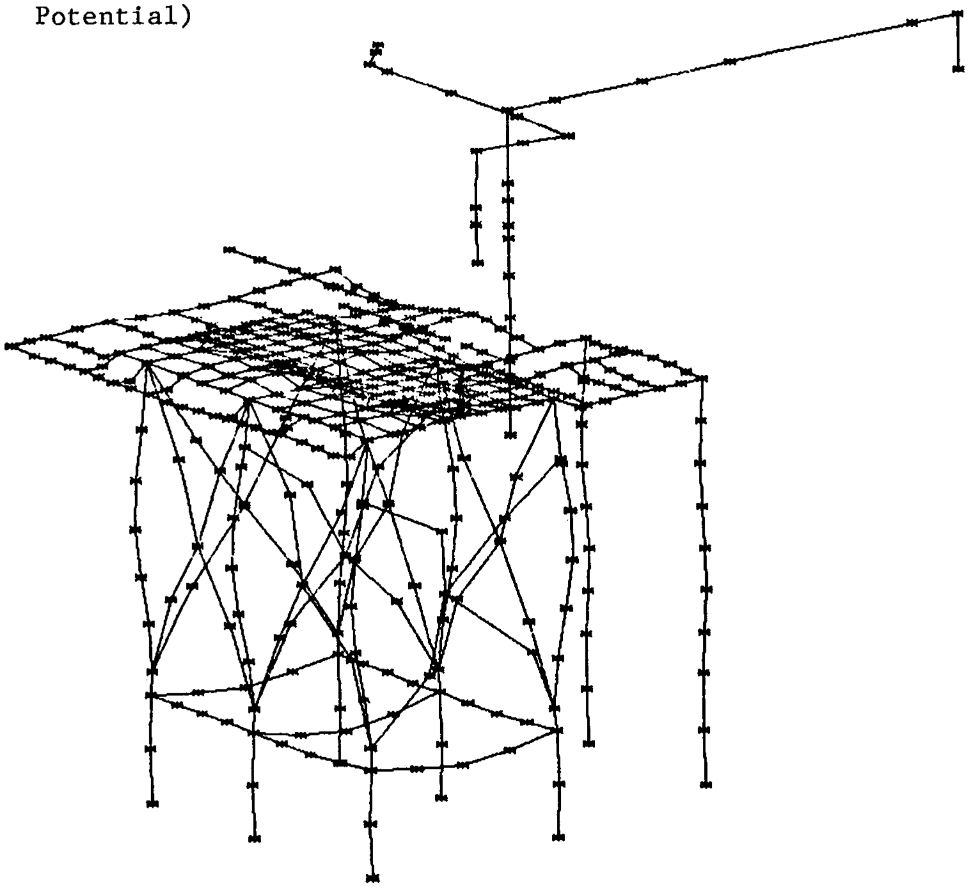


Table V: Modal Results from Model A Which Includes the Piping (110 to 130 cps)

Mode Number	Natural Frequency (cps, Hz)	Description of Mode	Mode Evaluation* (Damage Potential)	Applicable Figure	Nearest Steady State Forcing Frequency
2A-1	110.09		Minor		120
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
2A-11	120.39		Minor		120
2A-12	120.76	A major structrual mode involving columns, grating and portions of sole plate-	High	Figure 12	120
2A-13	122.65	A piping mode	Minor +		120
2A-14	124.21	A structural mode involving most columns and grating	Moderate +	- - - - - - - -	120
2A-15	124.91		Minor		120
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
2A-19	127.58		Minor		120
2A-20	128.72	A structural mode involving all major columns and horizontal concrete beams and sole plate motion between compressor and increaser.	High	- - - - - - - - -	120

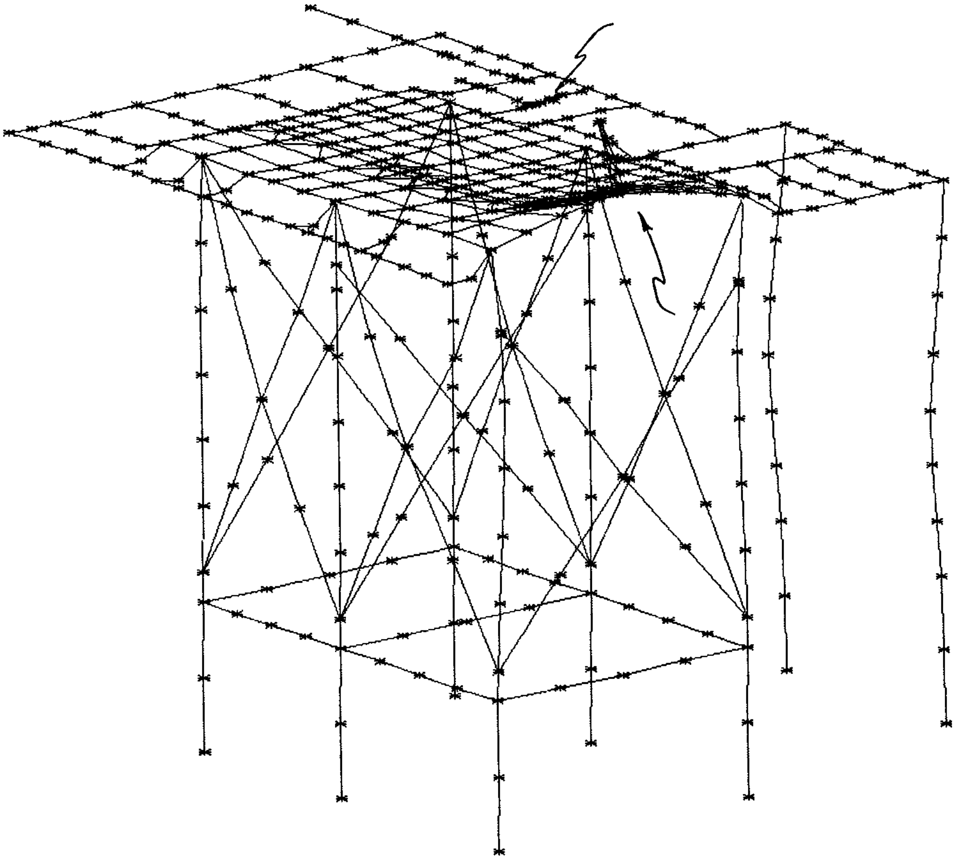
*Mode Evaluation (Damage Potential) is indicative of the probability of encountering support structure and/or equipment damage if the particular mode is excited in a resonant or near-resonant condition.

Discussion of Model B Analysis

The B model is identical to the A model except that the piping system was removed. Likewise, the boundary conditions at the bottom of the columns were the same as those of model A. The final results are presented in Table VI.

The modal results are quite similar to those of model A except that no piping modes are present. The first 15 modes are classified as minor. Mode 16 has a very high damage potential. It involves excessive motion of the compressor and the east portion of the sole plate as well as some column motion. As shown in Figure 13, considerable shaft deflection is also present for this 36.89 cps mode. Needless to say, excitation of this mode would lead to a rather dramatic failure.

Figure 13: Mode B-16 (36.89 csp): Major Compressor/East Sole Plate Mode With Major Shaft Deflections and Minor Movement of Some X-braces and Columns (Very High Damage Potential)



Two additional modes with high damage potentials occur at 47.65 and 49.94 cps. They are modes 22 and 23 and are shown in Figures 14 and 15. Mode 22 has the highest damage potential of the two since it involves motion of all major support columns.

Table VI: Modal Results from Model B (0-90 cps)

Mode Number	Natural Frequency (cps, Hz)	Description of Mode	Mode Evaluation* (Damage Potential)	Applicable Figure	Nearest Steady State Forcing Frequency
1	19.62		Minor		20
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
15	33.88		Minor		20
16	36.89	Major compressor/east sole plate mode with major shaft deflections	Very High	Figure 13	20
17	42.37		Minor		20
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
21	46.29		Minor		20
22	47.65	First major structural mode involving motion of complete structure. Sole plate motion at motor with considerable shaft motion from motor to gearbox.	High	Figure 14	20
23	49.94	West and north grating mode with considerable sole plate motion near the motor. Considerable motor shaft deflection.	High	Figure 15	83.78
24	52.02		Minor		83.78
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
45	68.52		Minor		83.78
46	71.14	2nd major structural mode involving all major columns	High	Figure 16	83.78
47	72.77	Mode of X-brace	Minor		83.78
48	75.01	Major structural mode involving motion of concrete portion of the columns and the X-braces	High	Figure 17	83.78
49	76.12	Mode of electrical panel support columns	Minor +		83.78
50	80.21	X-brace mode	Minor		83.78
51	81.34	A mode involving some columns and X-braces and shaft deflection	Moderate	Figure 18	83.78
52	82.49		Minor		83.78
|	|		|		|
|	|	Minor support member modes	|		|
|	|		|		|
63	90.05		Minor		83.78

*Mode Evaluation (Damage Potential) is indicative of the probability of encountering support structure and/or equipment damage if the particular mode is excited in a resonant or near-resonant condition.

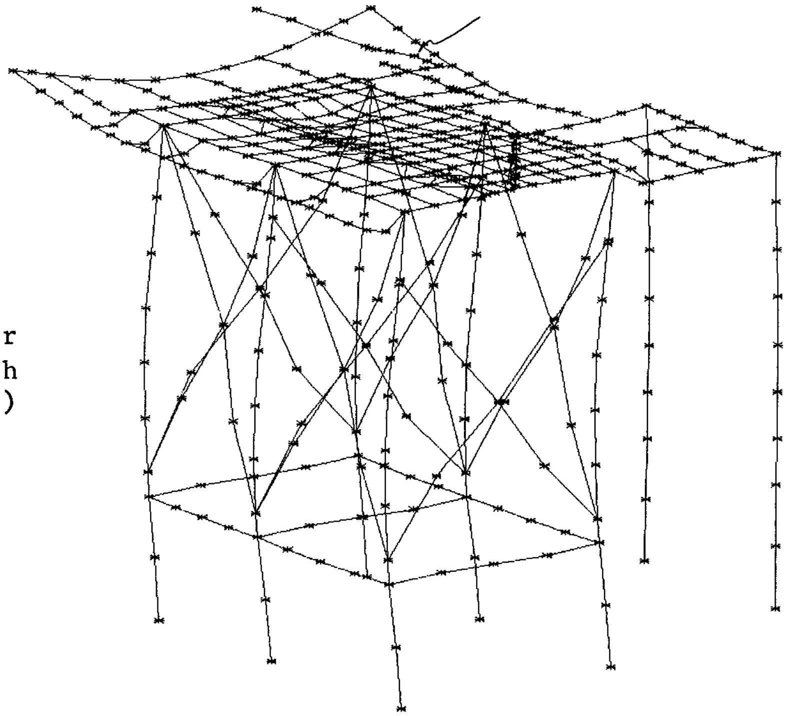
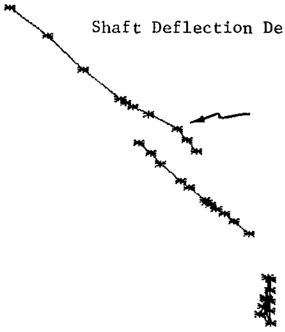
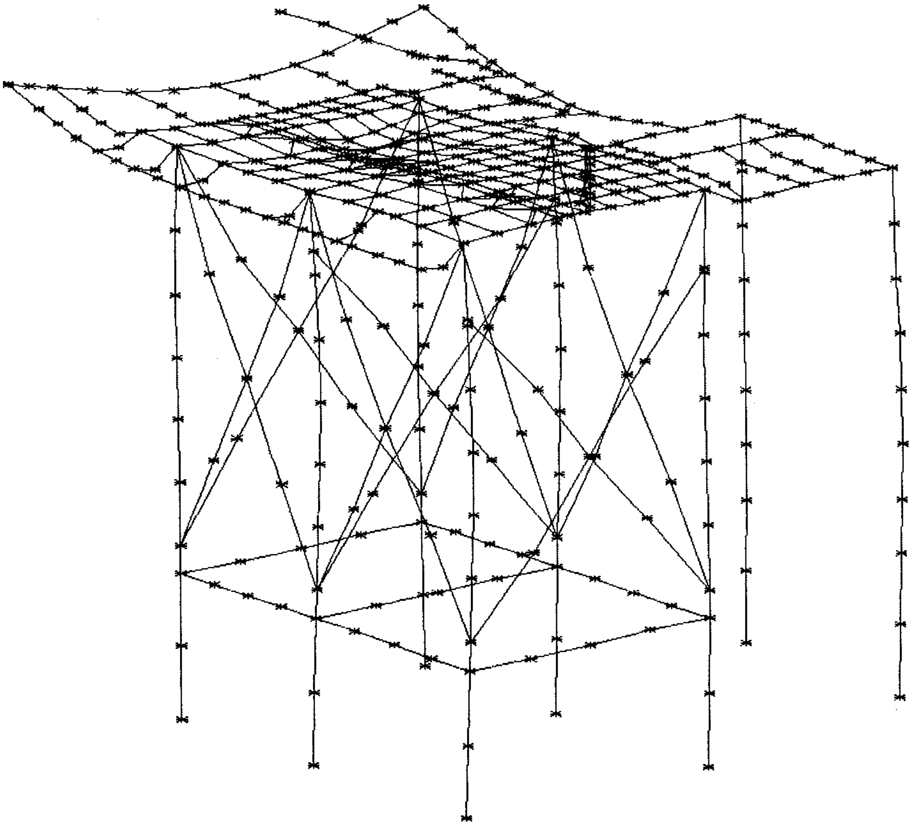


Figure 14: Mode B-22 (47.65 cps): First Major Structural Mode Involving Motion of the Complete Structure. Sole Plate Motion at Motor with Considerable Shaft Motion from Motor to Gear Box (High Damage Potential)

Figure 15: Mode B-23 (49.94 cps): West/North Grating Mode with Considerable Sole Plate Motion Near the Motor and Some Motor Shaft Delfection (Moderate to High Damage Potential)

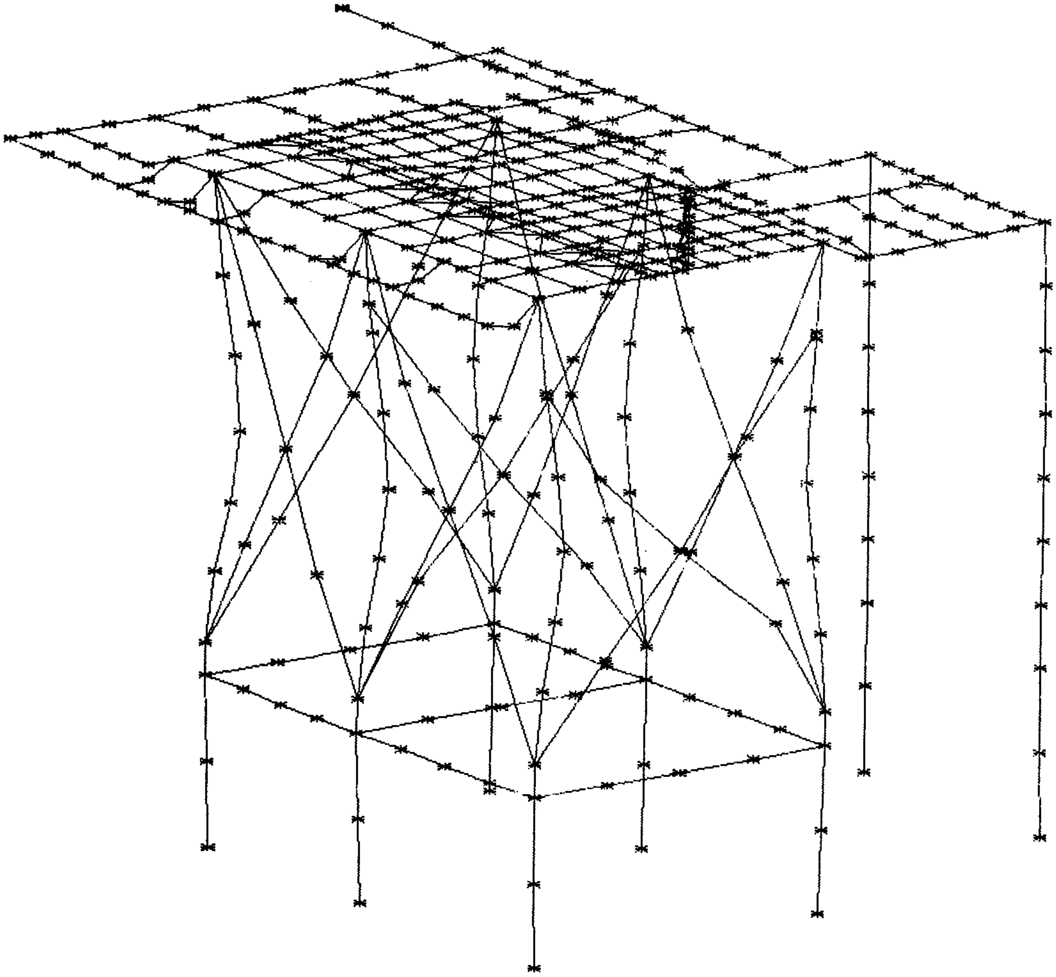


Shaft Deflection Detail



The second major support structure mode is number 46. This 71.14 cps mode involves large displacements of all major support columns. It is also a mode with a high damage potential. See Figure 16.

Figure 16: Mode B-46 (71.14 cps): Second Major Structural Mode Involving All Major Columns (High Damage Potential)



Mode 48 also has a high damage potential. It is the first mode to involve motion of the concrete portion of the structure. The X-brace motion of this 75.01 cps mode as shown in Figure 17 is quite severe. Mode 51 could also have a relatively high damage potential. Shaft deflection associated with mode 51 is shown in Figure 18.

Figure 17: Mode B-48 (75.01): Second Major Structural Mode Involving Motion of the Concrete Portion of All Columns (Quite High Damage Potential)

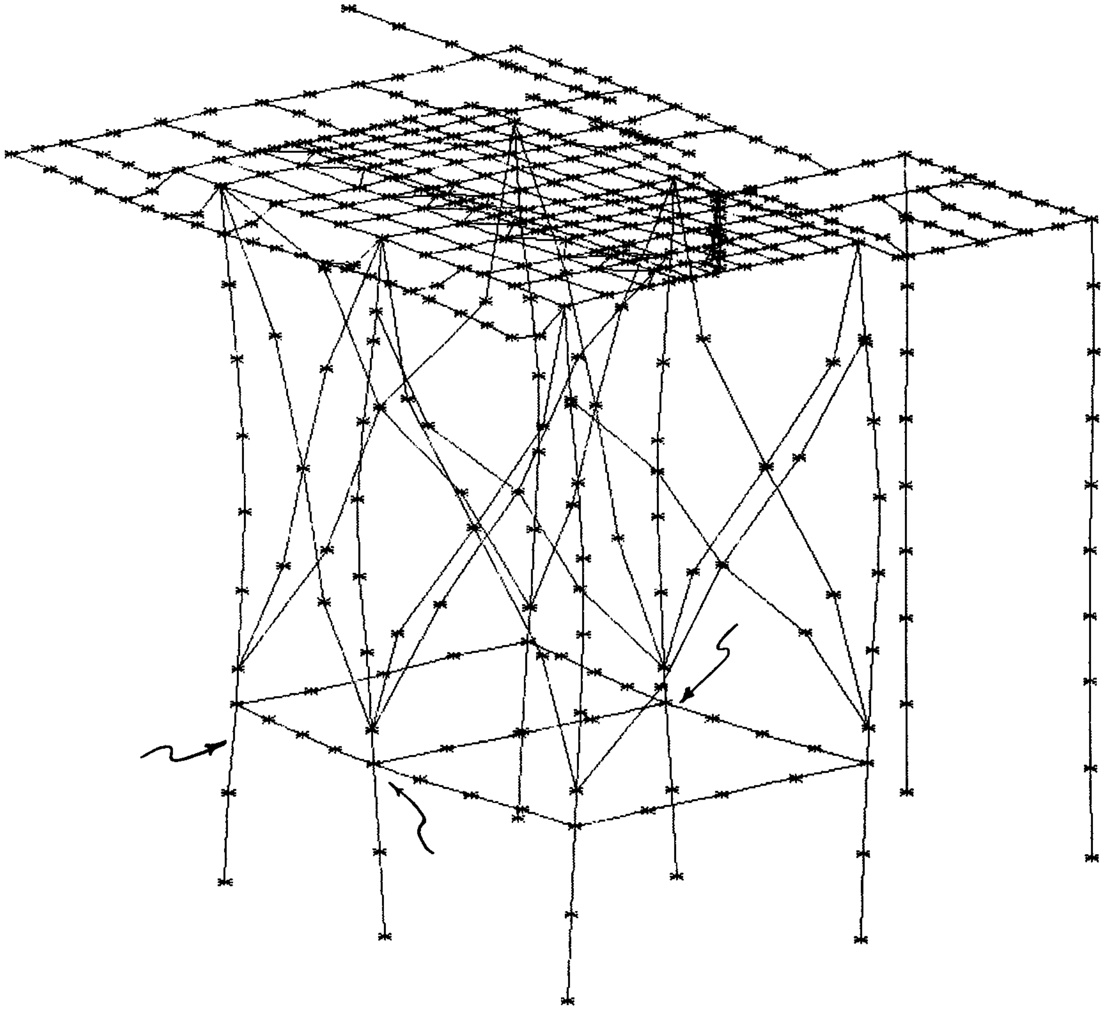
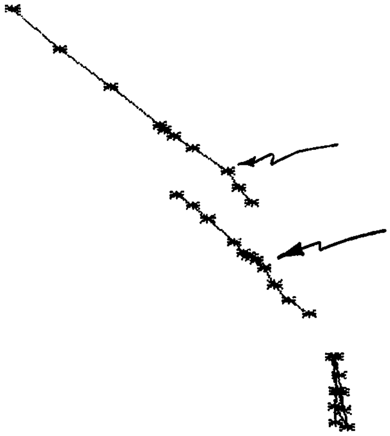


Figure 18: Mode B-51 (81.34 cps): Shaft Deflection Associated With Mode B-51



The next group of modes, as shown in Table VII, are in the 120 cps range. Only one mode (number 2-6) in this region has a high damage potential. This 122.2 cps mode is shown in Figure 19. This mode has a high damage potential because it involves motion of nearly the complete structure.

Figure 19: Mode 2-6 (122.2 cps): A Major Structural Mode Involving Nearly All of the Structure (High Damage Potential)

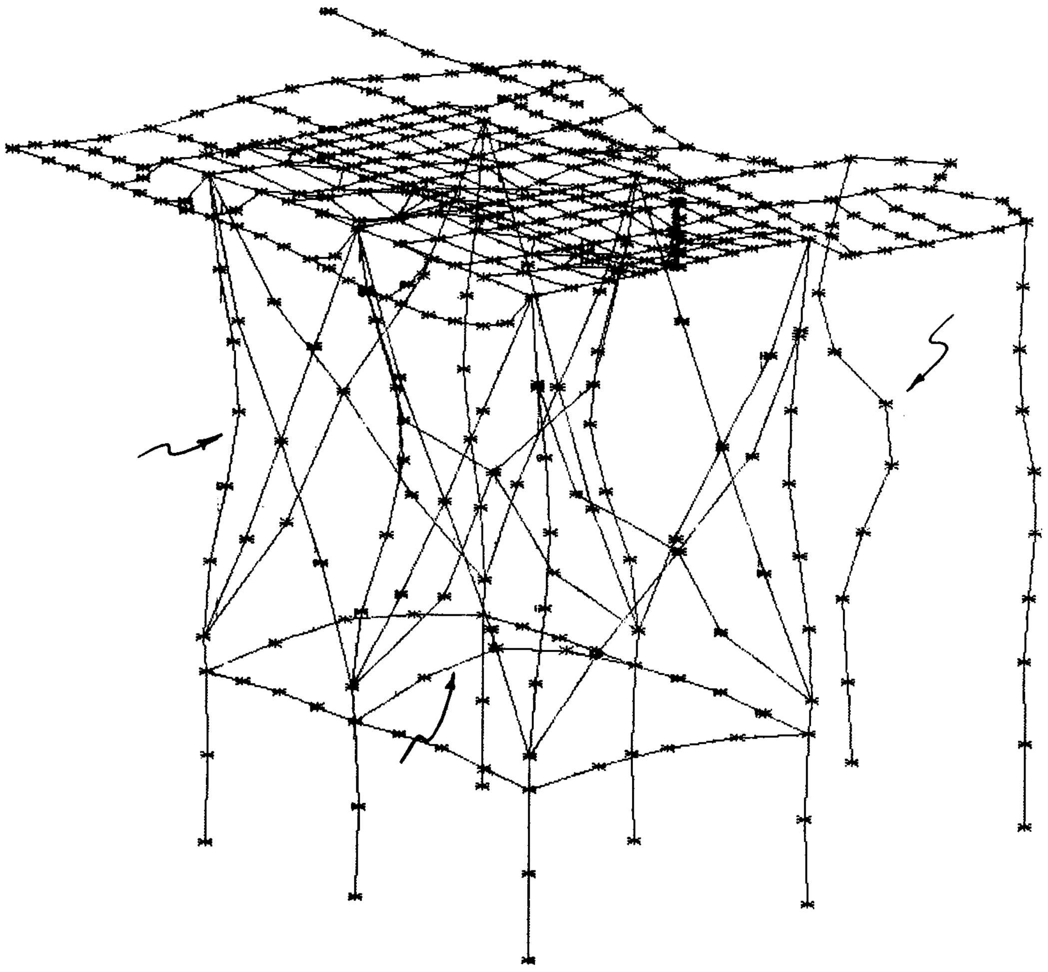


Table VII: Modal Results from Model B in the 114 to 125 cps and 820 to 850 cps Frequency Ranges

Mode Number	Natural Frequency (cps, Hz)	Description of Mode	Mode Evaluation* (Damage Potential)	Applicable Figure	Nearest Steady State Forcing Frequency
2-1	114.8		Minor		120
|	|	Minor support member modes	|		|
2-5	120.47		Minor		120
2-6	122.20	A major structural mode involving nearly all of the structure- - - - - - - - - - - - - - - -	Very High	- - - Figure 19 - -	120
3-1	820.86		Minor		837.8
|	|	Minor support member modes	|		|
3-3	825.92		Minor		837.8
3-4	831.16	Mode involving most of the structure with quite severe deformation of the increaser shaft- -	High - - - - - -	Figure 20 - -	837.8
3-5	838.21		Minor to Moderate		837.8
|	|	Minor support member modes	|		|
3-10	850.85		Minor to Moderate		837.8

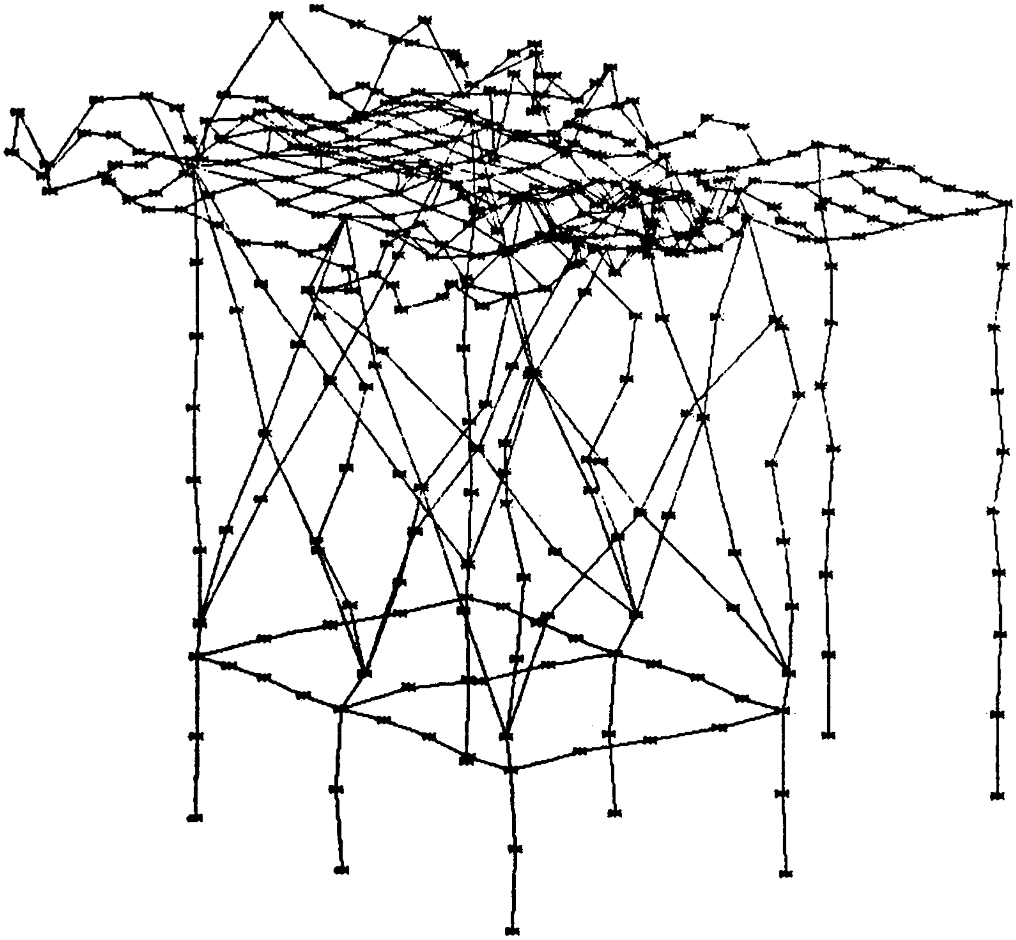
Table VIII: Modal Results from Model C (Piping Excluded, Fill Dirt Boundary Conditions)

Mode Number	Natural Frequency (cps, Hz)	Description of Mode	Mode Evaluation* (Damage Potential)	Applicable Figure	Nearest Steady State Forcing Frequency
C-1	19.96		Minor		20
|	|	Minor support member modes	|		|
C-9	24.51		Minor		20
C-37	64.79	Mode involving motion of all columns as well as electrical panel support structure - - - - -	Moderate +	- - - - - - - - -	83.78
C-38	65.82		Minor		83.78
|	|	Minor support member modes	|		|
C-46	72.76		Minor		83.78
C-47	80.89	Major structural mode with deformation at compressor, severe shaft bending and sole plate motion between motor and increaser. Also includes column and X-brace motion.	Very High	Figure 21	83.78
2C-5	112.4		Minor		120
|	|	Minor support member modes	|		|
2C-10	120.5		Minor		120
2C-11	126.3	Mode involving grating, electrical support panel, sole plate, and some columns - - - - - - -	Moderate - - - - - - - - - - -		120
2C-12	127.5	Mainly a grating mode with some sole plate motion behind compressor as well as some electrical support panel motion	Moderate		120

*Mode Evaluation (Damage Potential) is indicative of the probability of encountering support structure and/or equipment damage if the particular mode is excited in a resonant or near-resonant condition.

Another computer run was made to investigate the high frequency region around 837.8 cps. See Table VII. Of the ten modes obtained, five were rated as having moderate to high damage potentials. This is a rather large percentage. The mode with the highest damage potential was number 3-4 which has a frequency of 831.16 cps. It is shown in Figure 20. This mode, along with modes 3-1, 3-7, 3-8, 3-9, and 3-10, show considerable shaft deformation. This indicates that shaft bending modes may be prevalent in this frequency range. A detailed study might be desirable if unusual bearing or seal wear is encountered. Such a study would have to include elastic simulation of the bearings and their supports for the results to be meaningful.

Figure 20: Mode 3-4 (831.16 cps): A Mode Involving Most of the Structure with Quite Severe Increasor Shaft Deformation (High Damage Potential)



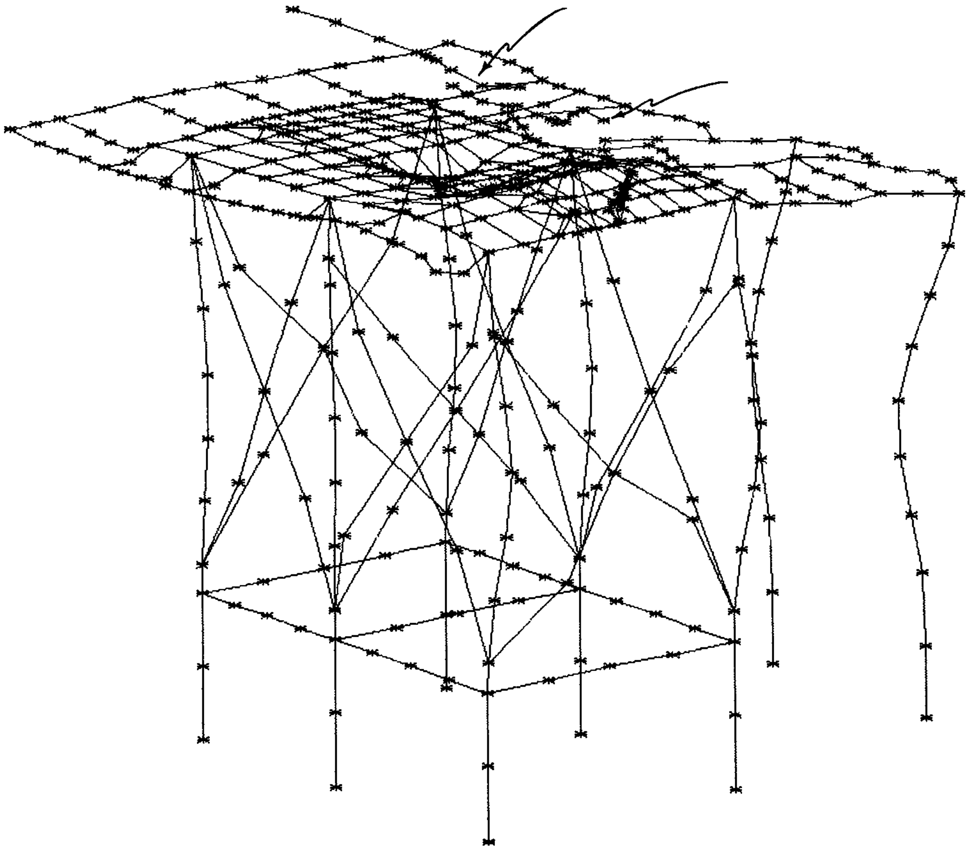
Discussion of Model C Analysis

Model C is identical to model B except that the boundary conditions are different. Various degrees of freedom were constrained to better simulate the effect of the fill dirt. The modal results are presented in Table VIII.

The first computer run covered the 19 to 30 cps range. All modes in this frequency range were classified as minor. They were generally X-brace or grating modes and for the most part were identical to those from the B model in the same frequency range.

The second run was used to investigate the frequency shift of several moderate to high damage potential modes that might be encountered due to the fill dirt. A frequency shift was expected for any modes from models A and B that had involved some motion of the concrete portion of the structure. Most of the modes in this region were again classified minor to moderate. However, two modes, C-37 and C-47, were classified as having "moderate to very high damage potentials." The C-37 mode (64.79 cps) is so classified due to the large response of several of the major support columns. Mode C-47 which is shown in Figure 21 does indeed have a very high damage potential. Excitation of this 80.89 cps mode could lead to a major failure. The deflections in the vincinity of the compressor and the severe shaft deflections are proof of the consequences of exciting this mode.

Figure 21: Mode C-47 (80.89 cps): A Major Structural Mode Involving Deflections at the Compressor, Severe Shaft Bending and Column and X-brace Motion (Very High Damage Potential)



The next run covered the 110 to 132 cps range. As shown in Table VIII, no high damage potential modes were found in this region. Modes 2C-11 and 2C-12 were classified as moderate. Mode 2C-7 is a plate bending mode involving a section of the sole plate between the motor and increaser.

Modal Comparisons

Because various conditions such as including or excluding the piping, changes in support boundary conditions, etc., can result in a sizeable shift in the natural frequency of various modes, and in some cases eliminate certain modes, it was necessary to compare the modes from the different models and assess any potential problems associated with different boundary conditions.

If you exclude the pure piping modes, then from 0 to 35 cps you can generally find a good correspondence between the A-i, B-i, and C-i modes. Some of these modes are not identical but in groups they are collectively similar to each other. The general conclusion that can be reached concerning the 0 to 35 cps region is that including the piping slightly decreased the natural frequency of equivalent modes while the fill dirt boundary conditions of model C-i generally resulted in a slight increase in the natural frequencies. This is not unexpected since most of the modes in this region are minor or do not pertain to a portion of the structure that would be significantly affected by the piping or the boundary conditions at the base.

However, mode B-16, which was classified as having a very high damage potential, is not even present in the A-i modes. From this, one can conclude that any modes in models B-i and C-i that involve compressor motion will either be eliminated or have a substantially different frequency than the corresponding modes of model A due to the piping.

Mode number A-29, which has a very high damage potential, has essentially the same frequency as the corresponding B mode number 22. This is because this mode does not involve appreciable motion in the compressor/pipe region. The same is true for modes 31 and 23 of models A and B respectively.

High damage potential mode A-33 does not appear to have a B counterpart. However, in some ways it is similar to mode 16 of model B. This mode could be the result of adding the piping to B mode 16.

In the 65 to 68 cps range, the fill dirt constraint of model C served to eliminate the high damage potential modes 57 and 46 of models A and B. They may have been shifted above the 90 cps level.

Another moderate to high damage potential mode occurs at 70.33 cps for model A. Removal of the piping resulted in this mode's frequency moving upward about 5 cps. (Mode 48 of model B). Another 5 cps increase in this mode occurred with the fill dirt constraint (Mode C-47). In both of these cases the mode's damage potential increased. In this case inclusion of the piping prevents the development of a mode with a very high damage potential at a frequency very close to the steady state operating speed.

No other modes up to the 87 cps level appear to have a very high damage potential. The next region of modal comparison is from 110 to 132 cps. Only one really high damage potential mode exists in this region. It is 2A-12, 2-6, and 2C-11 for models A, B, and C respectively. This mode for model A is far too close to the forcing frequency of 120 cps. Fortunately, the fill dirt constraint would serve to increase the frequency of mode 2A-12 to a value of about 124 cps as indicated by the frequency of mode 2C-11 of model C. This value is reduced from that of mode 2C-11 because the addition of the piping should reduce this frequency by about 2 cps; i.e., from 126.3 to about 124 cps. Removal of the piping in this frequency range tended to produce a 2 cps frequency increase. The other high damage potential mode, 2A-20, is above the forcing frequency of 120 cps and thus should not be a problem.

Discussion of Steady State Operation

The modes of model A are the most representative of the actual structure. But some of these modes need to have their frequency adjusted to account for the fill dirt restraint. In any event, there does not appear to be a serious problem at steady state operation provided the piping is attached. Only in the 120 cps range is their some question about the response. This situation should be monitored during the initial year of operation.

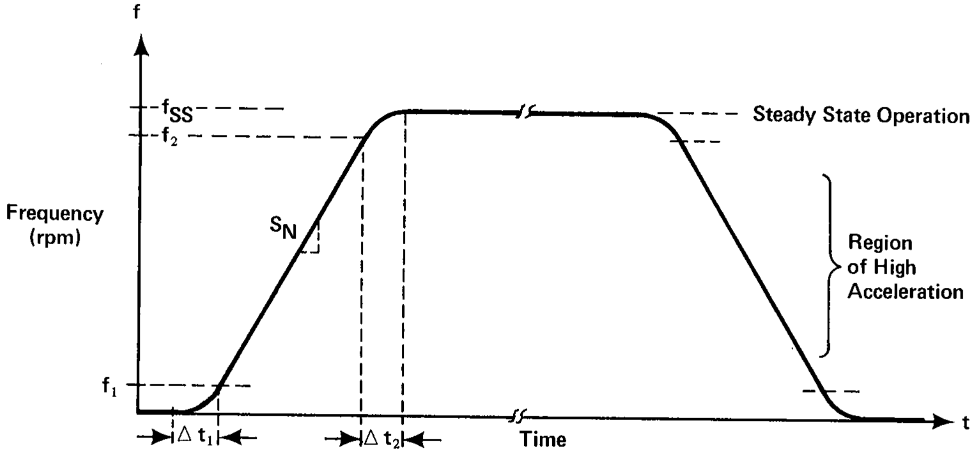
However, if the system was run without the piping attached, the results of models B and C would be applicable. In fact, the results from these models indicate that the system should not be operated without the piping attached. An imbalance in this situation could readily excite several high damage potential modes.

In the region of the cut-off frequency (837.8 cps), there does not appear to be an immediate problem. However, there are several modes involving shaft bending in this region that could result in increased bearing and/or seal wear if they were excited. A more detailed analysis of the shafting would be required to determine if a significant problem exists. If unusual bearing or seal problems are encountered, such a study may be warranted.

Discussion of Transient Response (Start-up, Shutdown, Coast Down)

In this case, some reasonable conclusions relative to the transient response of the support structure can be inferred from the modal results. The first step in such a discussion involves establishing the frequency range of the various forcing functions. They vary from 0 to 20 cps for the motor, 0 to 83.7 cps for the compressor/increaser, 0 to 837.8 cps for the compressor (cut-off frequency) and a 120 cps line frequency. Generally, structural natural frequencies at the upper or lower region of these frequency ranges cause problems. To better understand the situation, consider a typical frequency time curve associated with start-up.

Figure 22: Typical Start-Up Curve



Any natural frequencies that exist below f_1 or in the region from f_2 to f_{SS} can cause serious transient oscillations because the forcing function will stay at or near that structural natural frequency for a relatively long period of time. In the high acceleration region from f_1 to f_2, the forcing frequency is usually going through the natural frequencies fast enough to not produce a noticeable resonant response.

Occasionally you can encounter an easily excitable mode which will tend to track the forcing frequency and thus get a much larger response than anticipated. In this case the natural frequency tends to change with the forcing frequency for a certain range before they become uncoupled. Some classical cases of this have been encountered with large stacks (chimneys) when excited by vortex shedding. In this situation, the two frequencies actually augment each other.

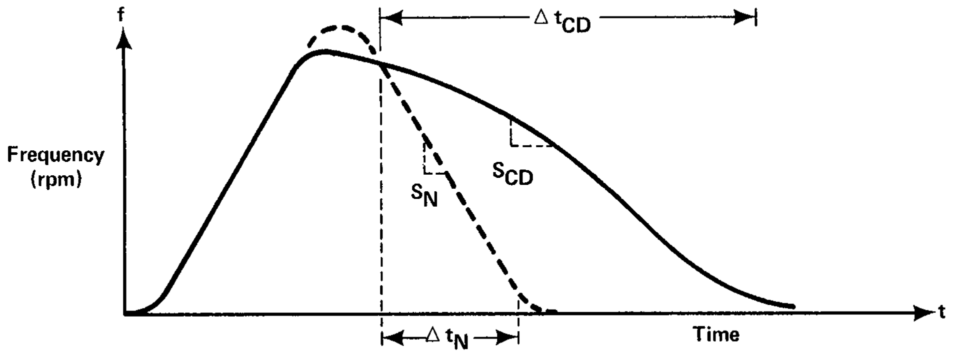
In an effort to minimize the possibility of large transient oscillations during normal start-ups and shutdowns, special start-up and shutdown procedures should be employed to maximize the acceleration and deceleration (rate of change of the rotational frequency) of the system. The major aspects of this procedure would involve:

1. Starting the system with the compressor unloaded until the synchronous speed is attained, then proceed to gradually load the compressor.

2. Shutting down the system with the compressor completely loaded until zero rpm is reached.

The situation that involves the greatest probability of exciting the high damage potential modes involves a coast down. In this situation, the slope of the rpm vs time curve would decrease dramatically. This is shown in Figure 23.

Figure 23: Possible Coast Down Curve



There are two or three conditions that could make a coast down much more serious. One would involve a structural failure which would produce a large imbalance (eccentric load). The other would involve a coast down just before or just as the motor reaches synchronous speed, but before the compressor has been loaded. Of course, a structural failure (eccentric loads) along with this latter situation would have a high probability of damaging the unit and/or support structure. The amount of damage would depend on the magnitude of the eccentric load.

Conclusions

The results of this NASTRAN static and modal analysis indicate:

1. No major static problems.

2. No major resonant condition exists at steady state operation. However, two minor modes (77 and 78) are quite close to the compressor speed of 83.78 cps. The structure should be monitored during several start-ups and shutdowns to determine if these two minor modes are being excited. If it appears these two modes are being excited to some extent, some minor structural changes should be undertaken.

3. Normal start-up and shut-down does not appear to pose a problem provided procedures are employed to minimize both start-up and shutdown times. Only around 837.8 cps does it appear that there could be a vibration problem. To minimize this possibility, every effort should be made to balance the compressor and properly align all shafting.

4. A serious vibration problem could be encountered if a coast down occurs, especially if a compressor or gear train imbalance is also encountered during the coast down. A compressor failure such as losing a section of a vane could cause some rather dramatic oscillations.

5. Test operation of the system without the piping attached has a much greater probability causing structural and/or equipment damage than encountered during normal operation, i.e., with the piping attached.

6. The absence of any major structural natural frequencies below 20 cps makes this particular support structure ideal for use of an isolation pad/spring system since such systems transmit low frequencies, usually below 10 cps, but not the higher frequencies in the operating range.

7. Most of the modes were independent of the boundary conditions at the base. In other words, the fill dirt constraint affected only a few of the calculated modes. Only the modes that involved motion of the concrete portion of the columns were affected by the boundary conditions. This is basically due to the very high relative stiffness of the concrete beams and columns. The inclusion of the piping had a much more dramatic effect.

The following conclusions were reached relative to the modeling of such structures:

1. You should include the piping in such analyses; otherwise, the results will not be correct for numerous pertinent modes.

2. The Fast Eigen Value Extraction Routine (FEER) in NASTRAN gave results that were identical to those of the Inverse Power Method. This was somewhat surprising since this method is rated for speed, but is reportedly not quite as accurate as the Inverse Power Method. It extracted the eigenvalues 1.8 times as fast as the Inverse Power Method.

3. The availability of an excellent deformed and overlay plot capability as available in NASTRAN was indispensable in reviewing the mammoth amount of data generated by the program.

Closing Comment

After installation, before and after the piping connections were made, a dynamic test of the structure using strain gages and accelerometers was performed. The results verified the major modes established in the analyses and supported the conclusions. The system has now been operating over three years without any major problems. This includes several normal start-ups and shutdowns using the recommended procedure. During this period a coast down has not occurred.

APPENDIX A

Table A-1: Weight and CG of Structure

Model ID	Description	Total Weight (lbs)	Center of Gravity X	Center of Gravity Y	Center of Gravity Z
A	Total Structure Including Piping	139,971	178.7"	106.4"	210.5"
B	Total Structure Excluding Piping	111,700	159.0"	94.5"	170.0"
--	Piping System Only	28,271	------	------	------
--	Support Structure	68,110	161.1"	85.3"	107.0"

Table A-2: Typical Structural Member Sizes

Member Description	Size
Sole Plate	1/2" thick
Main Columns (6, steel)	W10 x 68
Electrical Panel Support Columns (6, steel)	W6 x 15
Reinforced Concrete Footers (6)	22" x 18"
Reinforced Concrete Footer Under Electrical Panel	12" x 12"
Horizontal Reinforced Concrete Beams	24" x 22", 24" x 18"
X-braces (12)	WT4 x 9
Main Sole Plate Support Beams	W16 x 67
Minor Support Beams Under Electrical Panel	C8 x 11.5, W8 x 24
Grating Supports	C10 x 15.3, W8 x 18, W14 x 22
Electrical Panel Support Beams	C8 x 11.5, W8 x 24

Figure A-1: Shafting and Piping Grid Point Layout

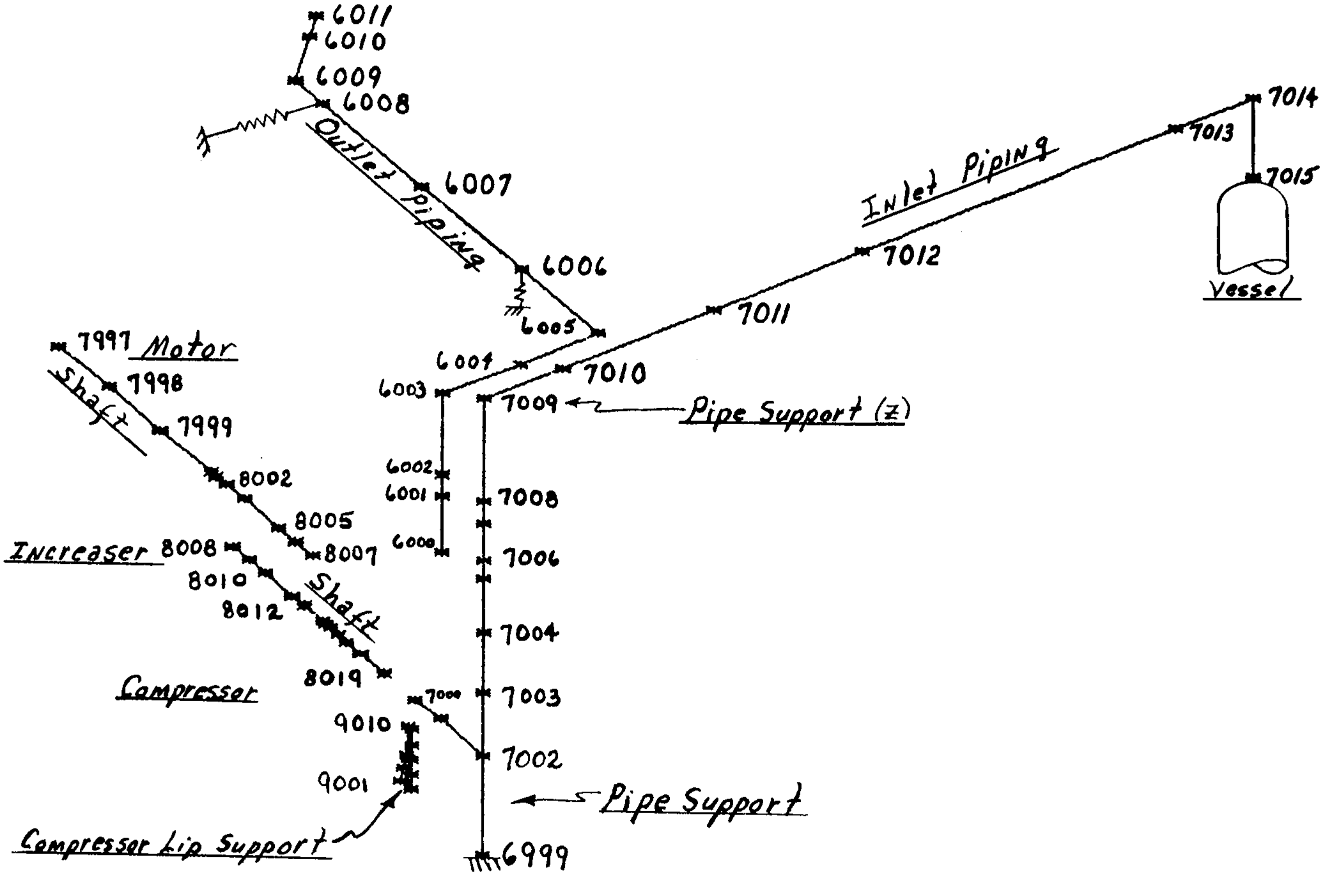


Figure A-2: Location of Equipment on the Sole Plate

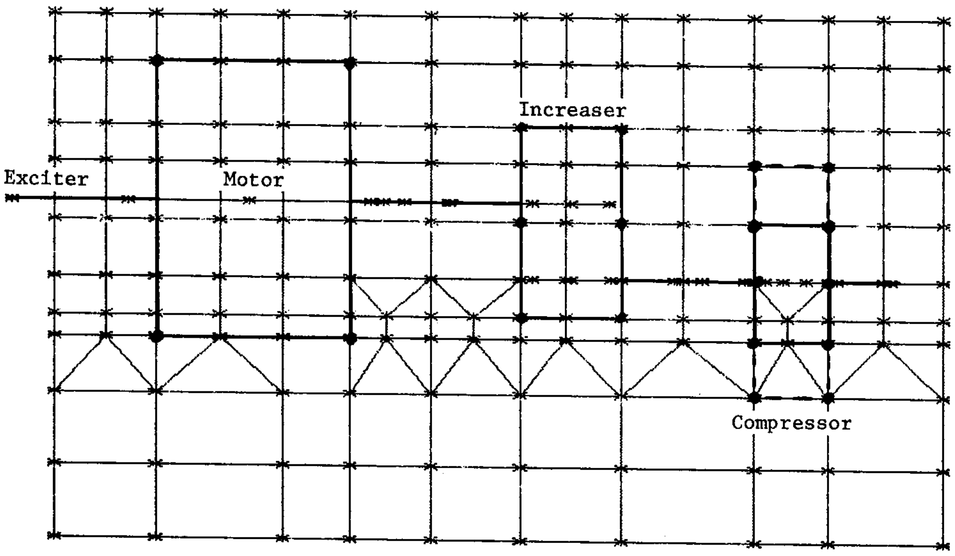


Figure A-3: Grid Point Layout for Sole Plate

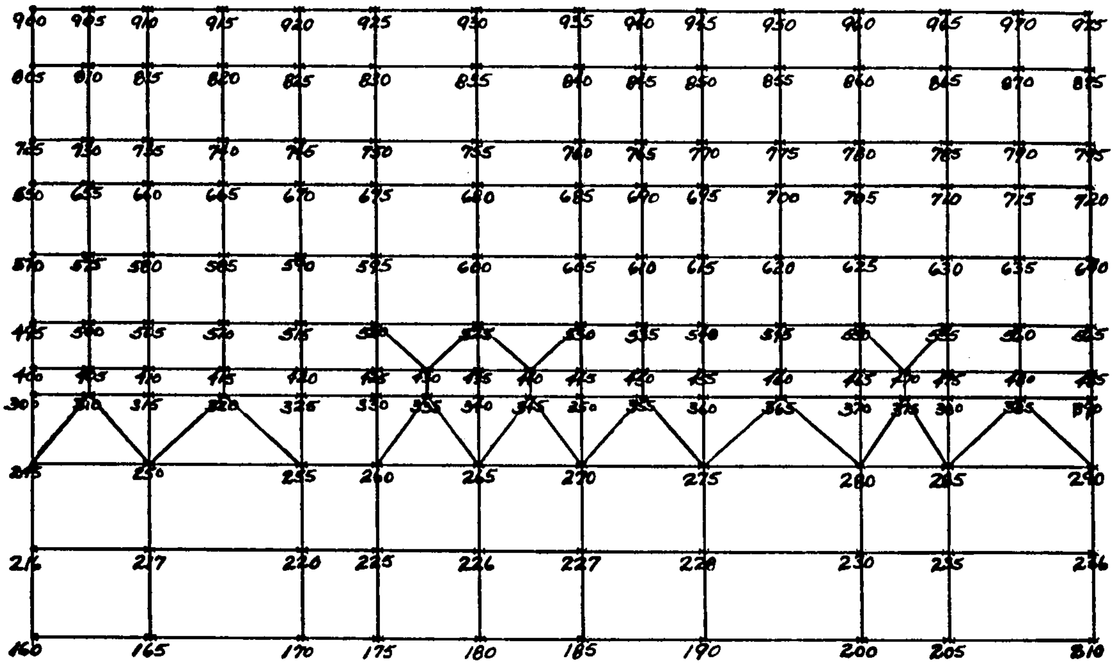
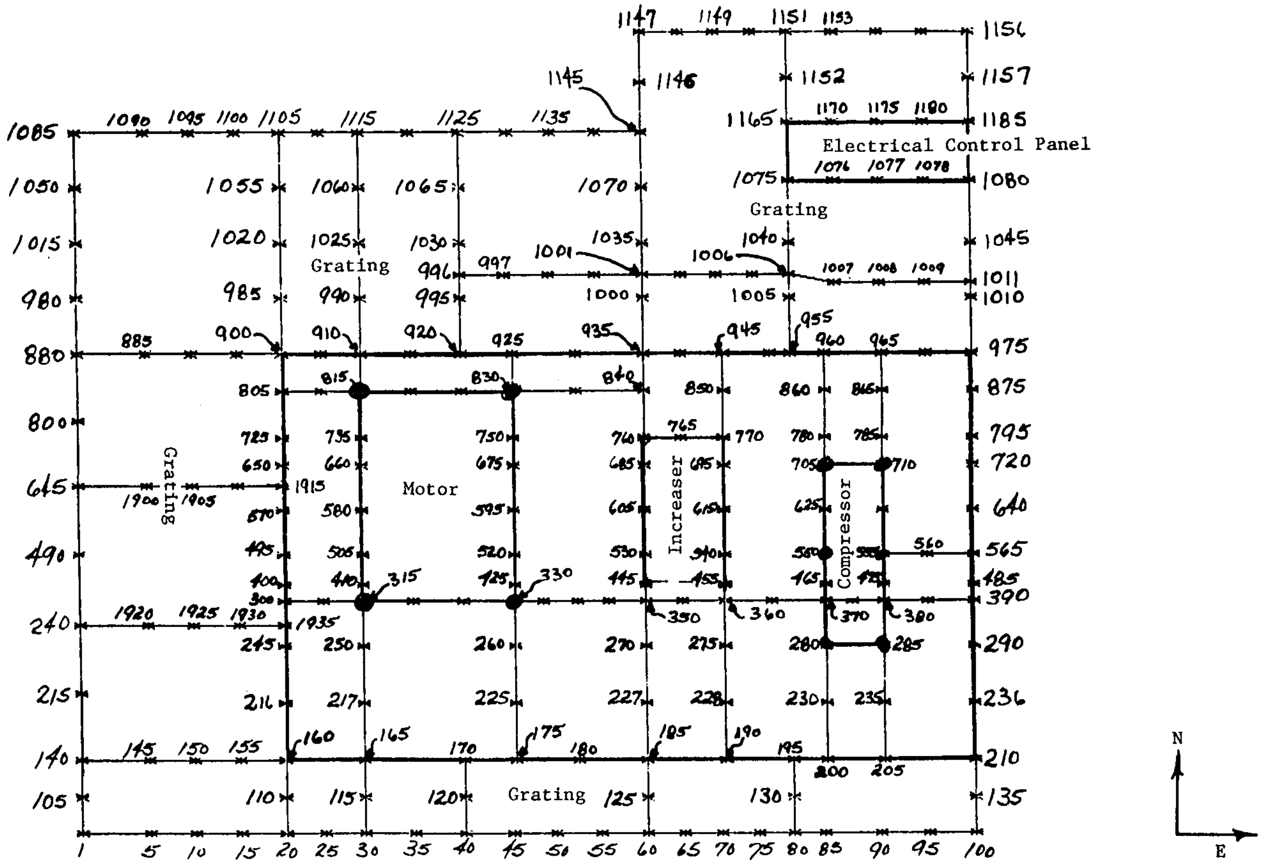


Figure A-4: Grid Point Layout for Sole Plate Support Structure



APPENDIX B

General References

1. The NASTRAN User's Manual, NASA SP-222.
2. Boeing Memorandum 5-9540-H-696 to NASA/MSFC entitled, "AS-503 C Prime POGO/Control System Coupled Response for Change Order 346," dated December 5, 1968.
3. Boeing Memorandum 5-9540-H-738 to NASA/MSFC entitled, "AS-504 Preliminary POGO/Control System Coupled Response for Change Order 346," dated January 16, 1969.
4. Boeing Memorandum 5-9570-H-597 to NASA/MSFC entitled, "Summary of AS-503 S-II Oscillation Assessment," dated 1969.
5. NASA CR-1539 and CR-1540 entitled, "Advancements in Structural Dynamic Technology Resulting from SATURN V Programs," Volumes I and II; dated June, 1970.