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Technical Paper

# Evaluation of Reciprocating Compressor Foundations Using Vibration Measurements

*presented by*

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## Abstract

Foundations for reciprocating compressors are an integral part of the structural system. In many cases, the foundation is required to provide additional lateral stiffness to the compressor frame to support the forces and moments generated by the compressor. Deterioration of the foundation can result in differential bending deflection of the frame between each main bearing, potentially causing crankshaft or other component failures. Therefore, the long-term reliability of reciprocating machinery depends to a large degree on the integrity of the foundation and anchor bolt system.

An approach will be demonstrated that can show deficiencies in the foundation and anchor bolt system using relatively simple vibration measurement techniques. Data will be presented illustrating several types of failures that were detected and monitored with the techniques. Using these data, it was possible to propose minor repairs and improved maintenance procedures which were effective in extending the life of the compressor and foundation, thus minimizing costly downtime.

## 1. Frame Flexibility in Foundation Design

When evaluating foundations for reciprocating machinery, it is important to recognize that the forces and moments transmitted to the foundation by the machine are a function of the frame stiffness and the effectiveness of the anchoring system. Compressor manufacturers typically provide values of primary and secondary shaking forces and moments. An example of the information supplied is shown in Figure 1. The forces and moments are computed from the rotating and reciprocating action of each crank throw and resolved to equivalent values applied at the center of gravity of the machine based on the assumption that the frame is rigid.

It can be shown [1] that the forces transmitted to the foundation at the tie-down locations (anchor bolts) can be significantly higher (than those expected based on the rigid frame assumption) when frame flexibility is considered. A qualitative illustration of maximum anchor bolt load versus frame flexibility is shown in Figure 2. The anchor bolt loads vary between two extremes as shown. The minimum transmitted force is computed by transferring the rigid body shaking forces to equivalent forces at each tie-down location. The maximum transmitted force is computed by neglecting any frame stiffness and transferring each main bearing load to the adjacent anchor bolt locations.

The consequences of underestimating the forces transmitted by the machine to its foundation are often not immediately evident. If the unit is attached to the foundation using a full bed grout, the grout may initially provide sufficient support; however, cracks due to differential thermal expansion or differential frame deflection can seriously degrade the performance of the grout. Marginal installations may have chronic maintenance problems, such as loosening bolts on inspection covers, oil leaks, etc. Excessive differential frame bending deflection can cause anchor bolts to loosen, foundation cracking, and even main bearing or crankshaft failures.

Consider typical static misalignment allowable tolerances for large horizontally opposed reciprocating compressor main bearing saddles. Allowable misalignment on the order of 0.001″ – 0.002″ is not uncommon. Since vibration amplitudes are a measure of the "dynamic misalignment" that the machine experiences, relatively low amplitudes of dynamic differential bending deflection (vibration) can be detrimental to reciprocating machinery reliability.

## 2. Vibration Measurement Techniques

There are two vibration measurement techniques that the authors have found useful for evaluating reciprocating compressor foundations. The first technique involves relatively simple measurements using two transducers and either a two-channel FFT analyzer, or an analog subtraction circuit and a single channel FFT analyzer or data logger. This technique is referred to as differential vibration measurement [2] [3]. The second technique makes use of commercially available experimental modal analysis software to measure and animate the operating mode shapes. These techniques are described in the following paragraphs.

## 2.1 Differential Vibration Measurements

The first step in obtaining differential vibration measurements on a reciprocating compressor is to identify the test point locations. It is important to select enough points to identify likely problem areas (e.g. base-to-grout slippage), but selecting too many points can complicate the data acquisition and analysis without providing additional useful information.

A sketch of a typical compressor installation with a grouted-in frame is shown in Figure 3. Recommended test points are illustrated. At each main bearing location, measurements at key elevations are suggested. The main bearing centerline and the base of the frame are usually measured. If possible, the grout cap and foundation are also included. Typically, magnetically mounted accelerometers are used for the measurements. Large flat washers can be epoxied onto the grout and concrete to facilitate the acquisition of vibration measurements at these locations.

Vibration data should be acquired at each main bearing location since the forces are transmitted at these locations. This results in 4 $\times$ N test points, where N = number of main bearing locations. Additional data is sometimes useful, for example across visible cracks; however, the test points illustrated are a good starting point.

As its name implies, the differential vibration measurement technique involves measuring the difference between two signals. As stated, magnetically mounted accelerometers are convenient to use. The signals are electronically double integrated to provide vibration readings in displacement units rather than acceleration or velocity. Special care in choosing the proper transducer and electronics is required to obtain reliable data in the low frequency range (<10 Hz) in which this type of machinery generally operates. When accelerometers are used, the performance of the electronic integrators is critical. Additionally, the ignition systems on many engine driven or integral machines can cause signal problems.

At each elevation, a stationary accelerometer is placed at an arbitrary reference point, for example main bearing #1. The second identically calibrated transducer is placed at main bearing #2. The difference between the two signals can be obtained by using an analog subtraction circuit, or by measuring the amplitude and phase (relative to a key phase mark) at each location and computing the difference vectorially. If a key phase mark is not available, the transfer function phase between the reference transducer and the stationary transducer can be used. This requires a two channel analyzer. The second transducer is moved sequentially along the length of the machine until all test points at a given elevation are measured.

An example of field measurements obtained on a machine with nine (9) main bearing locations is shown in Figure 4. The lower group of curves represents the absolute vibration at 1$\times$ compressor speed measured at the centerline elevation at each main bearing. Note that only the portion of the vibration spectrum around 1$\times$ compressor speed was plotted. The upper group of curves is the differential vibration signal obtained using a subtraction circuit. As shown, at main bearing #1, the differential vibration was not zero, indicating the degree of uncertainty in the measurements, about 0.6 mils in this case. This is the result of differences in accelerometer calibration and double integrator performance. This uncertainty can be minimized by carefully calibrating the electronics.

This display of differential vibration does not include the phase information; however, the phase relationship is predominantly a result of the rotating and reciprocating forces applied at the main bearings which is related to the crankshaft phasing. This effect can be visualized with the animated deflection shapes discussed in the following sections. For trending purposes, the differential display shown here has proven to be useful.

These measurements are obtained at each elevation desired, moving the reference accelerometer to the corresponding elevation each time. It is then convenient to make a summary plot of differential vibration data obtained from all elevations measured. A summary plot is shown in Figure 5.

Differential vibration measurements of the engine and foundation can reveal significant information about the unit as follows:

1. Large differential vibrations at the bearing centerline elevation indicate dynamic misalignment of the crankshaft which occurs each revolution. Great care is exercised to maintain static alignment along the crankshaft bore within a few mils; however, dynamic misalignment can be as high as 20–30 mils.
2. Large differential vibrations or large changes in slope of the differential vibrations along the engine frame can indicate high frame bending stresses.
3. Large differential vibrations between bearing webs can indicate excessive bearing load vectors, or inadequate frame stiffness.
4. Large differential vibrations across the engine base-soleplate-grout-foundation attachments can locate the weakest link in the engine tie down system.
5. The distribution of the relative vibrations can reveal if the foundation and engine attachment systems are adequate for the engine frame design.
6. The adequacy of the foundation-soil system can be determined.
7. For skid-mounted units, the adequacy of the skids and their attachment components can be evaluated.
8. The adequacy of engine anchor bolts and attachment design can be determined.
9. The integrity of the grout can be evaluated.

The analysis of this type of data is explained further in the case histories discussed in section 3.

## 2.2 Determining Foundation Integrity by Operating Mode Shape

Data provided by the differential vibration measurements can be difficult to interpret. An alternative technique which has proven to be useful is to display the relative vibration data in the form of an Operating Mode Shape (OMS). Such a display, which can be constructed using the animated mode shape display capabilities of off-the-shelf modal analysis software, provides both an intuitive and a quantitative description of the foundation motion. Anchor bolt system effectiveness, grout cap integrity, the severity of apparent cracks, and an indication of abnormal forces can be determined from the data.

The procedures necessary to develop an OMS of a system are;

- construct a geometric computer model of the foundation,
- acquire amplitude and phase data at every point in the model, and
- animate the geometric model using the acquired data.

Each of these procedures are discussed in detail in the following sections.

### 2.2.1 Model Definition

The complexity required of the geometric model is dependent upon the type of information that is being sought. Enough points should be selected to provide a recognizable shape (i.e., distinguishing the edges of the foundation and grout, and the basic structure of the machine). However, since data must be acquired for every point specified in the model, it is desirable to use only the minimum number of points required to describe the vibration mode shape of the structure. At features such as foundation cracks or the interface between a foundation and an anchor, extra points may be necessary to illustrate relative motion.

Consider the situation, shown in Figure 6, of an integral engine/compressor. The unit rests on a grout cap poured on top of the foundation. There are ten anchor bolt locations, each corresponding to a main engine bearing location. Vertical lines are drawn at each of these locations since forces are transmitted to the foundation at each bearing. Horizontal lines are drawn at the base and the top of the foundation, at the bottom and top of the grout cap, along the base of the engine, and at the crankshaft centerline. Additional lines may be required on either side of significant cracks in the foundation or grout. Data must be obtained at each intersection of these lines (60 locations). Note that there are not enough points specified to define the corners of the foundation. The lines are simply drawn at an angle from the top surface of the grout to the bottom of the engine. Although these corner points could be specified, they can usually be omitted without loss of information to save data acquisition time.

### 2.2.2 Data Acquisition

After the model is completed, measurements of vibration amplitude and relative phase must be obtained at every point. The number of directions in which data must be acquired is dependent upon the forces present and the expected reaction. For the example of Figure 6, all of the forces are expected to be in a plane perpendicular to the crank-shaft. Therefore, only vibration data perpendicular to the crank-shaft (vertical and horizontal) must be obtained. If the machine is balanced so that vertical forces cancel at each bearing, vertical vibration data can be omitted.

There are several methods available for obtaining the amplitude and phase data. The method selected depends upon the requirements of the modal analysis software being used and the instrumentation available. The two methods outlined below require the use of a two channel analyzer with transfer function capability.

| | |
|---|---|
| Key-phasor Method | This technique requires a once-per-revolution (key-phasor) signal. Such a signal may be obtained by detecting a mark or notch in the shaft, by detecting the reciprocating motion of a piston, or by measuring pressure spikes in a cylinder. The signal may be conditioned to provide a constant amplitude narrow spike. A vibration transducer is moved to each point and direction in the model. Computing a transfer function between the key-phasor signal and the vibration transducer will provide phase data. |
| Two Transducer Method | In cases where a key-phasor is not available, two vibration transducers may be used. One transducer is placed at some location on the system where significant energy exists (i.e., at the crank-shaft centerline at one end of the machine, but not at the base of the foundation). This transducer is used as the reference. The other transducer provides vibration data at each point and direction in the model. A transfer function is computed to obtain the phase information. |

In either case, amplitude information may be obtained from the frequency response function (FRF) or transfer function (Figure 7) or directly from the linear amplitude of the movable vibration transducer (Figure 8). Using the linear amplitude information is generally better, since the animations can be scaled. However, some modal analysis software can only utilize transfer function (FRF) data. The operating mode shape will be the same for either method.

It should also be noted that the phase information will be valid only at running speed and integer multiples. Improved accuracy can be obtained by using an input window that spreads the frequency over several spectral lines (e.g., a "flat-top" window) and averaging until the phase data is constant (see Figures 7 and 8).

A single channel balance analyzer may be used if a two-channel analyzer is not available. These analyzers can provide amplitude and phase information at running speed. However, a key-phasor signal is required. Since most modal analysis software packages do not support such analyzers, the amplitude and phase data obtained must be manually recorded and entered into the software.

Once the instrumentation is installed and properly set up, the time required to collect the data is primarily a function of the number of points in the model. Typically, approximately 30–60 seconds will be required to obtain data at each data point and direction. Careful selection of points and point ordering can minimize the time required. Analyzers with three or more channels can also speed data acquisition since more than one direction can be acquired simultaneously.

### 2.2.3 Animation Software

After the data has been acquired, the animation capabilities of the modal analysis software can be used to provide a moving image of the operating mode shape. The details for accomplishing this will vary from one vendor to the next; however, a few caveats should be mentioned.

If the "peak-pick" mode of the software is used to extract the amplitude and phase information from the stored data, a frequency band of only one or two spectral lines about running speed (or multiple) should be selected. The selected information should be checked to ensure accuracy.

Most software has two animation types; normal and complex. A *normal* mode animation assumes that the vibration is either in phase (0°) or out of phase (180°). This is the usual situation for "standing-wave" mode shapes corresponding to natural frequencies of a structure. A *complex* mode shape animation uses the actual measured values of phase (usually used for "traveling" mode shapes found in certain structures).

To animate a normal mode shape, the software creates an average phase reference relative to which the vibration is either in or out of phase. Consider the case where the data obtained had an average phase reference at 90°. However, two points were measured to have phase values of 89° and 91°. The normal animation type would display them as 0° and 180°, respectively. Selecting a complex animation type would correctly interpret the points as being only 2° apart in phase. Therefore, for animation of an operating mode shape, the *complex* animation type should be selected instead of the *normal* type to provide a realistic image.

## 3. Case Histories — Foundation Problems

Examples of field test results from two reciprocating compressor installations each with multiple units are presented to illustrate the use of foundation vibration monitoring techniques.

## 3.1 Case History #1

This installation included approximately 20 large motor-driven, horizontally opposed reciprocating compressors in an NGL complex. The various compressors operated in heat pump, residue gas, and nitrogen injection services. Discharge pressures ranged from 400 psig for the heat pumps to 6200 psig for the injection machines. The average machine was rated for 7500 BHP at 327 rpm.

The initial manifestation of problems was visible cracking of the foundations, Figure 9. The cracks were first monitored visually, using sketches and photographs, and were found to be growing. The most severe cracks were repaired using epoxy grout to patch the damaged areas. However, the cracks continued to grow.

Field testing was conducted with the intent of determining if the foundation cracking was detrimental to compressor reliability. It was also intended to develop a predictive maintenance tool to monitor the cracks with better certainty than the visual approach. Further discussion of the long term monitoring program developed can be found in reference [4].

### 3.1.1 Initial Measurements

Initially, differential vibration measurements were made at five elevations on the side of the #3 heat pump compressor. This was a horizontally opposed eight cylinder machine with nine main bearing locations. A sketch of the test point locations is shown in Figure 10.

The differential vibration readings are summarized in Figure 11. Note that these plots do not provide phase information, but are useful for trending a given machine, or comparing like machines. The shape of the curves is typical for this type of machine. Each traverse at a given elevation is similar in shape, with the amplitude diminishing at the lower elevations. Note that for this machine, the bearing centerline data was also plotted for the unloaded case. This illustrates that the differential vibration is primarily a function of the inertial forces generated by the compressor. This is particularly significant when diagnosing a variable speed machine, since the inertial forces vary with the speed squared. Comparisons of data acquired at different times must be made using data gathered at the same speed.

Unit #3 was measured first because it was visibly the "worst looking" machine. Data were then acquired from Unit #1. The summary differential plot is shown in Figure 12. Note the discontinuous shape in the vicinity of main bearing number 5. Note also that the "bottom-of-frame" and "grout-line" traverses are more separated than those for Unit #3. This can be an indication of inadequate attachment of the machine to the foundation.

Unit #1 had higher measured differential vibration than did Unit #3 and, therefore, would have a greater potential to develop maintenance problems or failures. However, its visible appearance was not as bad as Unit #3 (i.e. it had fewer, smaller cracks). This was attributed to the relatively "loose" attachment of the frame to the foundation, which limited the forces transmitted to the foundation. Of course this is undesirable, since excessive frame deflection can result.

It is difficult to quantify the allowable differential vibration for a reciprocating compressor frame. Recall the earlier comparison between static misalignment allowables and the concept of dynamic misalignment. After a trending program (described in reference 4) was established, the manufacturer of the eight cylinder machines recommended a maximum differential vibration level of 10 mils (pp) at the crankshaft centerline elevation.

### 3.1.2 Operating Mode Shape Measurements

In addition to the differential vibration data, a detailed three dimensional experimental model was developed for Unit #3. This was of interest, since the large crack shown in Figure 9 was not evaluated with the differential measurements. It was not known if this crack was detrimental to the machine operation, or just a cosmetic crack. A total of 116 test point locations were selected, which required 348 measurements. The model geometry is shown in Figure 13. The data were acquired using the two transducer technique, since a key phase indicator was not available at the time.

The data is best reviewed using the animation capabilities of the software. Several of the animation "frames" are shown in Figure 14 to illustrate the compressor frame flexibility. Observing the animation provides a qualitative look at the frame deflection. Loose attachment points and other anomalies become readily apparent when reviewing these data from several like machines. Quantitative information can be obtained from the OMS software as well. A table of amplitude and phase at each point in each direction can be printed, as shown in Figure 15.

### 3.1.3 Long Term Trending [Ref. 4]

The user company implemented a comprehensive trending program to apply the techniques of differential frame vibration measurements and operating mode shape data. This led to improved maintenance procedures, which included the use of an ultrasonic (pulse-echo) bolt tensioning device to accurately preload the anchor bolts. Proper bolt tensioning resulted in significant reduction of differential vibration levels.

One specific illustration of the benefits of the trending program involved a group of nitrogen compressors. These units were five cylinder horizontally opposed designs, again motor driven. Initial differential vibration summary plots are shown in Figure 16. These plots were typical for six of seven units. The seventh unit differential vibration summary is shown in Figure 17. A noticeable discontinuity at bearing number 4 existed. This unit exhibited severe cracking on one end and an oil soaked grout cap. The maintenance group recommended re-tensioning the anchor bolts and rechecking the differential frame vibration rather than taking a lengthy and expensive unscheduled shutdown for grout cap replacement.

The differential vibration summary after retensioning is shown in Figure 18. The maximum differential vibration had reduced from about 8.5 mils (pp) to about 4.7 mils (pp) and the shape of the curves was more like the other six units. The grout cap replacement could then be scheduled during a planned outage, which resulted in significant cost savings and minimal lost production.

### 3.2 Case History #2

This installation was a compressor station with nearly 100 compressors of various sizes and ages. Most of the machines were multiple stage units used in $N_2$ or $CO_2$ injection service at 4000–5000 psi. Approximately half were integral machines and the others were electric motor driven.

The users were experiencing excessive maintenance costs (oil leaks, grout failures, etc.) and had had a few crankshaft and connecting rod failures. Therefore, a program of general rehabilitation had been undertaken. Since the program required several years to complete, it was desirable to evaluate each unit as part of an overall ranking scheme in which units would be scheduled for repair. Additionally, the equipment user wanted to know what types of foundations seemed to last the longest and any other information that could be obtained from the relatively large data sample.

The large number of units involved necessitated that measurement procedures be chosen to minimize acquisition time but provide information to evaluate the foundation integrity. The OMS procedure was chosen because of its ability to provide an animated display of relative amplitudes of a unit and to have the exact amplitudes and phases available.

It is important to recognize when comparing the data from several units, that each display is scaled individually, i.e., an apparent motion of the geometric model of 50 screen units may represent 1 mil of vibration for one display, but 5 mils of vibration for another. For this reason, it is important to judge each foundation system based on the relative motions observed. Several examples of the foundation data are presented below.

A foundation system that is functioning properly will exhibit a "wave" of motion traveling from one end of the unit to the other (depending on internal crank phasing). All components in the model will appear to move in a uniform fashion. Such a foundation is shown in Figure 19. The lines representing the bottom of the grout and top of the grout move equally with the bottom of the frame and centerline of the crankshaft. As discussed in Section 2.2.3, for the display to appear as described, the animation should be a *complex* type, not a *normal* type. This effect can be observed by displaying the data shown in Figure 19 in a *normal* animation type (Figure 20).

A foundation with two separate problems is shown in Figure 21. The relative motion between the frame and foundation at anchor bolt locations 4 and 8 indicates that these bolts are ineffective (not torqued properly or broken). At the flywheel end of the foundation (bolt 1), the grout cap and foundation are moving together, but there is relative motion between the foundation and grout. This behavior indicates that the grout cap has separated from the foundation in this region.

The display in Figure 22 shows motion of the frame relative to the foundation at all points except near the flywheel end. It could be hypothesized that all of these anchor bolts are loose or broken. However, the bolts were checked and tightened prior to testing. Inspection of the unit revealed that from the middle to the non-flywheel end, the foundation surface was very oily. The lateral restraining force ($f$) provided by the anchor bolts is the product of the coefficient of friction ($\mu$) and the force in the bolt ($N$), $f = \mu N$. If the coefficient of friction between the foundation and frame is reduced to essentially zero, the restraining force will be nearly zero regardless of the bolt force (and hence the bolt torque). Therefore, it can be concluded that since the bolts were tightened properly, the oily foundation surface was compromising the integrity of the system. If the foundation/anchor bolt system was not designed to accommodate the resulting forces (from a non-rigid frame bending), damage to the foundation and ultimately the compressor could occur.

The unit shown in Figure 23 shows motion of the foundation at the flywheel end, relative to the unit. Inspection of the unit revealed that the foundation had obvious cracks in this area. Since the frame and crankshaft did not exhibit any excessive relative motion, it was thought that the foundation damage did not pose any immediate threat to the compressor. It was recommended that this unit be monitored to detect further deterioration.

All of the OMS animations presented were constructed with data acquired in two directions; perpendicular to the crank-shaft and vertical. The direction parallel to the crank-shaft (axial) was ignored since there were no mechanisms to generate high forces in this direction. For certain units, it may be possible to ignore the vertical direction. However, since a poorly balanced unit may generate unexpected forces, preliminary data in axial or vertical directions should be obtained and evaluated to determine the data requirements. A unit where vertical motion was present is shown in Figure 24. The vertical forces were thought to have originated from the vertical power cylinders of this integral compressor.

In addition to ranking the foundations for repair, recommendations were made to improve foundation design, based on the data collected. A major conclusion of the testing was that foundations that were oily (even recently rebuilt ones) all showed excessive frame deflection. Older foundations that were oily also showed damage, while foundations of the same age that were dry seemed intact. It is difficult to know if the oiliness resulted from failed inspection door seals (caused by excessive frame bending) or if the excessive oiliness caused the anchor bolts to become ineffective, thereby increasing frame bending. However, it is apparent that the two effects are complimentary. Foundations that were free of oil always had lower frame deflections than the oily ones.

## 4. Conclusions

Techniques have been demonstrated that have been shown to be useful for diagnostic and trending purposes. Both differential frame vibration measurements and operating mode shape tests can be used for these purposes; however, each technique has its own distinct advantages and requirements. The differential measurements require less sophisticated hardware and software, and can sometimes require less time to obtain data. OMS tests will provide a much more intuitive picture of frame/foundation deflection, as well as providing detailed amplitude and phase information.

The data presented also illustrated several important concepts.

1. Engine/compressor frames are not rigid. The anchor bolt/tie down system and the foundation should be designed based on flexible frame calculations.
2. Using appropriate monitoring procedures, foundation and mechanical problems can be minimized. Unnecessary repairs can be avoided. Conversely, potentially damaging situations can be identified and trended to evaluate repair schedules and maintenance procedures.
3. An anchor bolt/foundation system that is ineffective (whether from improper anchor bolt torque or an oily foundation surface) can cause forces to be transmitted to the foundation that are higher than the design loads. The data consistently showed that such situations had negative feedback, i.e., the damage and potential for failure accelerated.
4. The amount of "dynamic misalignment" that a given compressor can withstand is not generally provided by the manufacturer. Users should acquire baseline data on new installations or repairs, and apply the techniques described herein to identify potential problems.

## References


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3. Wachel, J.C., et al, "Vibrations in Reciprocating Machinery and Piping Systems", EDI Seminar Manual, EDI Report 21250, San Antonio, Texas, May, 1992.

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GENERAL COMPRESSOR INFORMATION

Compressor Manufacturer: XYZ COMPRESSOR COMPANY

Model: 11′ HOE-34 Rated Horsepower: 1300

Rated Speed: 318 RPM

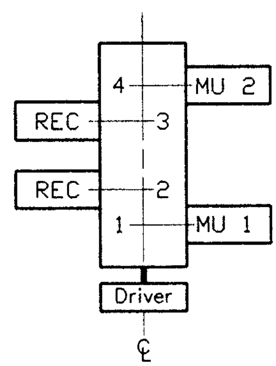
Actual Operating Speed Range: 318 RPM to 318 RPM

| Cylinder No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Service | MAKE-UP | | RECYCLE | | | | | |
| Stage | 1 | 2 | 1 | 1 | | | | |
| Cylinder Bore (in) | 10 3/4 | 8 | 6 1/2 | 6 1/2 | | | | |
| Cylinder Stroke (in) | 11 | 11 | 11 | 11 | | | | |
| Rod Diameter (in) | 3 | 3 | 3 | 3 | | | | |
| Tail Rod Diameter (in) | - | - | - | - | | | | |
| Crankshaft Throw Location | 1 | 4 | 2 | 3 | | | | |

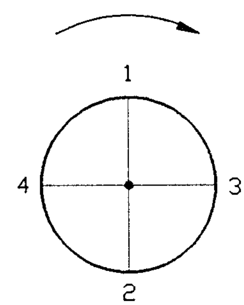
Cylinder Sequence

| Cyl. No. | Phase* @ TDC (Deg.) |
|---|---|
| 1 | 0 |
| 2 | 0 |
| 3 | 90 |
| 4 | 90 |
| 5 | |
| 6 | |
| 7 | |
| 8 | |

Physical Layout of Cylinders




Crankshaft Angle Diagram




*Time phase lag (Not physical angles)

COMPRESSOR MECHANICAL DATA

UNBALANCED FORCES AND MOMENTS

| | Horizontal | | Vertical | |
|---|---|---|---|---|
| Primary Force | 0 | (lbs) | 0 | (lbs) |
| Secondary Force | 0 | (lbs) | 0 | (lbs) |
| Primary Moment | 8770 | (ft lbs) | 9300 | (ft lbs) |
| Secondary Moment | 5080 | (ft lbs) | 0 | (ft lbs) |

COMPRESSOR ROD LOADING

Maximum Allowable-Tension 50000 (lbs)

Maximum Allowable-Compression 50000 (lbs)

Figure 1: General Compressor Information Including Rigid Body Shaking Forces and Moments

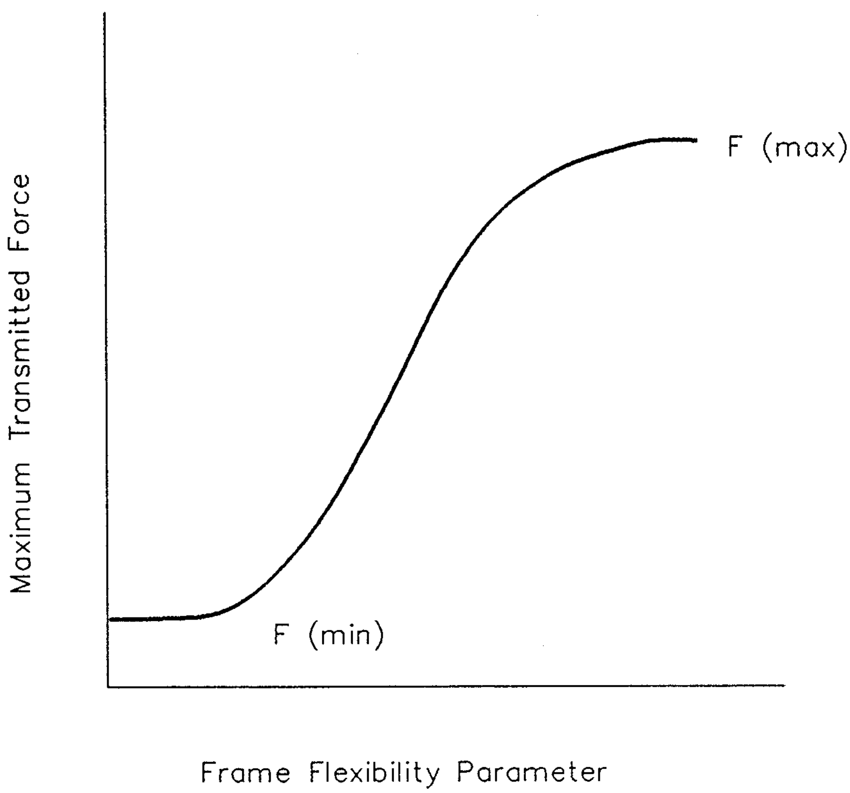



Figure 2: Transmitted Force Versus Frame Flexibility

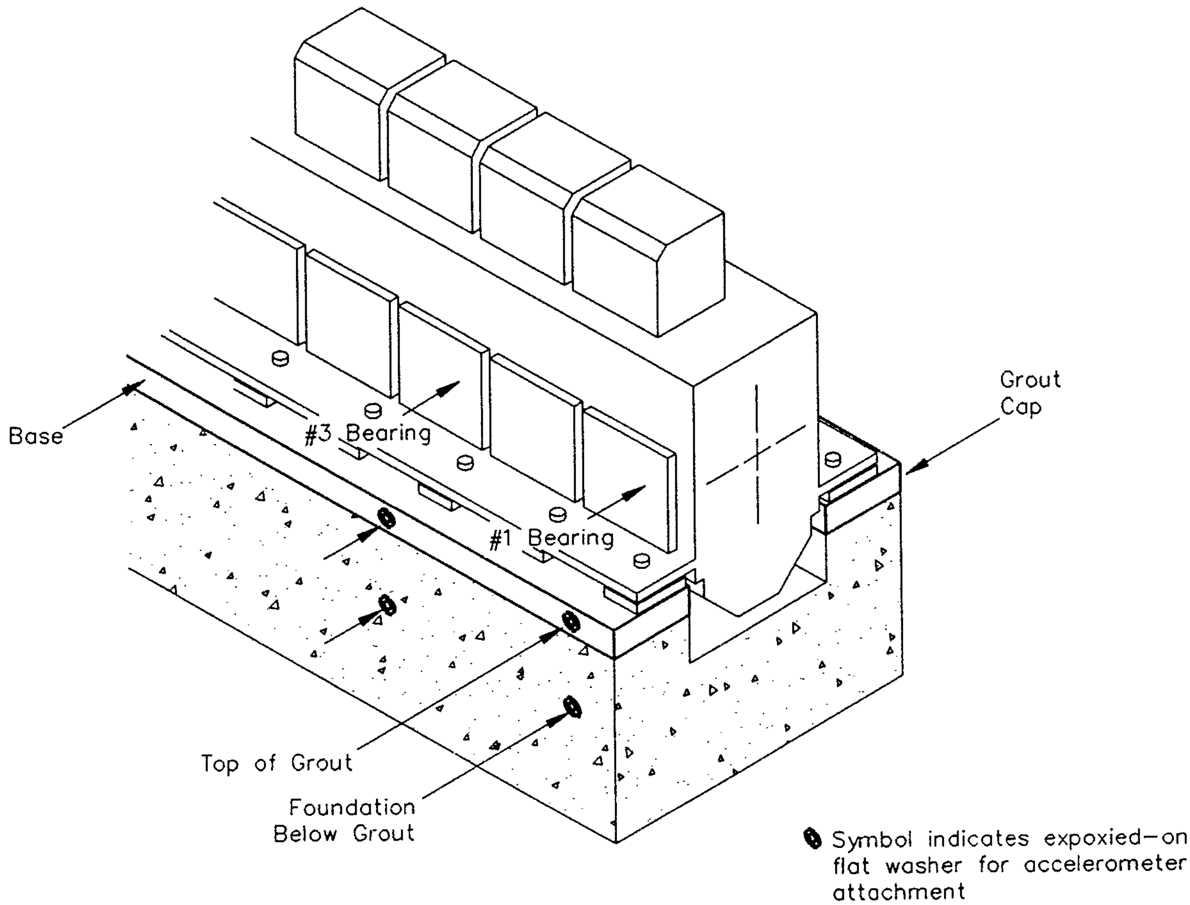



Figure 3: Typical Reciprocating Compressor on Foundation

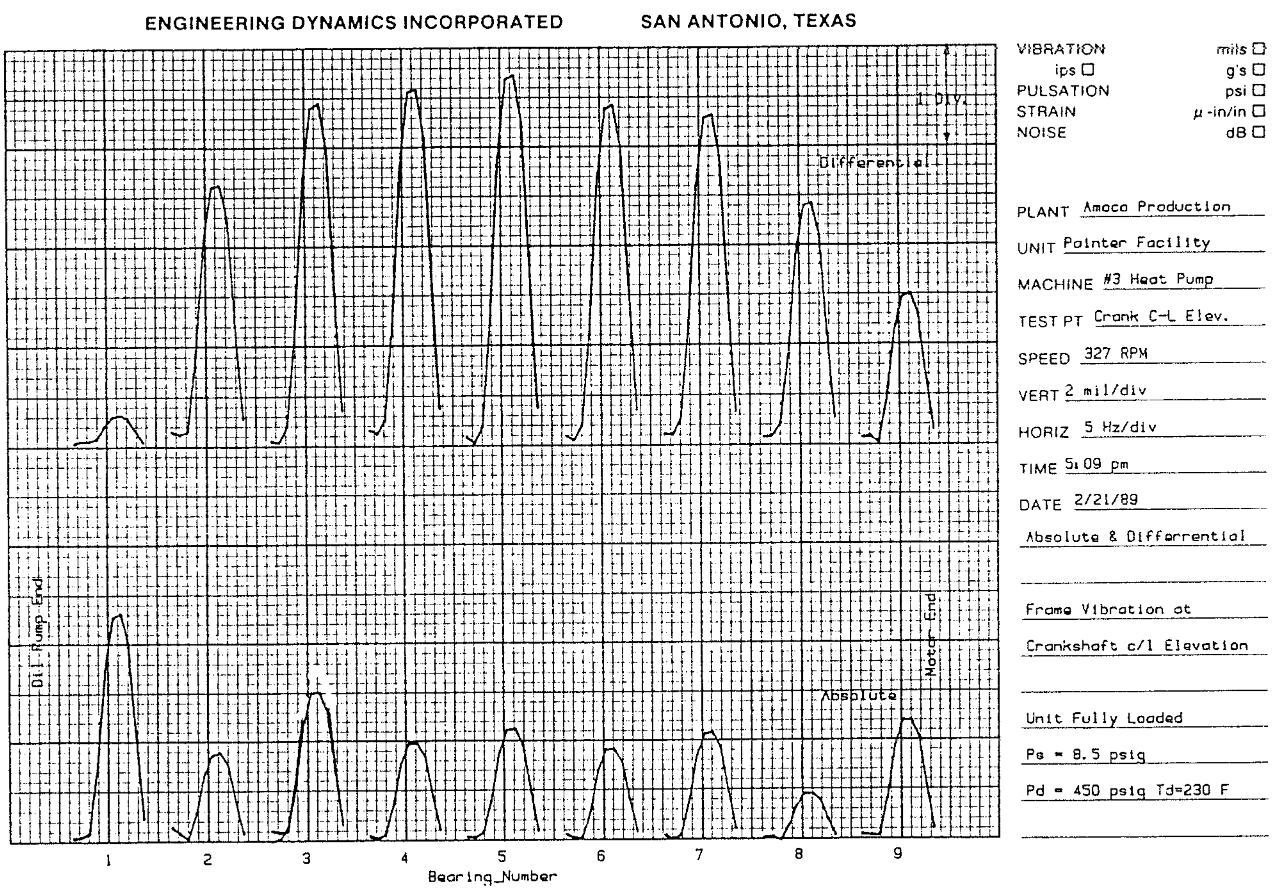



Figure 4: Absolute and Differential Frame Vibration Measurements

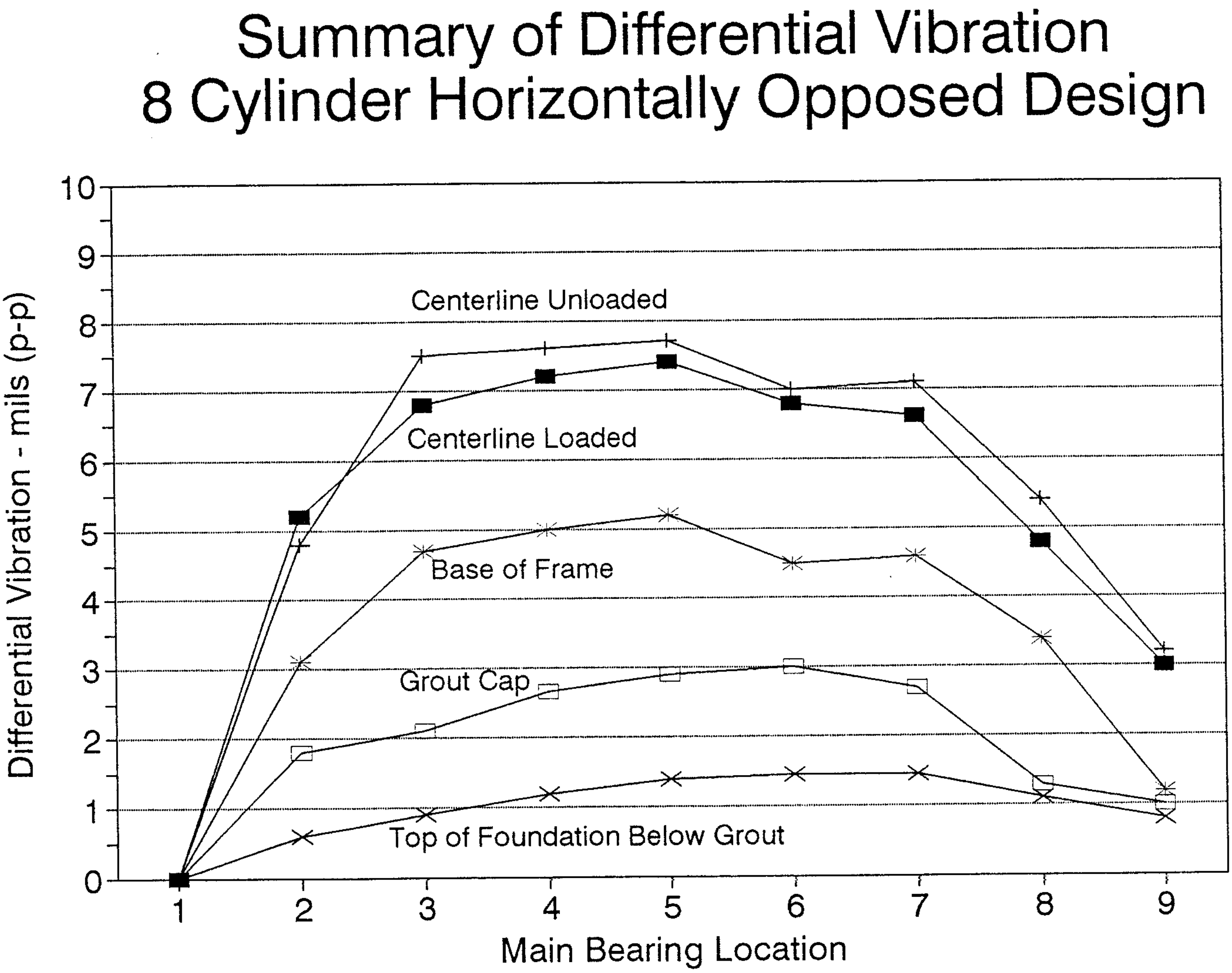



Figure 5: Example Differential Vibration Summary Plot

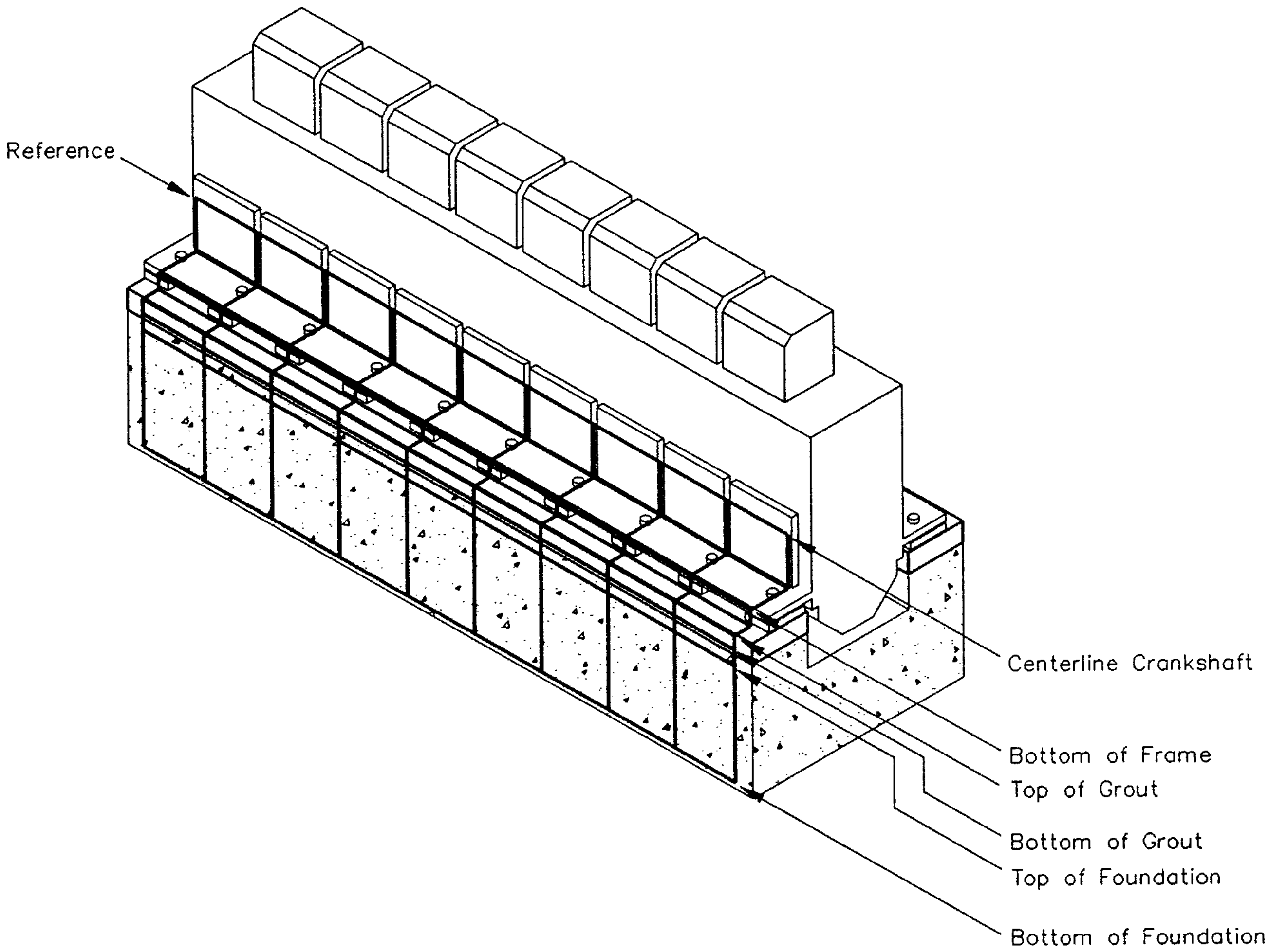



Figure 6: Typical Measurement Locations

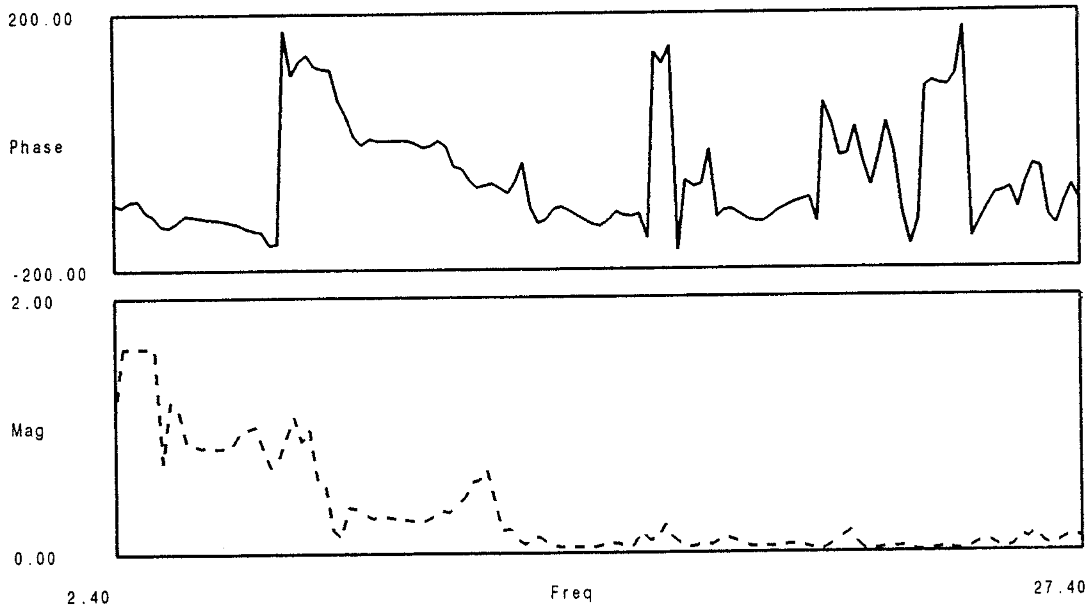



Figure 7: Data Acquired as a Transfer Function (F.R.F.)

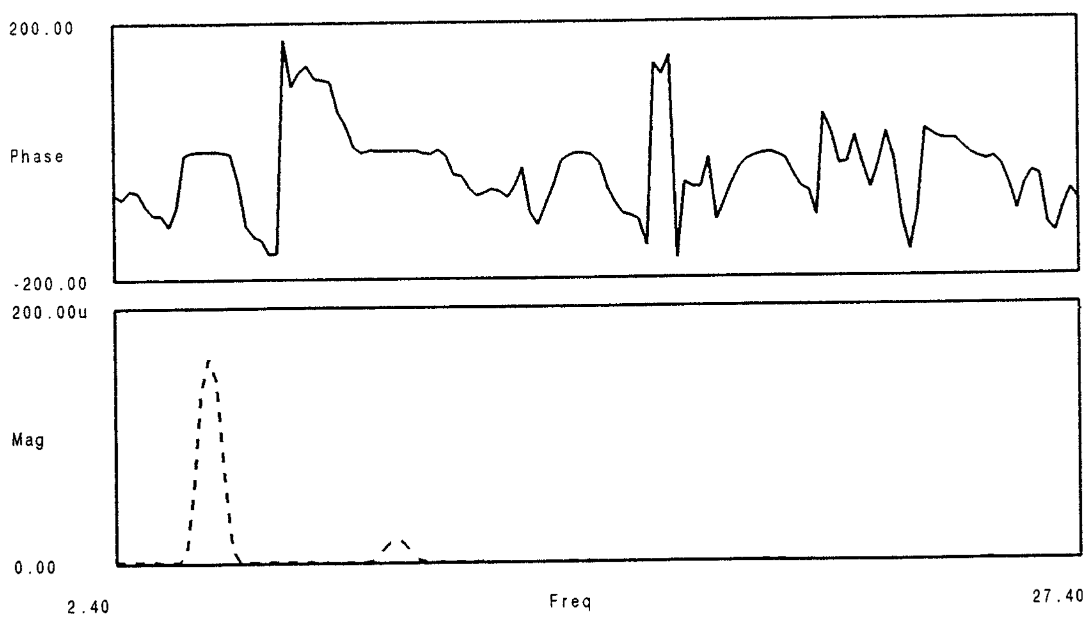



Figure 8: Data Acquired as Linear Amplitude, Transfer Function Phase

Figure 9: Foundation Cracking

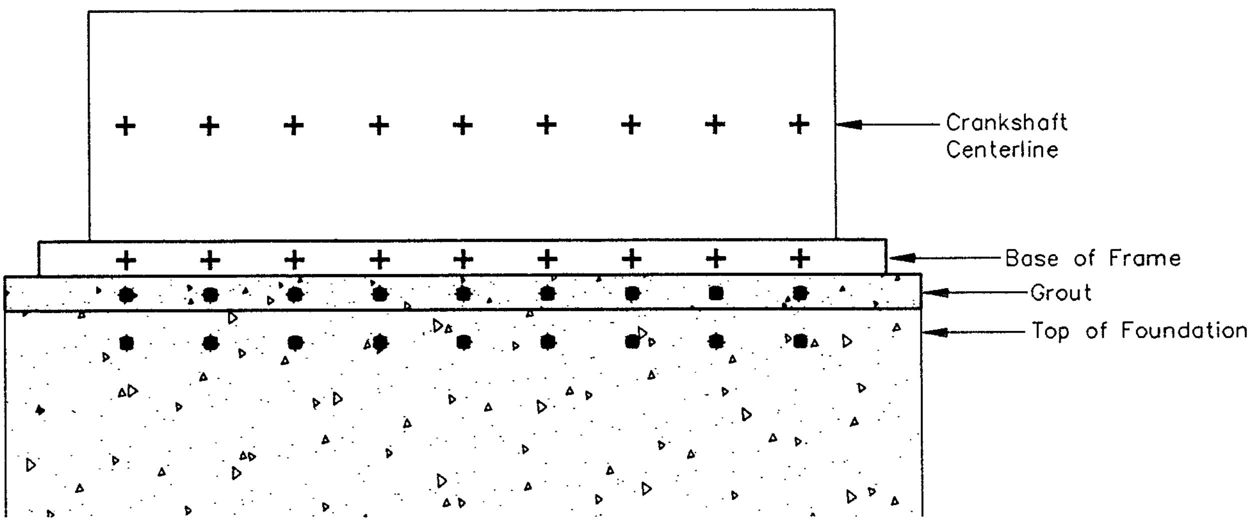



Figure 10: Test Points for Differential Vibration Measurements

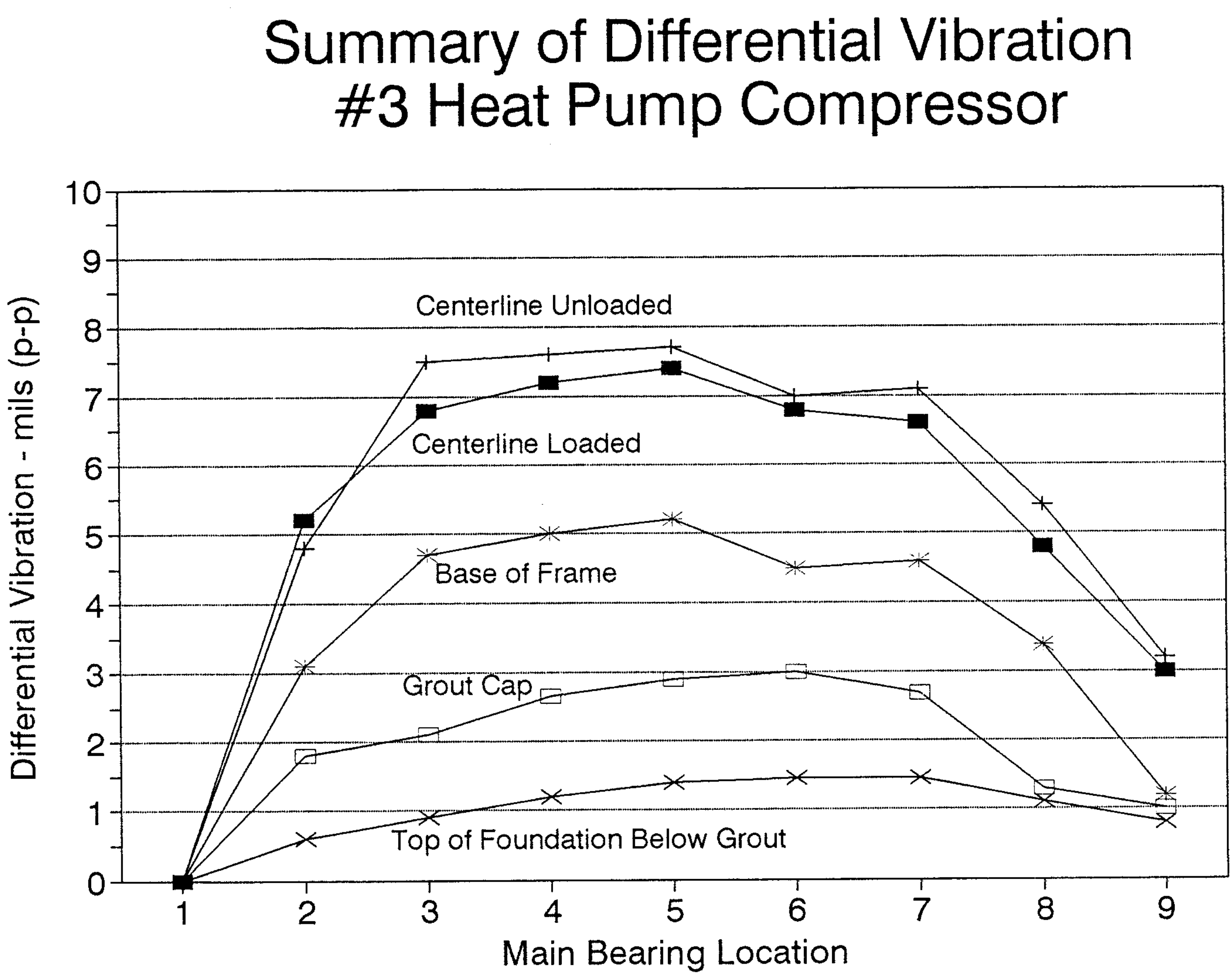



Figure 11: #3 Heat Pump Differential Vibration

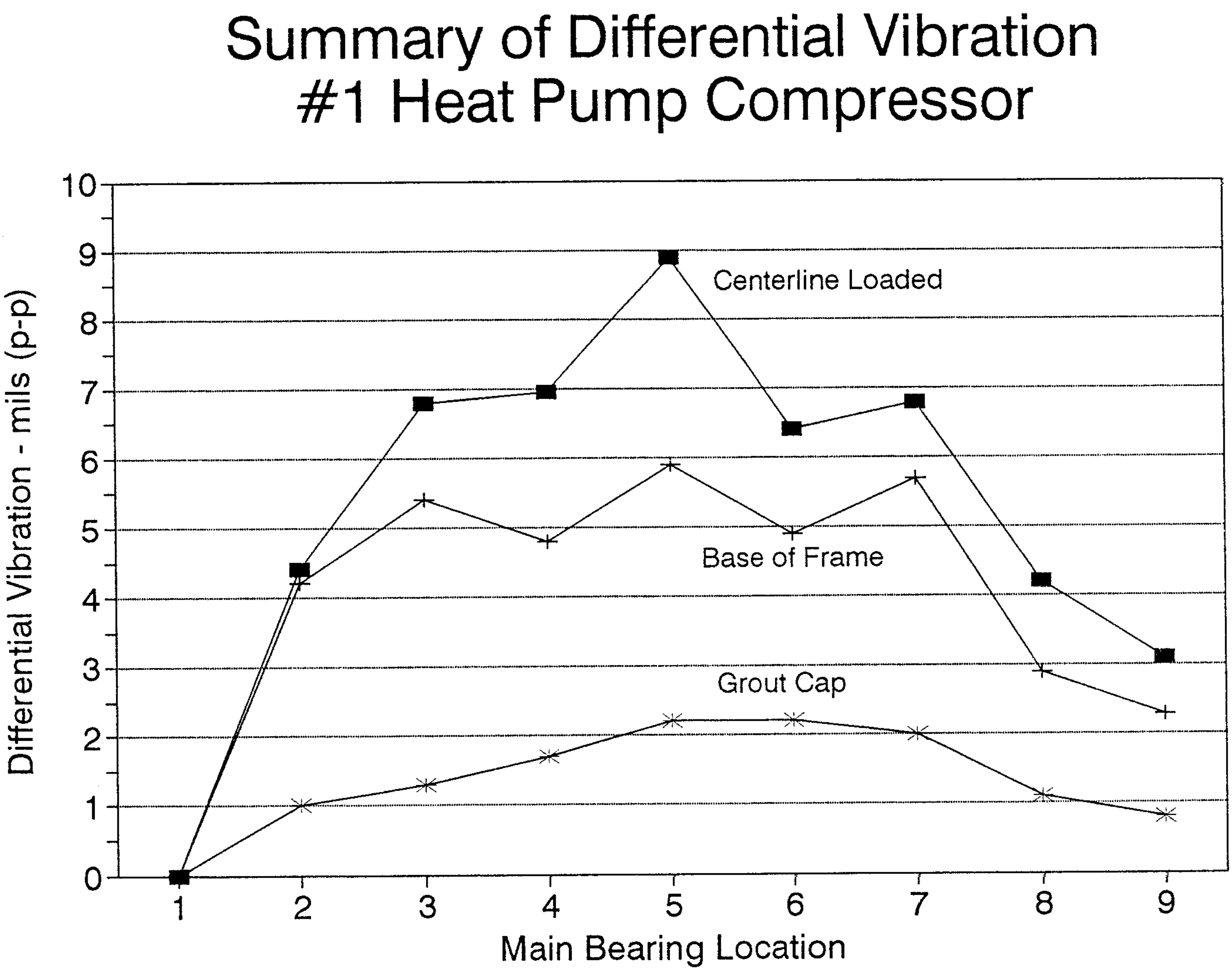
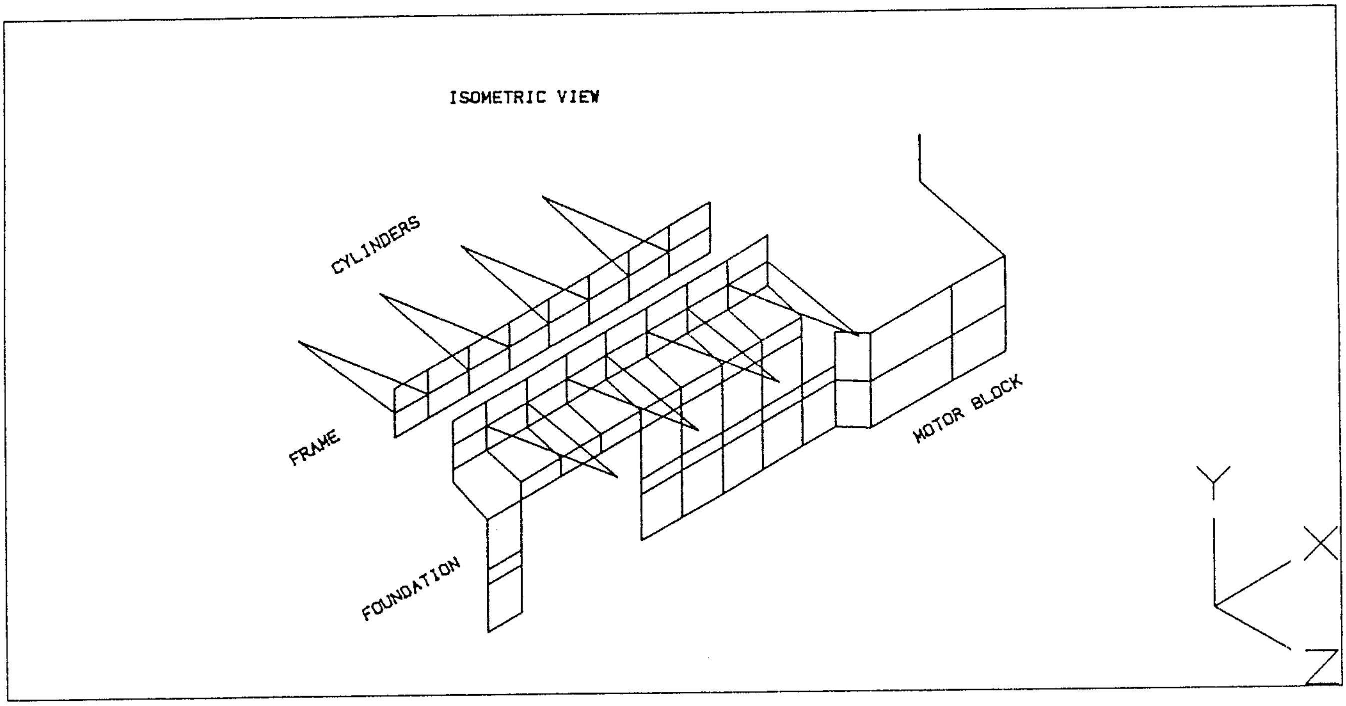



Figure 12: #1 Heat Pump Differential Vibration



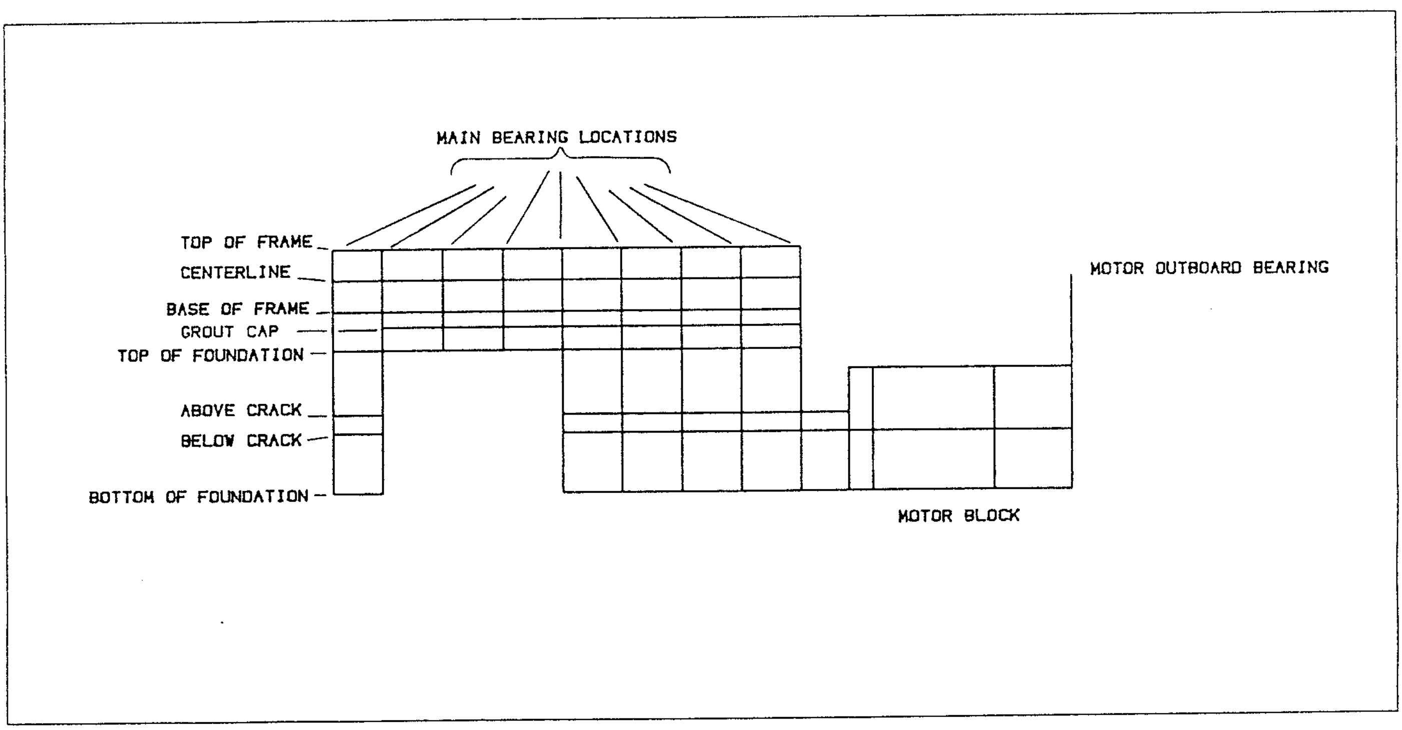




Figure 13: Model Geometry for Operating Mode Shape Measurements

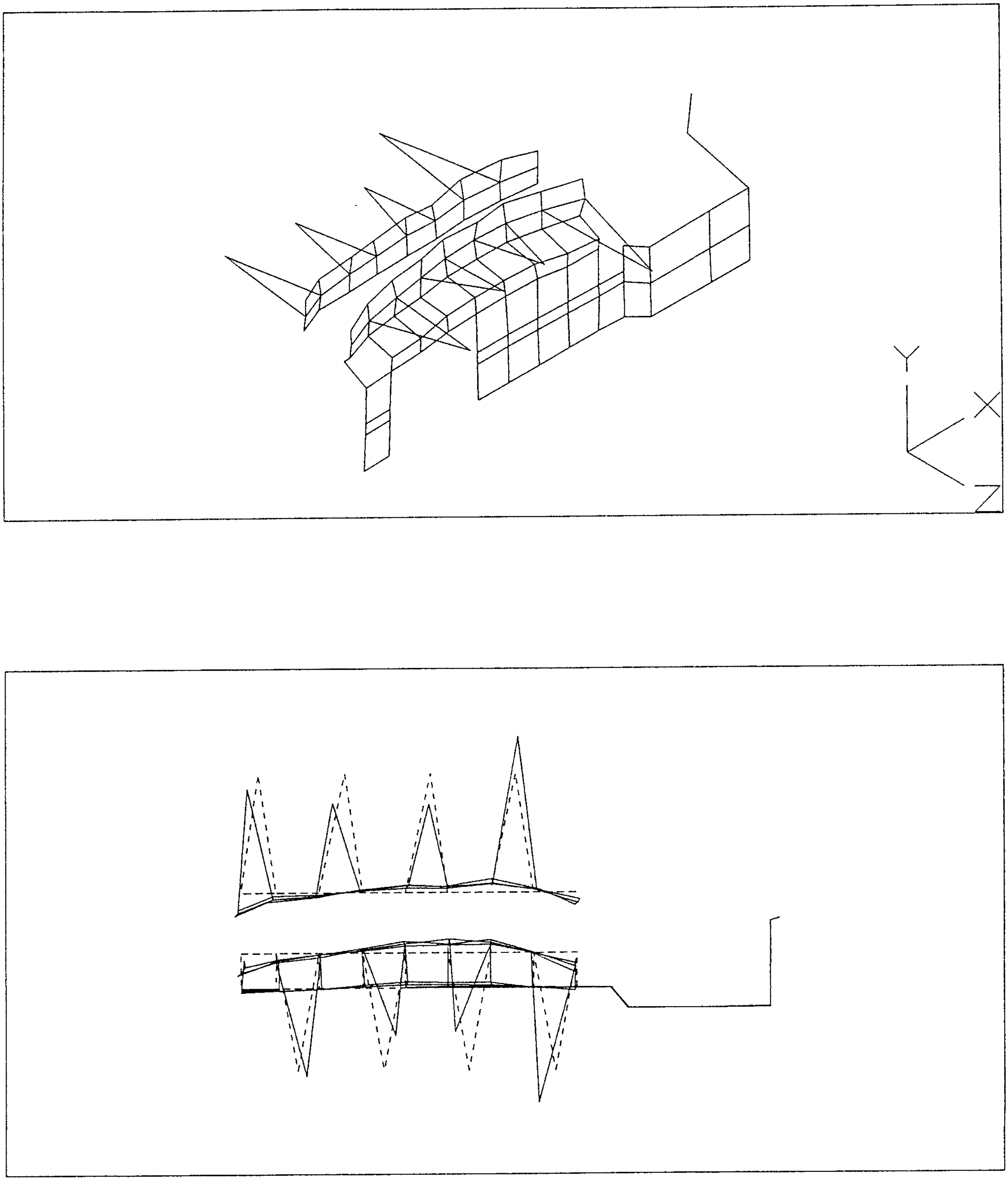



Figure 14: Operating Mode Shape

```
Filename: \PROJ\P621\STAR\HP3\HP3.MDL
Revcode: 2831C

Mode 1 Mode#1 5.60  Hz
Frequency: 5.600
Damping: 0.0000
Scale Factor =        5.27
Maxresidue:       2.0381 * 5.27 = 10.74
```

| Test Point | X-Direction Mag (mils) | X-Direction Phs (deg) | Y-Direction Mag (mils) | Y-Direction Phs (deg) | Z-Direction Mag (mils) | Z-Direction Phs (deg) |
|---|---|---|---|---|---|---|
| 1 | 0.84 | -171.72 | 2.29 | -99.01 | 5.59 | 96.66 |
| 2 | 0.70 | 141.41 | 2.10 | -105.01 | 4.88 | 91.98 |
| 3 | 1.40 | 107.48 | 1.98 | -95.04 | 3.13 | 86.53 |
| 4 | 0.97 | 103.20 | 1.16 | -87.12 | 1.28 | 61.64 |
| 5 | 0.31 | 109.06 | 0.47 | -106.21 | 0.80 | 35.36 |
| 6 | 3.25 | 146.98 | 1.44 | -70.97 | 1.95 | 15.01 |
| 7 | 0.66 | 139.20 | 0.63 | -127.92 | 1.83 | 48.15 |
| 8 | 1.09 | 113.96 | 0.50 | -132.85 | 1.34 | 23.23 |
| 9 | 0.77 | 93.95 | 1.17 | 161.97 | 1.48 | -11.07 |
| 10 | 0.49 | 85.08 | 0.99 | 160.30 | 0.93 | -6.20 |
| 11 | 0.52 | -98.21 | 0.39 | 111.37 | 3.44 | -23.03 |
| 12 | 0.41 | 76.68 | 0.47 | 110.26 | 2.98 | -20.03 |
| 13 | 0.29 | 88.45 | 0.64 | 148.14 | 2.06 | -25.97 |
| 14 | 0.60 | 87.66 | 1.09 | 155.53 | 1.44 | -24.97 |
| 15 | 0.54 | 78.69 | 0.74 | 157.07 | 0.95 | -27.14 |
| 16 | 0.91 | 49.47 | 0.45 | 179.50 | 2.22 | -65.02 |
| 17 | 0.18 | 66.37 | 0.29 | 107.10 | 1.86 | -60.01 |
| 18 | 1.03 | -37.93 | 1.23 | 136.56 | 1.23 | -60.04 |
| 19 | 0.41 | 45.52 | 0.82 | 89.22 | 1.23 | -72.11 |
| 20 | 0.41 | 49.16 | 0.62 | 94.89 | 0.82 | -57.84 |
| 21 | 0.20 | -136.04 | 0.00 | 0.00 | 2.68 | -92.03 |
| 22 | 0.19 | 171.87 | 0.12 | 4.87 | 2.29 | -84.05 |
| 23 | 0.02 | -13.00 | 0.29 | 60.12 | 1.75 | -88.96 |
| 24 | 0.54 | 41.82 | 0.93 | 78.88 | 1.57 | -90.00 |
| 25 | 0.51 | 5.89 | 0.66 | 91.95 | 0.84 | -92.86 |
| 26 | 0.57 | 16.60 | 0.14 | -143.97 | 1.77 | -117.10 |
| 27 | 0.58 | 19.27 | 0.33 | -113.68 | 2.78 | -131.00 |
| 28 | 0.23 | -13.39 | 0.23 | 12.09 | 1.61 | -127.02 |
| 29 | 0.41 | -31.85 | 1.07 | 28.21 | 1.25 | -136.02 |
| 30 | 0.35 | -41.92 | 0.82 | 28.38 | 0.70 | -109.80 |
| 31 | 0.18 | 156.37 | 0.10 | -57.99 | 2.78 | -149.93 |
| 32 | 0.21 | 22.62 | 0.23 | -54.46 | 2.25 | -150.00 |
| 33 | 0.04 | -14.18 | 0.33 | -27.80 | 1.81 | -148.07 |
| 34 | 0.29 | -36.03 | 1.13 | 10.73 | 1.26 | -146.98 |
| 35 | 0.37 | 13.24 | 0.76 | 16.43 | 0.66 | -133.05 |
| 36 | 0.95 | -60.02 | 0.37 | 153.07 | 0.78 | 164.74 |
| 37 | 0.64 | -72.16 | 0.20 | 143.43 | 1.19 | 147.43 |
| 38 | 0.39 | -87.00 | 0.06 | 149.04 | 0.77 | 149.37 |
| 39 | 0.20 | -106.56 | 0.82 | -64.92 | 0.21 | -163.86 |
| 40 | 0.37 | -81.87 | 0.58 | -48.72 | 0.25 | -177.01 |

Figure 15: Sample of Tabular Output from OMS Measurements

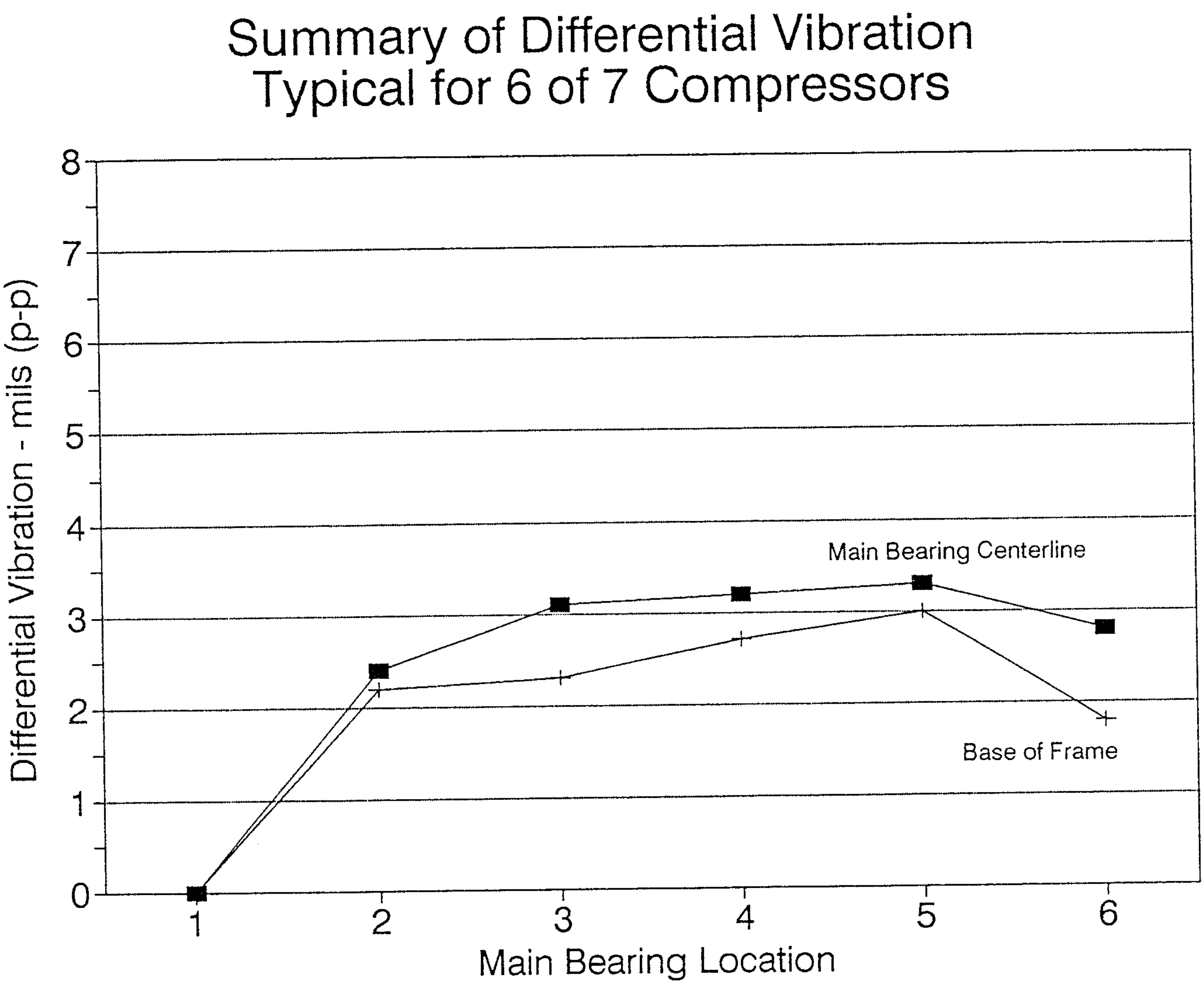



Figure 16: Differential Vibration for Compressors 1–6

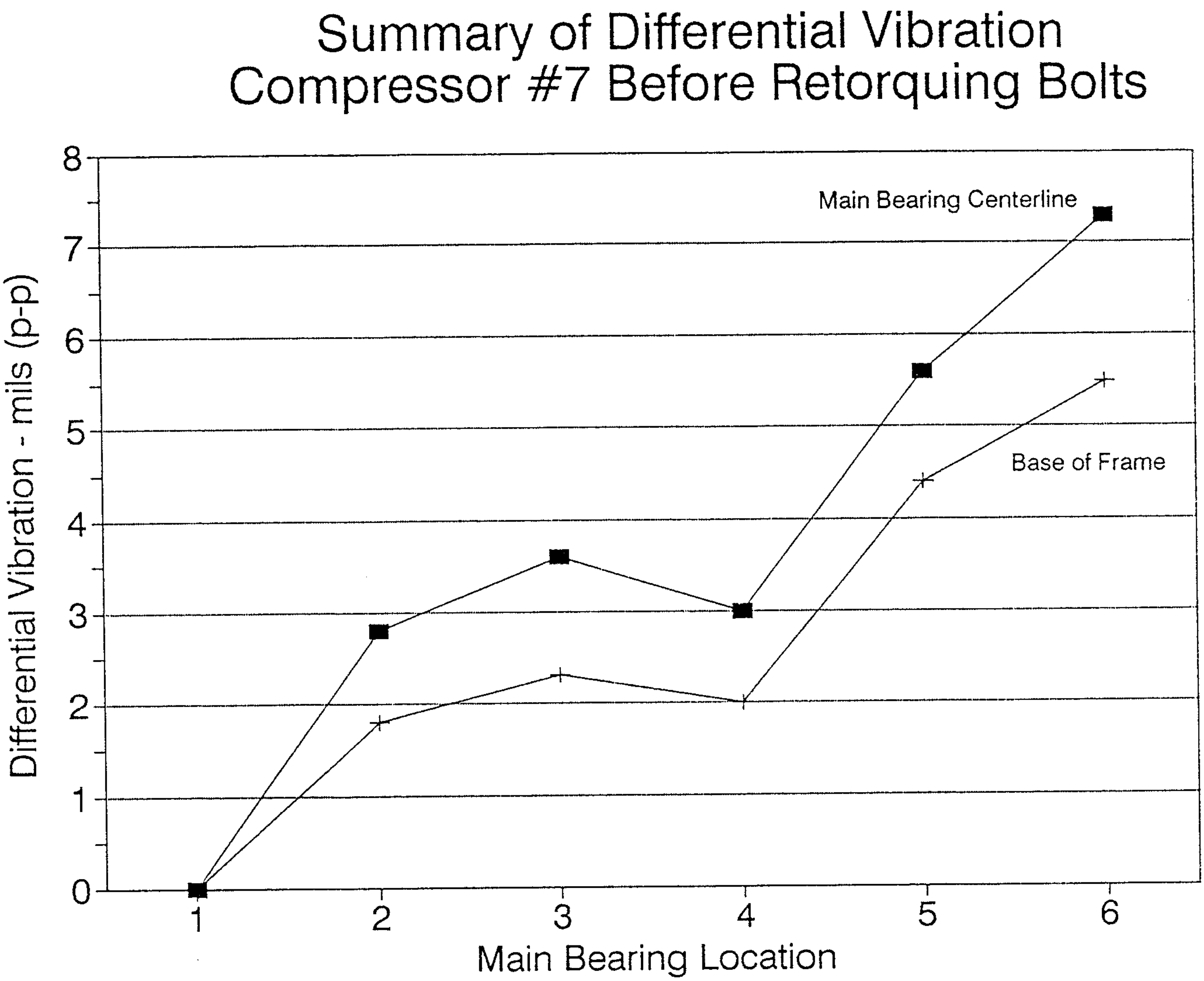



Figure 17: Compressor #7 Differential Vibration

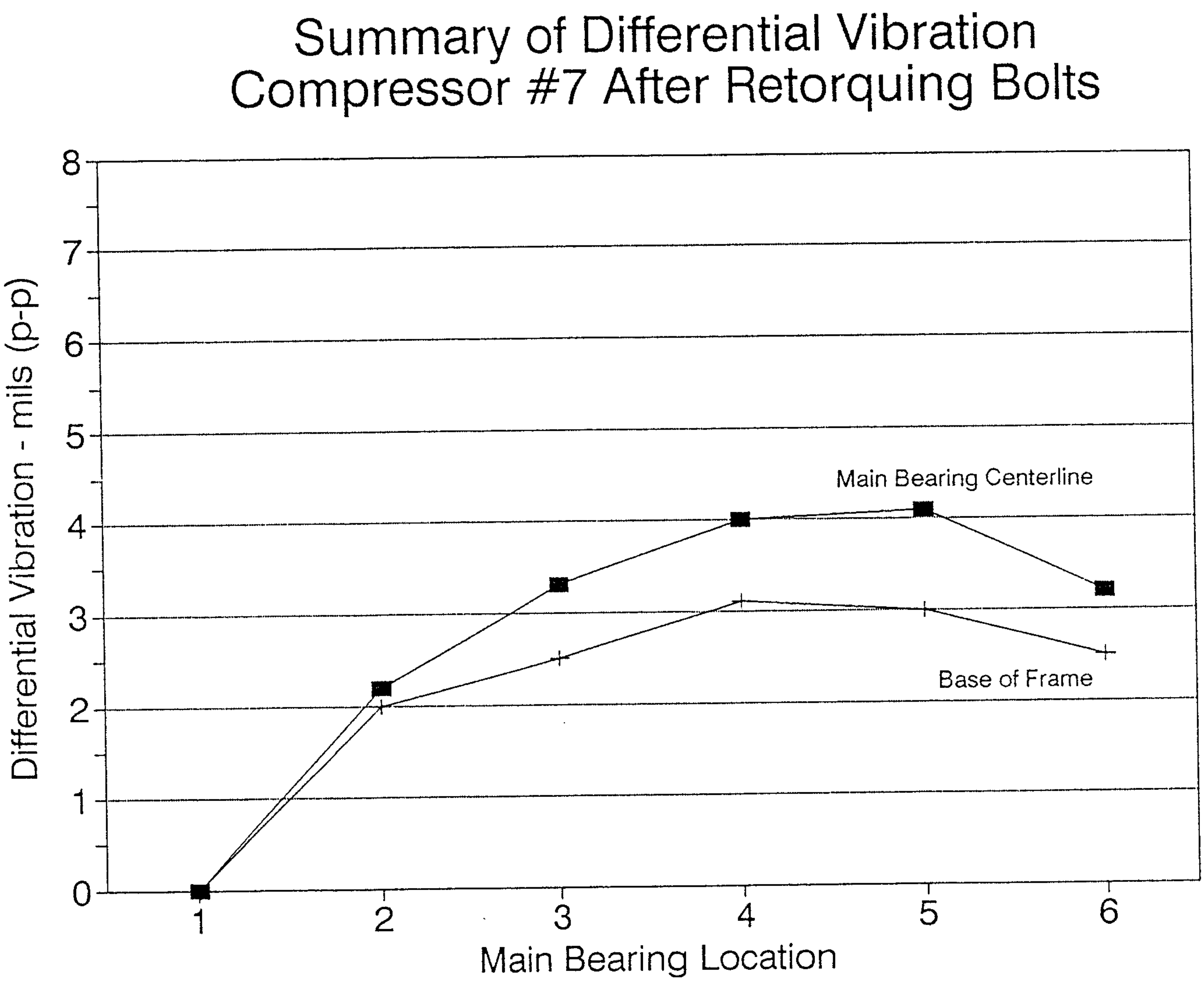



Figure 18: Differential Vibration for Compressor #7 After Retorquing Bolts

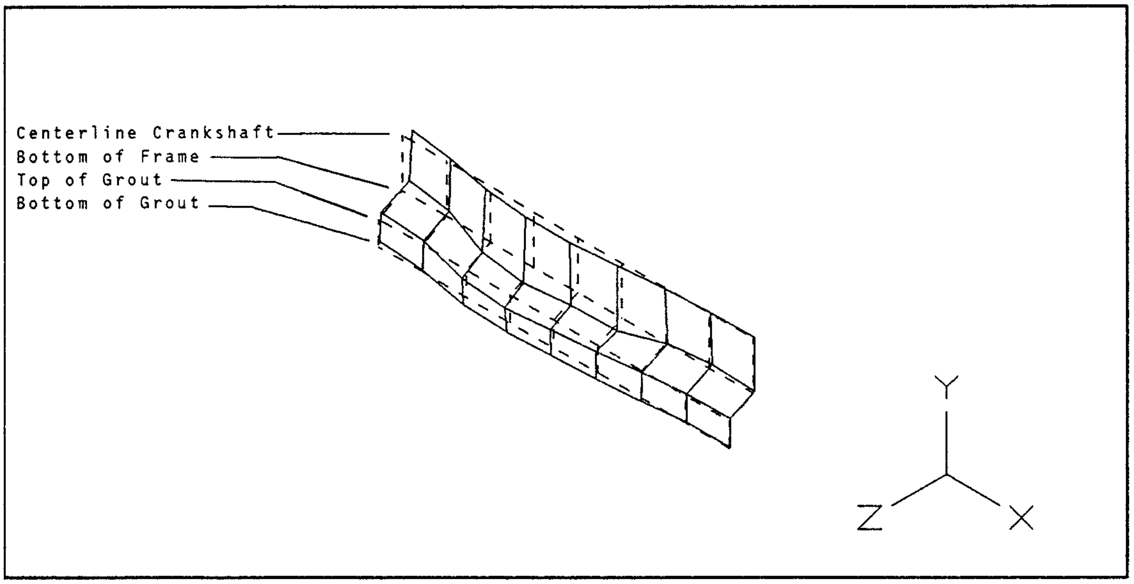



Figure 19: "Good" Unit

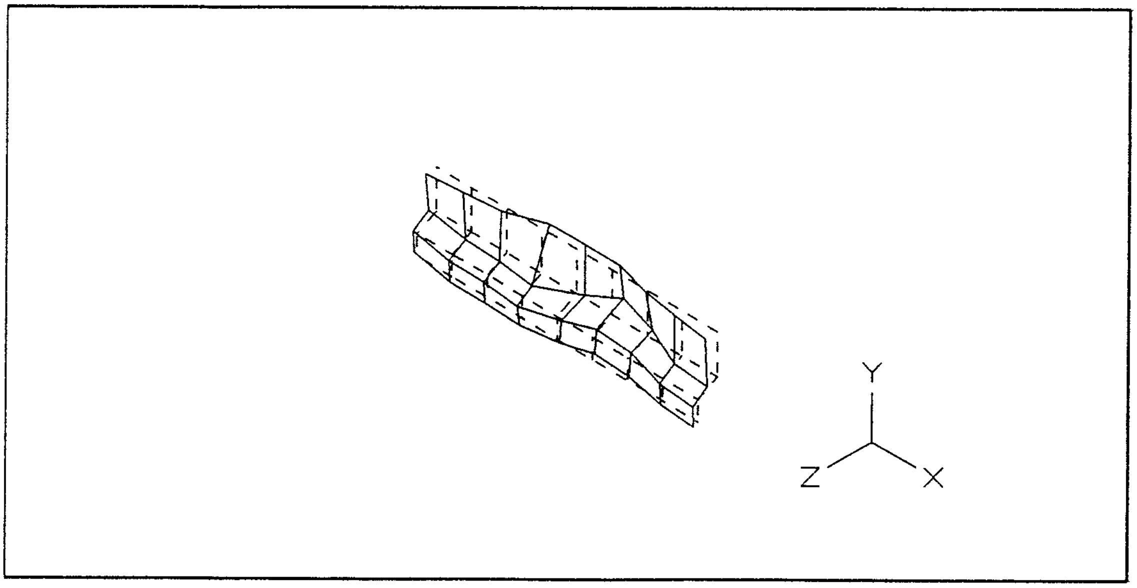



Figure 20: "Good" Unit Using Wrong Display Type

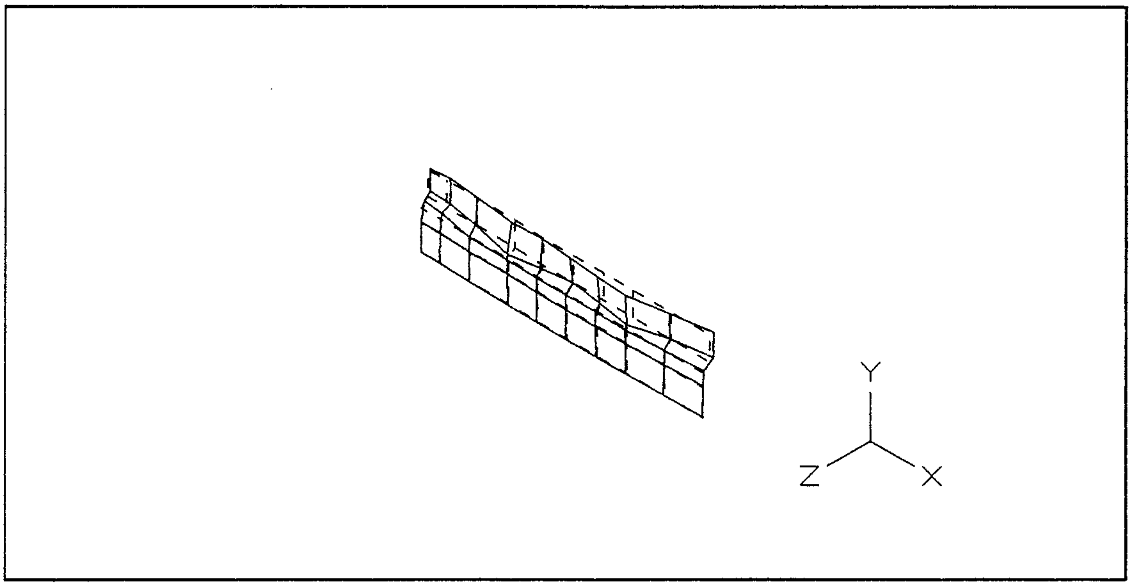



Figure 21: Loose Anchor Bolts at #4 and #8
Grout Cap Broken at #1 and #2

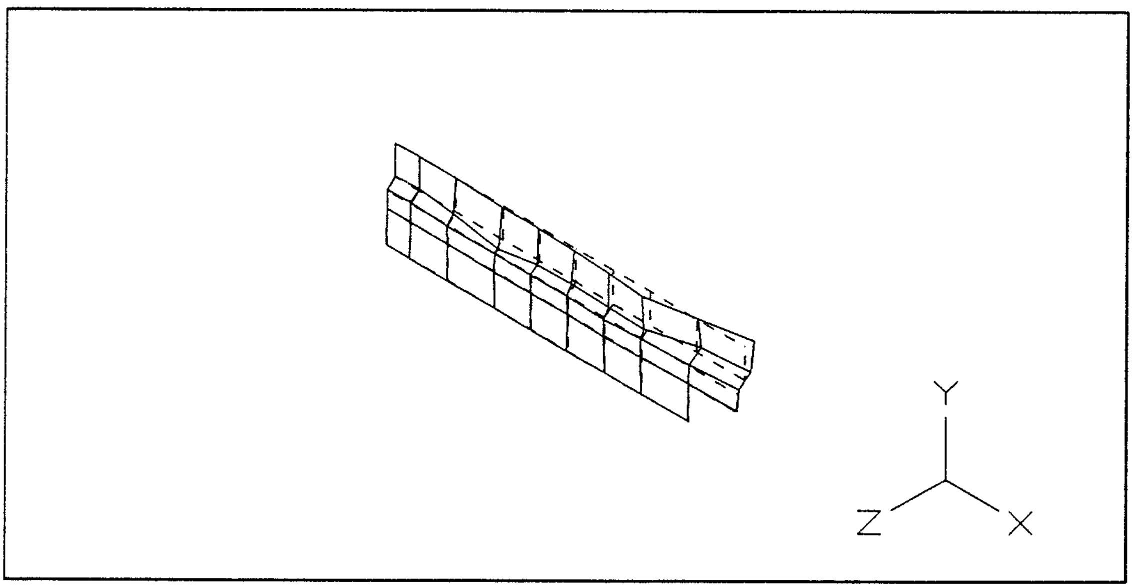



Figure 22: Oily at Near End

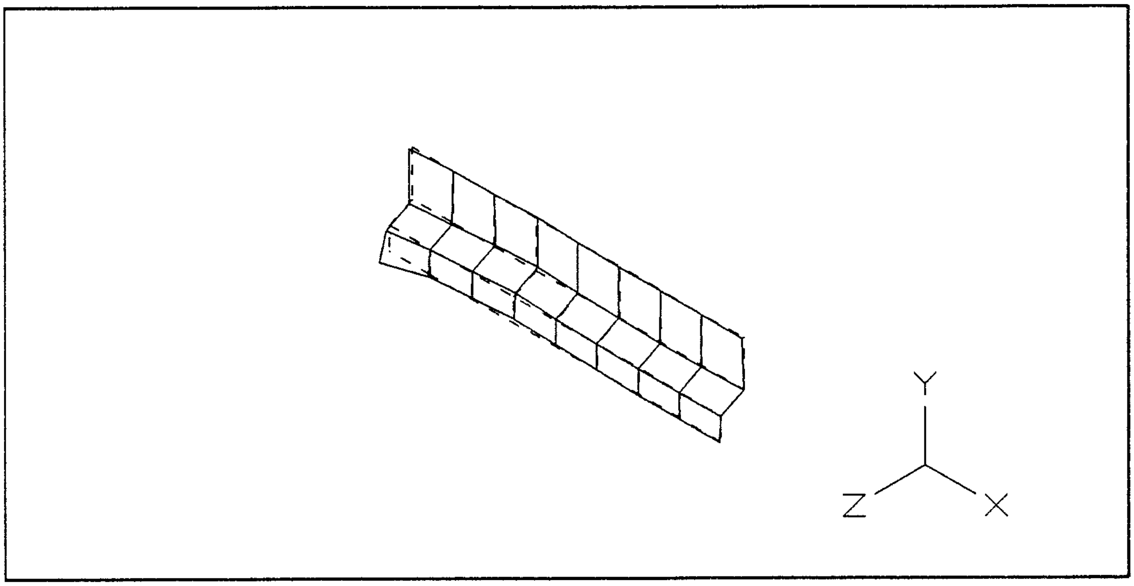



Figure 23: Broken Foundation at Far End

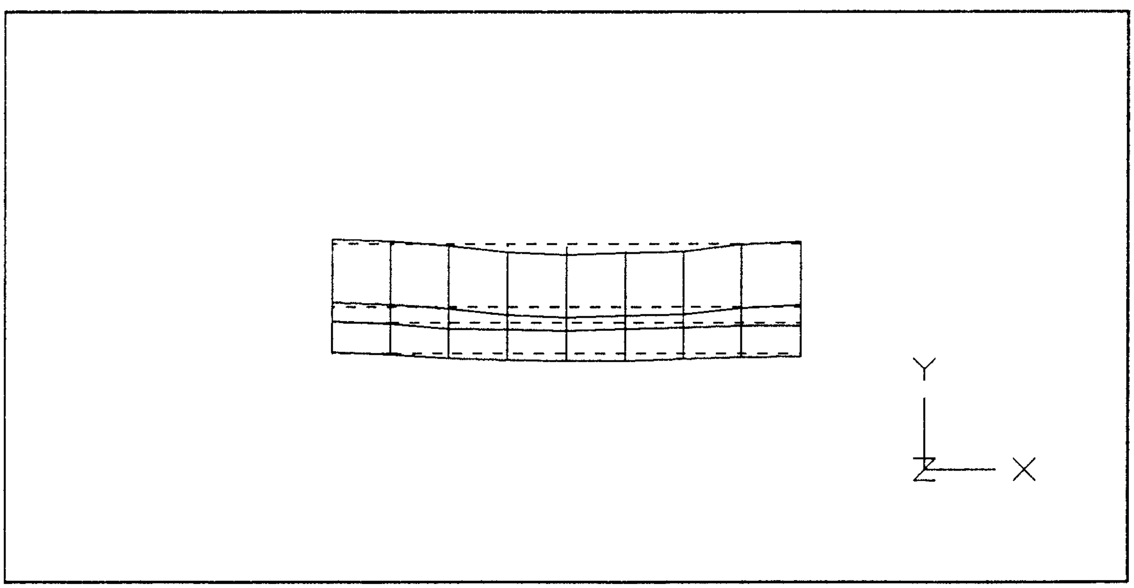



Figure 24: Elevation Showing Vertical Motion