Motor-Generator Vibration Problems Encountered When Restaging an FCCU Turboexpander

by
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This paper describes the solution of a vibration problem which resulted from the conversion of a single-stage power-recovery turbo expander train in an FCCU to a two-stage turbo expander. Details of the equipment train and operating speeds are given in Figure 1. During the start up of the upgraded expander train, high vibrations (in excess of 10 mils peak–peak) were experienced by the motor-generator. These high vibrations caused the unit to shut down as soon as it reached rated speed.

Because of high vibrations, the train was not able to operate for any length of time, however, it was operated long enough to obtain data to balance the motor-generator to allow further investigation of the problem. Accelerometers and permanently installed proximity probes were used to obtain the vibration data to determine the location of the critical speeds of the motor, one of which was near the operating speed. The motor-generator was field balanced to allow operation until a long-term solution could be developed.

Analytical Model

Because of the critical nature of the train, a critical speed analysis was initiated as soon as the testing identified the problem. The undamped critical speed map and mode shape plots are shown in Figures 2–4. The critical speed map shows that the second critical speed could be near 3600 cpm for a support stiffness of 2 million lb/in. The second mode at 3547 cpm has a maximum amplitude at the expander end coupling (Station 1), indicating a sensitivity to coupling weight.

Unbalanced response analyses were made of the original motor-generator design to determine the location and response amplitude of the critical speed. The response to an unbalance at the expander coupling is given in Figure 5. The unbalanced response analyses evaluated the sensitivity of the motor-generator to changes in bearing clearance, oil temperature, and coupling weights.

Critical Speed

The high vibration levels of the motor-generator were determined to be caused by a lateral critical speed near the operating speed. Peak responses were measured at about 2600 rpm and 3550 rpm in the vertical direction and 2600, 3150, and near 3600 rpm in the horizontal direction (Figure 6). During the field testing, the critical speeds were found to be sensitive to the oil bearing temperature. On the basis of this sensitivity, the bearing clearance was increased and the oil temperature was increased to move the critical speed below operating speed. These changes are described in more detail in the following sections. This made the unit easier to balance so that it could be operated with acceptable vibration levels until the next planned outage. Meanwhile, analyses were continued in an effort to develop a permanent solution.

Effect of Oil Temperature and Bearing Clearance Changes

The bearings installed on the motor-generator were cylindrical bearings with forced lubrication. The installed clearance of the original bearings was 9 mils (diametrical). As an attempt

to lower the critical speed away from operating speed, the lube oil was warmed up to 120°F. The effect of the bearing oil temperature reduced the critical speed to 3450 rpm with an amplitude of 7.7 mils and an amplification factor of 21.5 (Figure 7). This sensitivity to bearing oil film stiffness indicated that the critical speed could also be affected by a change in the bearing clearance.

The motor-generator manufacturer stated that the bearing clearance for this motor-generator could be increased to 15 mils. Larger clearance bearings were made and installed. The oil temperature was held within the range of 115 to 125°F maximum. The net effect of increasing the bearing clearance and increasing the oil temperature to 120°F resulted in lowering the critical speed to 3360 cpm, with an amplitude of 4 mils, and an amplification factor of 16. The results of the change in critical speed for the bearing clearance increase can be seen by comparing Figures 7 and 8. The vibration levels at the running speed of 3600 rpm were less than 2 mils peak–peak.

Field Balancing

The motor-generator was field balanced with the 15 mil clearance bearing and the oil temperature set at 120°. The balance correction brought the vibration levels down below 2 mils at all probes. After the unit heated up, the vibrations were as follows:

MIBV = 0.6 mils p–p	MOBV = 1.0 mil p–p
MIBH = 1.3 mils p–p	MOBH = 1.2 mils p–p

The vibration levels were considered acceptable and the cat cracking process was then started. The unit was monitored continuously during the start up and the vibration levels stayed relatively constant. Once the unit lined-out, the vibration levels were less than 1.5 mils peak–peak at all points.

After the unit had been running approximately one week, the vibration levels increased by approximately 1 mil and it was noted that they were not remaining constant over a period of time. During December 16–21, 1985, temperatures, flow rates, generated power and vibrations were recorded every thirty minutes. This data was taken to help identify the factors which might be causing a variation in the vibration amplitudes. The data was taken over approximately a 120 hour period.

Several statistical analyses were made of this data to determine the degree of correlation and the cause and effect relationship. The ambient temperature was shown to have the highest correlation on the motor-generator vibrations. It can be seen that this relationship is an inverse relationship by comparing Figure 9 with 10. Higher ambient temperature resulted in lower vibrations. The initial feeling was that Motor A was defective and should be replaced with Motor B (the spare motor-generator).

Shop Tests

The results of the lateral critical speed analysis was a recommendation that a reduced-moment coupling be installed on the motor-generator (expander end) to raise the lateral critical

speed which should decrease its sensitivity to imbalance. Since there was a 26 week lead time for the coupling, it was decided to test the main motor-generator (Motor A) in the factory with the existing coupling and with a reduced-moment simulator (actual weight and overhung moment) with emphasis on defining the location of the lateral critical speeds and the vibration sensitivity. If significant improvements could be attained with a reduced-moment coupling, the coupling would be ordered and installed at the next turnaround.

Vibration Sensitivity of Motor-Generator with Existing Coupling

Because the motor-generator (A) was very sensitive to unbalance on the expander end coupling, its reliability was questioned. Tests were performed on both the operating motor-generator (A) and the spare motor-generator (B) to compare the lateral critical speeds, vibration mode shapes and the sensitivity to unbalance. The tests were designed to obtain the necessary data to explain the high motor-generator vibrations which were a problem since the initial start up of the Power Recovery Train with the two-stage expander. The test results were used to decide if Motor A could meet the vibration specification with a reduced-moment coupling. If Motor A failed to meet the API vibration specifications then it would be removed and replaced with Motor B.

The differential vibrations caused by the addition of a trial balance weight were analyzed to show the sensitivity of the motor-generator to unbalance at each of the three balance planes. The vibration sensitivity was determined by vectorially subtracting the vibration amplitudes and phase of two subsequent speed runs (having different known balance weights) at each speed increment. The vibration sensitivity of Motor A was originally 1.40 mils/inch-ounce (vertical) at 3420 rpm (peak response) with the 15 mil clearance bearings (Figure 11).

Comparisons of tests showed that both motor-generators A and B were similar in location of critical speeds and unbalance sensitivity. Motor A or B would have similar operational characteristics in the Power Recovery Train.

The test results showed that the most significant factor which caused the motor-generator to be sensitive to unbalance was the location of a critical speed near 3600 rpm. The results of tests simulating various coupling configurations showed that the vibrational sensitivity to unbalance was a function of coupling overhung moment.

Lighter weight couplings, and those with smaller overhung moment, had lower sensitivity to unbalance as shown in Figure 12. The proposed Reduced Moment Coupling weighed 314 lbs and had an overhung moment of 4518 in–lbs compared to the existing coupling weight of 496 lbs and an overhung moment of 10108 in–lbs.

The vibration sensitivity of Motor A was originally 0.95 mils/inch–ounce (vertical) at 3600 rpm with the 15 mil clearance bearings and the existing coupling. Tests of Motor B established its maximum vibration sensitivity as 0.51 mils/inch–ounce (simulator). With the new reduced-moment coupling, the vibration sensitivity of the original system (single stage expander) should be attainable (0.23 mils/inch–ounce).

Lateral Critical Speeds

The calculated second lateral critical speed for the motor-generator with the new reduced-moment coupling was 4000 rpm. Since the lighter coupling raised the lateral critical speed, an additional increase in the critical could be attained by using the 9 mil clearance bearings, which would increase the oil film stiffness. The second lateral critical speed was expected to be a least 3900 rpm with the 9 mil clearance bearings.

Vibration Amplitude

The Power Recovery Train which included Motor A was originally purchased to meet API specifications. Therefore, it was recommended that acceptance of Motor A be based upon the API allowable vibration and balance specification which originally applied to the Power Recovery Train. The shop tests demonstrated that the motor-generator with the new reduced-moment coupling could be expected to meet the API vibration specification.

Based upon API criteria, the allowable vibration amplitude for operating at a speed of 3600 rpm would be 2.29 mils peak–peak including the allowance for runout. For the motor-generator operating solo, the maximum vibration did not exceed 1.0 mils peak–peak at 3600 rpm on any proximity probe. The reduced-moment coupling was installed on the motor-generator during the next spring turnaround (1987).

Startup Train Tests With Reduced-Moment Coupling

After installing the reduced-moment coupling on Motor A, tests were performed to confirm the sensitivity of the motor-generator to unbalance coupled in the train. The tests showed that Motor A had low sensitivity to coupling unbalance.

Motor A was trim balanced to a maximum vibration amplitude (corrected for mechanical and electrical runout) of 2.0 mils peak–peak on the expander end horizontal. Unbalance sensitivity tests were performed using the balance plane on the expander end coupling. The unbalance sensitivity plots for all proximity probes are given in Figure 13 and the values are given in Table 1.

Table 1: Unbalance Sensitivity
(with 6.55 inch-ounces on the expander coupling)

Probe Location	Differential Vibrations at 3600 rpm, mils p-p	Unbalance Sensitivity mils/in–oz
MIBV	0.2	0.03
MIBH	0.5	0.08
MOBV	0.4	0.06
MOBH	0.9	0.14

The maximum sensitivity to unbalance of Motor A was determined to be 0.14 mils/in-oz. The motor-generator vibration characteristics were stable and repeatable during the balancing procedure. Tracking the second order vibration signal during coastdown showed the second

lateral critical speed to be above 4000 cpm.

Data was taken with trial weights on all balance planes to make a final three plane balance. During these balance tests, the motor-generator was found to be relatively insensitive to the balance weights. The resulting vibrations of Motor A installed in the train with a final three plane balance are shown in Table 2.

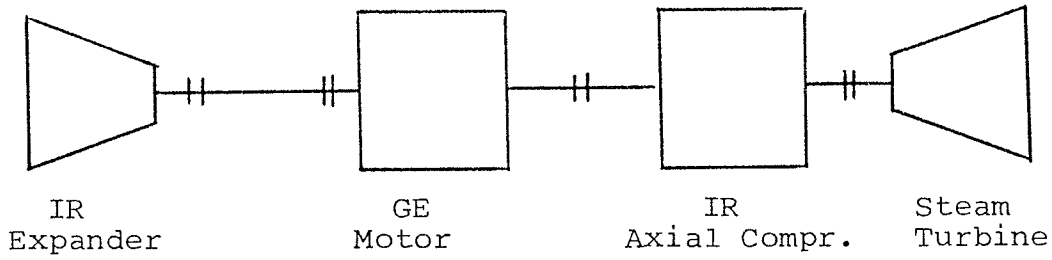
Table 2: Final Balance Vibrations – Motor A Coupled

Probe Location	Amplitude mils p–p	Phase Degrees
MIBV	0.9	314
MIBH	0.9	195
MOBV	2.0	351
MOBH	1.1	296

All of the vibration amplitudes listed in the tables were compensated for runout.

After the reduced-moment coupling was installed in 1987, the motor-generator has operated reliably with low vibrations and has no abnormal sensitivity to ambient temperature, oil temperature, or balance. The motor-generator has been through two turnarounds without incident. During the most recent turnaround in October, 1992, the motor-generator started with low vibrations and did not require any special balancing.

31-BL-1 Power Train



IR Axial Flow Compressor
1976 SN 4621
Type MTA-4015

Intake 14.4 psia 100 F
Discharge 55 psia
Sp Gr = 1.0

GE Motor 6000 HP 3580 RPM
Model SK861180C7

Rotation CW from Start
8611Z Frame Type K

IR Gas Expander FCC Flue Gas
Type E-248 SN E-5437 23630 HP
Inlet 55.7 psia 1350 F
Flow 8837 lb/Hr
MW = 29.1

Figure 1

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LATERAL CRITICAL SPEED ANALYSIS - CRITICAL SPEED MAP

31-BL-1 FCC POWER RECOVERY TRAIN EDI PROJ 85-319

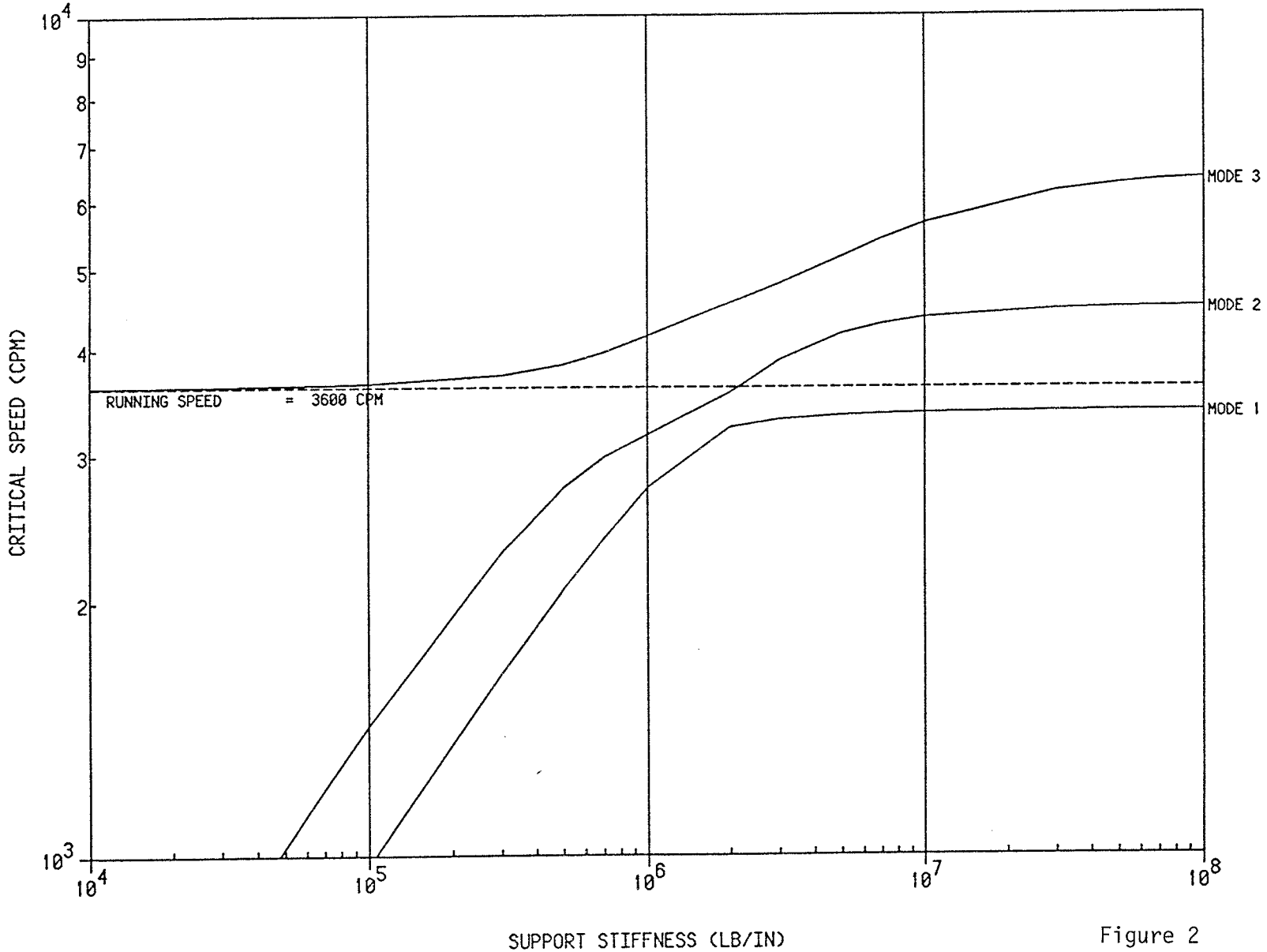

Figure 2

ENGINEERING DYNAMICS INCORPORATED
LATERAL CRITICAL SPEED ANALYSIS - ROTOR MODE SHAPES

31-BL-1 FCC POWER RECOVERY TRAIN EDI PROJ 85-319
ROTOR WT.= 7175.00 LBS. ROTOR LGTH = 130.13 IN. BRG SPAN = 89.00 IN

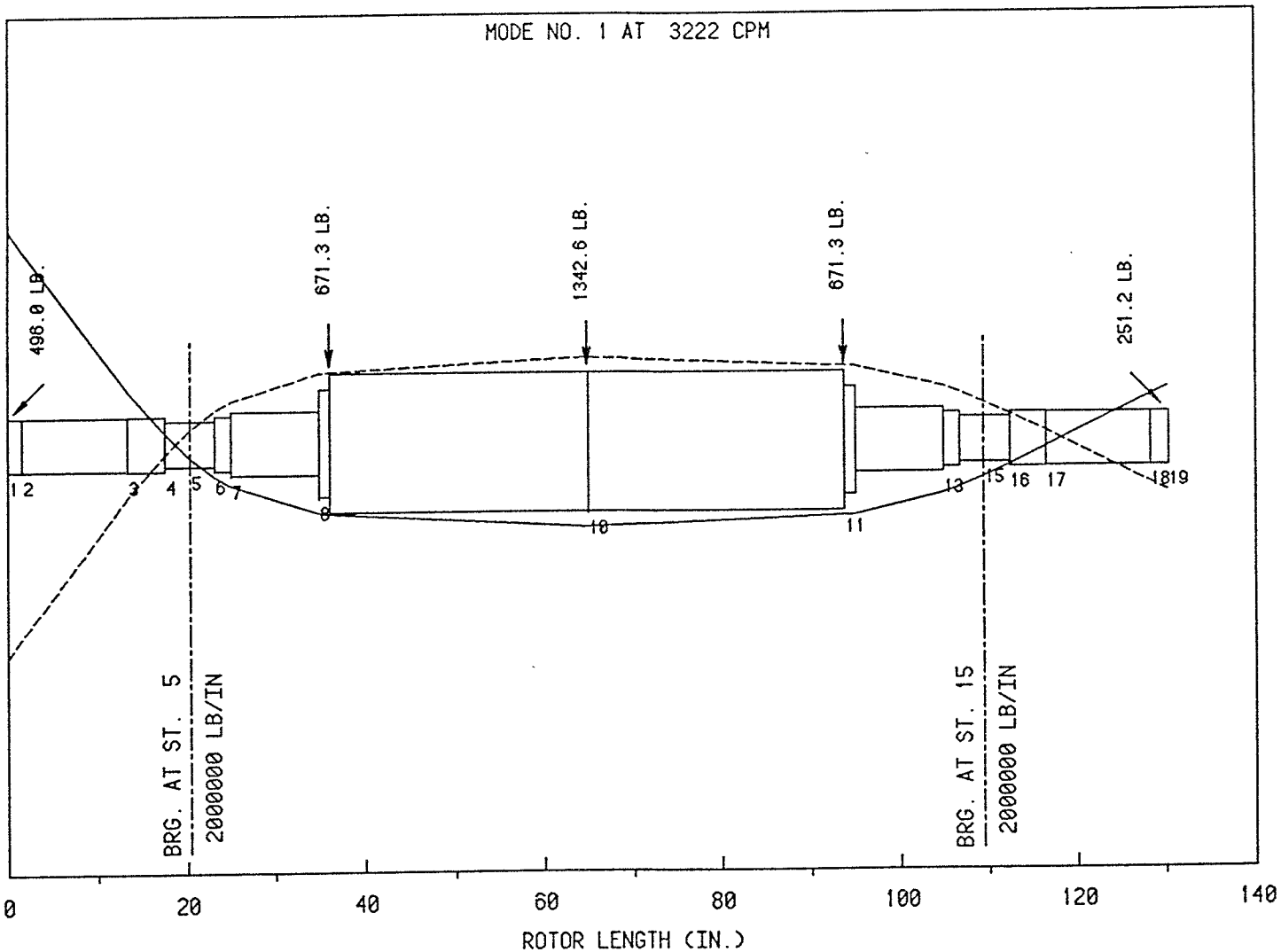

Figure 3

ENGINEERING DYNAMICS INCORPORATED
LATERAL CRITICAL SPEED ANALYSIS - ROTOR MODE SHAPES

31-BL-1 FCC POWER RECOVERY TRAIN EDI PROJ 85-319
ROTOR WT.= 7175.00 LBS. ROTOR LGTH = 130.13 IN. BRG SPAN = 89.00 IN

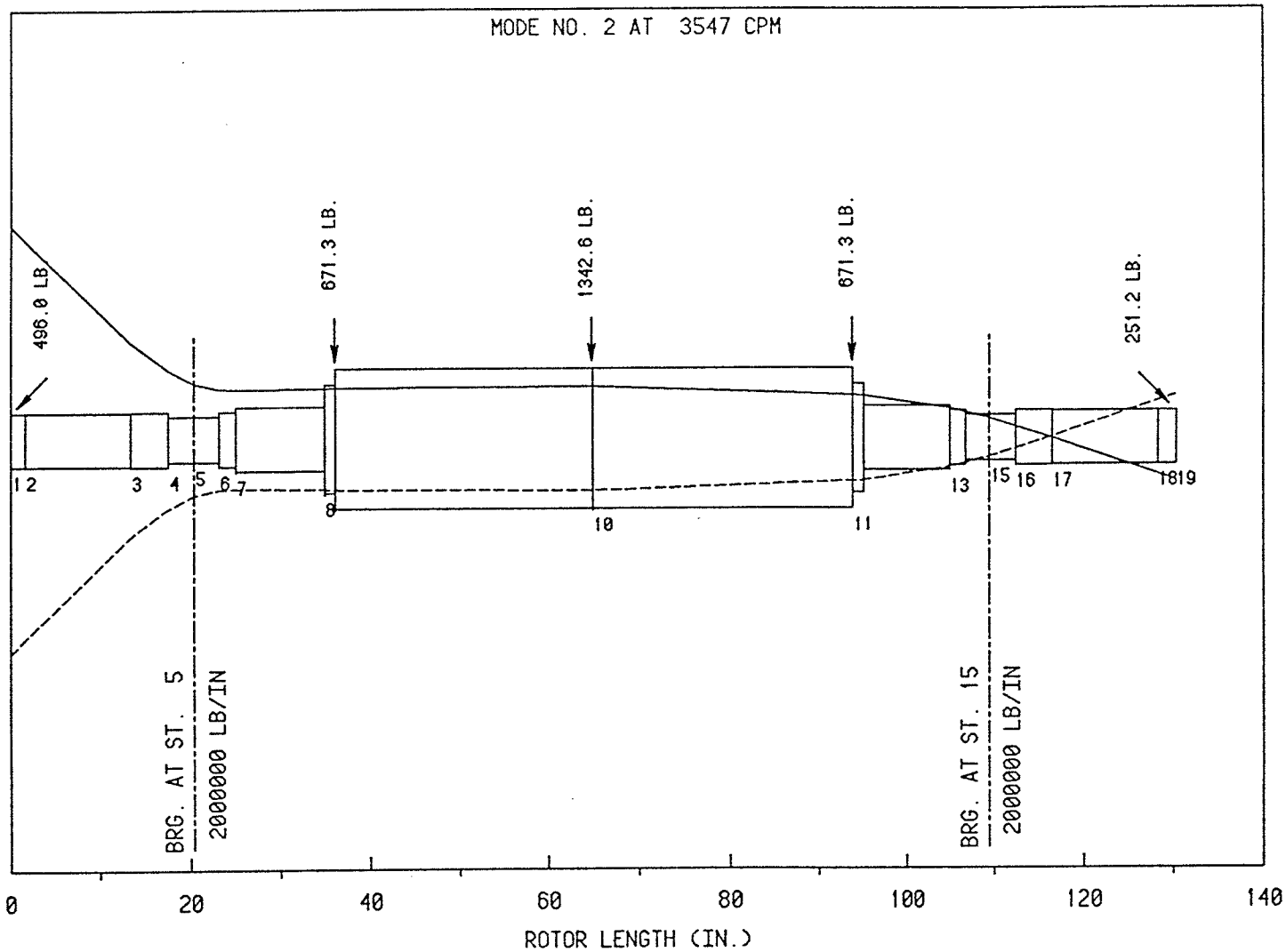

Figure 4

-EDI NO. 85319
BASELINE MODEL FILE=m3 EXP CPLG WT = 362 LBS
9 MIL DIAM. BRG CL - 120 DEG INLET OIL
UNBAL @ 1 - EXPANDER CPLG = 15.246 OZ-IN @ 0. DEG

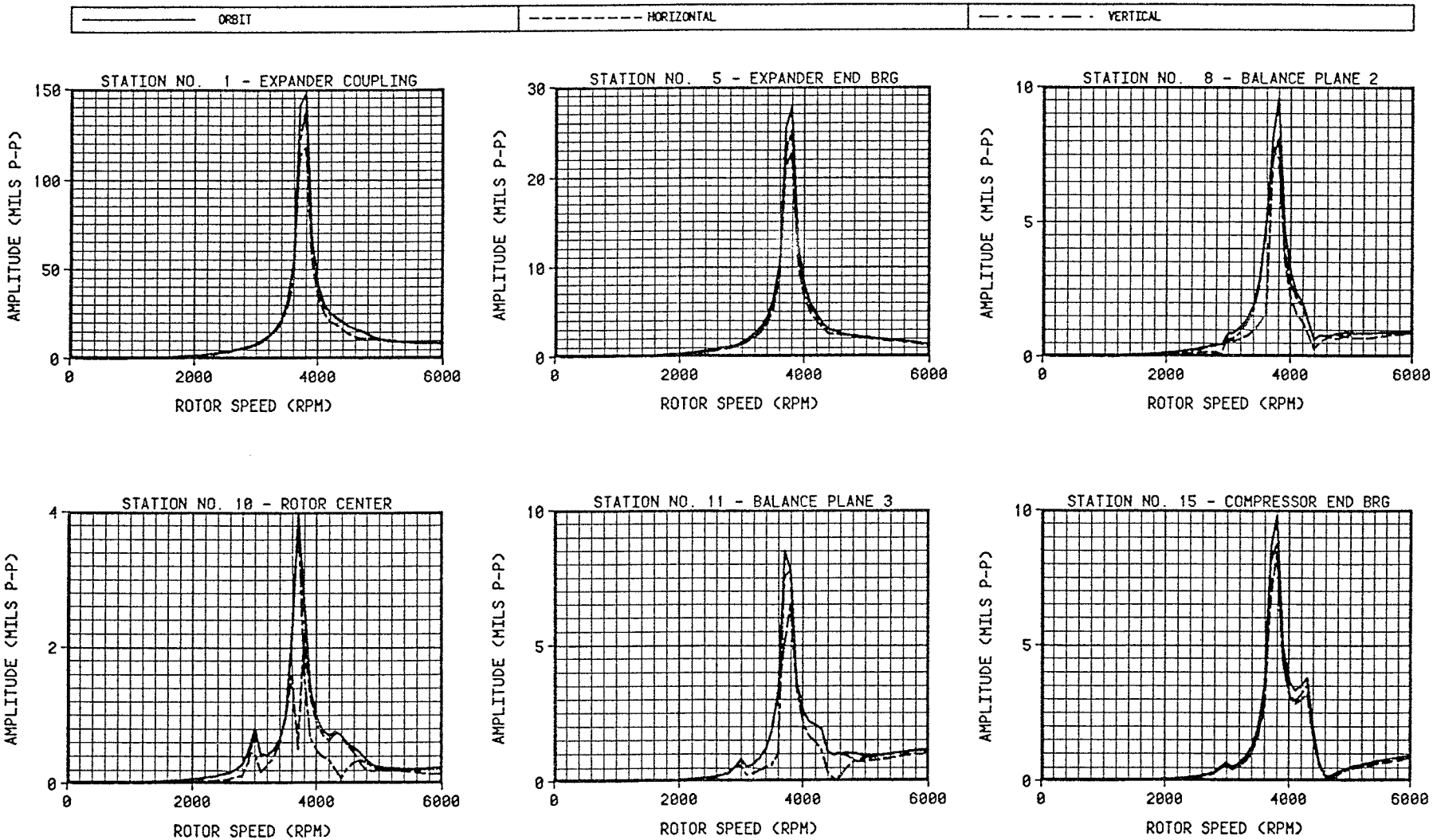

Figure 5

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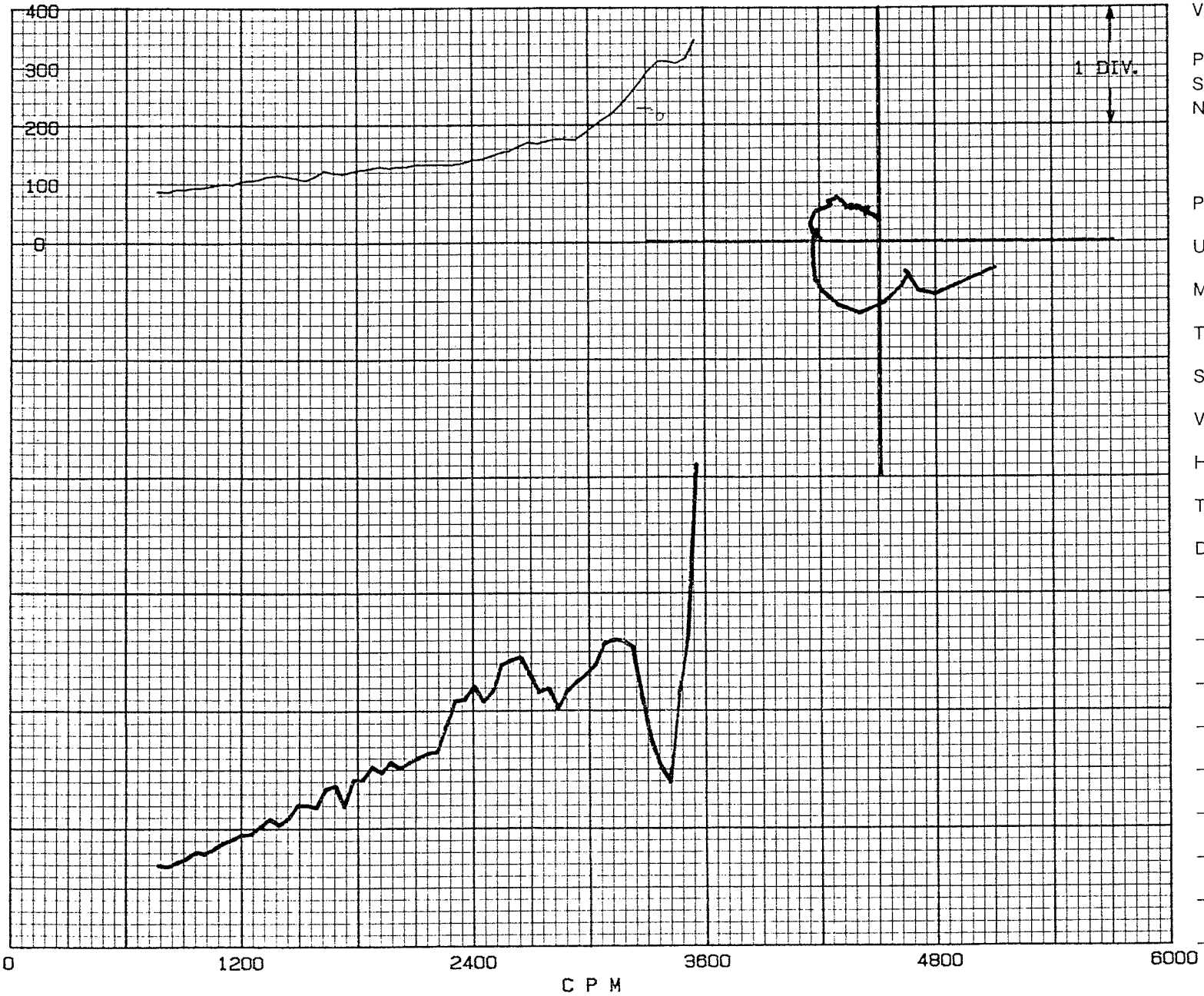


VIBRATION mils ☐
ips ☐ g's ☐
PULSATION psi ☐
STRAIN μ-in/in ☐
NOISE dB ☐

PLANT
UNIT 31-BL-1
MACHINE MOTOR-GENERATOR
TEST PT MIB-HORIZ
SPEED STARTUP
VERT 1.0 MIL/DIV
HORIZ 0 - 100 HZ
TIME 2:00 PM
DATE 10-23-85

Figure 6a

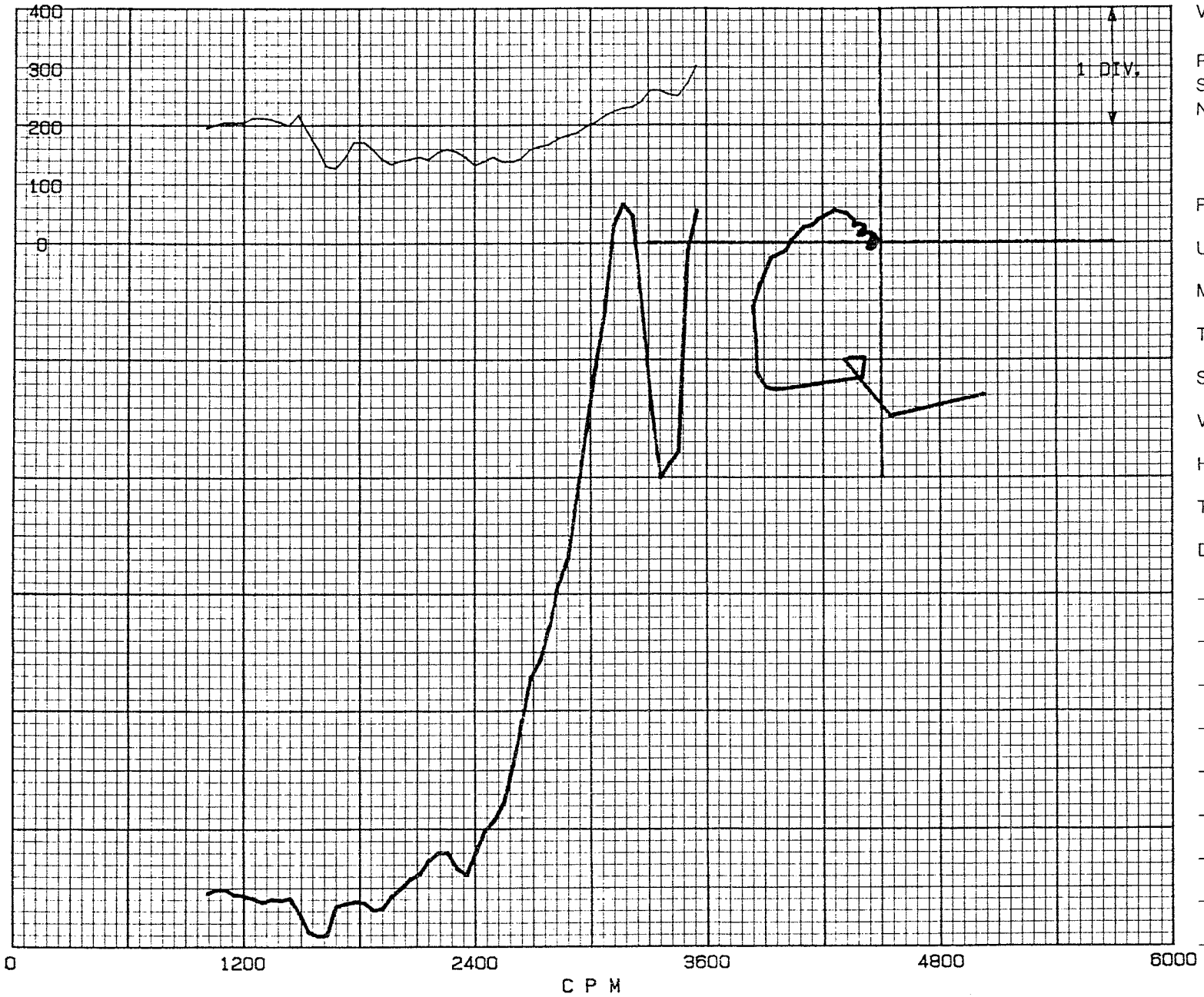
ENGINEERING DYNAMICS INCORPORATED SAN ANTONIO, TEXAS

VIBRATION mils ☐
ips ☐ g's ☐
PULSATION psi ☐
STRAIN μ-in/in ☐
NOISE dB ☐

PLANT
UNIT 31-BL-1
MACHINE MOTOR-GENERATOR
TEST PT MIB-VERTICAL
SPEED STARTUP
VERT 1.0 MIL/DIV
HORIZ 0 - 100 HZ
TIME 2:00 PM
DATE 10-23-85

Figure 6b

ENGINEERING DYNAMICS INCORPORATED SAN ANTONIO, TEXAS



VIBRATION mils ☐
ips ☐ g's ☐
PULSATION psi ☐
STRAIN μ-in/in ☐
NOISE dB ☐

PLANT
UNIT 31-BL-1
MACHINE MOTOR-GENERATOR
TEST PT MOB-HORIZ
SPEED STARTUP
VERT 1.0 MIL/DIV
HORIZ 0 - 100 HZ
TIME 2:00 PM
DATE 10-23-85

Figure 6c

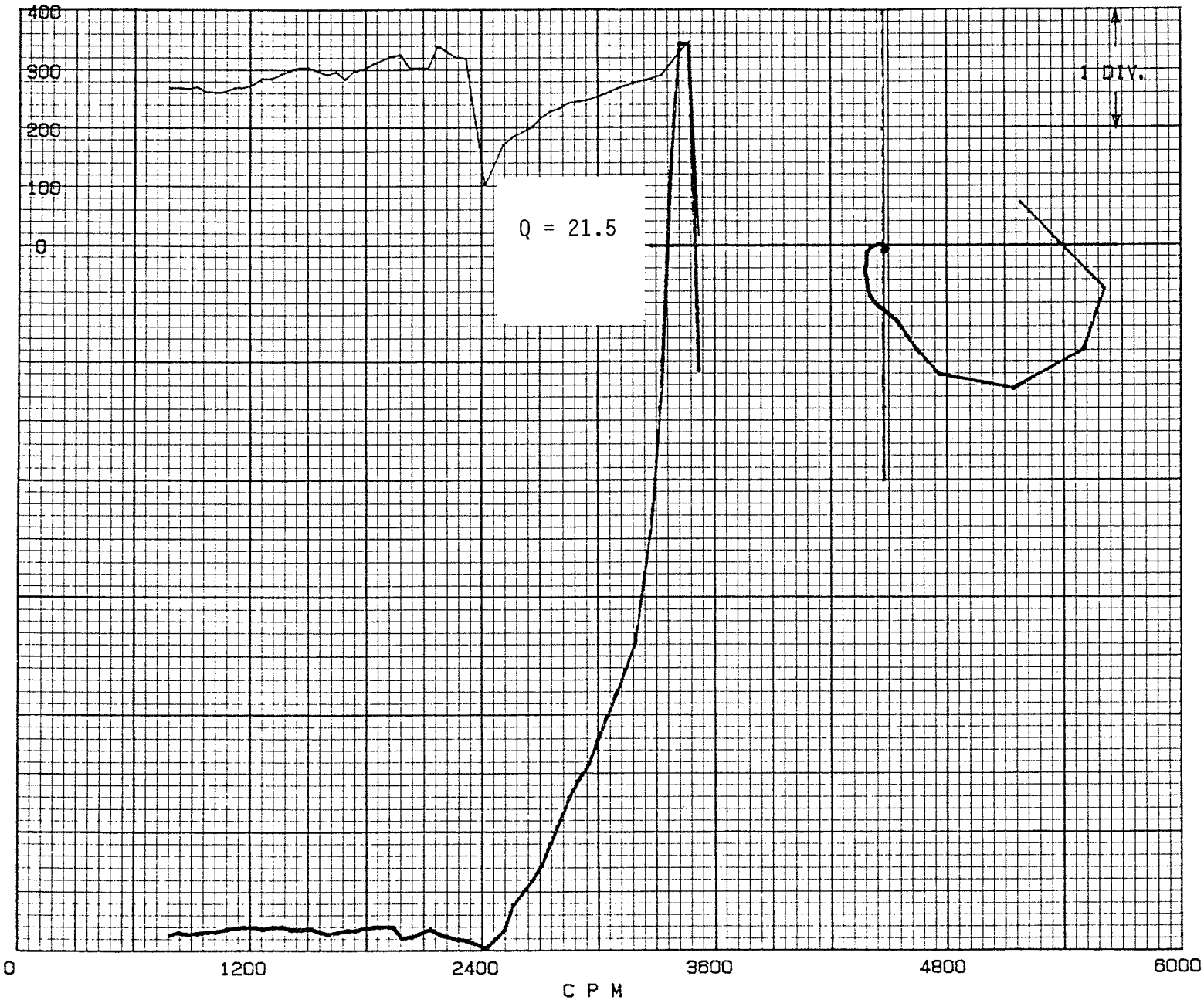
ENGINEERING DYNAMICS INCORPORATED SAN ANTONIO, TEXAS

VIBRATION mils ☐
ips ☐ g's ☐
PULSATION psi ☐
STRAIN μ-in/in ☐
NOISE dB ☐

PLANT
UNIT 31-BL-1
MACHINE MOTOR-GENERATOR
TEST PT MOB-VERTICAL
SPEED STARTUP
VERT 2.5 MIL/DIV
HORIZ 0 - 100 HZ
TIME 2:00 PM
DATE 10-23-85

Figure 6d

ENGINEERING DYNAMICS INCORPORATED SAN ANTONIO, TEXAS



VIBRATION mils ☐
ips ☐ g's ☐
PULSATION psi ☐
STRAIN μ-in/in ☐
NOISE dB ☐

PLANT
UNIT 31-BL-1
MACHINE MOTOR-GENERATOR
TEST PT MOB VERTICAL
SPEED COASTDOWN
VERT 1.0 MIL/DIV
HORIZ 0 - 100 HZ
TIME 1:50 PM
DATE 10-24-85
CORRECTION WTS.

OIL TEMP = 120 DEG F.
BRG CL. DIM. 9 MILS
CORRECTION WEIGHTS
PL 1 29 GM/177 DEG
PL 3 38.5GM/318 DEG

RUNOUT SUBTRACTED

Figure 7

ENGINEERING DYNAMICS INCORPORATED SAN ANTONIO, TEXAS

VIBRATION mils ☐
ips ☐ g's ☐
PULSATION psi ☐
STRAIN μ-in/in ☐
NOISE dB ☐

PLANT
UNIT 31-BL-1
MACHINE MOTOR-GENERATOR
TEST PT MOB VERTICAL
SPEED COASTDOWN
VERT 1.0 MIL/DIV
HORIZ 0 - 100 HZ
TIME 7:30 PM
DATE 10-24-85
CORRECTION WTS.

OIL TEMP = 120 DEG F.
BRG CL. DIM. 15 MILS
CORRECTION WEIGHTS
PL 1 29 GM/177 DEG
PL 3 38.5GM/318 DEG

RUNOUT SUBTRACTED

Figure 8

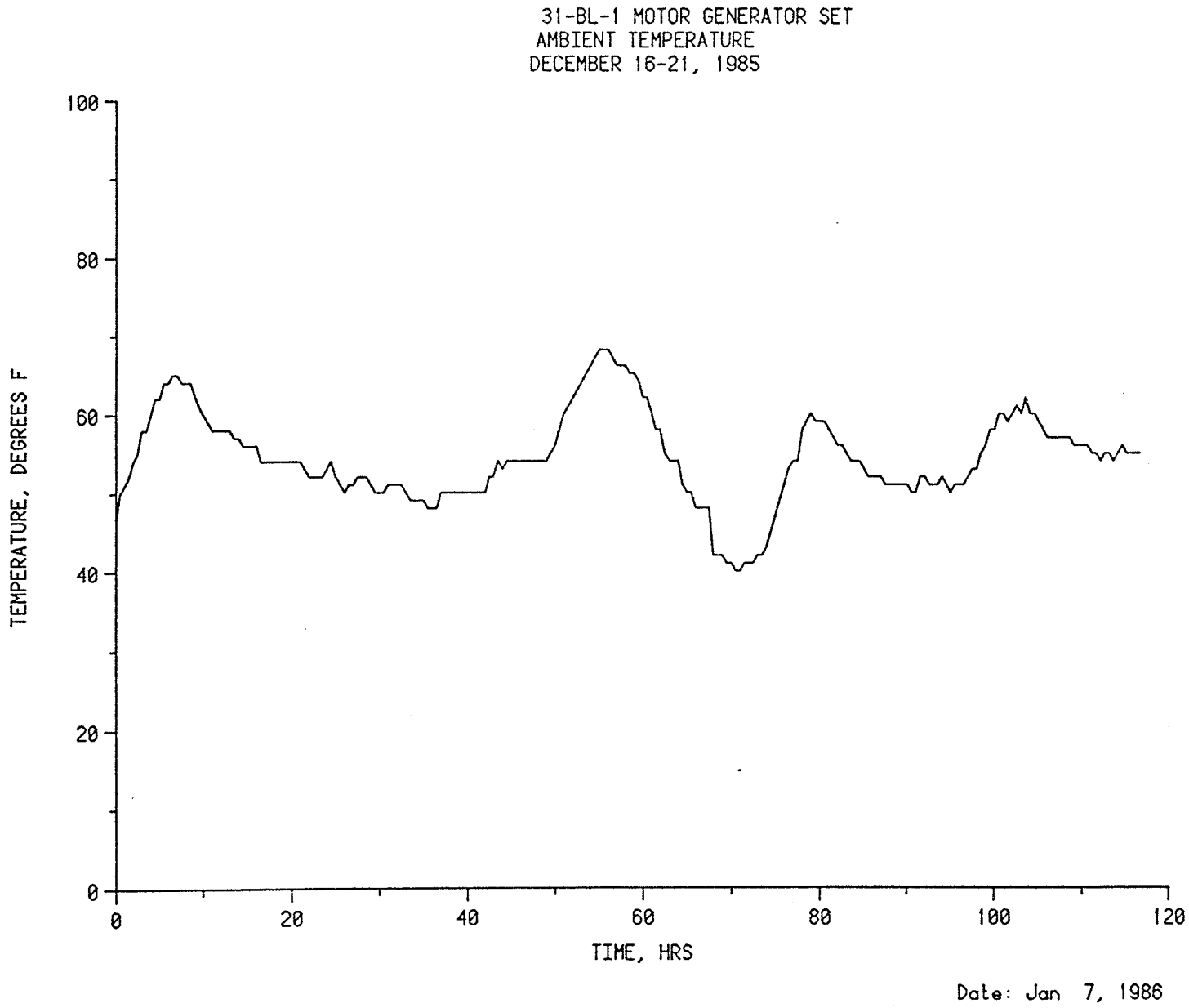


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Figure 9

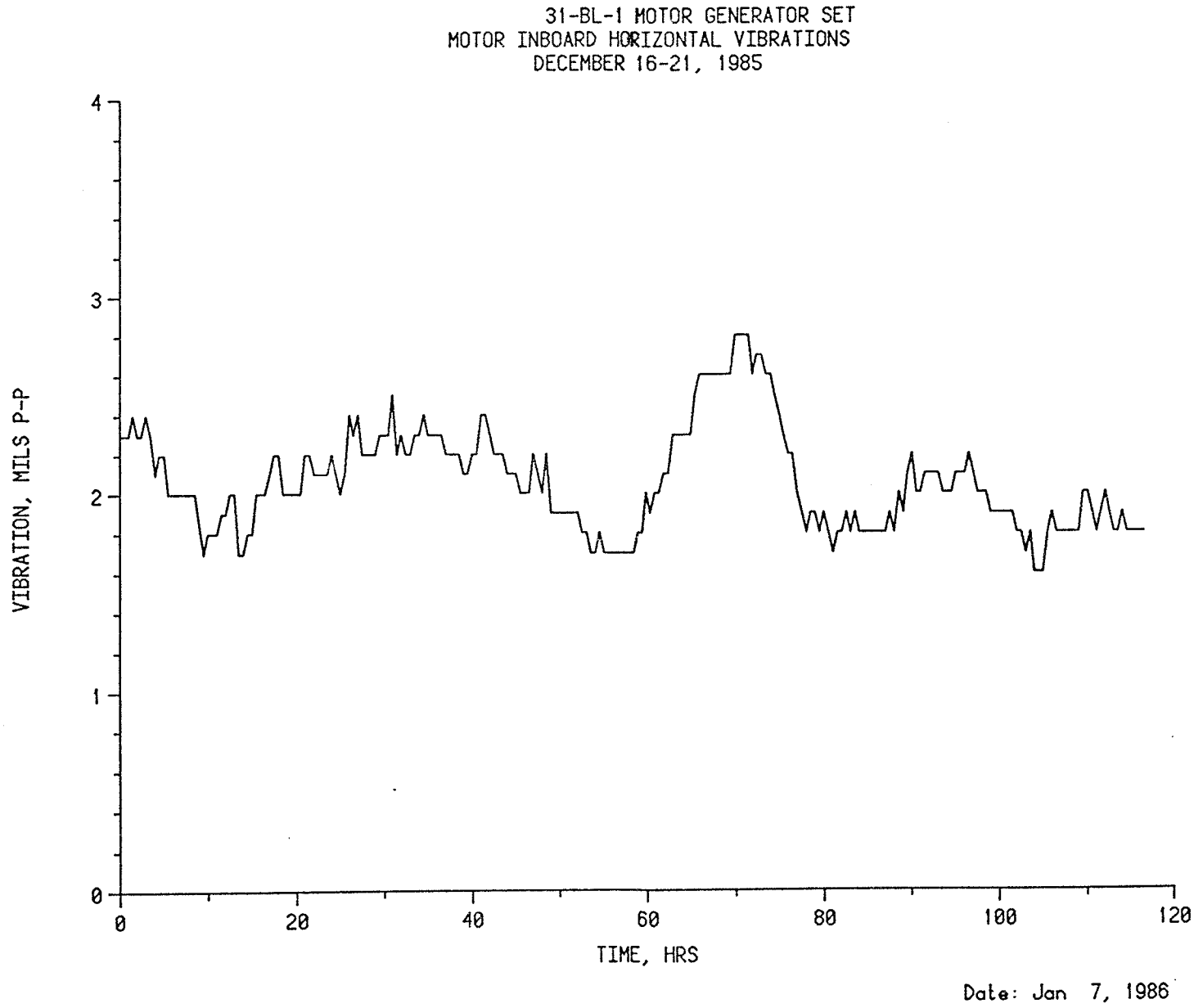

Figure 10

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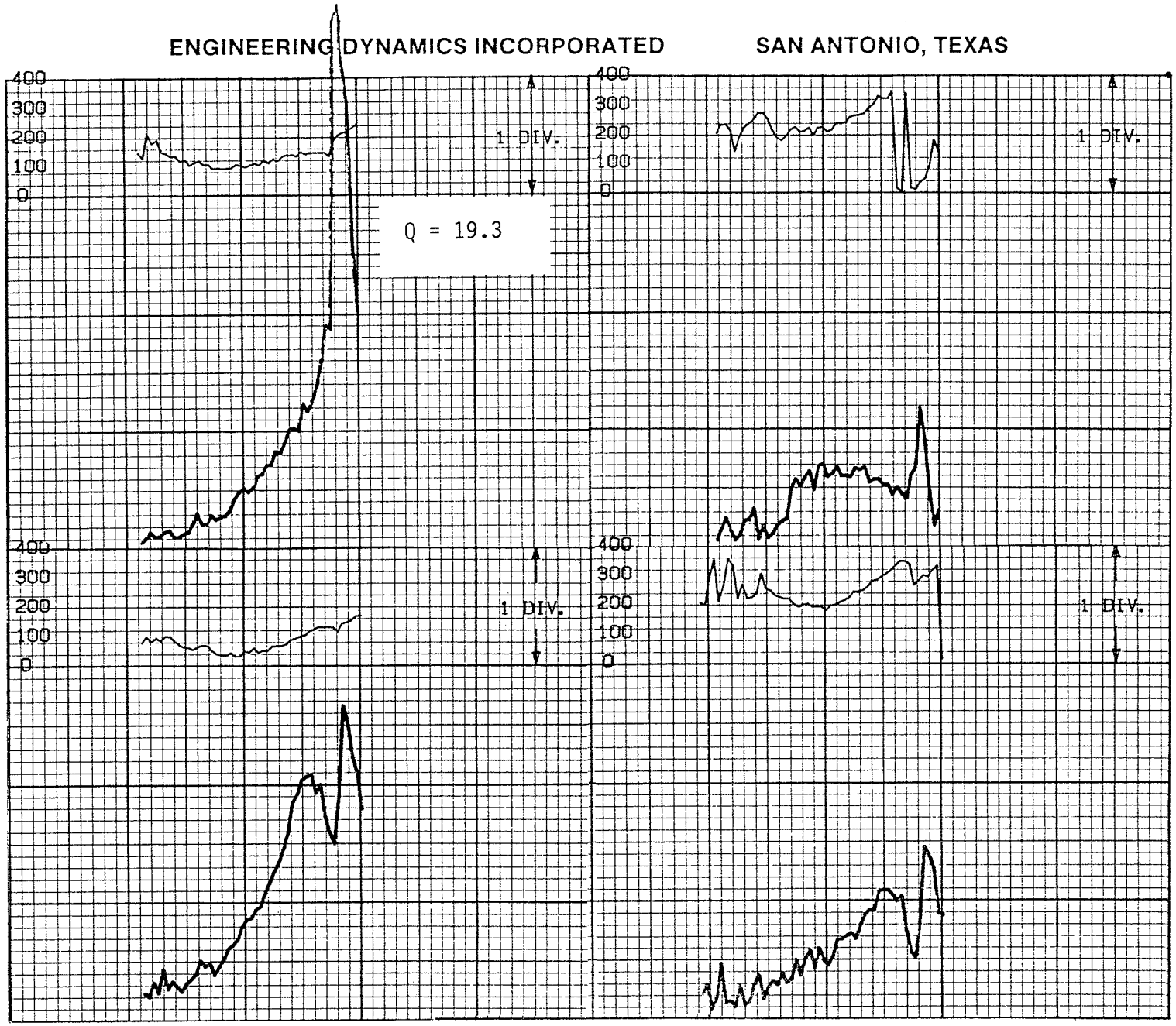
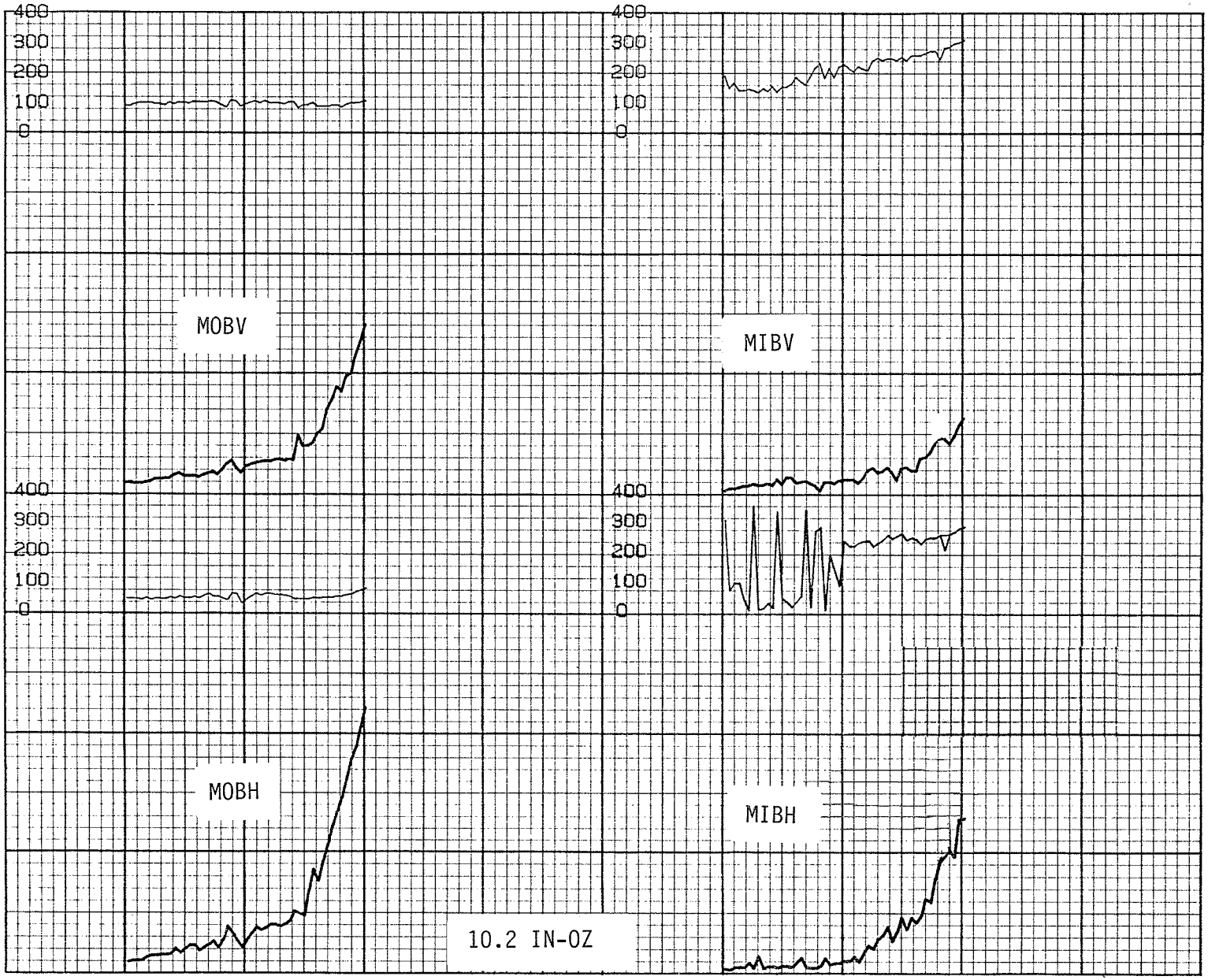


VIBRATION mils ☐
ips ☐ g's ☐
PULSATION psi ☐
STRAIN μ-in/in ☐
NOISE dB ☐

PLANT
UNIT
MACHINE
TEST PT MIB-V
SPEED COASTDOWN
VERT 2.0 MIL/DIV
HORIZ 0 - 100 HZ
TIME
DATE 10-25-85
DIFFERENTIAL BODE PLOTS
TRIAL WEIGHT LOCATION 1
22. GM

Figure 11

ENGINEERING DYNAMICS INCORPORATED SAN ANTONIO, TEXAS

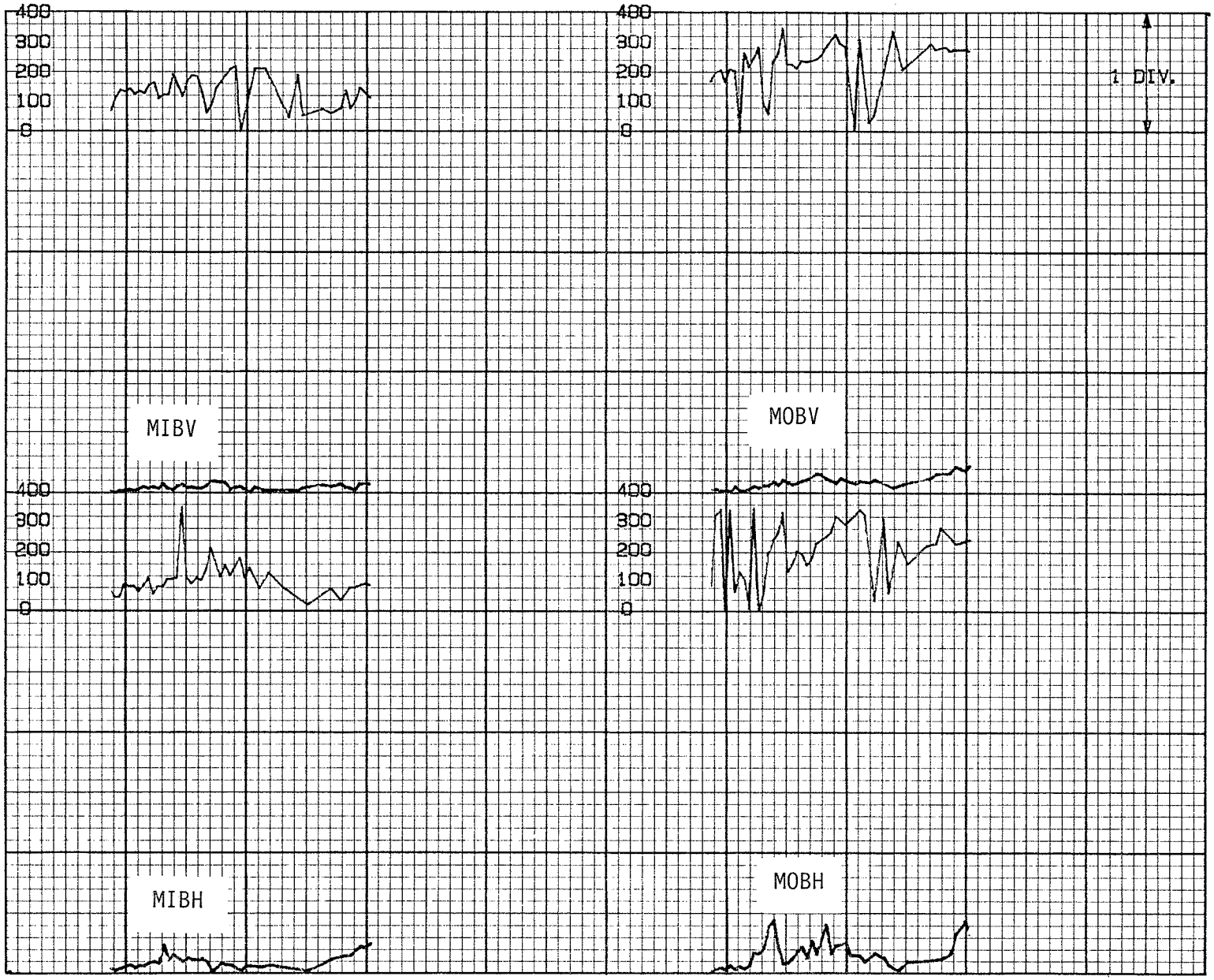


VIBRATION mils ☐
ips ☐ g's ☐
PULSATION psi ☐
STRAIN μ-in/in ☐
NOISE dB ☐

PLANT
UNIT POWER RECOVERY
MACHINE 31-BLM-1-A
TEST PT NOTED
SPEED 3630-1200 RPM
VERT 2 MIL/DIV
HORIZ 0-100 HZ
TIME 12:15 PM
DATE 3/27/86
COASTDOWN STEAM DRIVEN
(MOTOR NOT ENERGIZED)
REDUCED MOMENT SIMULATOR
ON EXP END - AFTER BAL'D
ON MANDREL
DIFFERENTIAL VIBRATIONS
ADDED 33 GM @ 203 DEG
RUN 35 - BASELINE RUN
RUN 36 - R.M. SENS TEST

Figure 12

ENGINEERING DYNAMICS INCORPORATED SAN ANTONIO, TEXAS



VIBRATION mils ☐
ips ☐ g's ☐
PULSATION psi ☐
STRAIN μ-in/in ☐
NOISE dB ☐

PLANT
UNIT POWER RECOVERY
MACHINE 31-BLM-1-A
TEST PT NOTED
SPEED 3600-900 RPM
VERT 2.0 MIL/DIV
HORIZ 0-100 HZ
TIME 4:50 PM
DATE 4-4-87

COASTDOWN WITH R.M. CPLG
9 MIL BRGS WITH SHIMS

SHOWS JUST EFFECT OF
6.55 OZ-IN ON EXP CPLG
(30 GM AT 8 DEGREES)

UNBAL SENSITIVITY TEST

Figure 13