

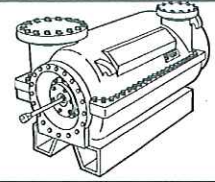
ANALYSIS REPORT

## Lateral Rotordynamic Analysis Summary

<b>Job:</b> Mustang <b>Date:</b> 05-13-09 <b>Application:</b> Refrigeration	<b>S.O.#:</b> 08-177539-01 <b>Compressor Designation:</b> 555BA <b>Design Speed:</b> 3234 rpm
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Prepared by:

Keith Heimberger  
Principal Engineer



## ANALYSIS REPORT

### **1. Summary**

A comprehensive lateral rotordynamic analysis of the compressor (including the effects of the complete driveline, Appendix A) was performed for this order\*. The analysis includes an undamped critical speed analysis, an unbalance response analysis and a stability analysis. Results show that the compressor has adequate separation margins from critical speeds based on API-617, 6<sup>th</sup> ed. In addition, the stability analysis predicts sufficiently large logarithmic decrements at the design speed. Based on these results, the compressor is predicted to operate satisfactorily with regard to lateral vibration.

\*Appendix A will be included in revision 1 of this report.

### **2. Introduction**

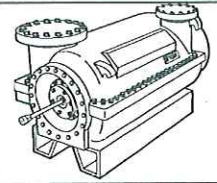
The compressor train consists of the gearbox pinion, Riverhawk coupling and the compressor rotor. The rotor model schematic is shown in Figure 1. The lateral rotordynamic analyses of the model was completed using a polynomial transfer matrix method computer program. The bearings, shown as springs in the geometry plots, are modeled as forces applied at their respective locations. In the uncoupled model, the effect of the coupling overhung mass is accounted for by applying a point mass on the model at the coupling CG location per Figure 1.

### **3. Undamped Critical Speed Analysis of the Compressor Model**

The undamped critical speed map for the compressor is shown in Figure 2. The graph shows the three critical speeds as a function of bearing stiffness. Overlaid on the plot are the compressor dynamic bearing stiffnesses as a function of speed. The dynamic bearing stiffnesses were calculated at the compressor suction and discharge end positions. The intersection of the dynamic bearing stiffness curves with the critical speeds approximately determines the critical speed location. Figure 3 shows the first undamped mode shape corresponding to a support stiffness of  $3 \times 10^6$  lbs/in. for the compressor suction bearing and discharge bearing. Mode 2 is shown in Figure 5 and Mode 3 is shown in Figure 7. The model is shown superimposed on the plots in Figures 4, 6 and 8. The resulting first two undamped critical speeds are 4579 cpm, 11298 cpm, respectively.

### **4. Damped Unbalance Response Analysis**

The synchronous response of the compressor rotor due to unbalance was investigated. Speed dependent pinion and compressor bearing coefficients (maximum, nominal and minimum bearing clearances for compressor suction and discharge ends) were used for



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this analysis. In order to excite the compressor modes, the following nominal unbalance were applied to the model:

$$U = 8(4W/N),$$

Where:

U = Unbalance Input

W = Compressor Rotor or Coupling

N = Speed

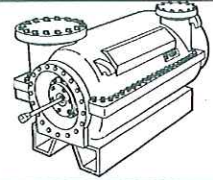
Station #	Description	Angle (deg)	Amount (oz-in)
32	Compressor Mid-Span	0	15.0

(Note from Figure 6 that the frequency associated with the overhung coupling mass is 3.5 times run speed.)

The response plots at the critical locations for the range of bearing clearance conditions for the coupling and compressor locations are presented in Figures 9 through 17. The amplification factors are considered for the first compressor mode that is above the run speed for compressor stations 11 (suction bearing), 32 (rotor mid-span) and 48 (discharge bearing). Separation margins are calculated using the maximum continuous speed of 3234 rpm. The results at critical locations were calculated and are summarized below. Since the horizontal and vertical amplitudes have been considered separately, the calculation work sheets have been included as appendix B.

Maximum Compressor Bearing Clearance  
Horizontal and Vertical Values Shown  
(Figures 9 thru 11):

Response Location	Critical Speed (rpm)	Amplification Factor	Separation Margin (%)	API Required Margin (%)
Compressor Suction End	4360	5.8	34.8	23.8
Compressor Discharge End	4340	8.5	34.1	24.9
Compressor Suction End	4060	2.9	25.5	15.0
Compressor Discharge End	4360	8.0	34.8	24.8



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Compressor	4260	4.1	31.7	20.9
Mid-Span	4360	8.7	34.8	24.9

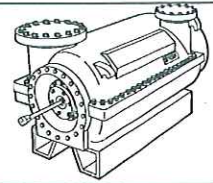
Nominal Compressor Bearing Clearance (Figures 12 thru 14):

Response Location	Critical Speed (rpm)	Amplification Factor	Separation Margin (%)	API Required Margin (%)
Compressor Suction End	3980 4420	3.7 9.9	23.1 36.6	17.0 25.1
Compressor Discharge End	4020 4420	4.0 8.5	24.3 36.6	20.0 24.9
Compressor Mid-Span	4120 4440	4.0 10.5	27.3 37.3	20.0 25.2

Minimum Compressor Bearing Clearance (Figures 15 thru 17):

Response Location	Critical Speed (rpm)	Amplification Factor	Separation Margin (%)	API Required Margin (%)
Compressor Suction End	4120 4500	4.4 11.9	27.3 39.1	21.7 25.3
Compressor Discharge End	4160 4500	4.8 10.1	28.6 39.1	22.6 25.2
Compressor Mid-Span	4200 4520	4.2 13.1	29.8 39.7	21.0 25.4

Results show that all separation margins are acceptable. The following table shows the comparison of actual compressor minimum bearing clearances with the calculated amplitude response at critical locations.



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Location	Response (pk to pk) for 8(4N/W) unbalance	Response (pk to pk) for 2(4N/W) unbalance per API	75% of Minimum Design Clearance at Location
Comp. Suction End Brg. (min clearance bearings)	0.002" (Figure 15)	0.0005" (calculated)	.0045"
Comp. Disch. End Brg. (min clearance bearings)	0.0055" (Figure 10)	0.0014" (calculated)	0.0022"
Comp. Midspan (min clearance seals)	0.025" (Figure 17)	0.0062" (calculated)	0.018"

In all cases the response calculated per API is less than 75% of the minimum design clearance.

**5. Compressor Rotor Analysis (Stability)**

A damped eigenvalue or stability analysis was completed for the uncoupled model. The stability was evaluated by investigating the logarithmic decrement (log dec), a measure of amplitude rate of decay. Log dec versus result is shown for the first forward precession mode in Figure 18. The mode exhibits a high log dec (1.2) indicating stable operation.

Geo Plot

08-177539-01

MUSTANG

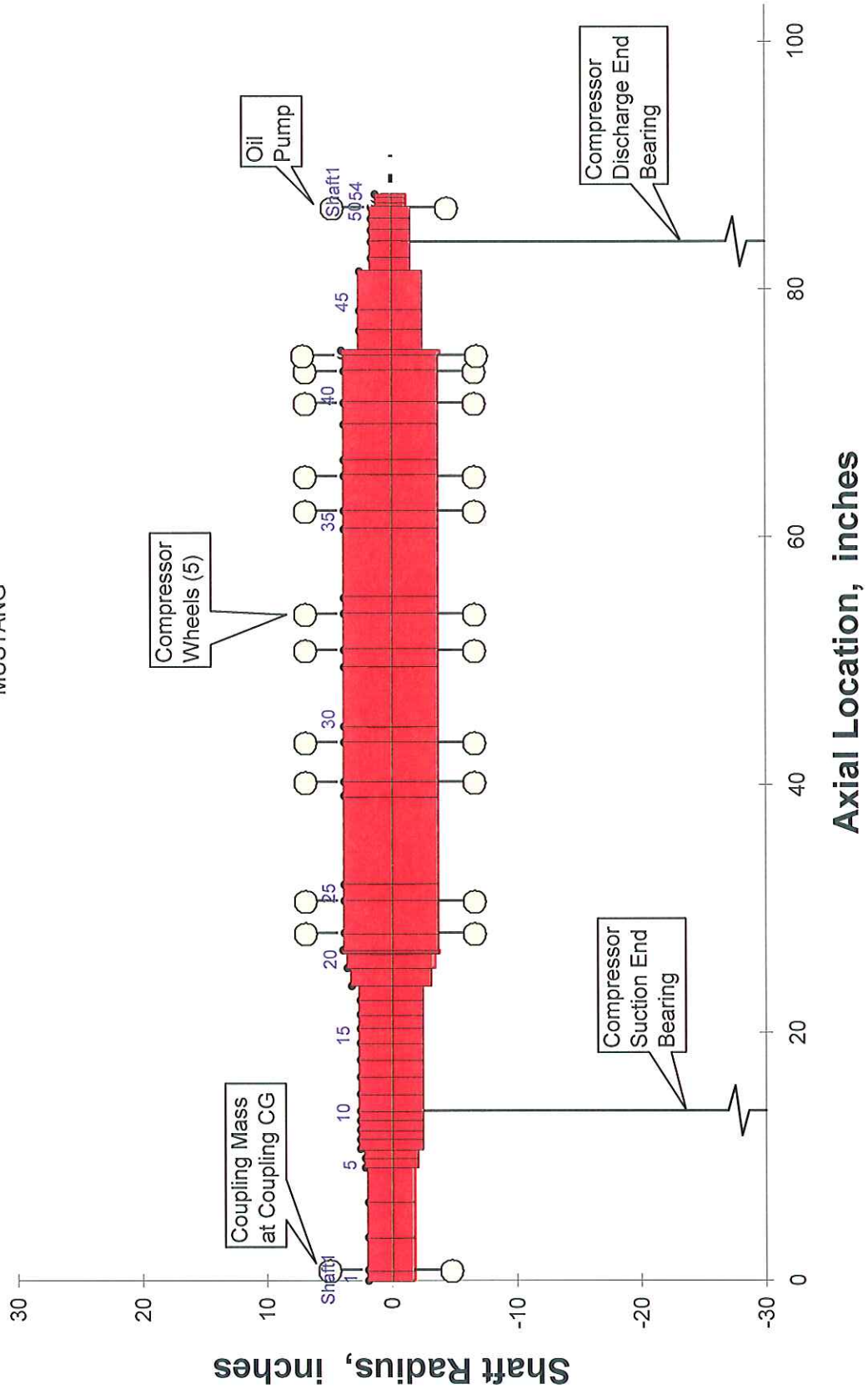


Figure 1

# Undamped Critical Speed Map

08-177539-01  
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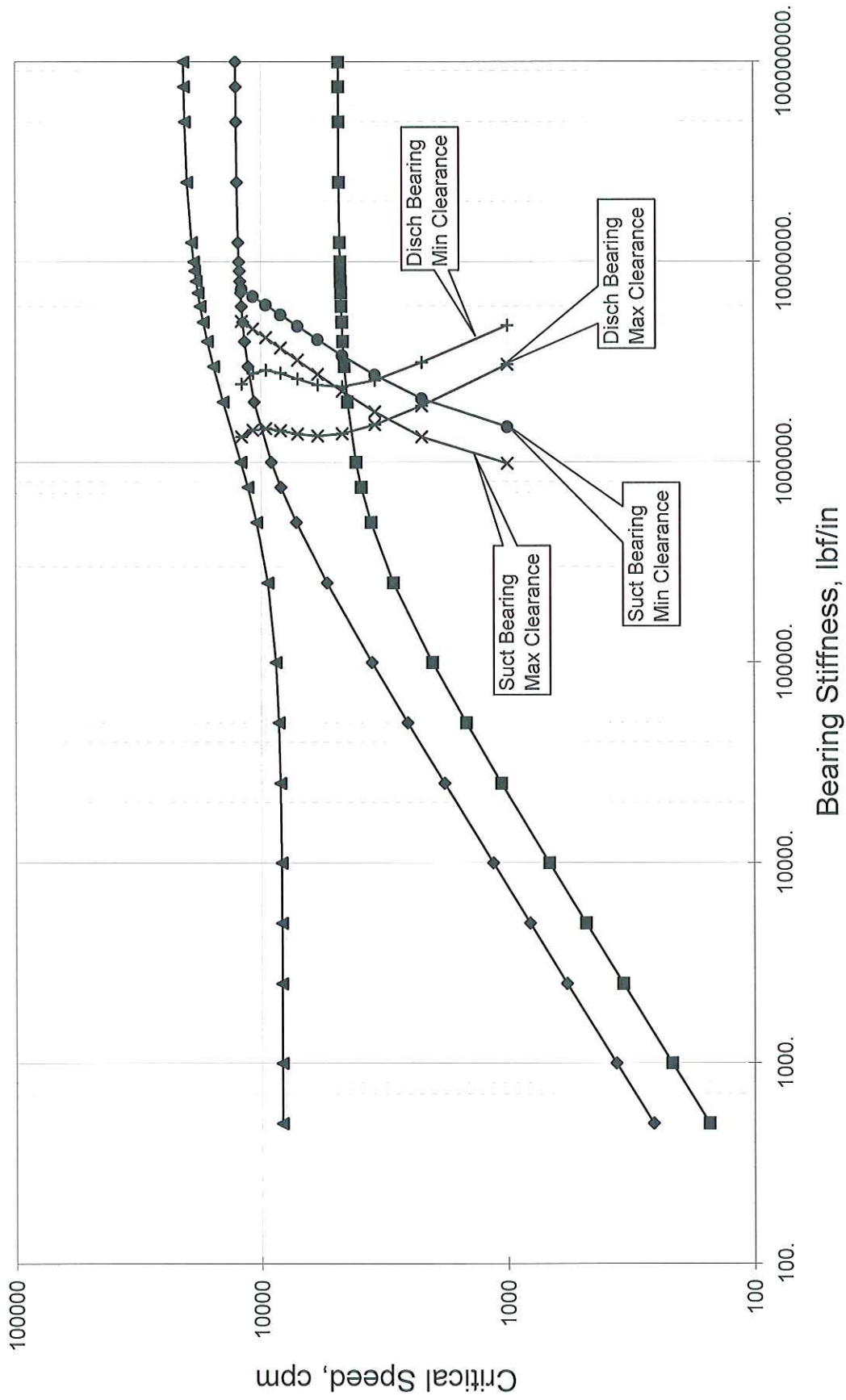


Figure 2

# Undamped C.S. Mode Shape Plot

08-177539-01  
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— forward  
— backward

f=4579.5 cpm  
K=3000000 lb/in

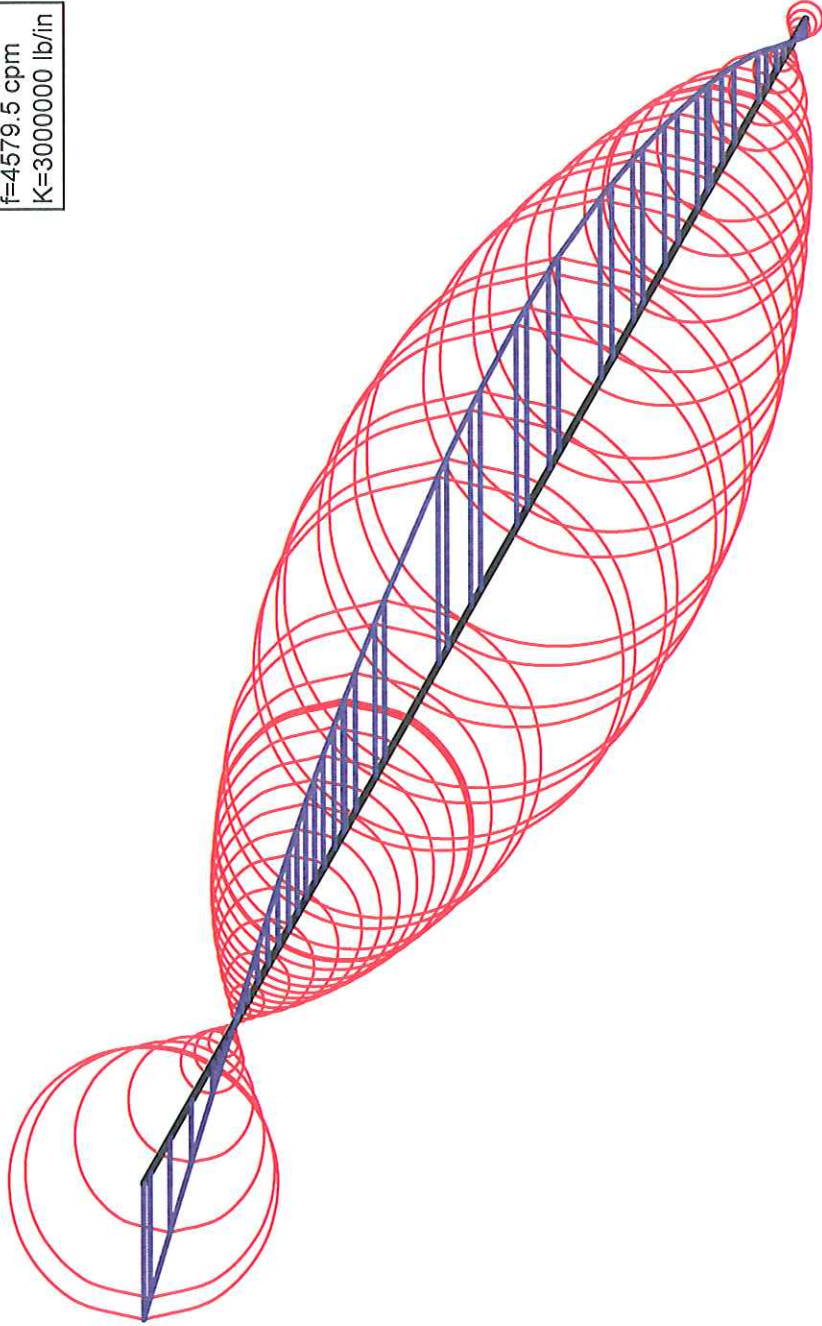


Figure 3

Re(x)

08-177539-01

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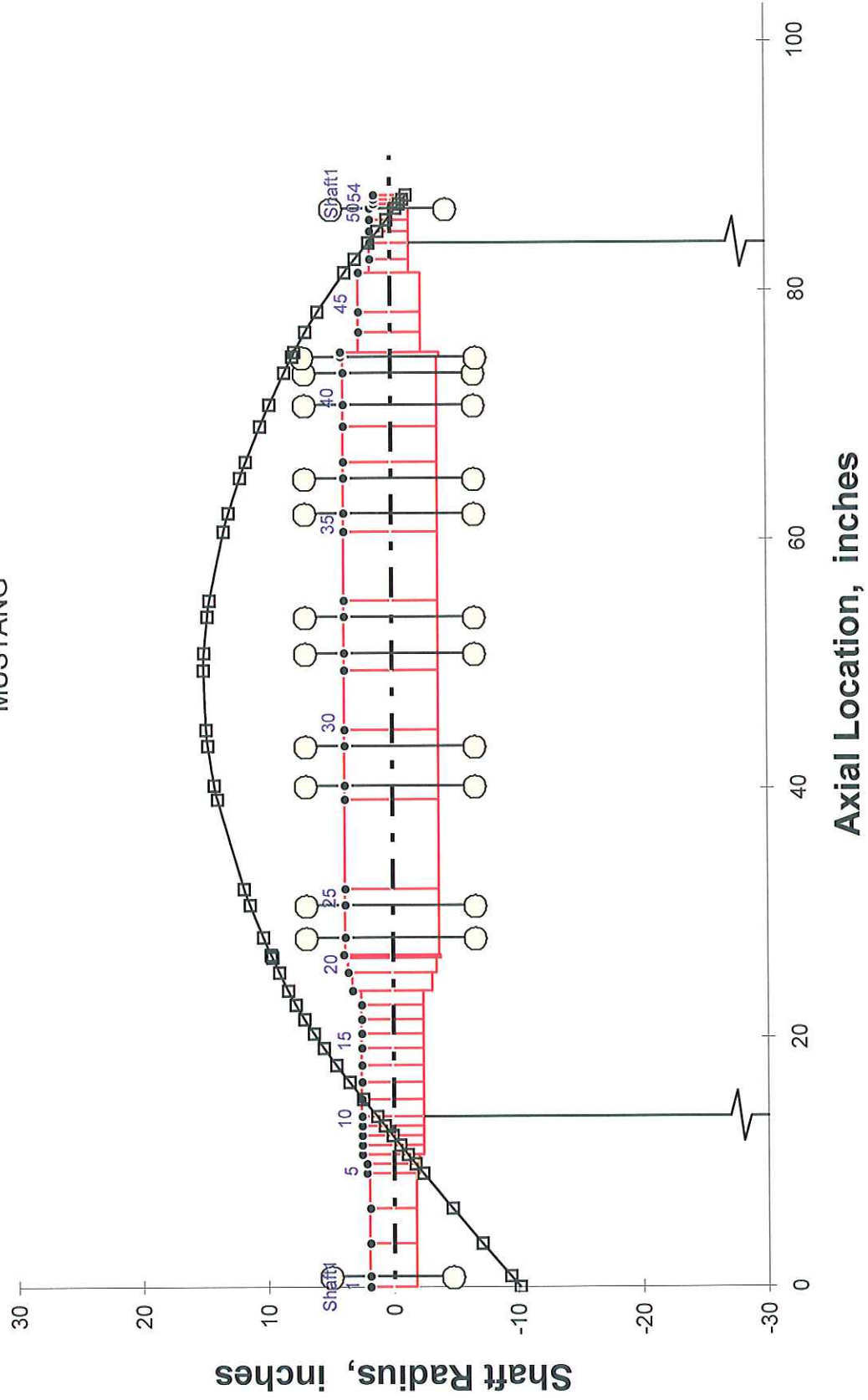


Figure 4

# Undamped C.S. Mode Shape Plot

08-177539-01  
MUSTANG

forward  
backward

$f=11298. \text{ cpm}$   
 $K=3000000 \text{ lb/in}$

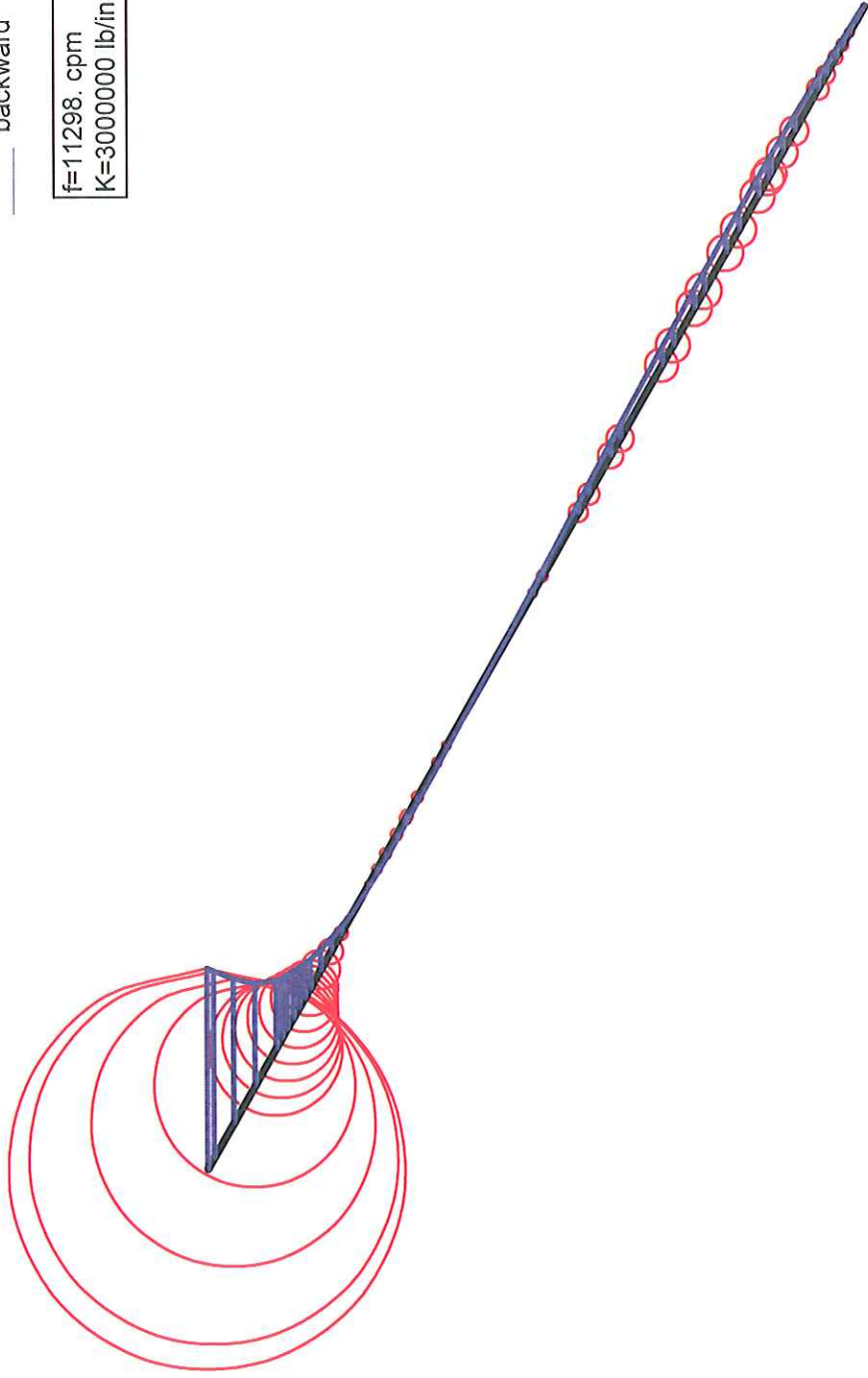


Figure 5

Re(x)

08-177539-01

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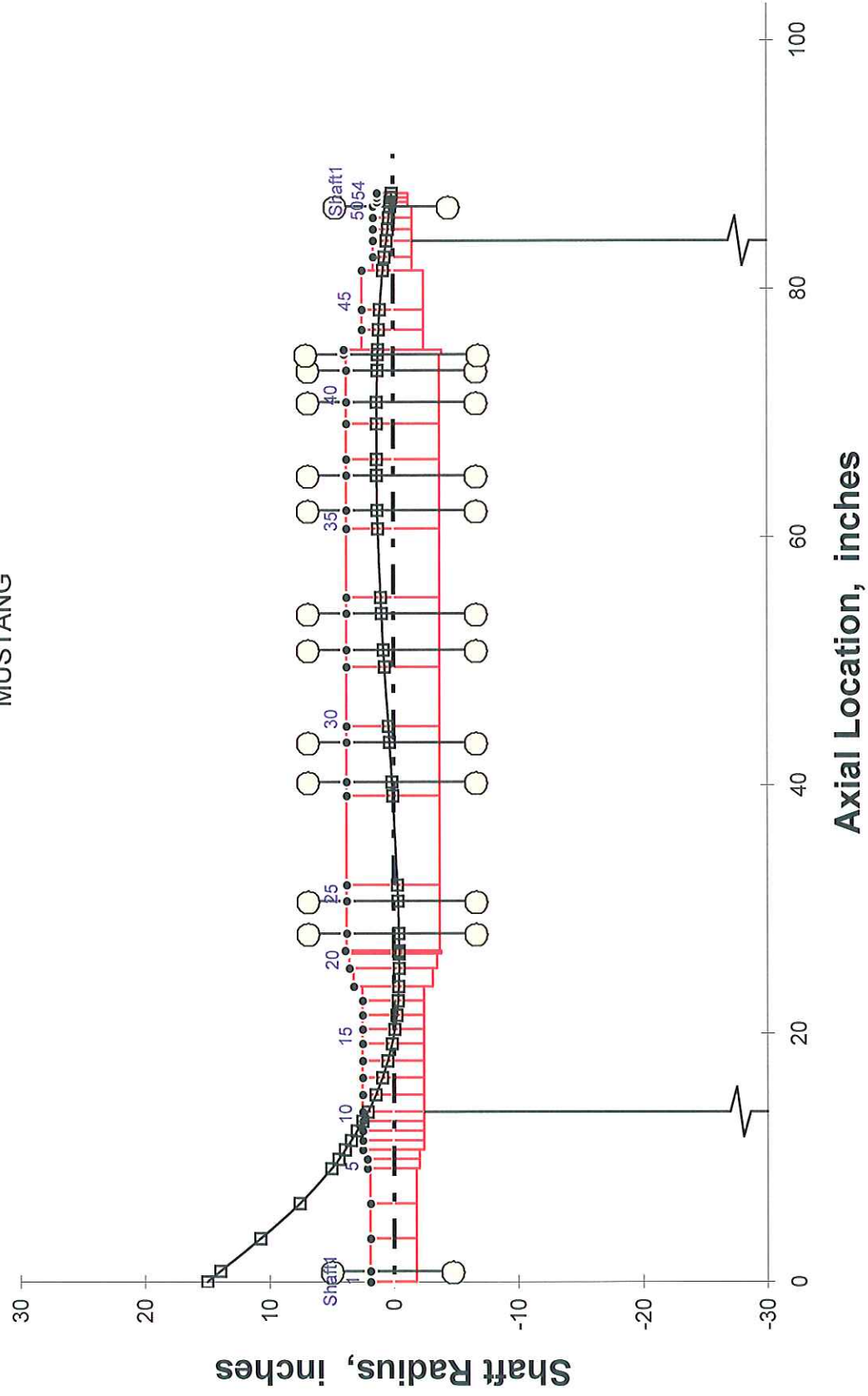


Figure 6

# Undamped C.S. Mode Shape Plot

08-177539-01  
MUSTANG

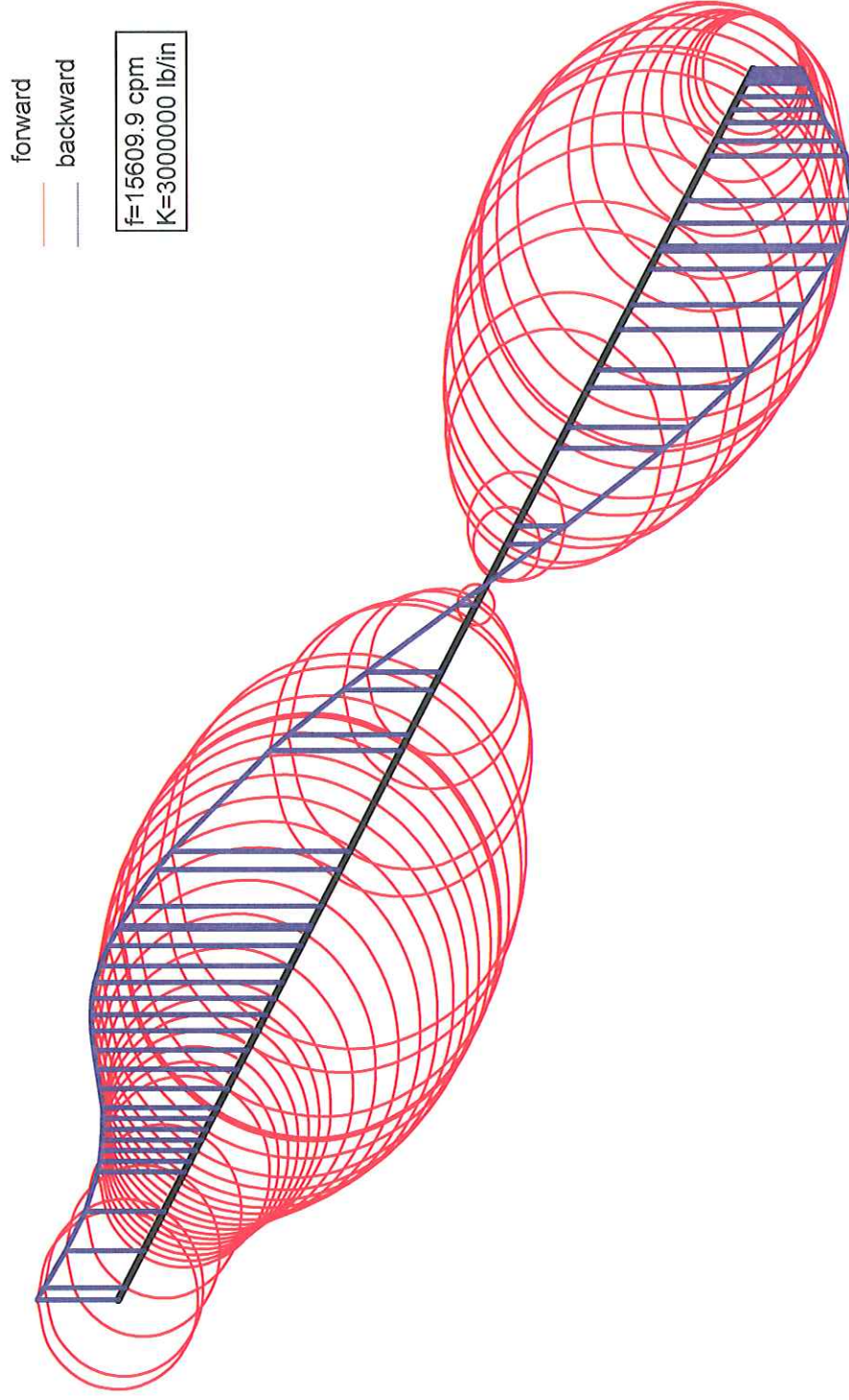


Figure 7

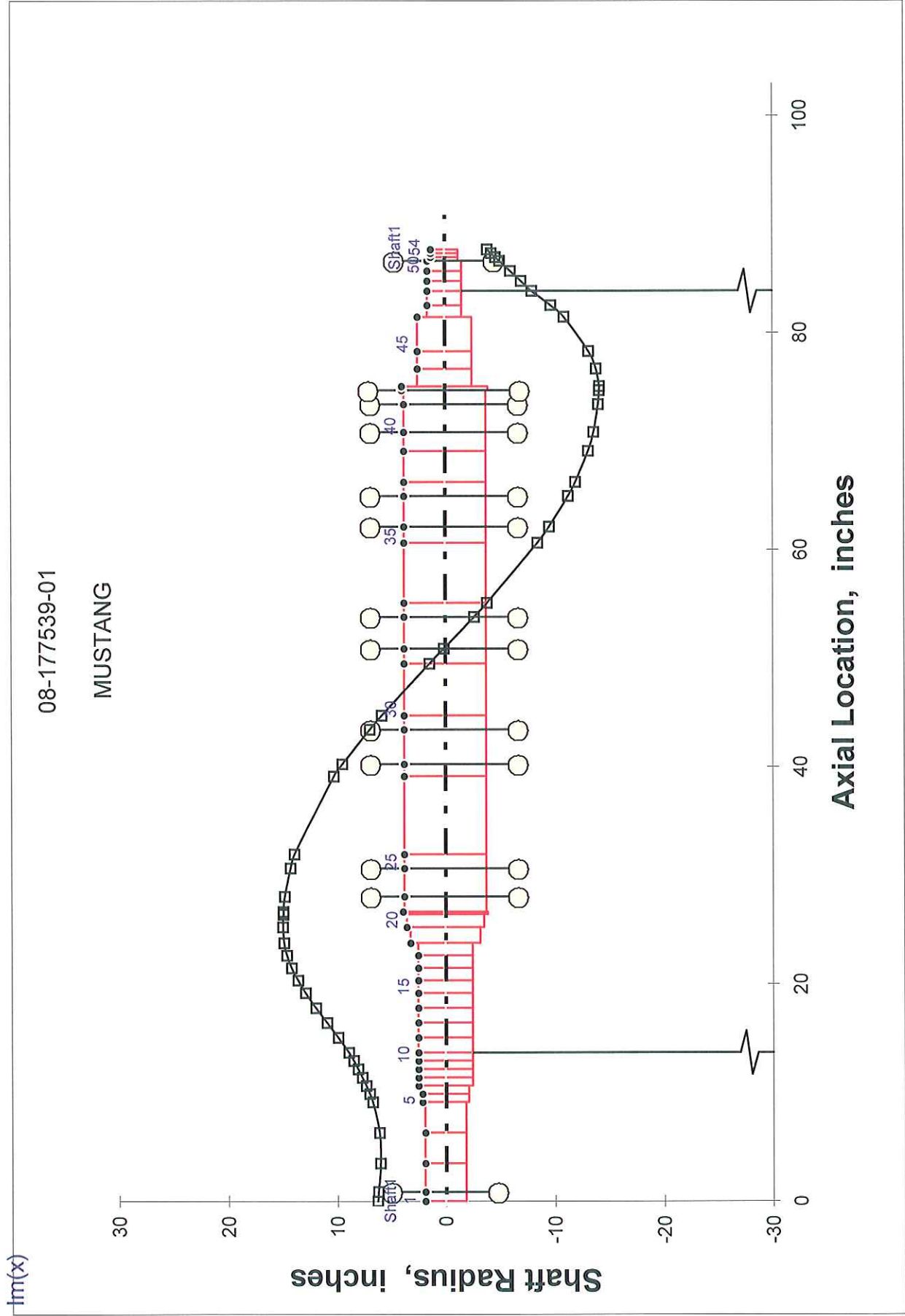
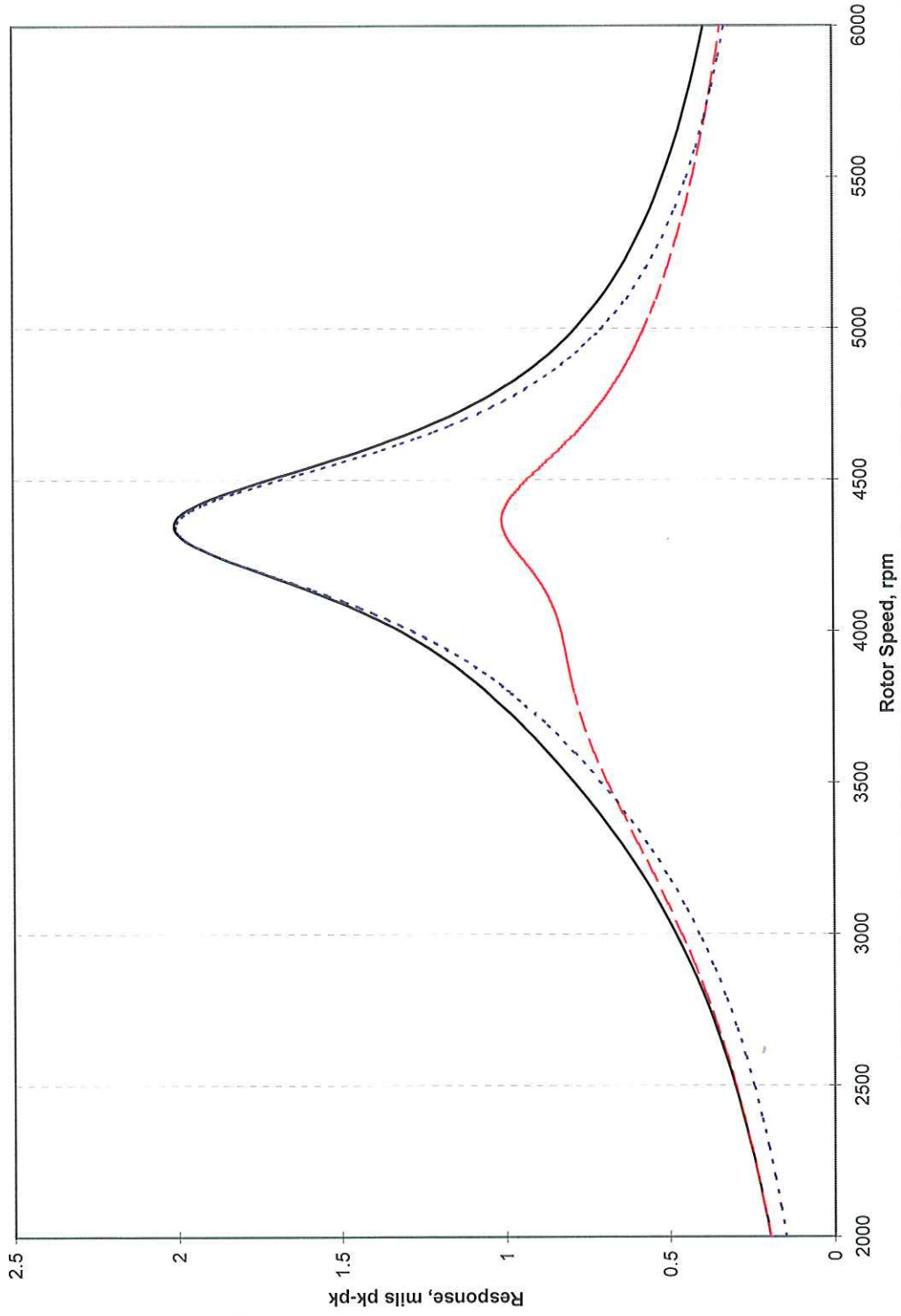


Figure 8

# Rotordynamic Response Plot

08-177539-01  
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Sta. No. 11: Suction End Bearing (Max Bearing Clearance)



Excitation = 1x

Figure 9

# Rotordynamic Response Plot

08-177539-01  
MUSTANG

Sta. No. 48: Discharge End Bearing (Max Bearing Clearance)

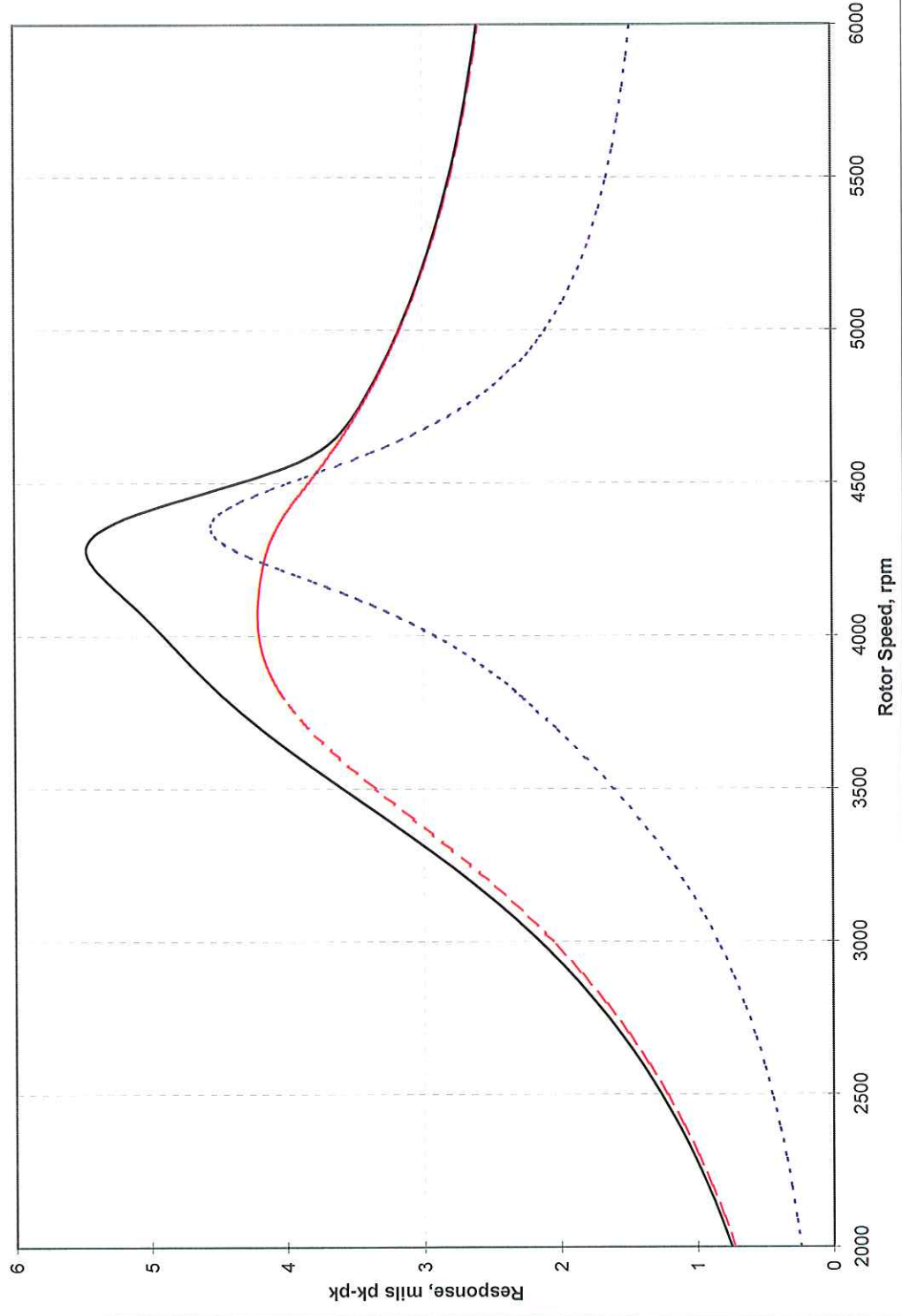


Figure 10

# Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 32: 3rd Stage Impeller (Max Bearing Clearance)

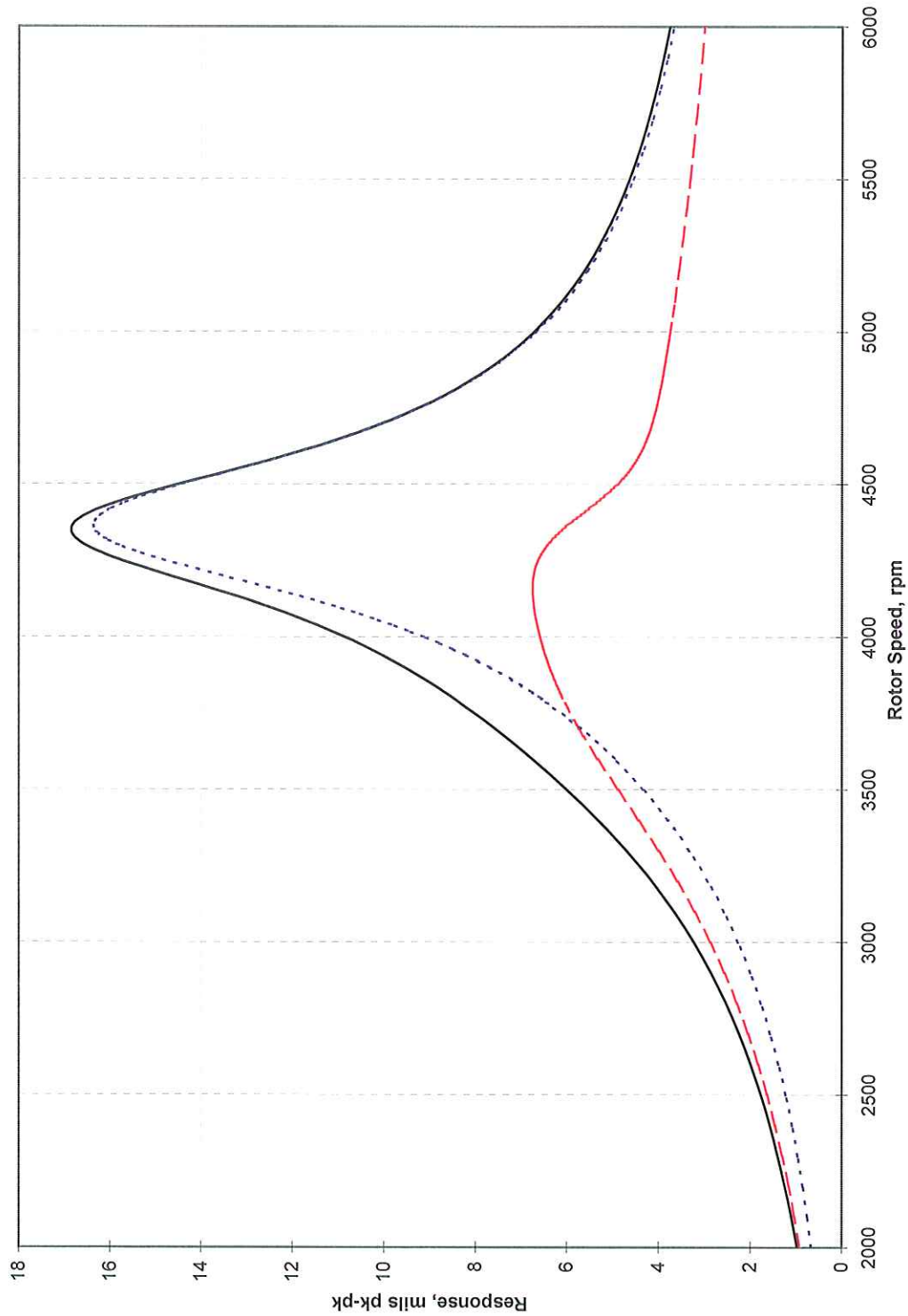


Figure 11

# Rotordynamic Response Plot

06-177539-01  
MUSTANG  
Sta. No. 11: Suction End Bearing (Min Bearing Clearance)

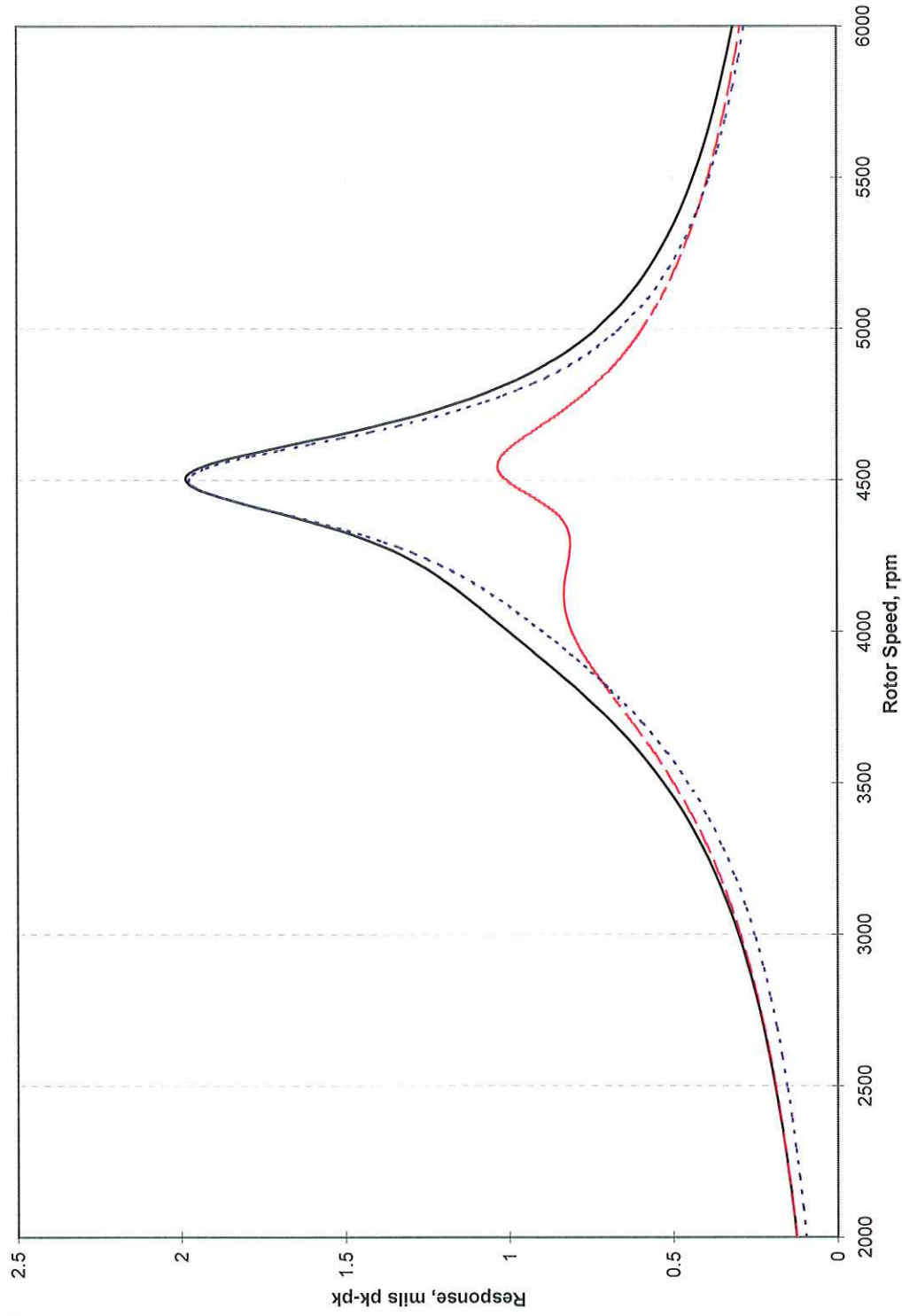
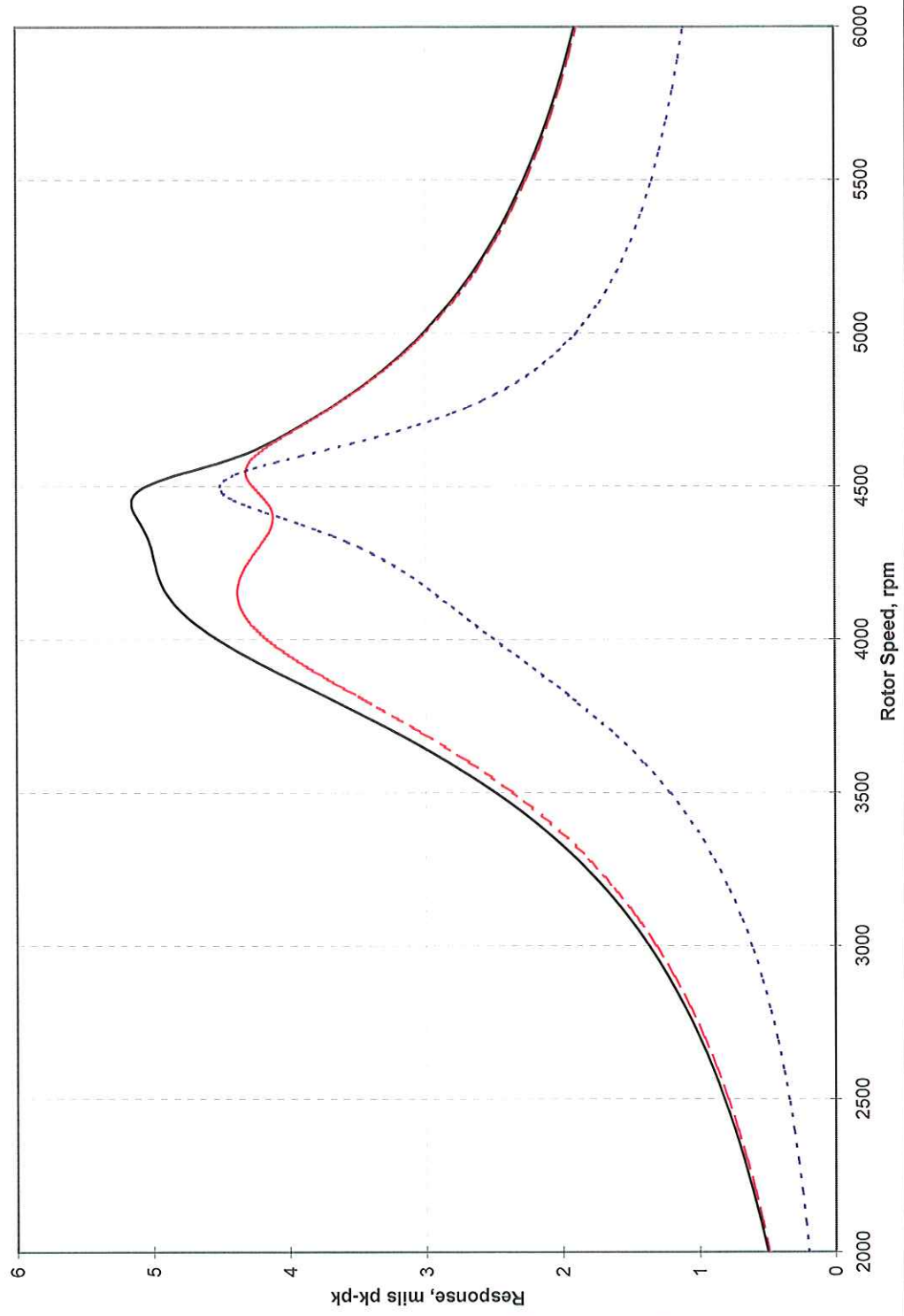


Figure 12

# Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 48: Discharge End Bearing (Min Bearing Clearance)

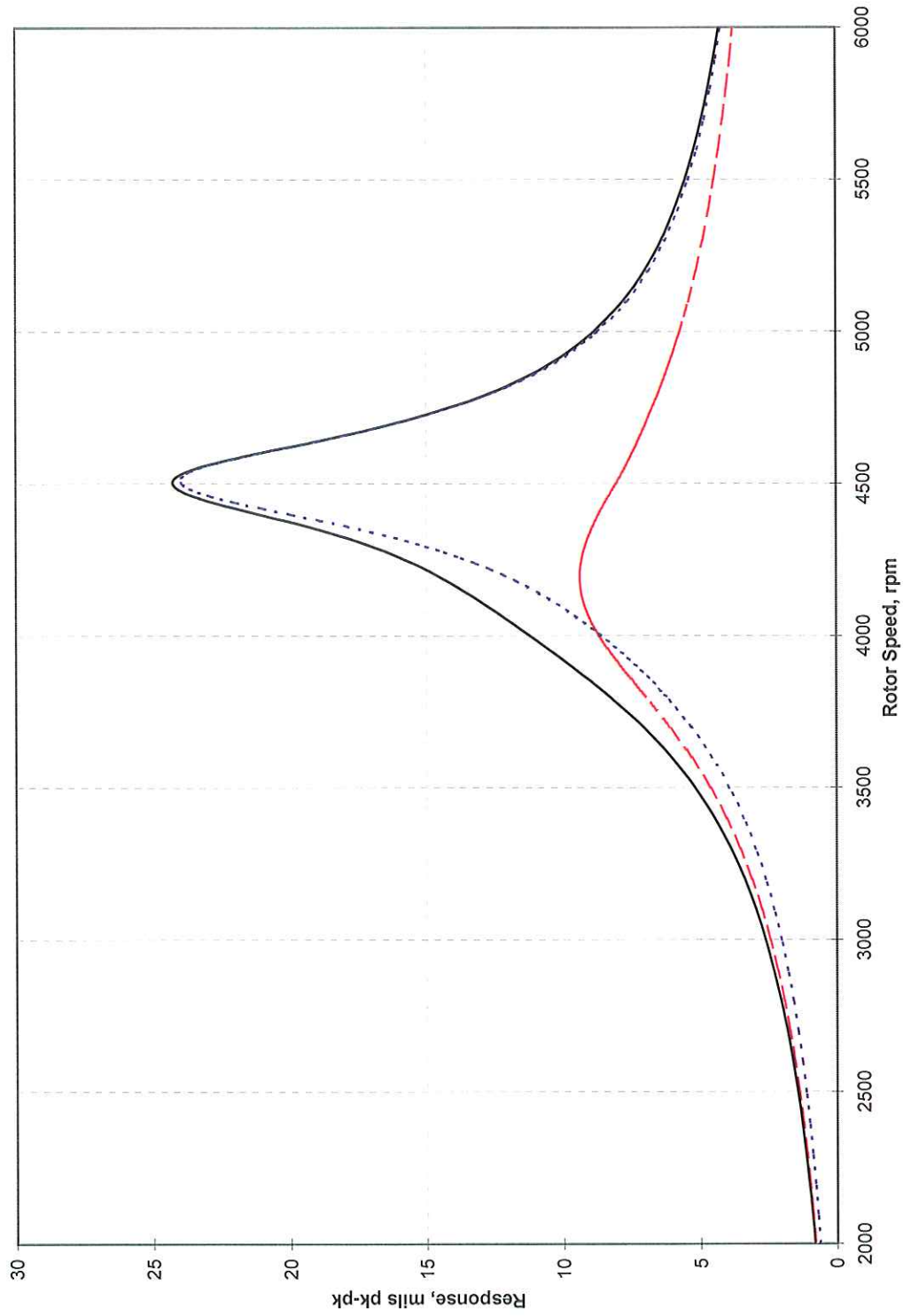


Excitation = 1x

Figure 13

# Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 32: 3rd Stage Impeller (Min Bearing Clearance)



Excitation = 1x

Major Amp  
Horiz Amp  
Vert Amp

Figure 14

# Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 11: Suction End Bearing (Nom Bearing Clearance)

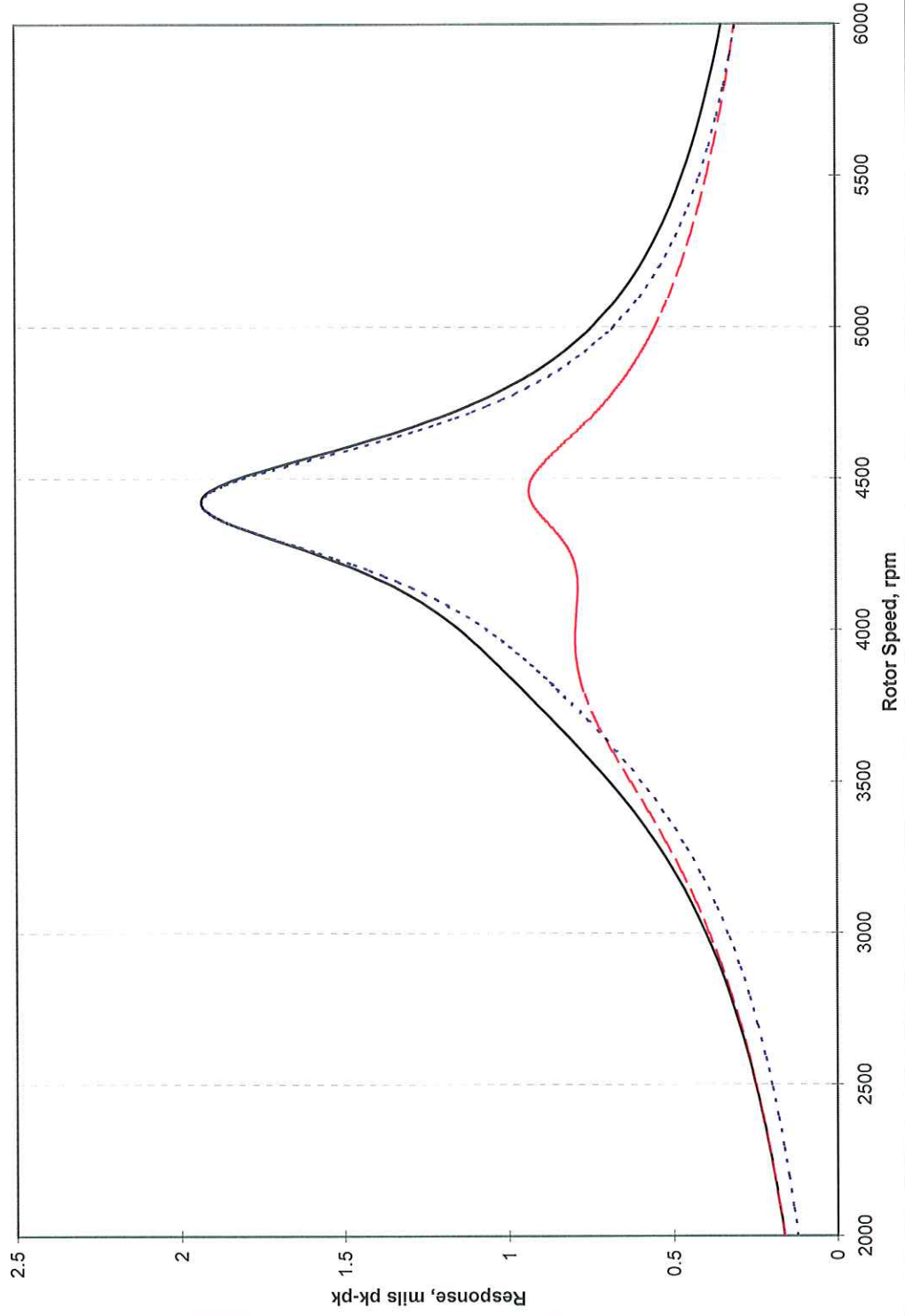
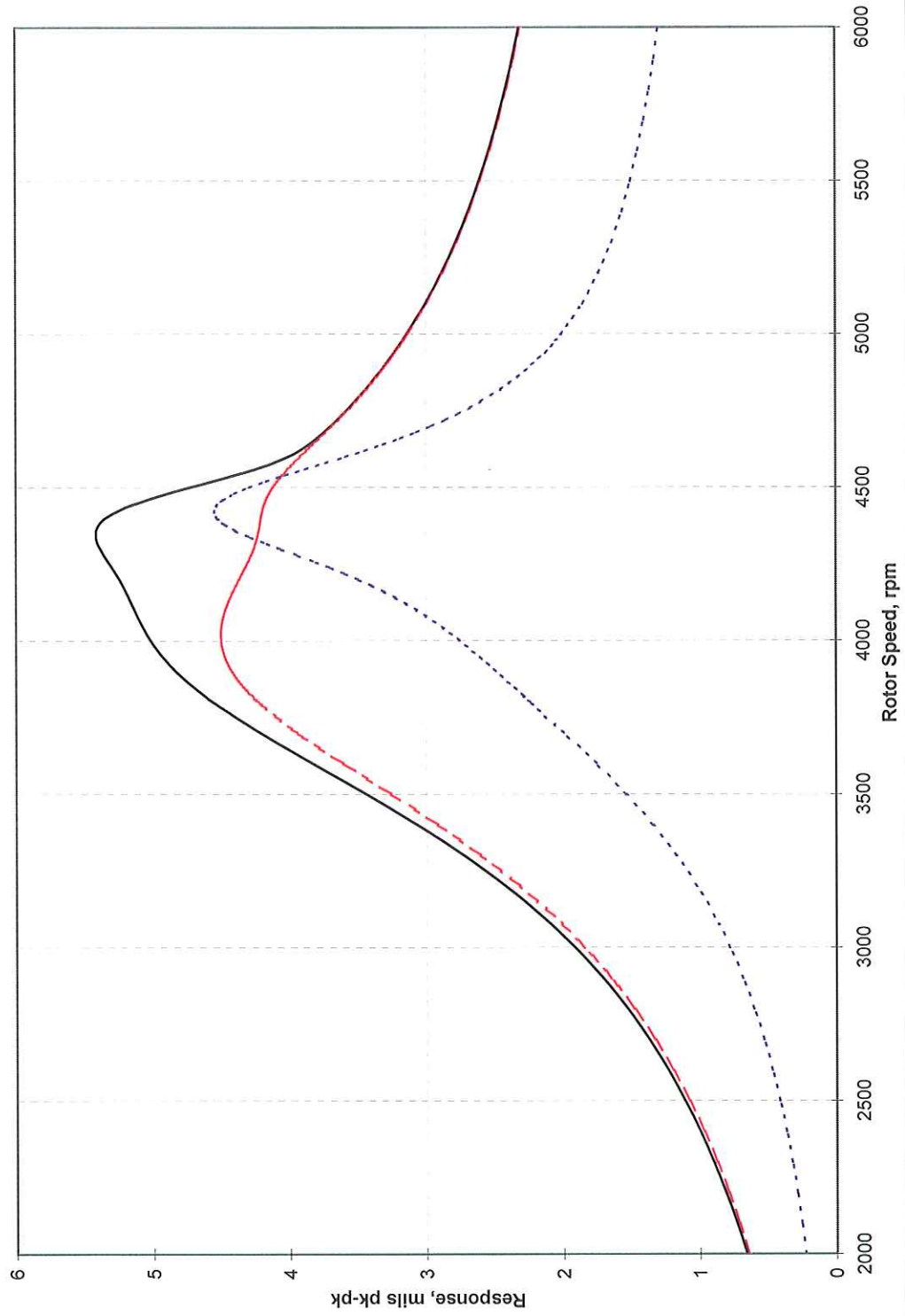


Figure 15

# Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 48: Discharge End Bearing (Nom Bearing Clearance)

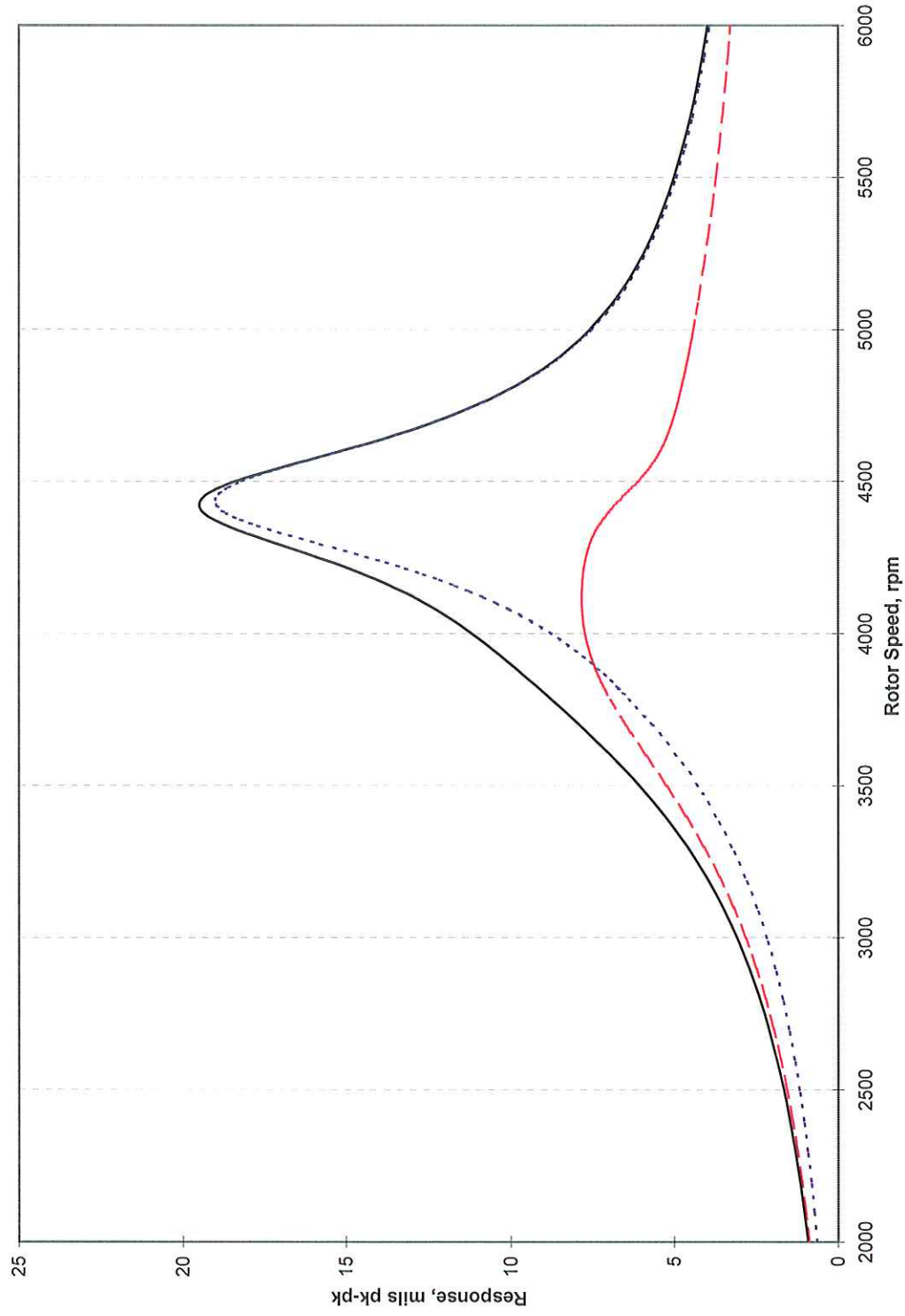


Excitation = 1x

Figure 16

# Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 32: 3rd Stage Impeller (Norm Bearing Clearance)



Excitation = 1x

Figure 17

# Damped Eigenvalue Mode Shape Plot

08-177539-01  
MUSTANG

forward  
backward

f=3723.8 cpm
d=1.2556 logd
N=3217 rpm

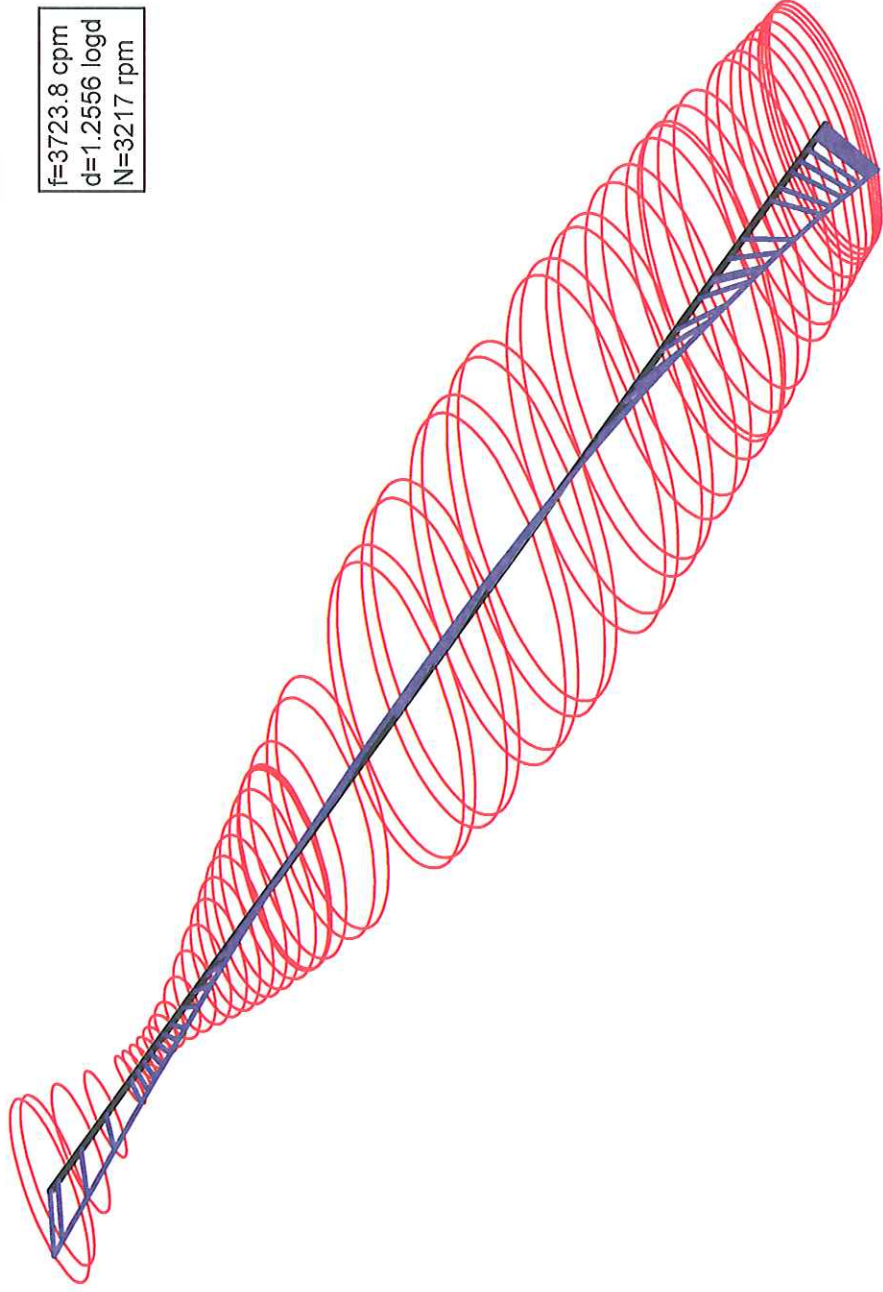
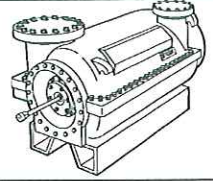


Figure 18



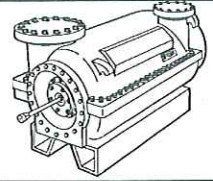
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**Appendix A Coupled Model Results**

(will be supplied in Rev 1 of report)



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### Appendix B Compressor Work Sheets

$$AF_H = 4360 / 755 = 5.8$$

$$AF_V = 4340 / 511 = 8.5$$

$$SM_{Req.H} = (126 - \frac{6}{5.8-3}) - 100 = 23.8$$

Act. = 34.8 OK

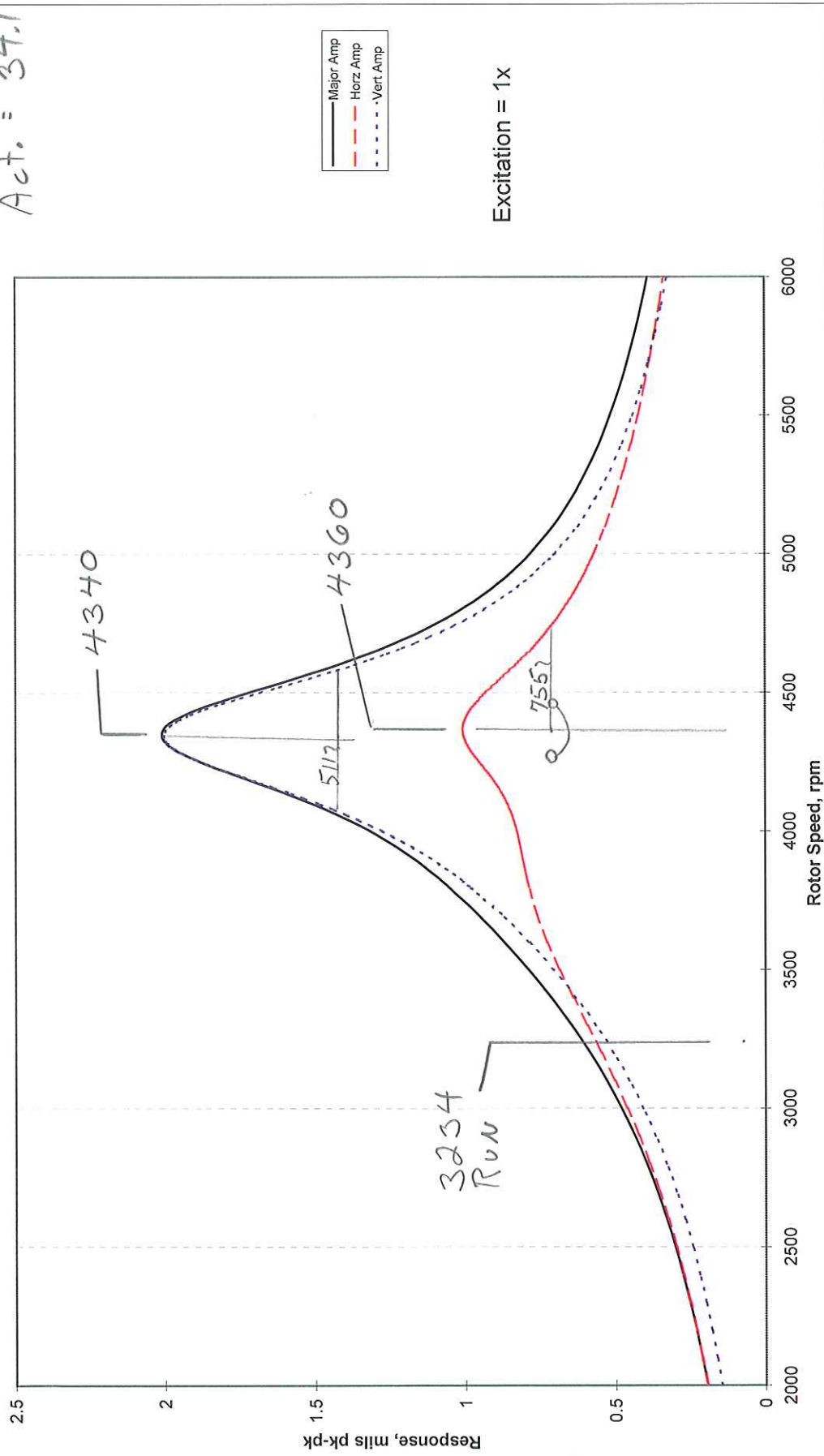
$$SM_{Req.V} = (126 - \frac{6}{8.5-3}) - 100 = 24.9$$

Act. = 34.1 OK

Rotordynamic Response Plot

08-177539-01  
MUSTANG

Sta. No. 11: Suction End Bearing (Max Bearing Clearance)



(Fig. 9)

\* API 617, 6<sup>th</sup> ed, eq 2.9.2.5 d.

$AF_H = 4060 / 1390 = 2.9$   
 $AF_V = 4360 / 543 = 8.0$

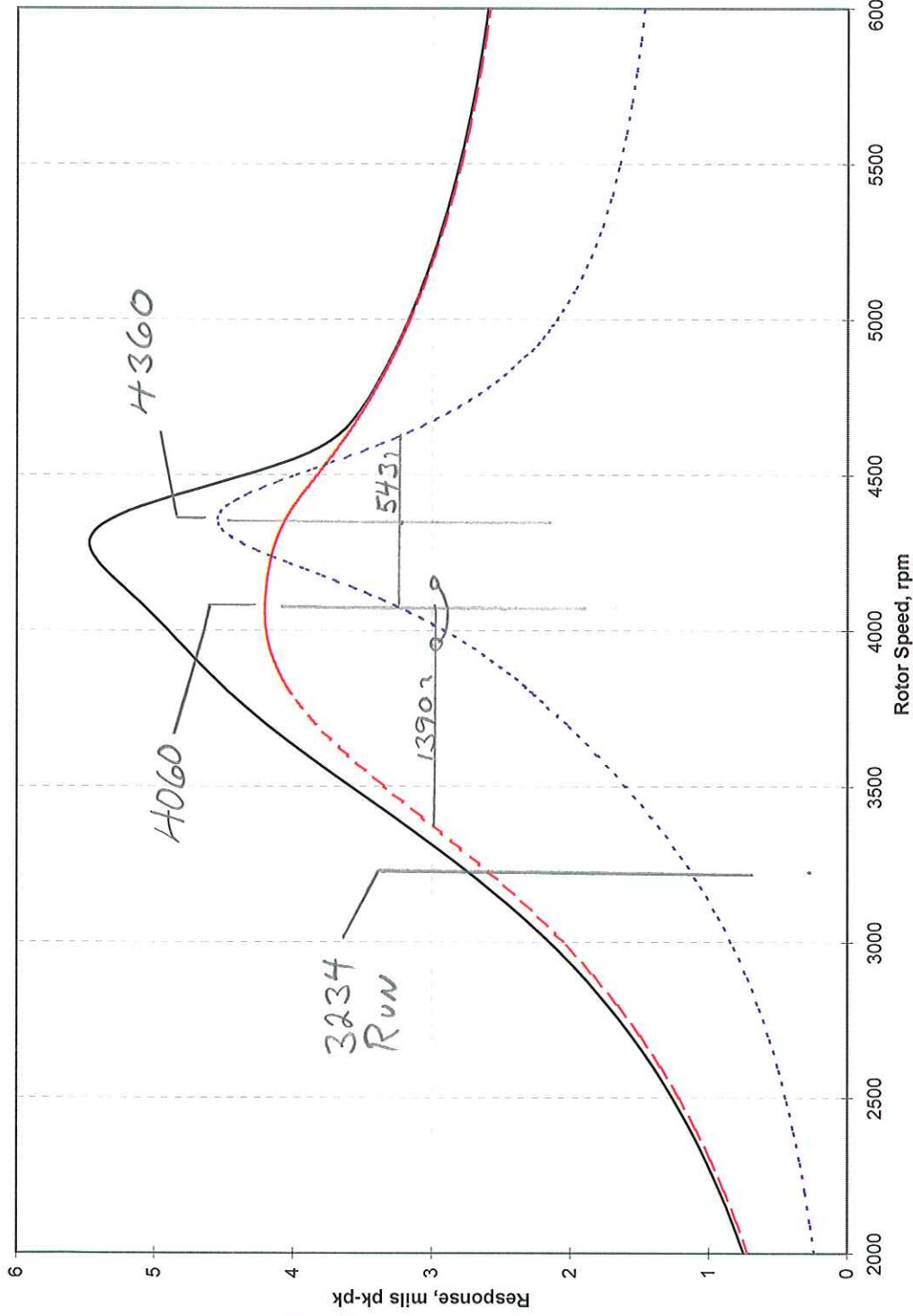
$SM_{Req H} = 15\%$   
 $Act. = 25.5\%$  OK

$SM_{Req V} = (126 - \frac{6}{8-3}) - 100 = 24.8\%$   
 $Act. = 34.8\%$  OK

Rotordynamic Response Plot

08-177539-01  
MUSTANG

Sia. No. 48: Discharge End Bearing (Max Bearing Clearance)



\*API-617, G<sup>th</sup>, eq 2.9.2.5 b.

(Fig. 10)

$$AF_H = 4260 / 1021 = 4.17$$

$$AF_V = 4360 / 500 = 8.7$$

$$SM_{Req. H} = (126 - \frac{6}{4.17-3}) - 100 = 20.9\%$$

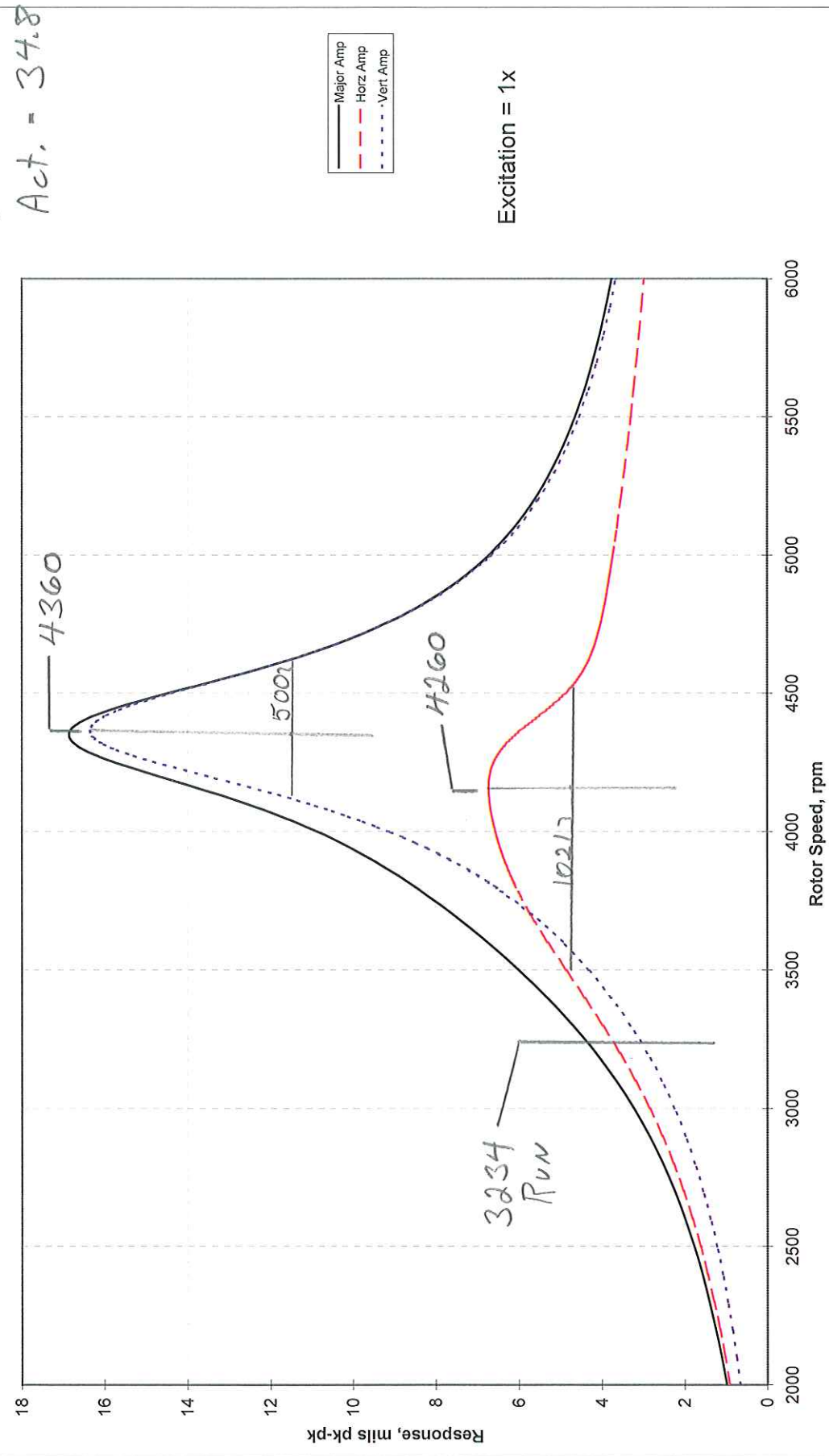
$$Act = 31.7\% \text{ OK}$$

$$SM_{Req. V} = (126 - \frac{6}{8.7-3}) - 100 = 24.9\%$$

$$Act. = 34.8\%$$

Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 32: 3rd Stage Impeller (Max Bearing Clearance)



(Fig. 11)

$$AF_H = 3980 / 1087 = 3.66$$

$$AF_V = 4420 / 446 = 9.9$$

$$SM_{Req. H} = (126 - \frac{6}{3.66 - 3}) - 100 = 17.0\%$$

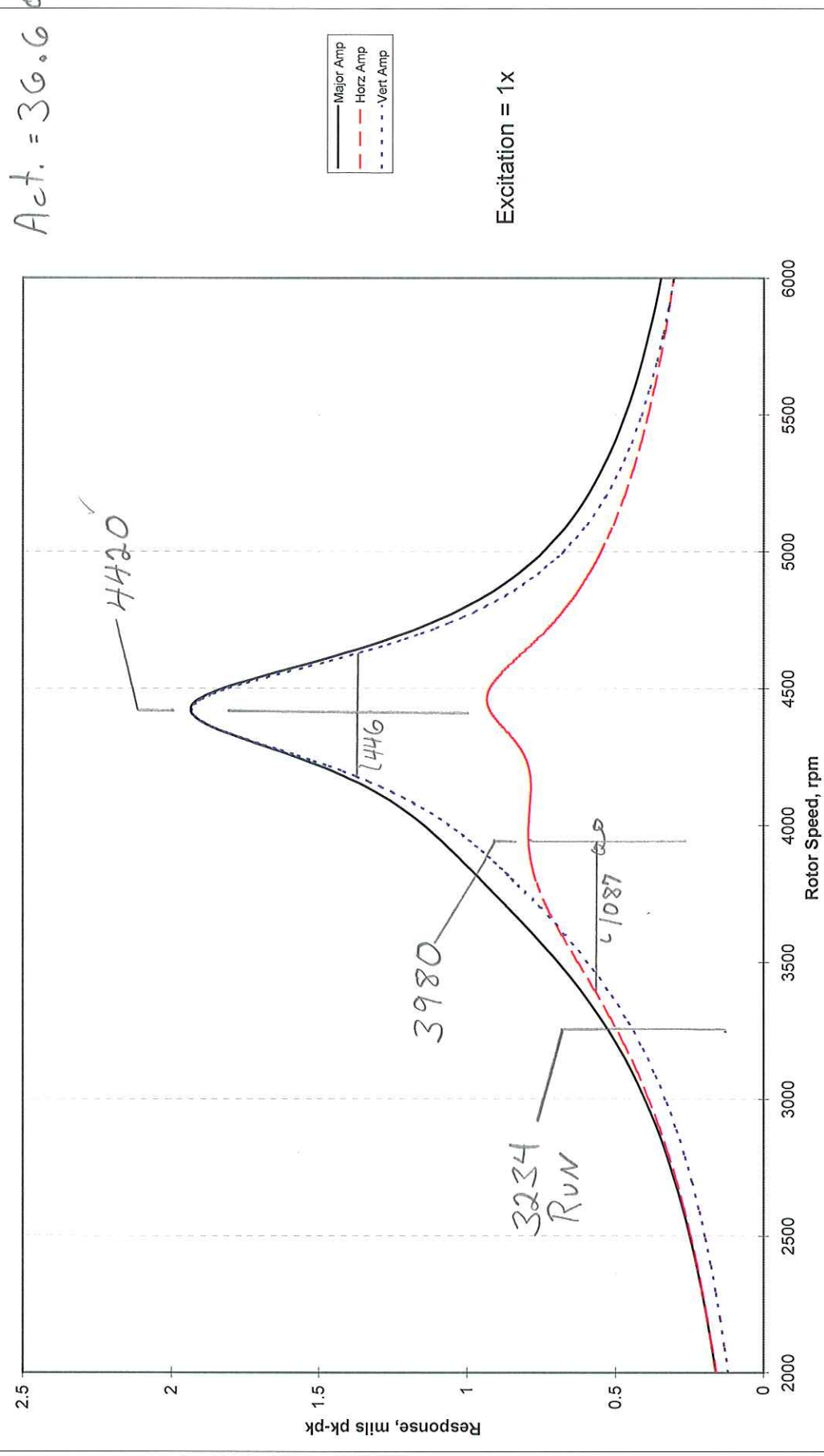
$$Act. = 23.1\% \text{ OK}$$

$$SM_{Req. V} = (126 - \frac{6}{9.9 - 3}) - 100 = 25.1\%$$

$$Act. = 36.6\% \text{ OK}$$

Rotordynamic Response Plot

06-177539-01  
MUSTANG  
Sta. No. 11: Suction End Bearing (Nom Bearing Clearance)



(Fig. 12)

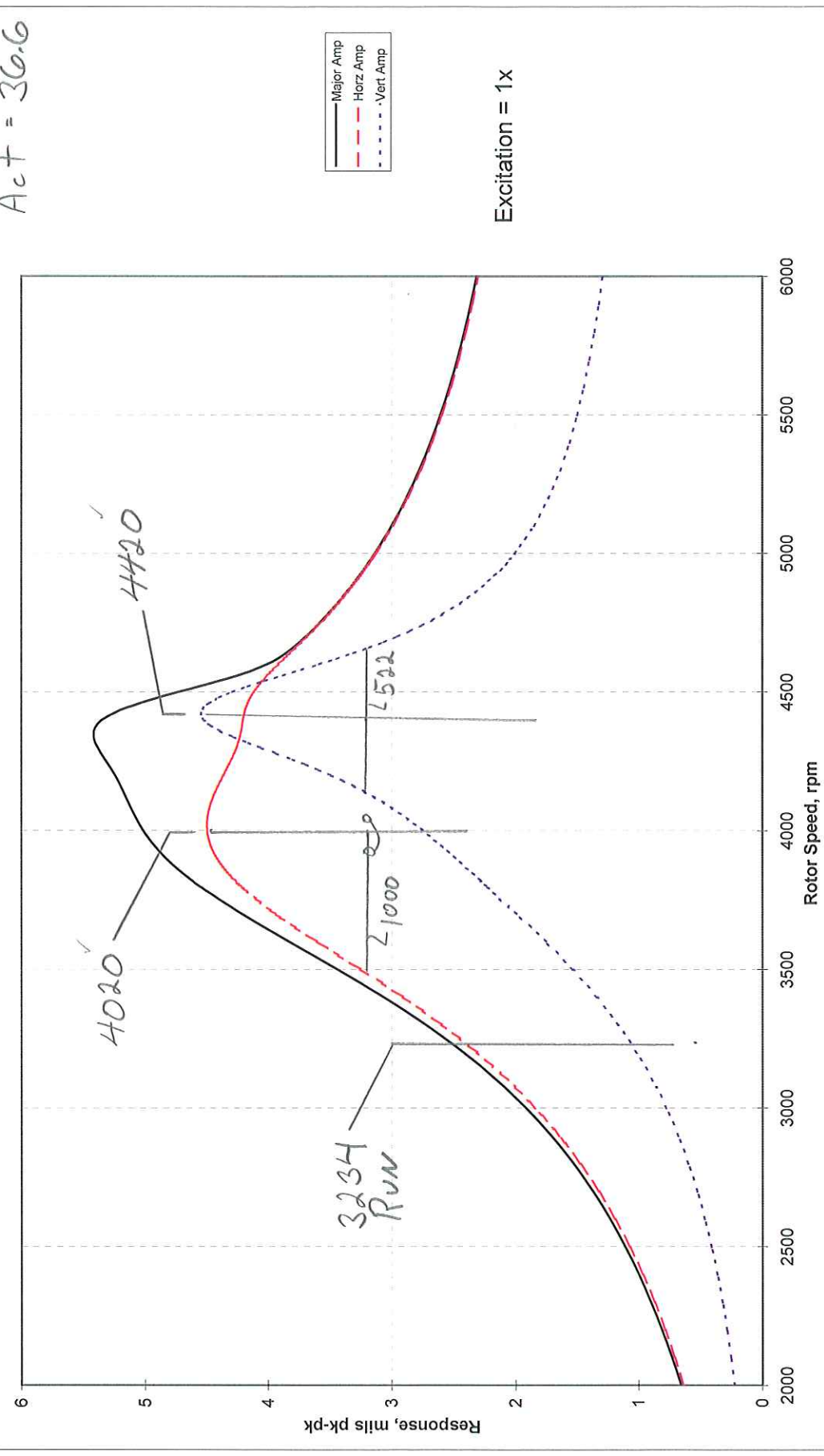
$AF_H = 4020/1000 = 4.0$   
 $AF_V = 4420/522 = 8.47$

$SM_{Req. H} = (126 - \frac{6}{4.0 - 3}) - 100 = 20\%$   
 $Act. = 24.3$  OK

$SM_{Req. V} = (126 - \frac{6}{8.47 - 3}) - 100 = 24.9$   
 $Act. = 36.6$  OK

Rotordynamic Response Plot

08-177539-01  
 MUSTANG  
 Sta. No. 48: Discharge End Bearing (Nom Bearing Clearance)



(Fig. 13)

$$AF_H = 4120/1021 = 4.0$$

$$AF_V = 4440/424 = 10.5$$

$$SM_{Req. H} = (126 - \frac{6}{4.0-3}) - 100 = 20\%$$

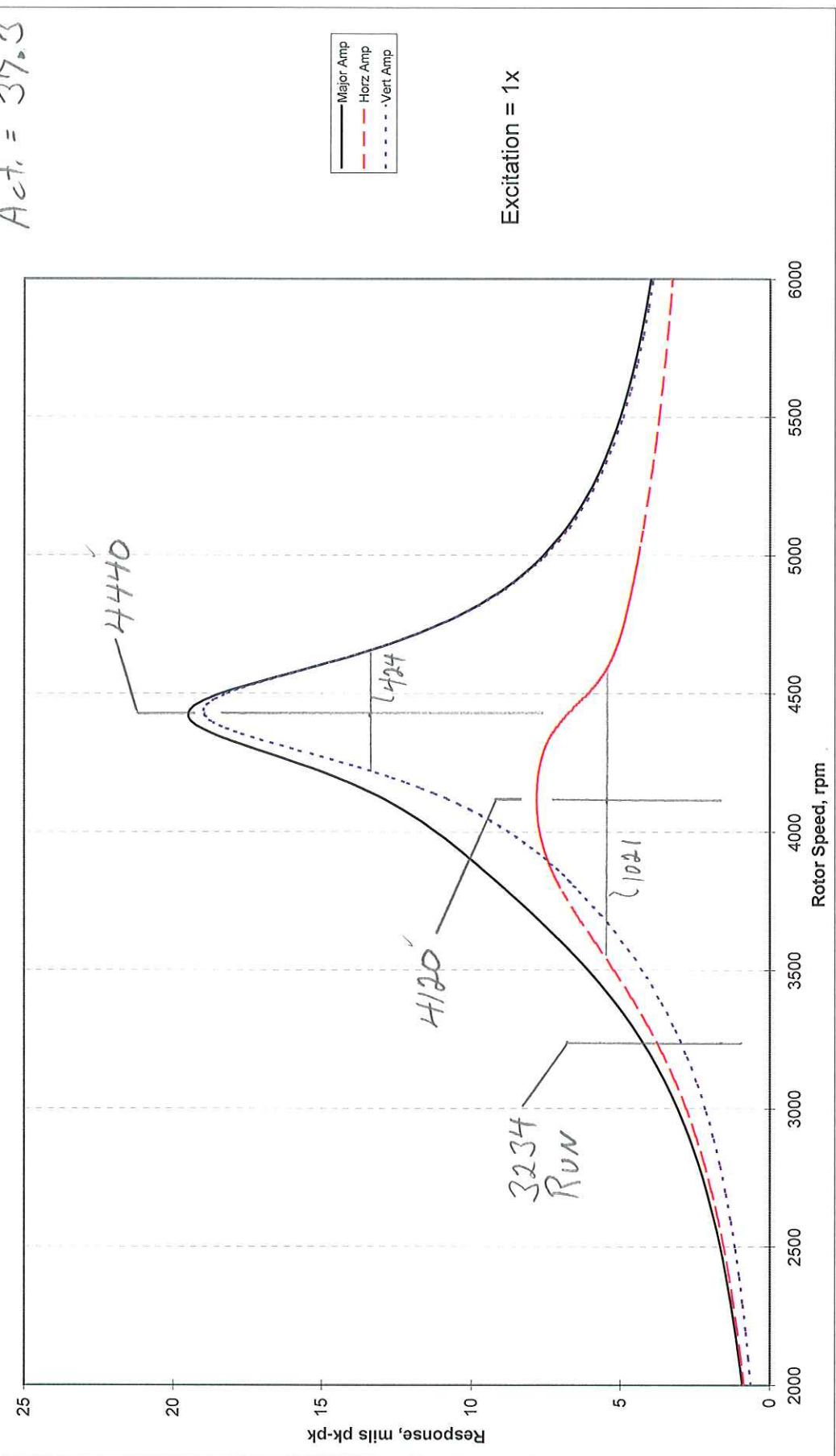
$$Act. = 27.3 \text{ OK}$$

$$SM_{Req. V} = (126 - \frac{6}{10.5-3}) - 100 = 25.2\%$$

$$Act. = 37.3 \text{ OK}$$

Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 32: 3rd Stage Impeller (Norm Bearing Clearance)



(Fig. 14)

$$SM_{Req, H} = (126 - \frac{6}{4.4-3}) - 100 = 21.7\%$$

$$Act = 27.3\% \text{ OK}$$

$$SM_{Req, V} = (126 - \frac{6}{11.9-3}) - 100 = 25.3\%$$

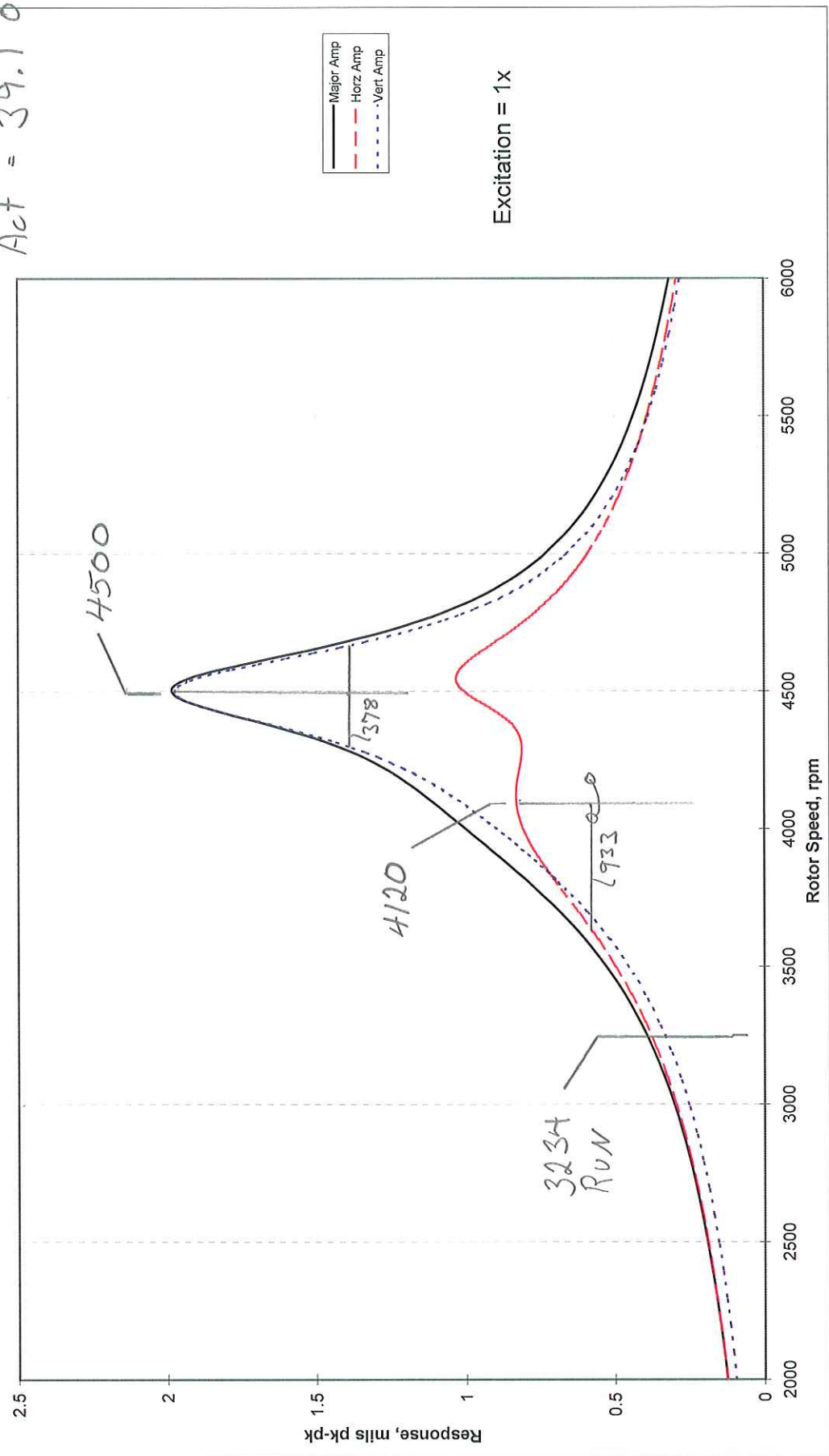
$$Act = 39.1\% \text{ OK}$$

$$AF_H = 4120/933 = 4.4$$

$$AF_V = 4500/378 = 11.9$$

Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 11: Suction End Bearing (Min Bearing Clearance)



(Fig. 15)

$$AF_H = 4160 / 869 = 4.79$$

$$AF_V = 4500 / 445 = 10.1$$

$$SM_{Req H} = (126 - \frac{6}{4.79-3}) - 100 = 22.6\%$$

Act = 28.6 OK

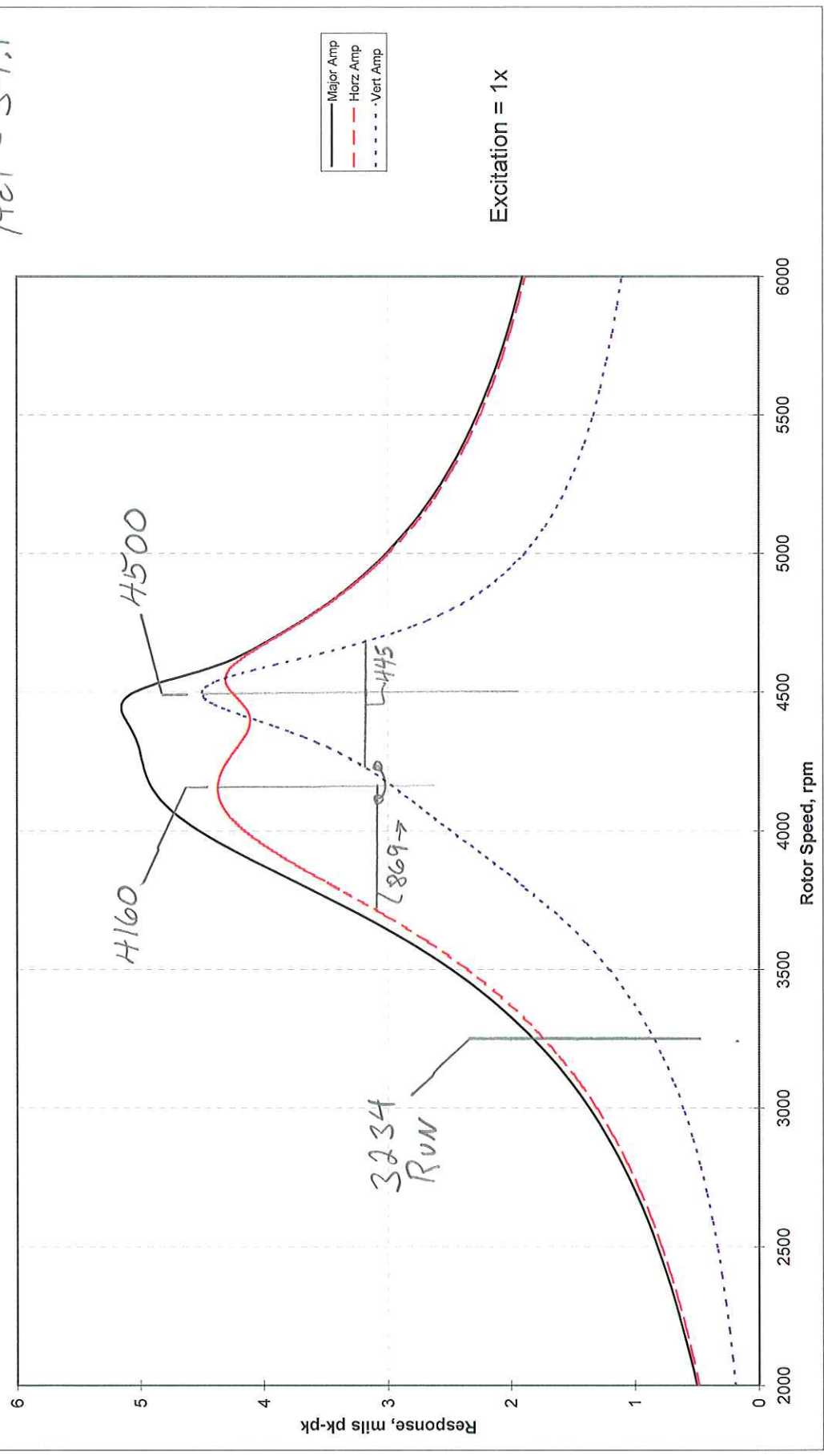
$$SM_{Req V} = (126 - \frac{6}{10.1-3}) - 100 = 25.2\%$$

Act = 39.1 OK

Rotordynamic Response Plot

08-177539-01  
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Sta. No. 48: Discharge End Bearing (Min Bearing Clearance)



(Fig. 16)

$$AF_H = 4200 / 1000 = 4.2$$

$$SM_{Req. H} = (126 - \frac{6}{4.2 - 3}) - 100 = 21\%$$

$$Act = 29.8$$

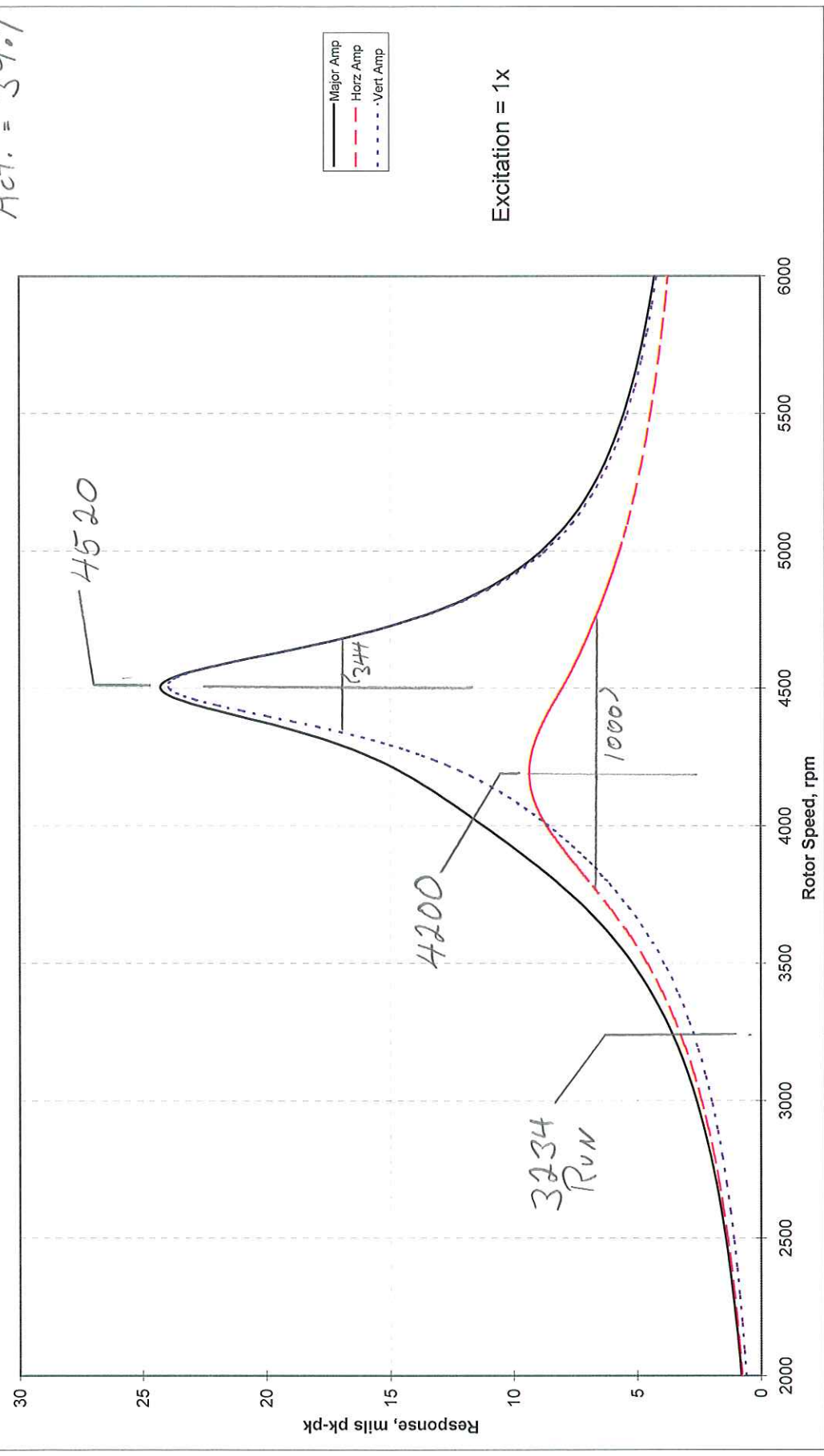
$$AF_V = 4520 / 344 = 13.1$$

$$SM_{Req. V} = (126 - \frac{6}{13.1 - 3}) - 100 = 25.4$$

$$Act. = 39.7$$

Rotordynamic Response Plot

08-177539-01  
MUSTANG  
Sta. No. 32: 3rd Stage Impeller (Min Bearing Clearance)



(Fig. 17)