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Final Report for FY-92

Stability Codes for a Liquid Rocket

Implemented for Use on a PC

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Final Report for FY-92

Stability Codes for a Liquid Rocket

Implemented for Use on a PC

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Summary

The high frequency code has been made an interactive code using FORTRAN 5.0 (1). The option to plot n-τ curves was added using the graphics routines of FORTRAN 5.0 (2) and GRAFMATIC (3). The user is now able to run with input values non-dimensional (as in the original code) or dimensional. Input data may be modified from the keyboard.

The low and intermediate frequency codes have been run through a set of input variations. This will help the user to understand how the stability of a configuration will change if any of the input data changes.

In addition to the final report, the following will be furnished:

1. User manuals for all four codes
2. Microsoft FORTRAN 5.0 manuals and disks
3. Grafmatic manual and disks
4. Briefing notes with homework problems

Table of Contents

1.0 Introduction

The development of codes for stability analysis of liquid propellant rockets by UAH contract no. NAS8-36955 began in 1989. The primary reference was Harrje and Reardon (4). The first low frequency codes were written for the Macintosh using MATHEMATICA. Intermediate frequency equations were developed from Harrje and Reardon. And for the high frequency effort, the code developed by Mitchell (5,6) at Colorado State University was obtained. The codes on the Mac were slow, therefore they were programmed in FORTRAN for the PC. The first years work culminated in the report UAH 5-32176 (7).

The FORTRAN codes were expanded to include accumulators, pumps, and pipes split into identical lines. Graphics were added to the low and intermediate codes. The high frequency code was run on the PC for several configurations. The second years work was presented in the report UAH 5-32441 (8).

This year the low and intermediate codes were refined for easier use. Also, the split pipe option was expanded to allow the splitting of a pipe into different lines. This included the ability to handle multiple tanks and multiple engines. Briefing notes for these three codes were developed. The notes included two sample runs and a homework problem.

The high frequency code was a major effort this year. The input was compressed and simplified. The input can now be dimensional as well as non-dimensional (as with Mitchell's original version). The output was also simplified and reformatted to fit into 80 columns. Plots of the n-τ curve are available if running option 3. The input data may be modified interactively.

This report will first cover the effort on the high frequency code (HIFREQ). Then, the effect of input variations on the low and intermediate frequency codes (ADMIT, NYQUIST, SSFREQ) will be discussed.

2.0 High Frequency Code (HIFREQ)

The high frequency code was obtained under the auspices of the USAF and we have been in contact with the author, Dr. Mitchell at Colorado State University. The program was written for a VAX computer and has been modified to run on a PC. Other enhancements have been made.

2.1 Introduction and Background

Dr. Mitchell, at Colorado State University, and his students began a number of years ago to develop codes to predict the high frequency oscillations in a liquid propellant engine (9). These codes and associated theory were developed over the years. All of these codes were developed for mainframe or mini computers.

In 1989, Mitchell developed FDORC for the Air Force (5,6). This code was developed to run on a VAX mini-computer. The Air Force released a copy of this code and the report describing the code for use on this project.

The code was converted at UAH to run on a PC. This mainly consisted of reducing the size of certain arrays (that the code had already specified an upper limit smaller than the dimensions).

2.2 Brief Description of Mitchell's Code

FDORC represents the full three-dimensional combustor model. The code includes a distributed combustion analysis which allows the combustion zone to be split into several equal length zones of varying mass release profiles. Three modes of oscillation are handled; radial, transverse, and longitudinal. No coupling with the piping is considered because of the high frequencies the program is designed to analyze. The effect of different acoustic cavity types can be investigated. Cavity types available are the following: quarter wave tube, Helmholtz resonator, long aperture resonator, and variable geometry -variable mean temperature absorber. Multi-tuned absorbers oriented radially or axially can be examined.

The code has three main running options:

1 - a given combustion response is input and the resulting complex frequency is calculated.

2 - interaction index (n) and time lag (τ) are input and the resulting complex frequency is calculated.

3 - for a given frequency the combustion response, n, and τ are determined. This is the option used to generate data for n-τ stability maps.

The code requires the input to be non-dimensionalized and the output is also non-dimensionalized. The input is read on up to 7 different files. The number of input files depends upon the problem to be solved. If no absorbers are present and no pressure profiles desired, then only two input files are necessary.

All input is from and to files because the code was written for batch operation only. Thus, to obtain a n-τ plot, the file 'NTPLOT' or 'ZNTAU' had to be input into a plot program. Changes to the input data had to be made between runs.

2.3 Description of the Changes Made to Code

The program was extensively modified to allow the user more control, easier input, graphic output, and interactive data modification. The changes can be grouped into three general areas: input, output, and interactive.

Input Changes:

1. Input may be input dimensional or non-dimensional.
2. If input is dimensional, chamber radius, pressure, temperature, and molecular weight must be input.
3. If input is dimensional, frequency may be in Hertz or rad/sec.
4. Input was expanded and regrouped into logical units.
5. Input was compacted into one file, not seven files.
6. The input is checked for invalid modes.
7. On input, where flags were used to signal the code to read in a counter, the flags have become the counters and the separate read for the counters has been removed.
8. If DELOM is an integral number, then it is used as the number of frequencies desired. If not integral, it is used as the frequency increment.

Output Changes:

1. If input is dimensional, output may be dimensional or non-dimensional.
2. Formats were modified to allow dimensional output.
3. Output was limited to 80 columns in order to be viewed on the screen.
4. The output file 'NTPLOT' was removed as it is not needed.

Interactive Additions:

1. The program may be run in batch or interactive mode.
2. n, τ, and Ω are written to the screen in interactive mode with OPTION=3.
3. n vs τ plots may be made in interactive mode with OPTION=3.
4. Input may be changed interactively with the keyboard.
5. For a given mode, the user has the option to compute and display fundamental frequency. Then the user may input the frequency range desired.

The n-τ plots for both dimensional (fig. 1) and non-dimensional (fig. 2) data for a sample case furnished by Dr. Mitchell are given. Since they are for the same configuration and frequency range, the graphs are the same.

3.0 Effect of Input Variations

In order to get a feel for the codes and how various input affect the results, a series of runs were made on variations on a straight pipe. A one foot diameter pipe 86 feet long was used as the basis. The effects of various parameters on the output from the three programs were studied by choosing a basic configuration and varying the input one parameter at a time. When the admittance looking toward the tank was affected, the output of all three programs were affected. When the admittance looking toward the tank was unchanged (or had a small change) for a change in tank, piping, or engine input, the results from NYQUIST and SSFREQ are unaffected.

Another effect to notice is that bends in a pipe do not greatly affect the admittance looking toward the tank. The only effect of a bend is the change in effective length and diameter of the pipe on the admittance looking toward the tank. However, bends do affect the admittance when looking toward the engine. Thus, bends have an effect on the pressure transfer function.

For the 3-way equally split pipe, only the results from one engine is presented because the three lines are almost identical. The 3-way unequal split pipe has lines 1 and 3 the same therefore only engine 1 and engine 2 results are presented.

This study will first present the results of the basic configuration. The piping variations will be run next. Following these, tank and engine variations are presented. Changes that only affect the results of NYQUIST are given next followed by those that only affect SSFREQ results. Description of the input is given in the users manuals.

Variations used by ADMIT, NYQUIST, and SSFREQ

1. Basic configuration
   1' diameter straight pipe 86' long
   tank volume = 4,055 ft^3
   mass flow = 2,264 lbm/sec
   bulk modulus = 1.185883E+07 lbf/ft^2
   density = 72.13 lbm/ft^3
   manifold volume = 4.5 ft^3
   bulk modulus = 1.183346E+07 lbf/ft^2
   engine mass flow = 3,112 lbm/sec
   pressure = 95,040 lbf/ft^2
   pressure drop = 44,640 lbf/ft^2

Piping variations

2. 20' shorter length
   1' diameter straight pipe 66' long

3. Double diameter - 2'
   2' diameter straight pipe 86' long

4. 10' 90 deg bend (middle section 10' long)
   1' diameter straight pipe 30' long
   -90 deg bend 1' diameter
   1' diameter straight pipe 4' long
   +90 deg bend 1' diameter
   1' diameter straight pipe 10' long
   +90 deg bend 1' diameter
   1' diameter straight pipe 4' long
   -90 deg bend 1' diameter
   1' diameter straight pipe 30' long

5. 30' 90 deg bend (middle section 30' long)
   1' diameter straight pipe 20' long
   -90 deg bend 1' diameter
   1' diameter straight pipe 4' long
   +90 deg bend 1' diameter
   1' diameter straight pipe 30' long
   +90 deg bend 1' diameter
   1' diameter straight pipe 4' long
   -90 deg bend 1' diameter
   1' diameter straight pipe 20' long

6. 50' 90 deg bend (middle section 50' long)
   1' diameter straight pipe 10' long
   -90 deg bend 1' diameter
   1' diameter straight pipe 4' long
   +90 deg bend 1' diameter
   1' diameter straight pipe 50' long
   +90 deg bend 1' diameter
   1' diameter straight pipe 4' long
   -90 deg bend 1' diameter
   1' diameter straight pipe 10' long

7. 3-way equal split (only engine #1 plotted - all the same)
   1' diameter straight pipe 64' long
   (3 pipe split)
   1) 0.57735' diameter pipe 22' long
      engine mass flow = 1,037.333 lbm/sec
      pressure = 95,040 lbf/ft^2
      pressure drop = 44,640 lbf/ft^2
   2) 0.57735' diameter pipe 22' long
      engine mass flow = 1,037.333 lbm/sec
      pressure = 95,040 lbf/ft^2
      pressure drop = 44,640 lbf/ft^2
   3) 0.57735' diameter pipe 22' long
      engine mass flow = 1,037.333 lbm/sec
      pressure = 95,040 lbf/ft^2
      pressure drop = 44,640 lbf/ft^2

8. 3-way unequal split (engines #1 and #2 plotted - #3 = #1)
   1' diameter straight pipe 64' long
   (3 pipe split)
   1) 0.5' diameter pipe 22' long
      engine mass flow = 777.8 lbm/sec
      pressure = 95,040 lbf/ft^2
      pressure drop = 44,640 lbf/ft^2
   2) 0.70711' diameter pipe 22' long
      engine mass flow = 1,556 lbm/sec
      pressure = 95,040 lbf/ft^2
      pressure drop = 44,640 lbf/ft^2
   3) 0.5' diameter pipe 22' long
      engine mass flow = 777.8 lbm/sec
      pressure = 95,040 lbf/ft^2
      pressure drop = 44,640 lbf/ft^2

Tank variations

9. Doubled tank volume
   tank volume = 8,110 ft^3

10. Halved mass flow
    tank mass flow = 1,132 lbm/sec

11. Doubled bulk modulus
    tank bulk modulus = 2.371766E+07 lbf/ft^2

12. Doubled density
    tank density = 144.26 lbm/ft^3

Engine variations

13. Doubled engine mass flow
    engine mass flow = 6,224 lbm/sec

14. Doubled engine pressure
    engine pressure = 190,080 lbf/ft^2

15. Doubled engine dP
    engine pressure drop = 89,280 lbf/ft^2

Used only by NYQUIST

1. Basic configuration
   taut = 0.001 sec
   cstar = 6,219 ft/sec
   rbar = 2.67
   thetac = 0.00233 sec
   dc/dr = -315

16. Doubled taut
    taut = 0.002 sec

17. Doubled cstar
    cstar = 12,438 ft/sec

18. Doubled rbar
    rbar = 5.34

19. Doubled thetac
    thetac = 0.00466 sec

20. Doubled dc/dr
    dc/dr = -630

Used only by SSFREQ

1. Basic configuration
   4' long combustion zone with constant pressure (95,040 lbf/ft^2) and temperature (4000 °R). Two stations used.
   invariant time lag = 0.000697 sec
   mixture ratio interaction index = 0.01
   damping = 0.0
   chamber diameter = 3.214 ft
   throat diameter = 2.232 ft
   chamber length = 4.0 ft
   ratio of specific heats = 1.2
   gas constant = 1,716 (ft/sec)^2/°R
   maximum overpressure = 142,500 lbf/ft^2
   mixture ratio = 2.67
   dcs/dr = -315 ft/sec
   dhl/dr = 0.01 (ft/sec)^2
   liquid mass/chamber volume = 0.44 lbm/ft^3
   axial component liquid velocity = 1965 ft/sec

21. Doubled chamber diameter
    chamber diameter = 6.428 ft

22. Halved throat diameter
    throat diameter = 1.116 ft

23. 20% longer chamber length
    chamber length = 4.8 ft

24. Doubled dcs/dr
    dcs/dr = -630 ft/sec

25. Doubled dhl/dr
    dhl/dr = 0.02 (ft/sec)^2

26. Doubled rholo
    liquid mass/chamber volume = 0.88 lbm/ft^3

27. Doubled ulo
    axial component liquid velocity = 3,930 ft/sec

3.1 ADMIT

The results of the ADMIT runs are displayed with each figure containing 3 plots; piping layout and admittance, surface plot of pressure transfer function, and contour plot of pressure transfer function. The basic configuration is shown in fig. 3. The variations will be compared to this plot.

Changing the length of the pipe only changes the number of cycles present, but the shape and amplitude are not changed (fig. 4). Changing the diameter does change the shape of the admittance curve (fig. 5). It also changes the pressure transfer function.

If bends are added which do not change the effective length and diameter of a pipe, the admittance is not affected (figs. 6, 7, & 8). The additions of bends do change the pressure transfer function. The placement of the bends also has an affect on the pressure transfer function.

When a pipe splits into several pipes, there is an effect on both the admittance and the pressure transfer function. The effects of a 3-way equal split (fig. 9) and for an unequal split (figs. 10 & 11) are shown. Note that for the unequal split the admittance for different engines are different, but the pressure transfer function is almost the same.

Changing tank volume has little effect on the results (fig. 12). Changing mass flow primarily affects amplitude (fig. 13). A change in bulk modulus (fig. 14) or density (fig. 15) changes the number of cycles in the admittance curve and the number of nodes in the pressure transfer function.

A change in engine mass flow changes the amplitude of the admittance, but has no effect on the pressure transfer function (fig. 16). Changes in engine pressure has a similar effect (fig. 17) except the amplitude changes in the opposite direction. A change in the pressure drop across the orifice affect the shape of the admittance curve and the amplitude of both the admittance curve and pressure transfer function (fig. 18).

3.2 NYQUIST

The NYQUIST results are shown for only the LOX piping present. When there is little or no change in the admittance curve, there will be little or no change in the NYQUIST curves. Each figure gives the Nyquist plot and the phase-gain plots. Compare the variation results to the basic configuration (fig. 19).

A length change only changes the number of cycles present (fig. 20). Changing the diameter of the pipe changes the shapes of the curves (fig. 21). As the insertion of bends had little effect on the admittance curve, they have little effect on the Nyquist and phase-gain plots (figs. 22, 23, & 24).

A pipe split has a profound effect on the results. The 3-way equal split is shown in fig. 25. The two different engine results are different from each other and the basic configuration (figs. 26 & 27).

As before, changing tank volume has little effect on the NYQUIST results (fig. 28). Changing mass flow primarily affects amplitude (fig. 29). A change in bulk modulus changes the number of cycles in the Nyquist curve and the shape of the phase-gain curves (fig. 30). A density variation changes the number of cycles in the Nyquist and phase-gain curves (fig. 31).

A change in engine mass flow (fig. 32) and in engine pressure (fig.33) mainly change the amplitude. A change in the pressure drop across the orifice affect the shape and amplitude of the curves (fig. 34).

The final variations were the NYQUIST only changes. Doubling the values had very little effect for transport lag (fig. 35), characteristic velocity (fig. 36), or mixture ratio (fig. 37). Changing characteristic time constant (fig. 38) and change in characteristic velocity with mixture ratio (fig. 39) show more change in the Nyquist plot and/or the phase-gain plot.

3.3 SSFREQ

The intermediate mode code requires both the LOX and fuel line to be present. The fuel line was identical to the lox line except for the mass flow (848 lbm/sec). As only one plot (in most cases) is produced per configuration, three figures are placed on a page. Again, compare the variation results to the basic configuration results (fig. 40).

Note that the frequency for the intermediate mode is considerably higher than for the low frequency codes. For most cases, simply look at the amplitude of n as most of the curve shapes are the same. An exception is for the doubled engine mass flow.

The effects of length (fig. 41) and diameter (fig. 42) show changes in the level of minimum n. The additions of length and diameter preserving bends have little effect (figs. 43, 44, & 45). Both equal splits (fig. 46) and unequal splits (fig. 47 & 48) show a shift in the minimum n value.

Changes in tank volume (fig. 49), mass flow (fig. 50), bulk modulus (fig. 51), and density (fig. 52) show primarily level changes, some small and some large.

Doubling engine mass flow actually makes it go unstable at 110 Hertz (fig. 53). Changing engine pressure (fig. 54) and pressure drop across the orifice (fig. 55) have smaller effects.

The SSFREQ changes are presented next. The level of the minimum n value is the primary effect. The results are given for doubled chamber diameter (fig. 56), halved throat diameter (fig. 57), 20% longer chamber length (fig. 58), doubled change in characteristic velocity with mixture ratio (fig. 59), doubled change in enthalpy with mixture ratio (fig. 60), doubled liquid density (fig. 61), and doubled liquid axial velocity (fig. 62). Some of the changes also tended to flatten out the n-τ curve.

4.0 Conclusions and Recommendations

Four codes have been developed for the PC to analyze the stability of liquid propellant rockets. The low and intermediate frequency codes were developed in their entirety at the UAH Research Institute. The high frequency code is the result of extensive modifications of a code developed by Dr. Mitchell at Colorado State University.

The four codes have interactive capability, plot results on-line, and allow input data to be modified from the keyboard. Each of the codes have a users manual to help with running the program. The low and intermediate frequency codes have a set of briefing notes to assist in teaching the use of the codes. A homework problem is included in the briefing notes.

It is recommended that the user becomes familiar with the codes to the extent that he may make FORTRAN changes to allow the codes to remain current. Also, more or different graphics may be desired. No program is static, it is dynamic. Therefore, changes must be made or the code will die.

5.0 References

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4. Harrje, David T., Ed. and Reardon, Fredrick H., Assoc. Ed., 'Liquid Propellant Rocket Combustion Instability", NASA SP-194, 1972.

5. Mitchell, Dr. C. E., 'Stability Design Methodology Vol. 1', USAF Final Report AL-TR-89-041, October 1989.

6. Mitchell, Dr. C. E., 'Software Users Manual Vol. 2', USAF Final Report AL-TR-89-041, October 1989.

7. Doane, G. B., III and Armstrong, W., 'PC Programs for the Prediction of the Linear Stability Behavior of Liquid Propellant Propulsion Systems And Application to Current MSFC Rocket Engine Test Programs', UAH 5-32176, June 1990.

8. Doane, G. B., III and Armstrong, W. C., 'Propulsion Stability Codes for Liquid Propulsion Systems Developed for Use on a PC Computer', UAH 5-32441, June 1991

9. Mitchell, C. E. and Eckert, K., 'A Simplified Computer Program for the Prediction of the Linear Stability Behavior of Liquid Propellant Combustors', NASA CR 3169, 1979.

6.0 Figures

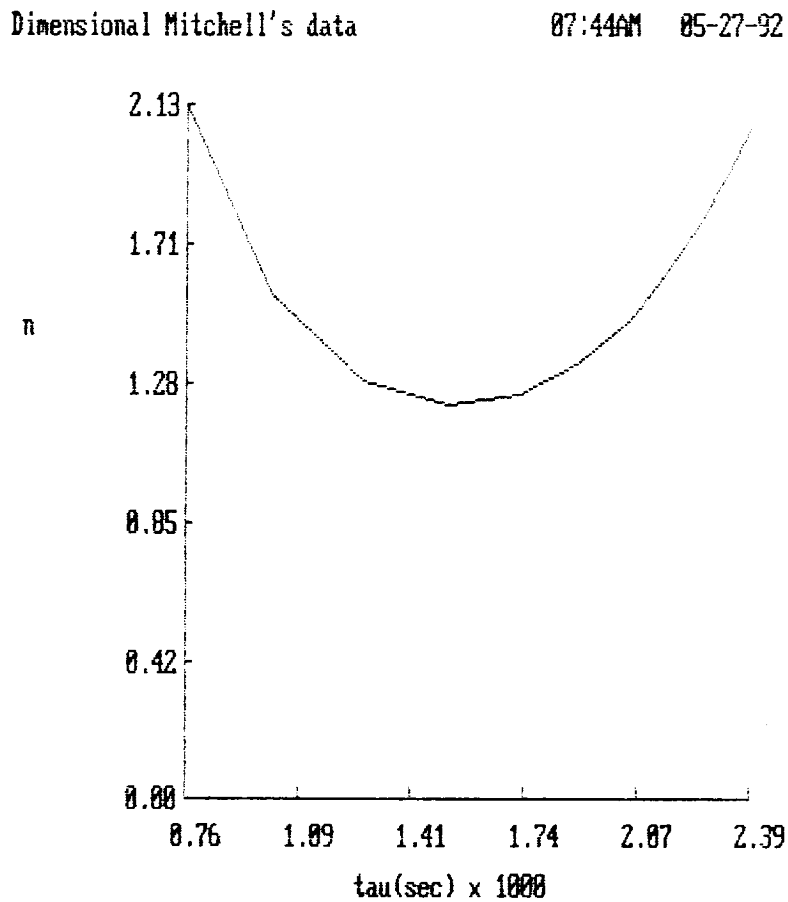
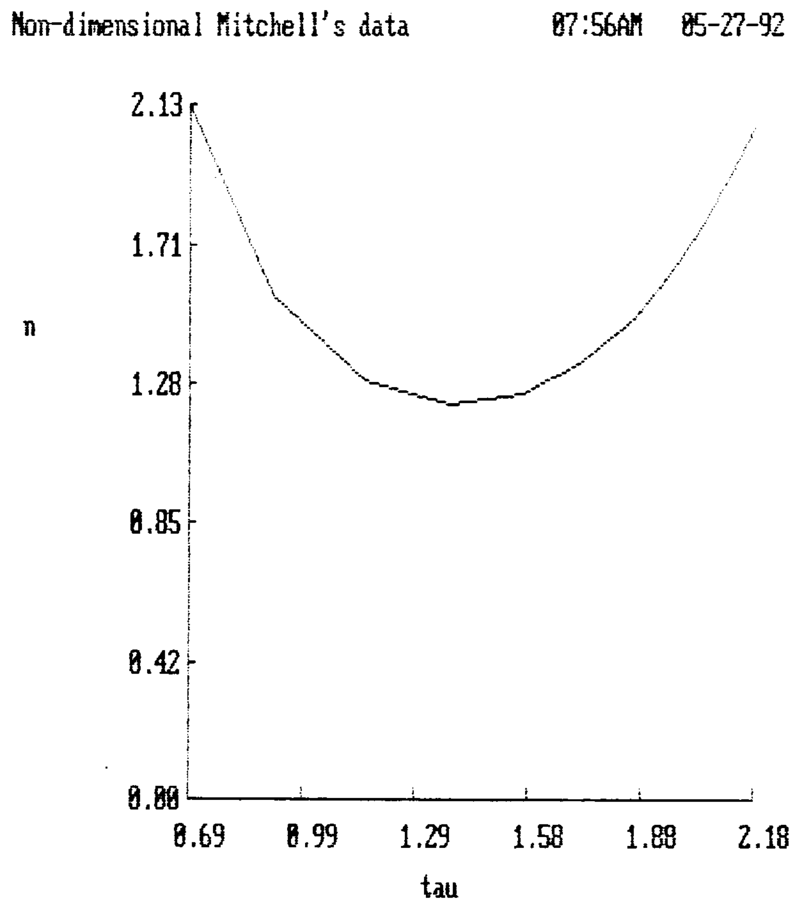

Dimensional Mitchell's data
07:44AM 05-27-92
2.13
1.71
1.28
0.85
0.42
0.00
n
0.76
1.09
1.41
1.74
2.07
2.39
tau(sec) x 1000

Figure 1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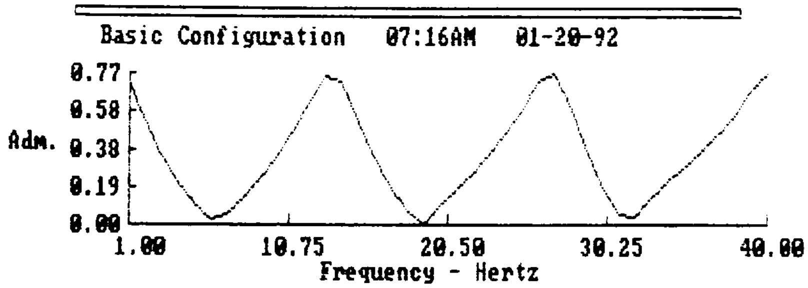
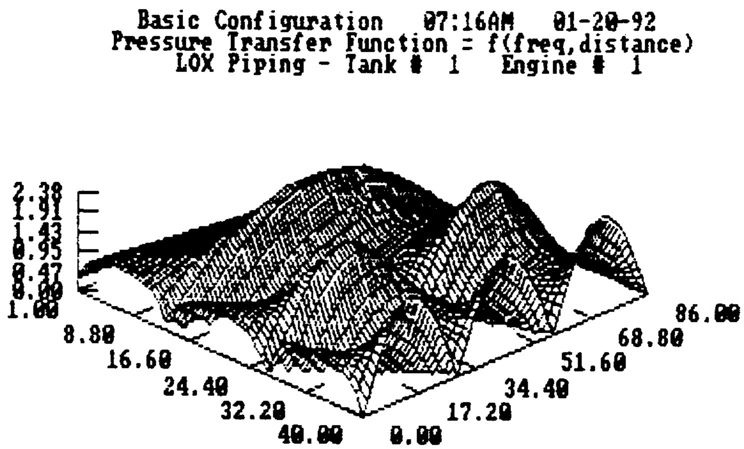
1.71
1.28
0.85
0.42
0.00
n
0.69
0.99
1.29
1.58
1.88
2.18
tau

Figure 2

LOX Piping - Tank # 1 Engine # 1





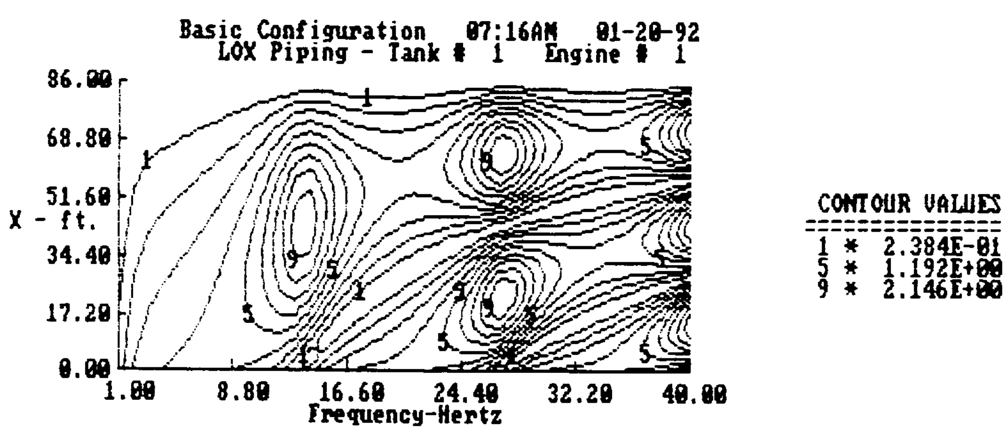
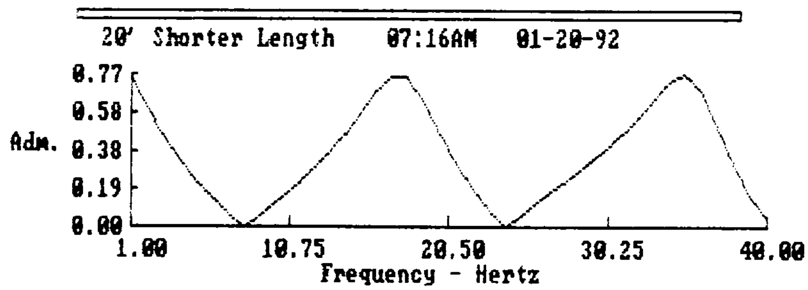
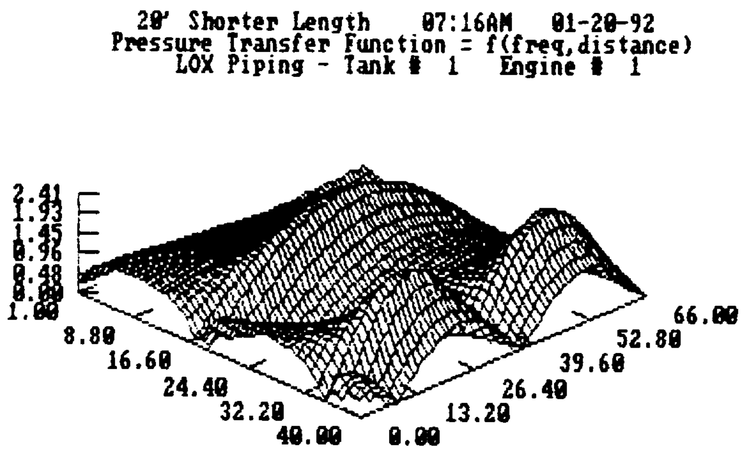


Figure 3

LOX Piping - Tank # 1 Engine # 1





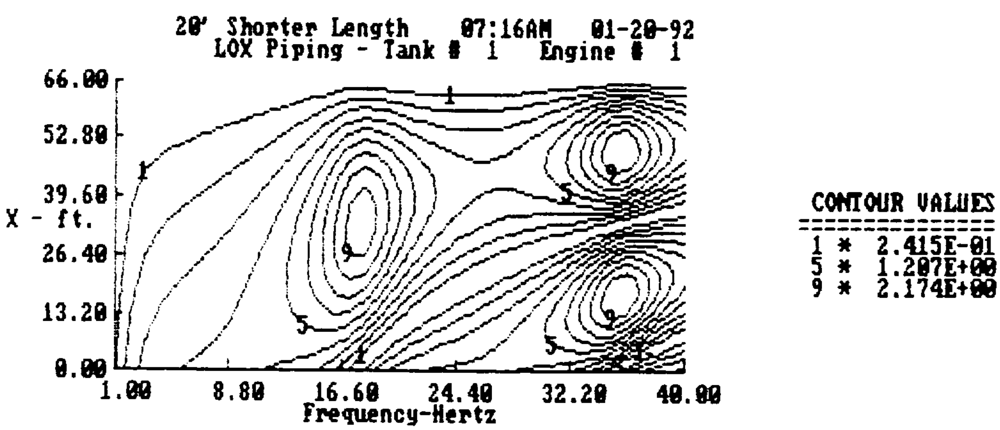
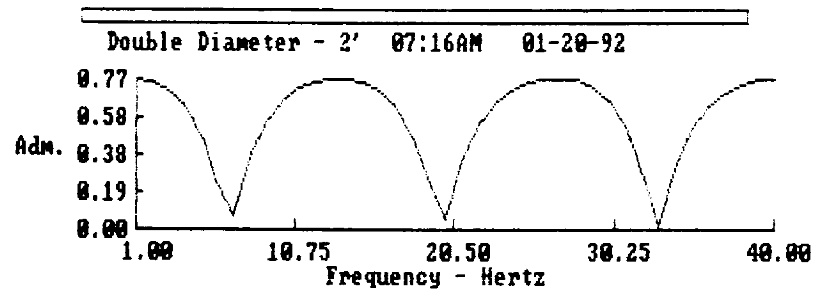
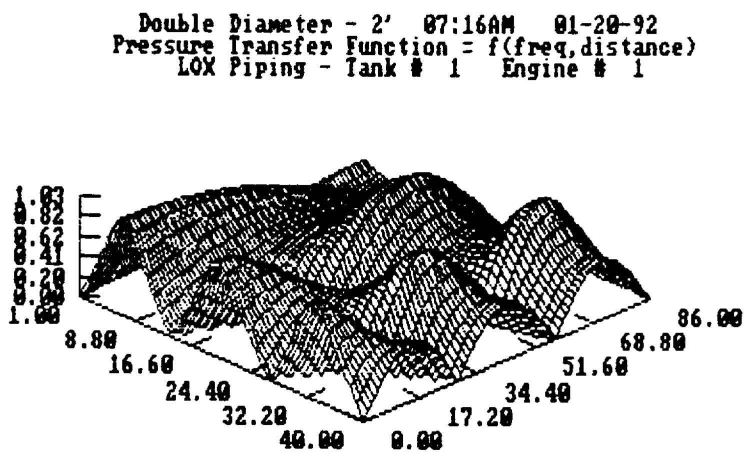


Figure 4

LOX Piping - Tank # 1 Engine # 1





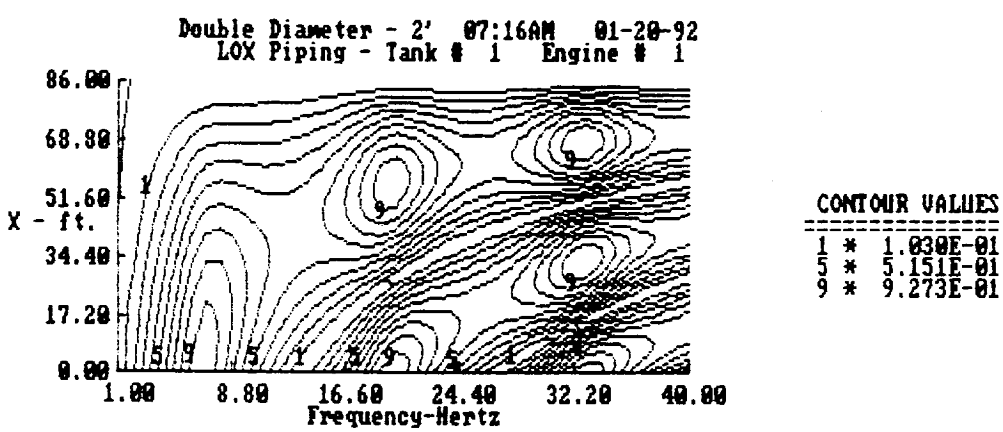
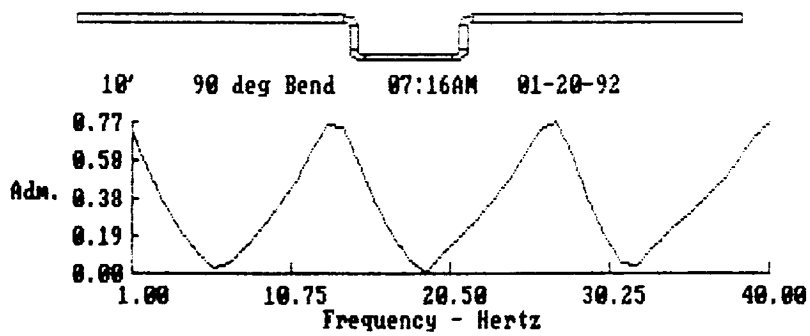
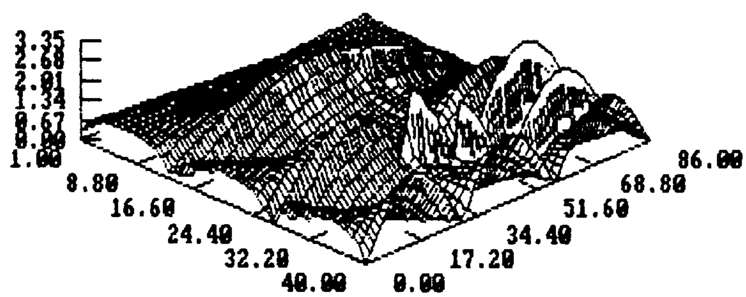


Figure 5

LOX Piping - Tank # 1 Engine # 1



10' 90 deg Bend 07:16AM 01-20-92
Pressure Transfer Function = f(freq,distance)
LOX Piping - Tank # 1 Engine # 1



10' 90 deg Bend 07:16AM 01-20-92
LOX Piping - Tank # 1 Engine # 1

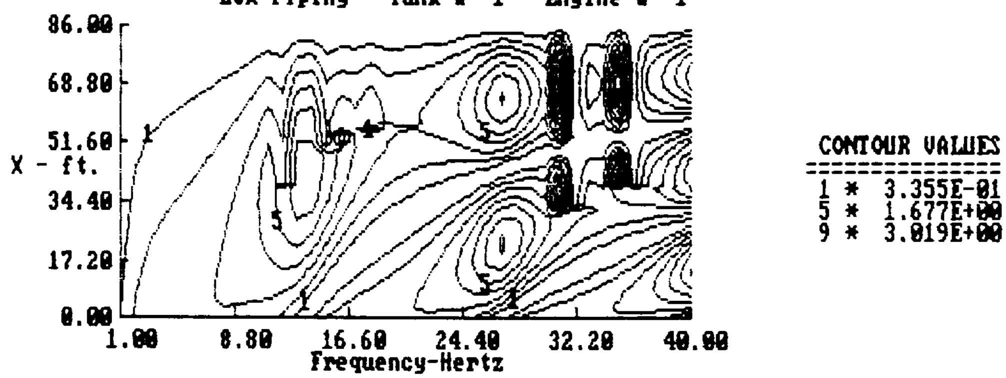
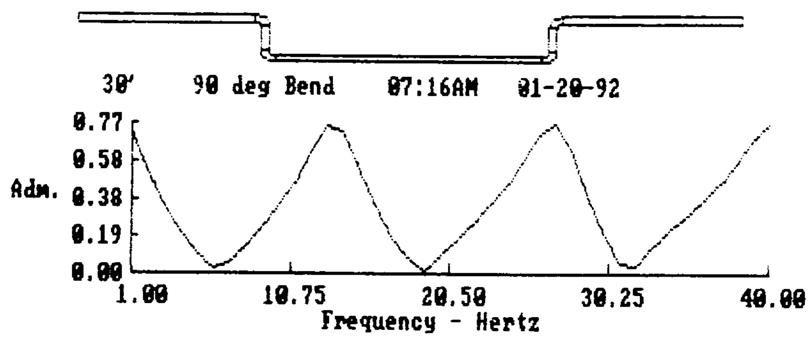
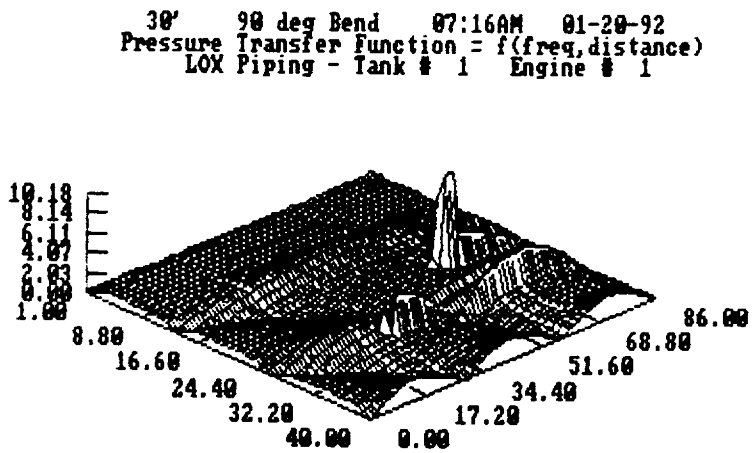


Figure 6

LOX Piping - Tank # 1 Engine # 1





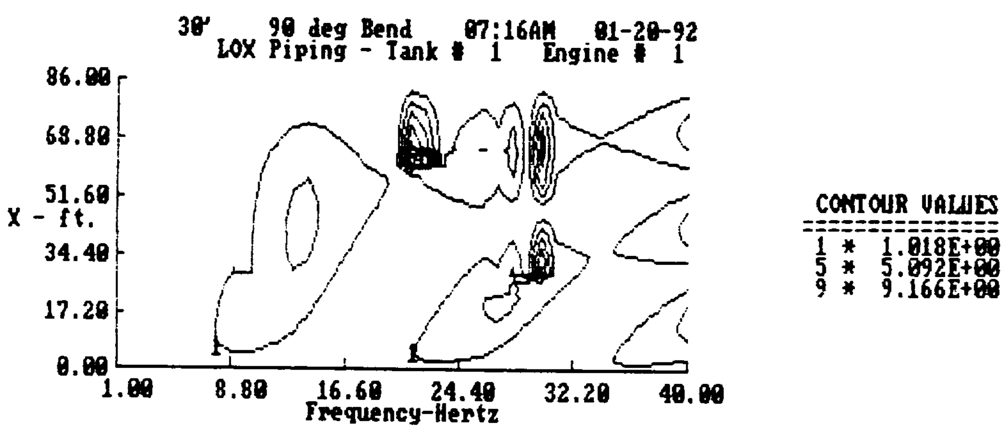
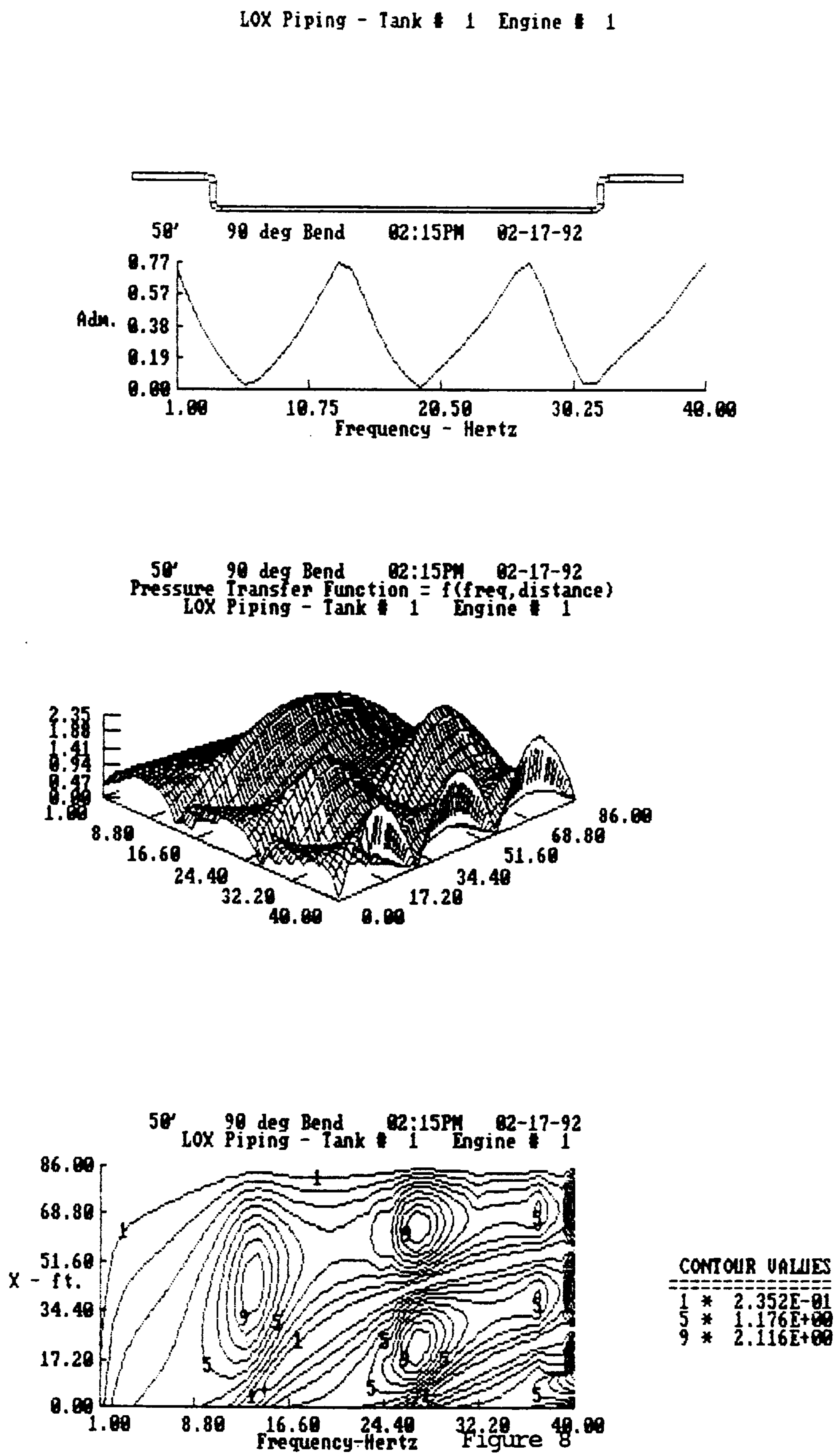


Figure 7



LOX Piping - Tank # 1 Engine # 1
50' 90 deg Bend 02:15PM 02-17-92
Adm.
0.77
0.57
0.38
0.19
0.00
1.00
10.75
20.50
30.25
40.00
Frequency - Hertz
50' 90 deg Bend 02:15PM 02-17-92
Pressure Transfer Function = f(freq,distance)
LOX Piping - Tank # 1 Engine # 1
2.35
1.88
1.41
0.94
0.47
0.00
1.00
8.80
16.60
24.40
32.20
40.00
0.00
17.20
34.40
51.60
68.80
86.00
50' 90 deg Bend 02:15PM 02-17-92
LOX Piping - Tank # 1 Engine # 1
86.00
68.80
51.60
X - ft.
34.40
17.20
0.00
1.00
8.80
16.60
24.40
32.20
40.00
Frequency-Hertz
CONTOUR VALUES
1 * 2.352E-01
5 * 1.176E+00
9 * 2.116E+00

Figure 8

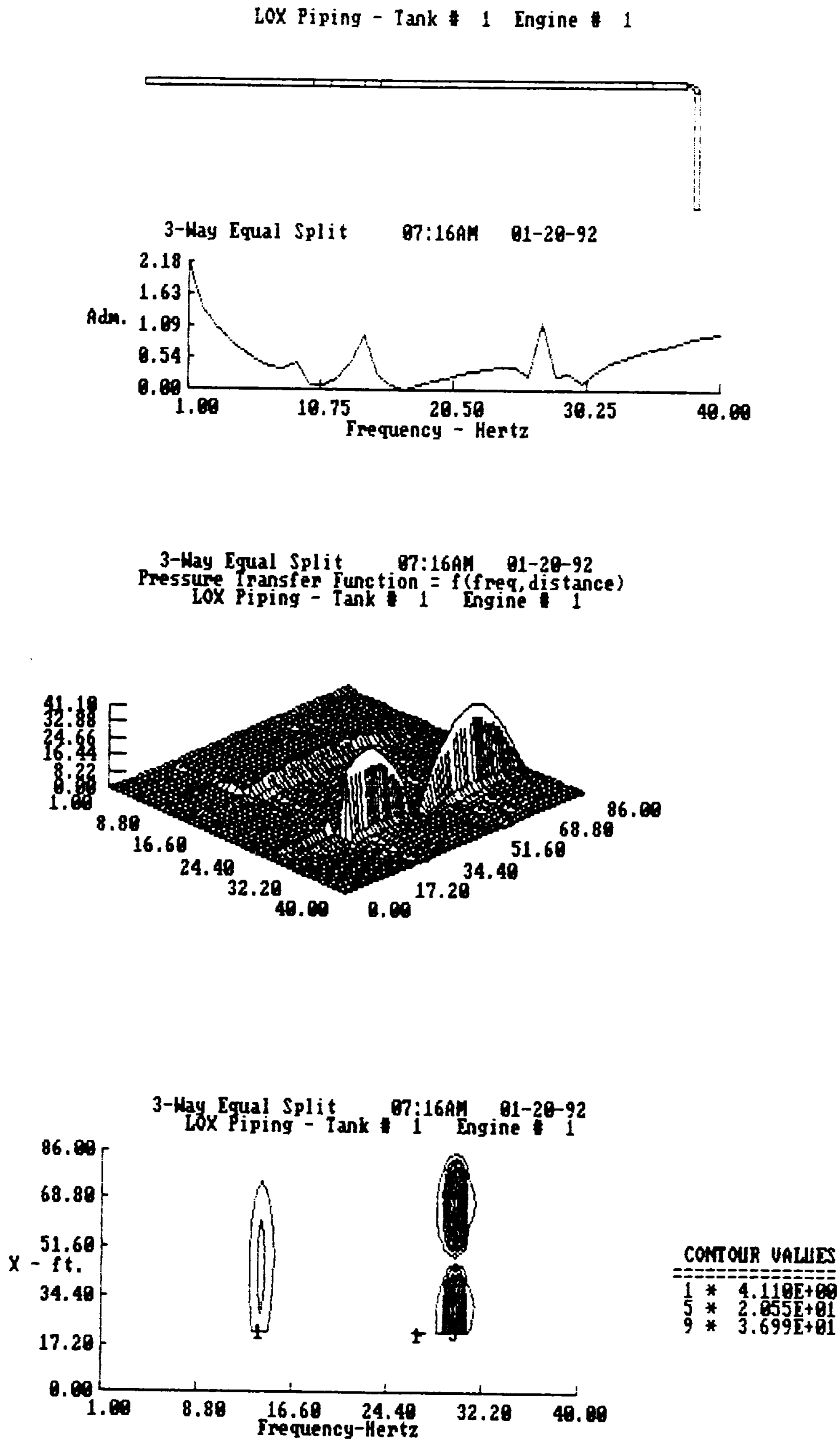

LOX Piping - Tank # 1 Engine # 1
3-Way Equal Split 07:16AM 01-20-92
Adm.
2.18
1.63
1.09
0.54
0.00
1.00
10.75
20.50
30.25
40.00
Frequency - Hertz
3-Way Equal Split 07:16AM 01-20-92
Pressure Transfer Function = f(freq,distance)
LOX Piping - Tank # 1 Engine # 1
41.10
32.88
24.66
16.44
8.22
0.00
1.00
8.80
16.60
24.40
32.20
40.00
0.00
17.20
34.40
51.60
68.80
86.00
3-Way Equal Split 07:16AM 01-20-92
LOX Piping - Tank # 1 Engine # 1
86.00
68.80
51.60
X - ft.
34.40
17.20
0.00
1.00
8.80
16.60
24.40
32.20
40.00
Frequency-Hertz
CONTOUR VALUES
1 * 4.110E+00
5 * 2.055E+01
9 * 3.699E+01

Figure 9

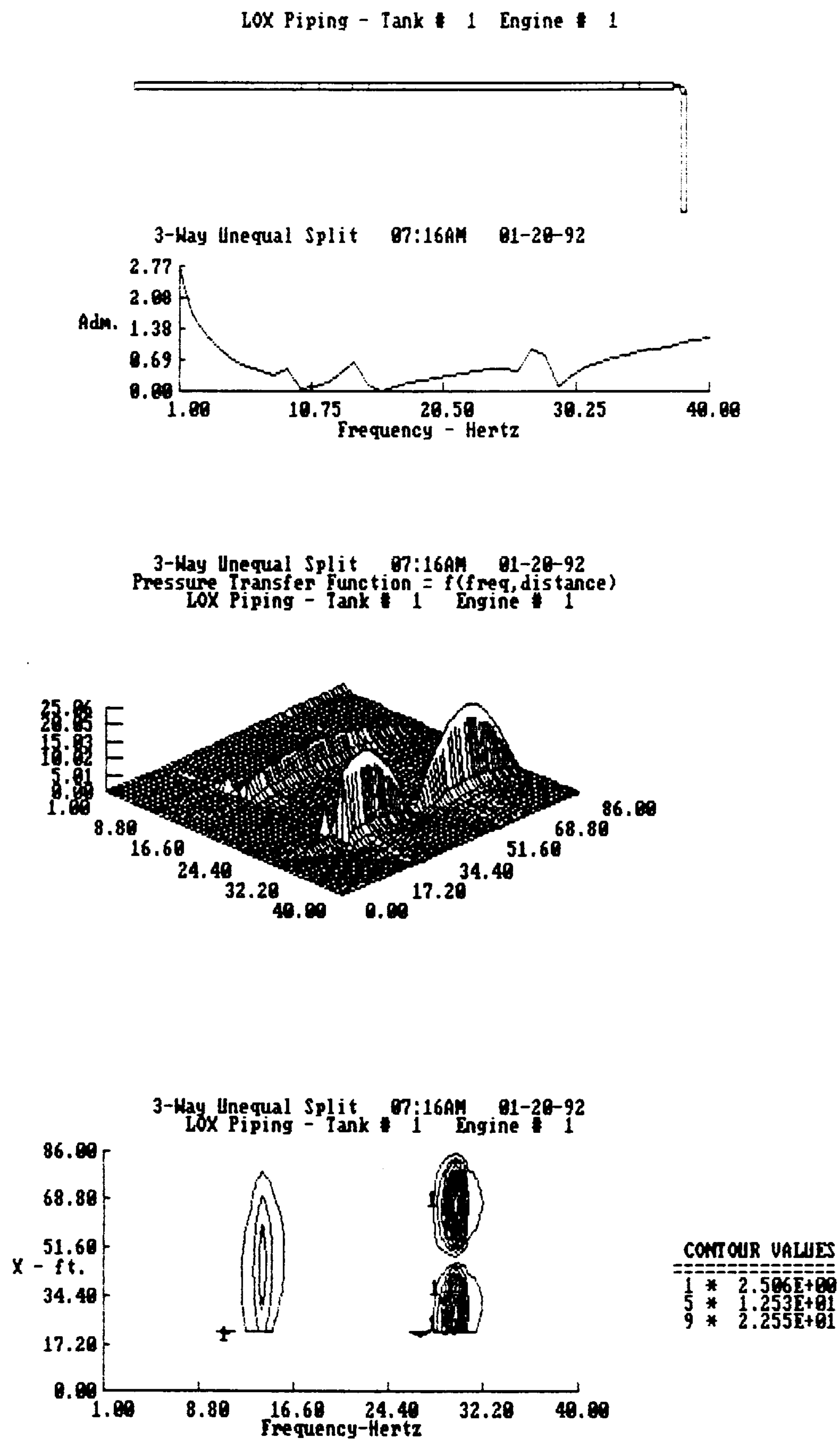

LOX Piping - Tank # 1 Engine # 1
3-Way Unequal Split 07:16AM 01-20-92
Adm.
2.77
2.08
1.38
0.69
0.00
1.00
10.75
20.50
30.25
40.00
Frequency - Hertz
3-Way Unequal Split 07:16AM 01-20-92
Pressure Transfer Function = f(freq,distance)
LOX Piping - Tank # 1 Engine # 1
25.06
20.05
15.03
10.02
5.01
0.00
1.00
8.80
16.60
24.40
32.20
40.00
0.00
17.20
34.40
51.60
68.80
86.00
3-Way Unequal Split 07:16AM 01-20-92
LOX Piping - Tank # 1 Engine # 1
86.00
68.80
51.60
X - ft.
34.40
17.20
0.00
1.00
8.80
16.60
24.40
32.20
40.00
Frequency-Hertz
CONTOUR VALUES
1 * 2.506E+00
5 * 1.253E+01
9 * 2.255E+01

Figure 10

LOX Piping - Tank # 1 Engine # 2

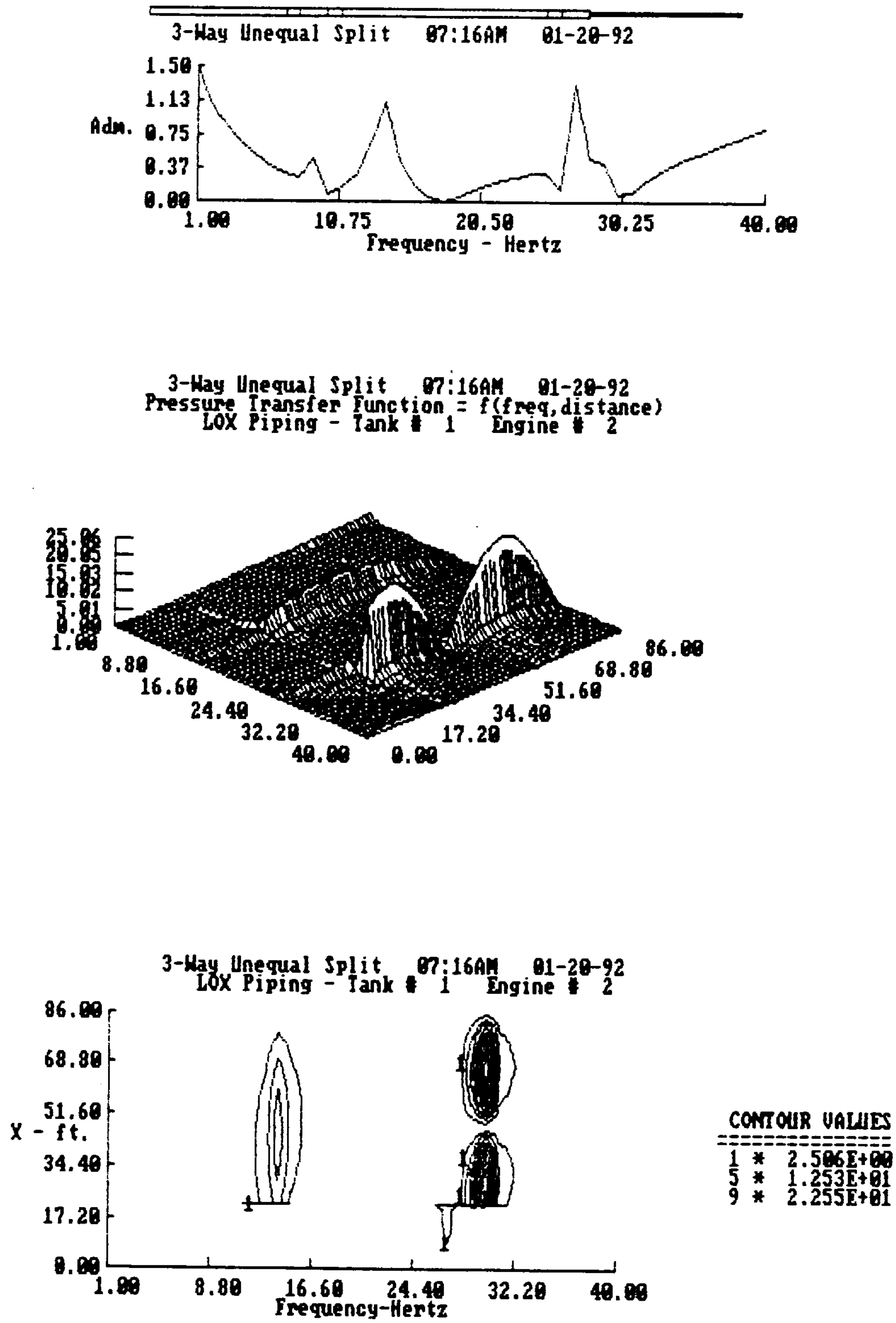
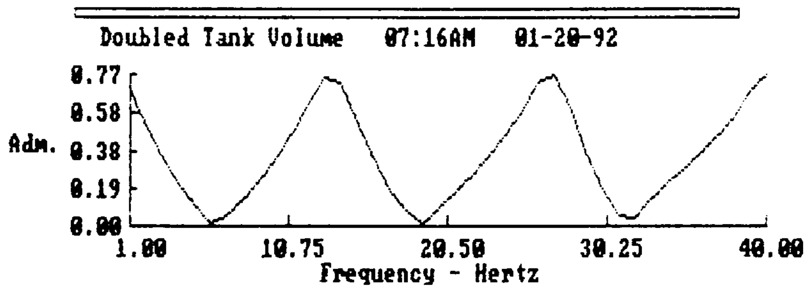
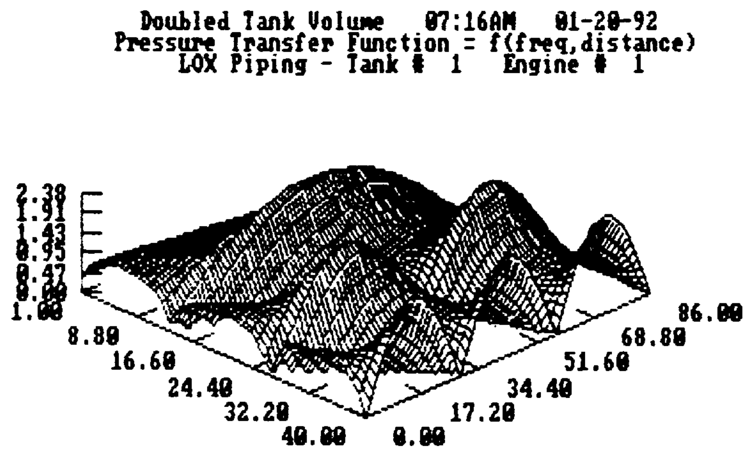


Figure 11

LOX Piping - Tank # 1 Engine # 1





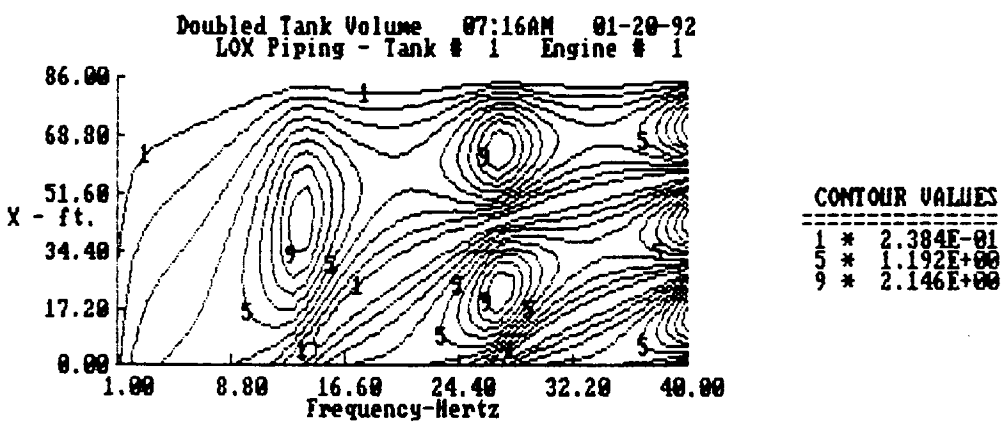
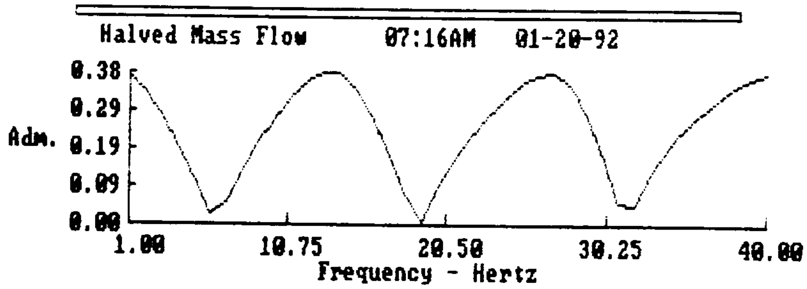
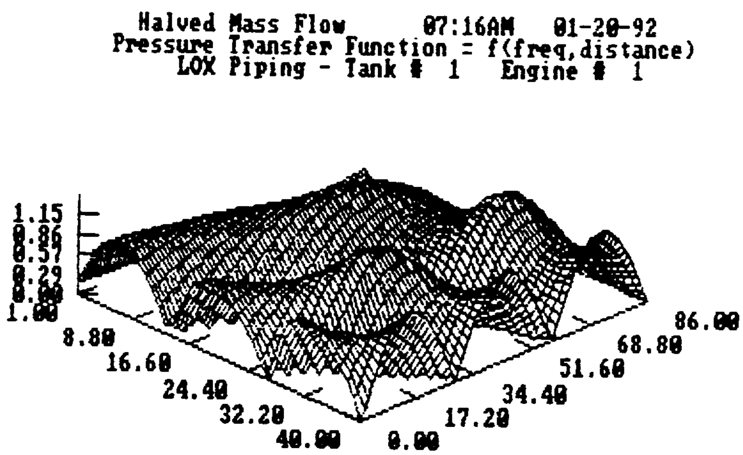


Figure 12

LOX Piping - Tank # 1 Engine # 1





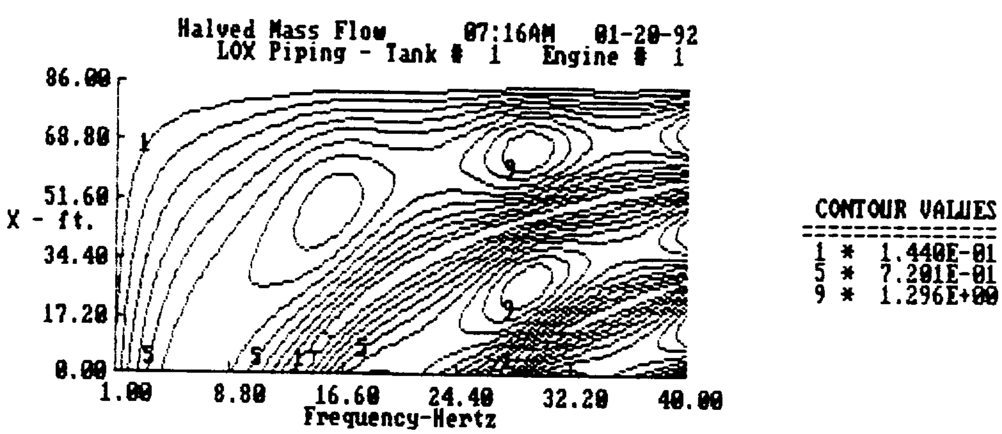
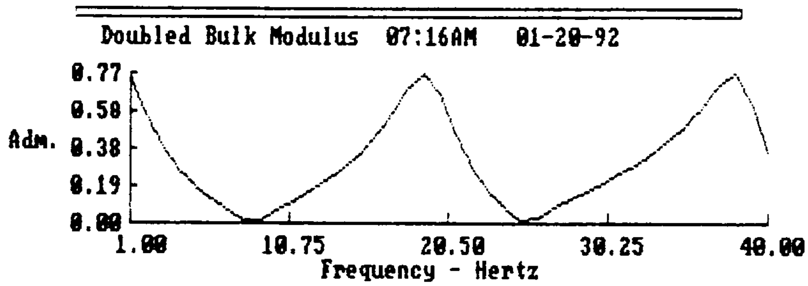
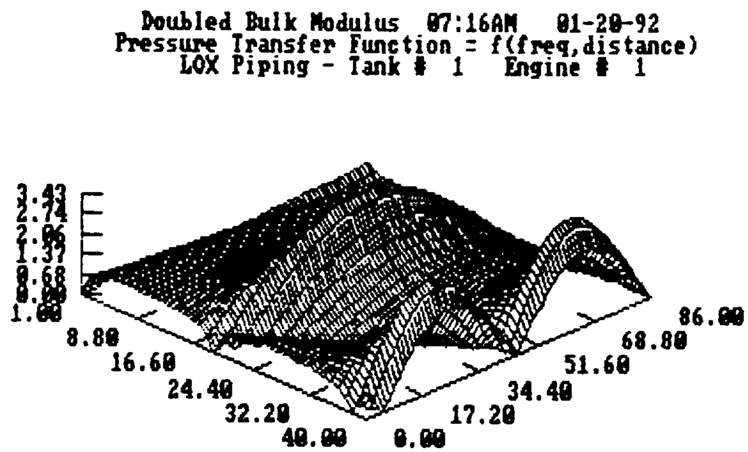


Figure 13

LOX Piping - Tank # 1 Engine # 1





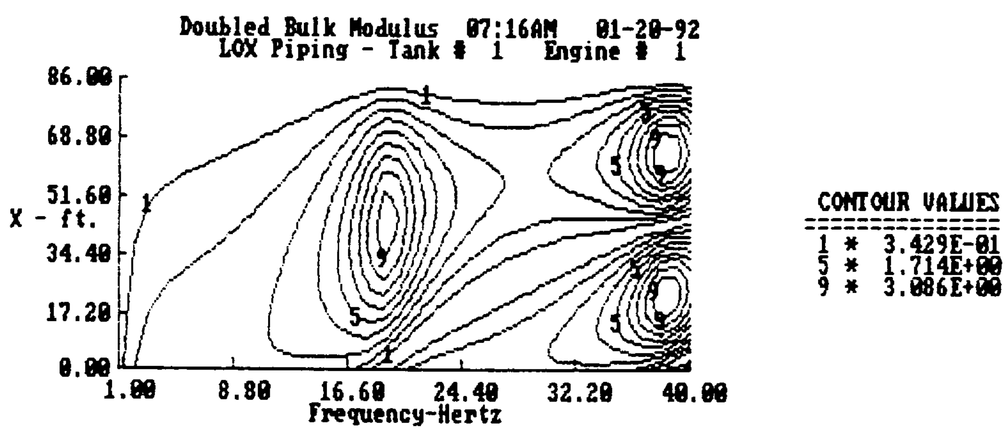
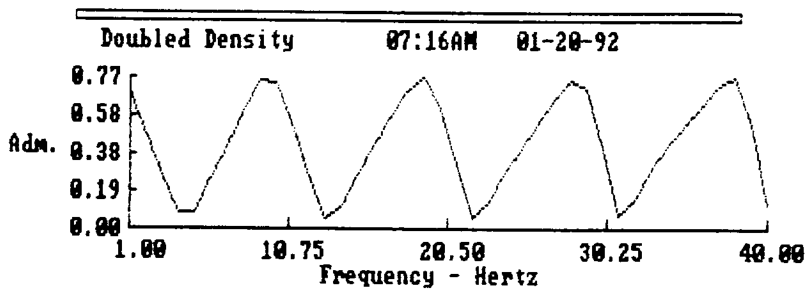
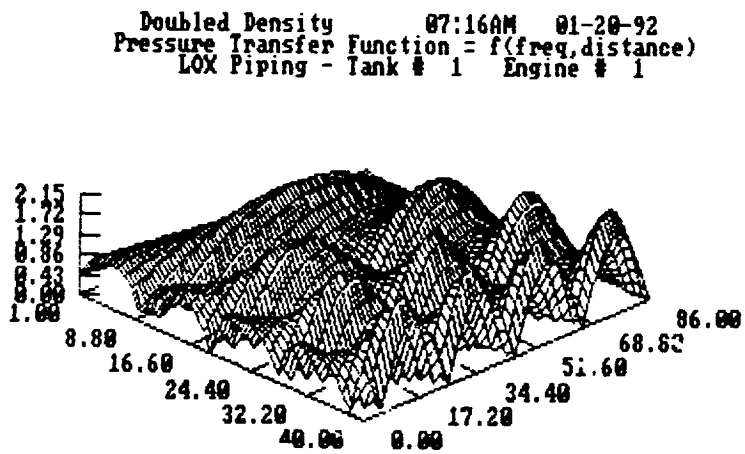


Figure 14

LOX Piping - Tank # 1 Engine # 1





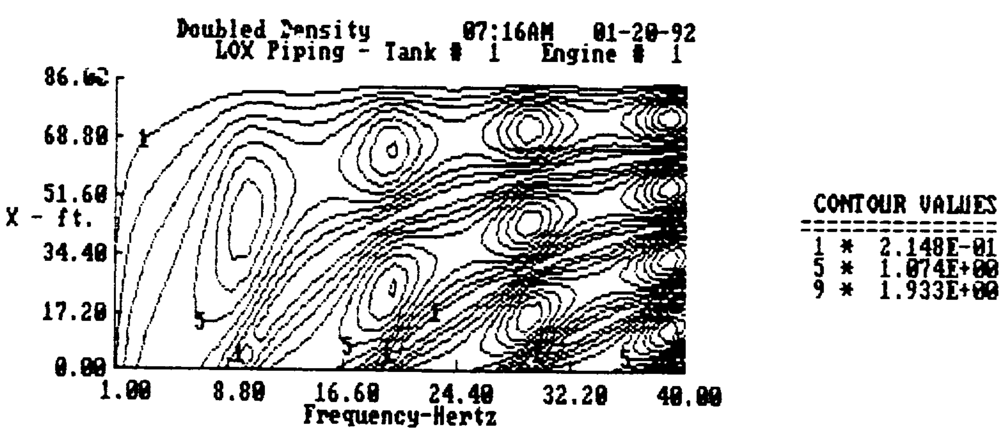
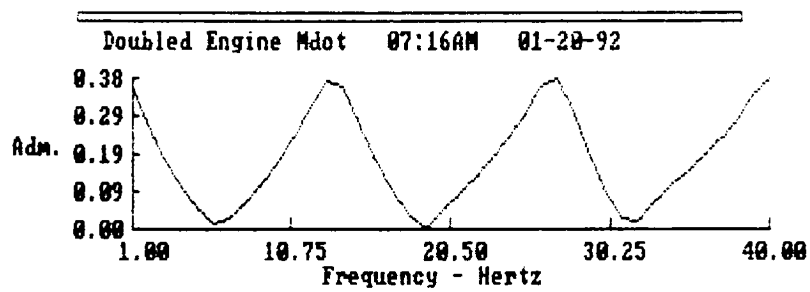
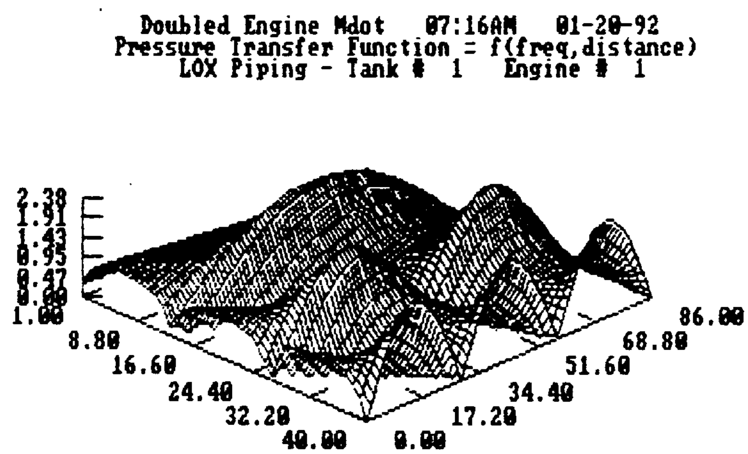


Figure 15

LOX Piping - Tank # 1 Engine # 1





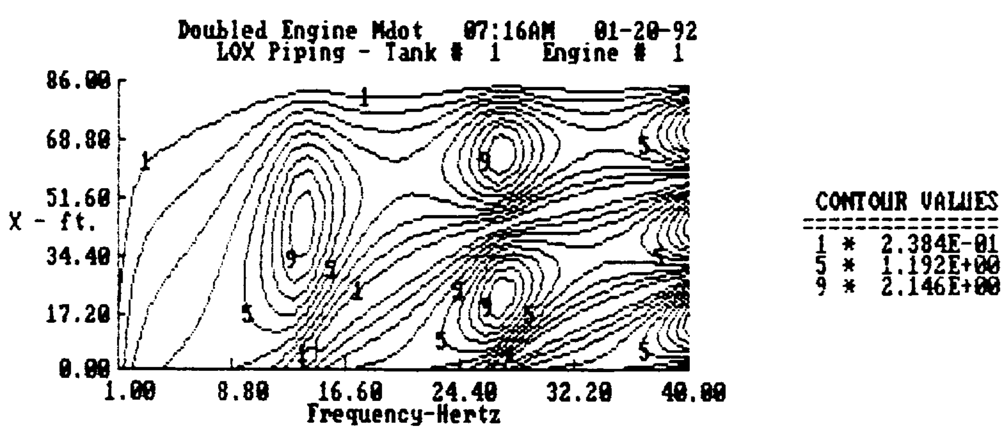
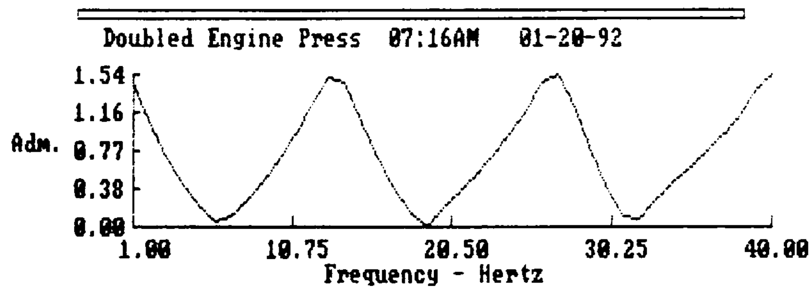
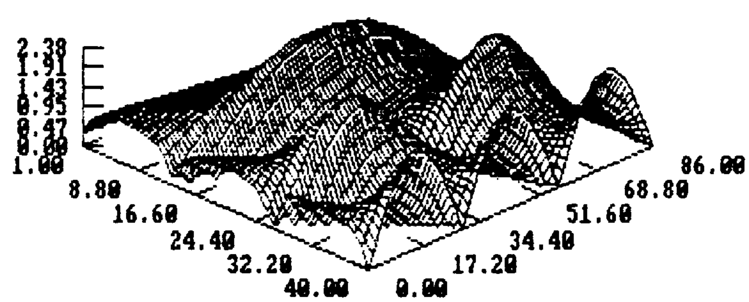


Figure 16

LOX Piping - Tank # 1 Engine # 1



Doubled Engine Press 07:16AM 01-20-92
Pressure Transfer Function = f(freq,distance)
LOX Piping - Tank # 1 Engine # 1



Doubled Engine Press 07:16AM 01-20-92
LOX Piping - Tank # 1 Engine # 1

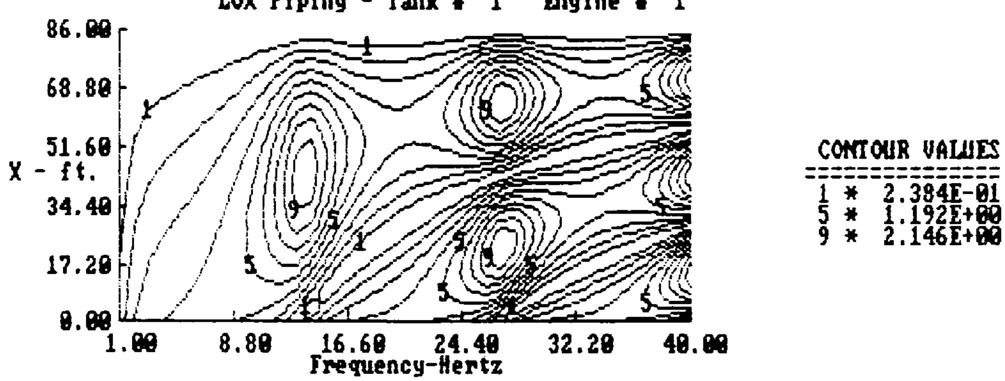
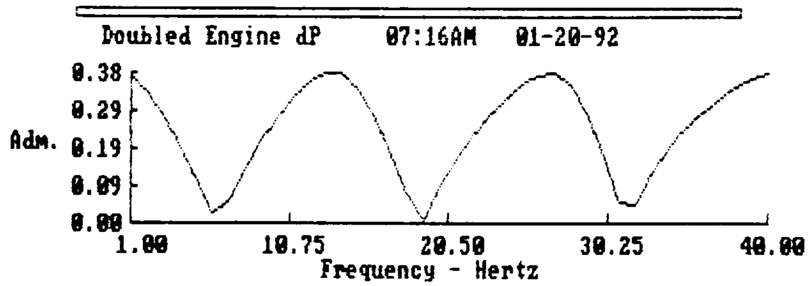
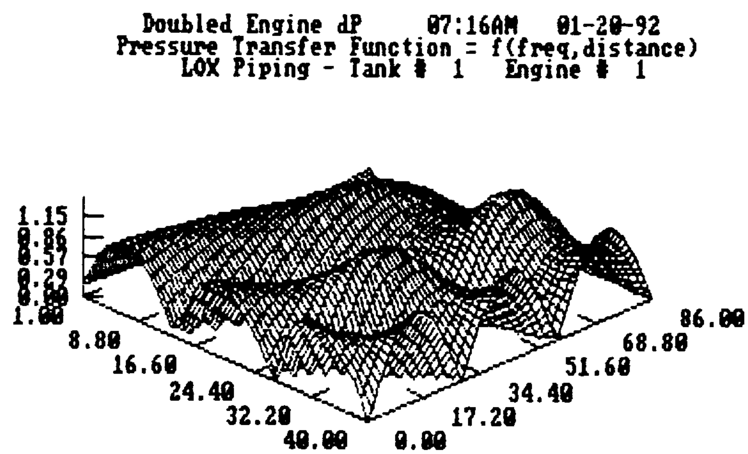


Figure 17

LOX Piping - Tank # 1 Engine # 1





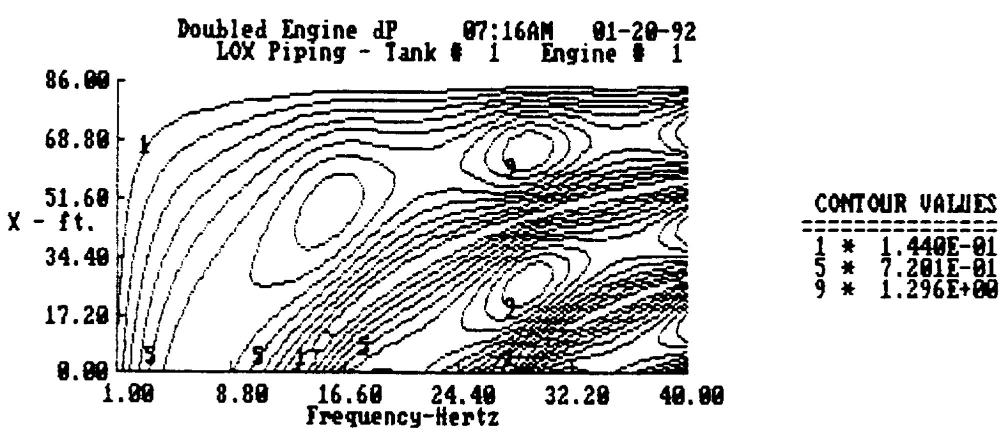
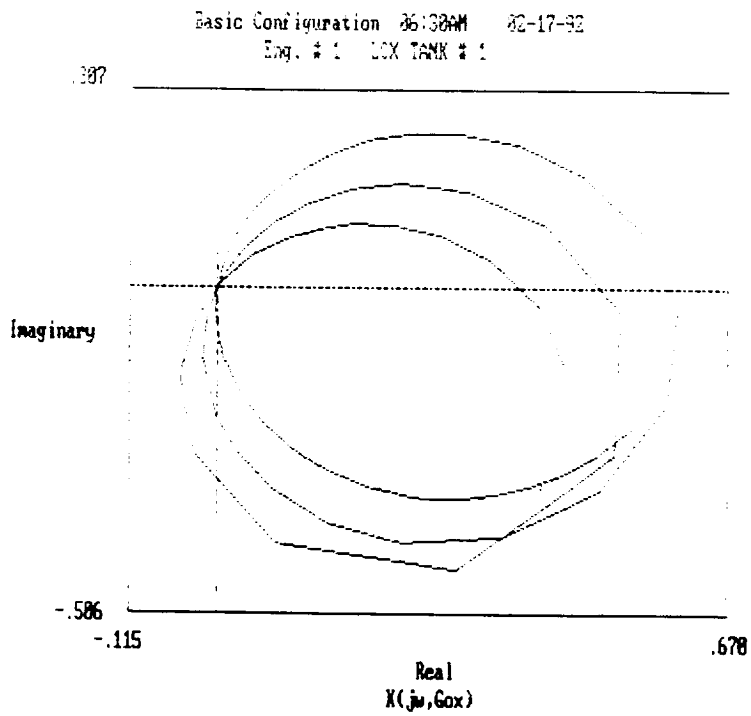


Figure 18


Basic Configuration 06:30AM 02-17-92
Eng. # 1 LOX TANK # 1
.307
Imaginary
-.586
-.115
.670
Real
X(jw,Gox)

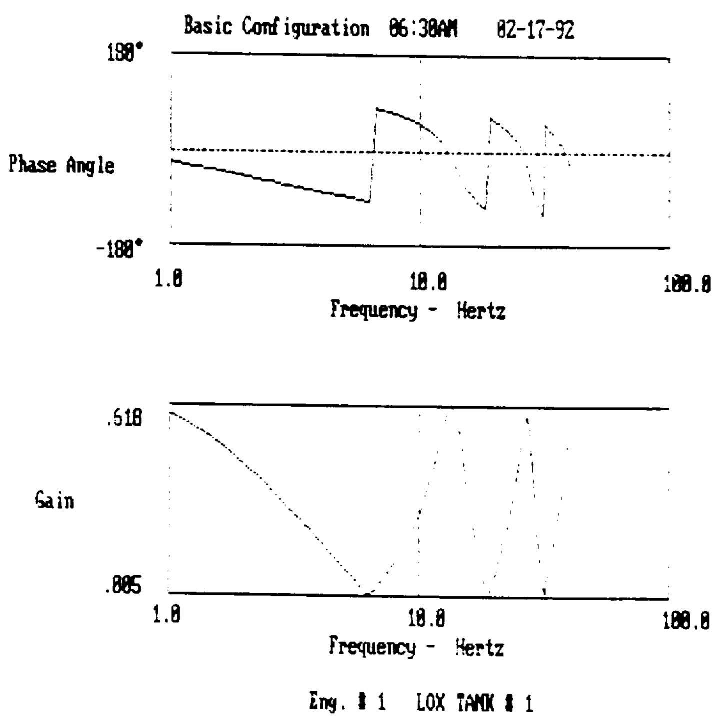
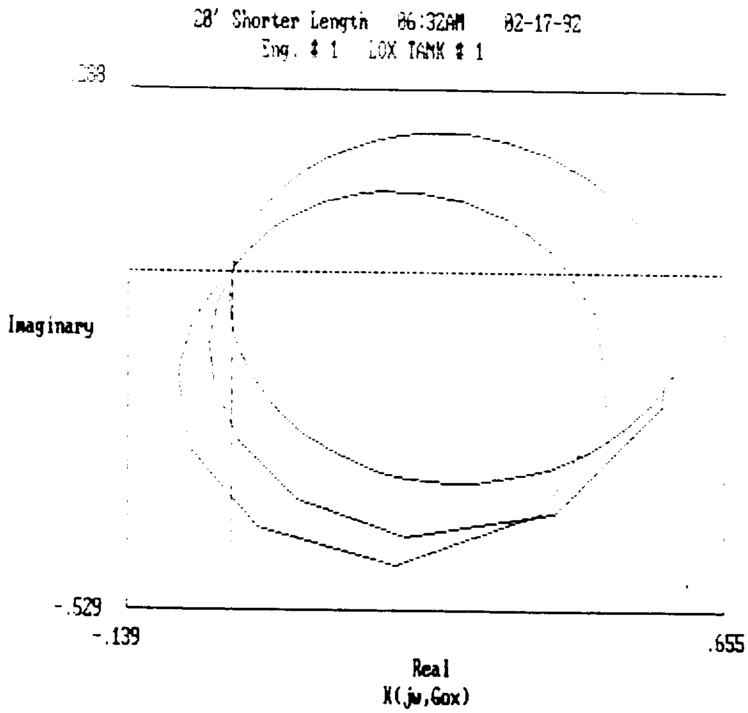
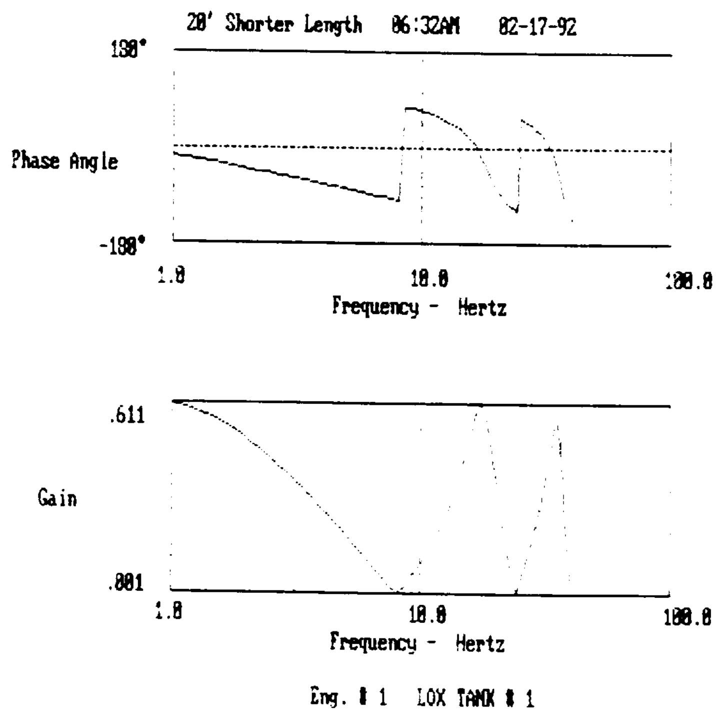

Basic Configuration 06:30AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.518
Gain
.005
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 19



28' Shorter Length 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
Imaginary
-.529
-.139
.655
Real
X(jw,Gox)



28' Shorter Length 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.611
Gain
.001
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 20

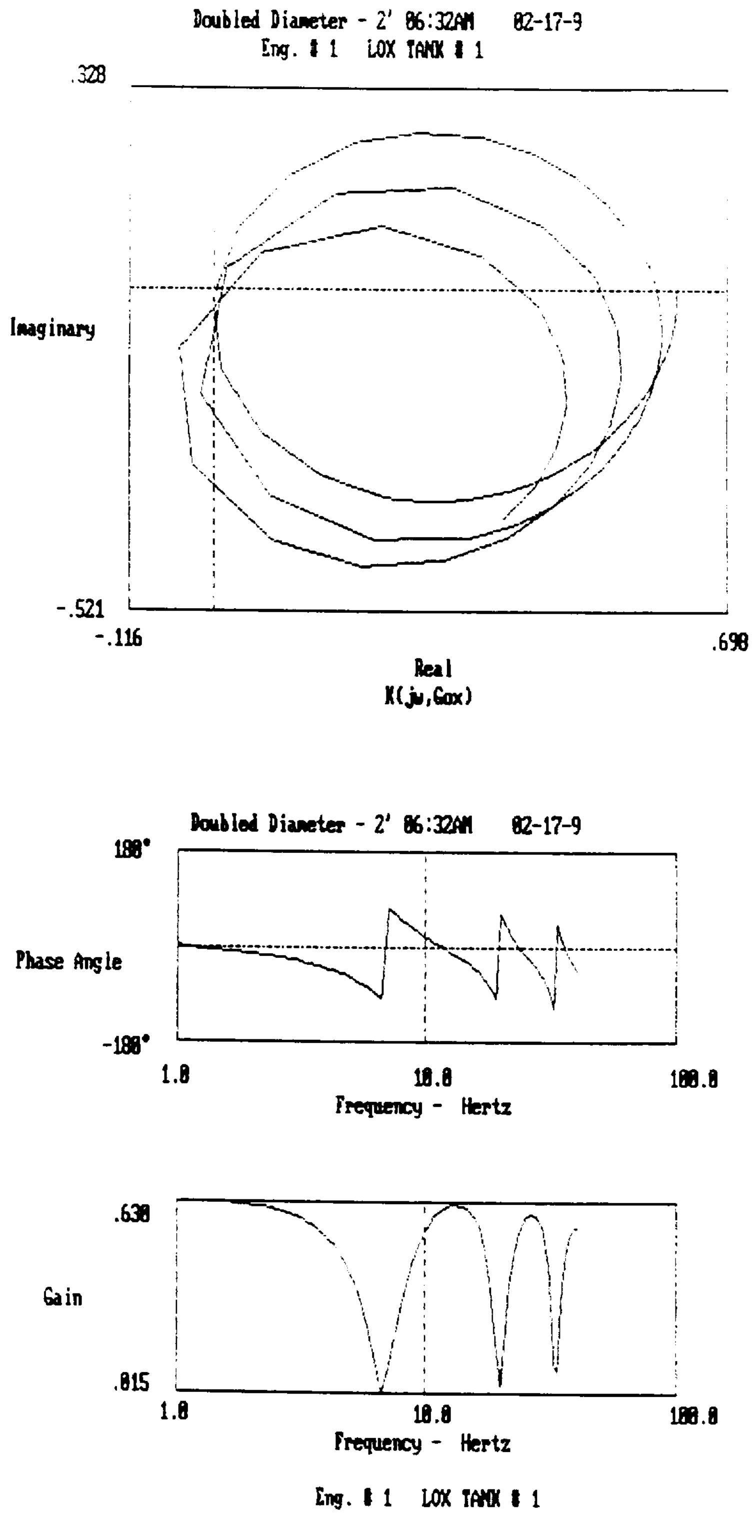
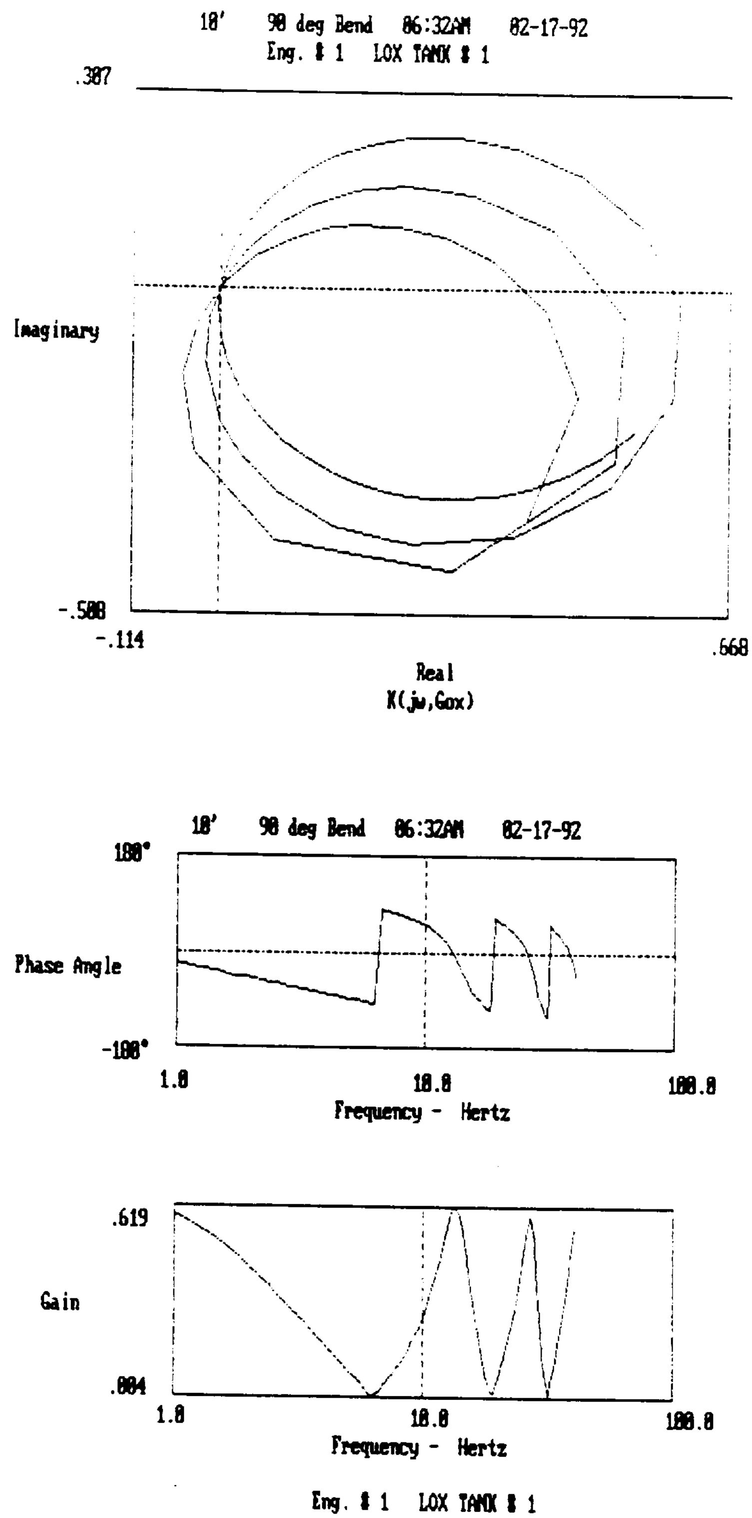

Doubled Diameter - 2' 06:32AM 02-17-9
Eng. # 1 LOX TANK # 1
.328
Imaginary
-.521
-.116
.698
Real
K(jw,Gox)
Doubled Diameter - 2' 06:32AM 02-17-9
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.630
Gain
.015
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 21



10' 90 deg Bend 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.387
Imaginary
-.500
-.114
.668
Real
K(jω,Gox)
10' 90 deg Bend 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.619
Gain
.004
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 22

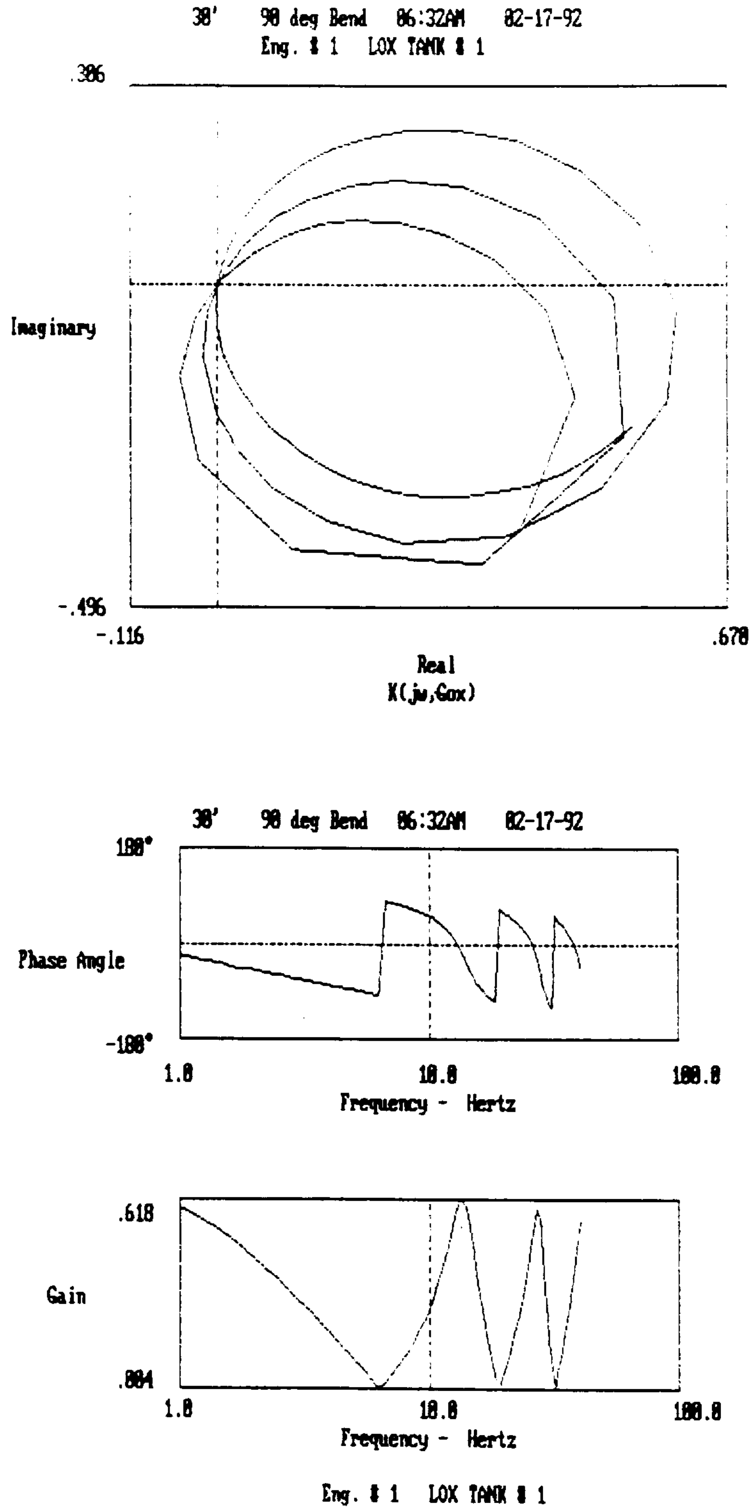

30' 90 deg Bend 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.306
Imaginary
-.496
-.116
.670
Real
X(jw,Gox)
30' 90 deg Bend 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.618
Gain
.004
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 23

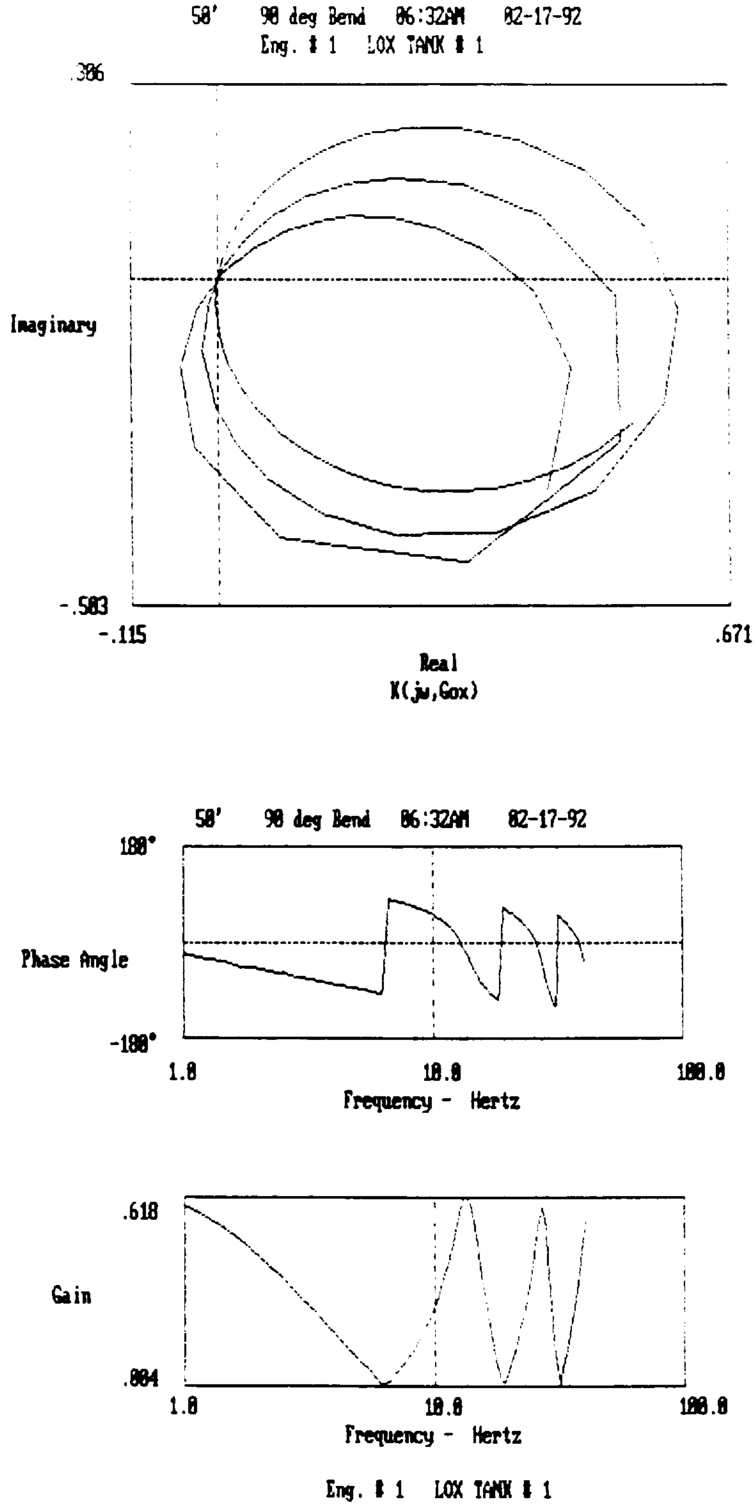
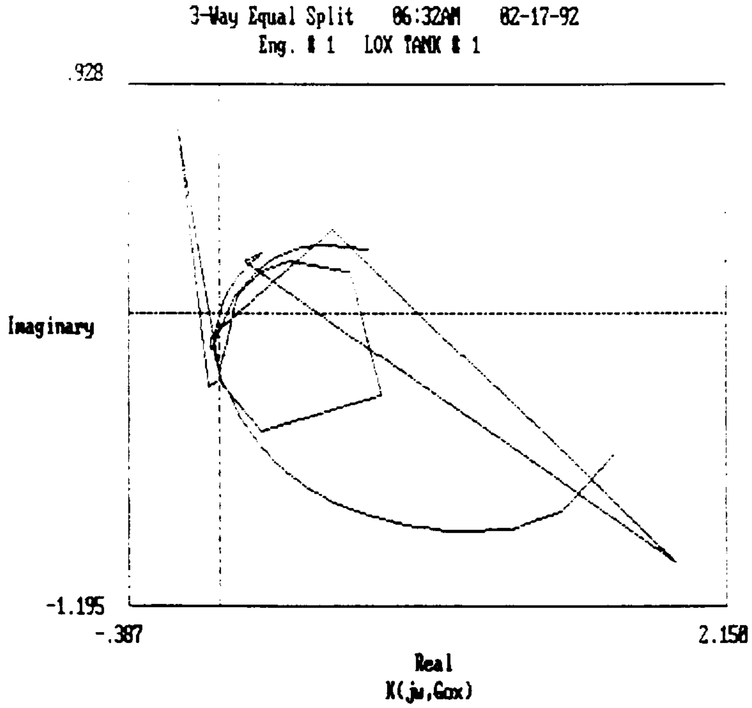

58' 90 deg Bend 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.306
Imaginary
-.503
-.115
.671
Real
X(jw,Gox)
58' 90 deg Bend 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.618
Gain
.004
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 24


3-Way Equal Split 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.928
Imaginary
-1.195
-.387
2.150
Real
X(jw,Gox)

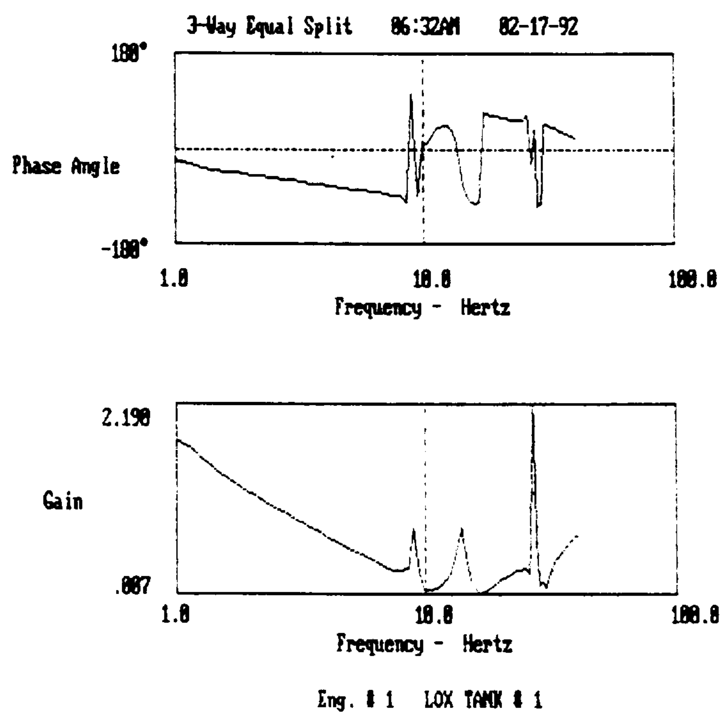
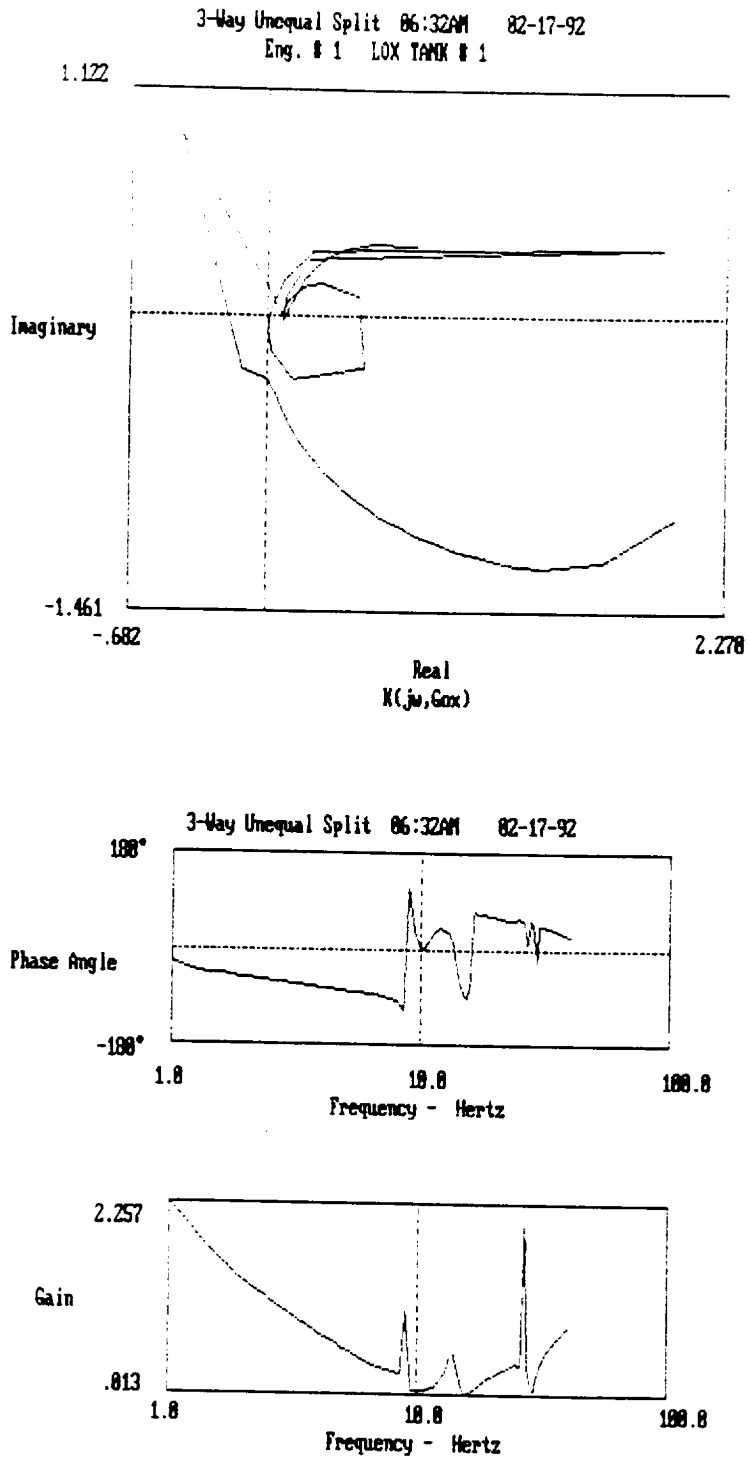

3-Way Equal Split 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
2.190
Gain
.007
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 25



Eng. # 1 LOX TANK # 1

Figure 26

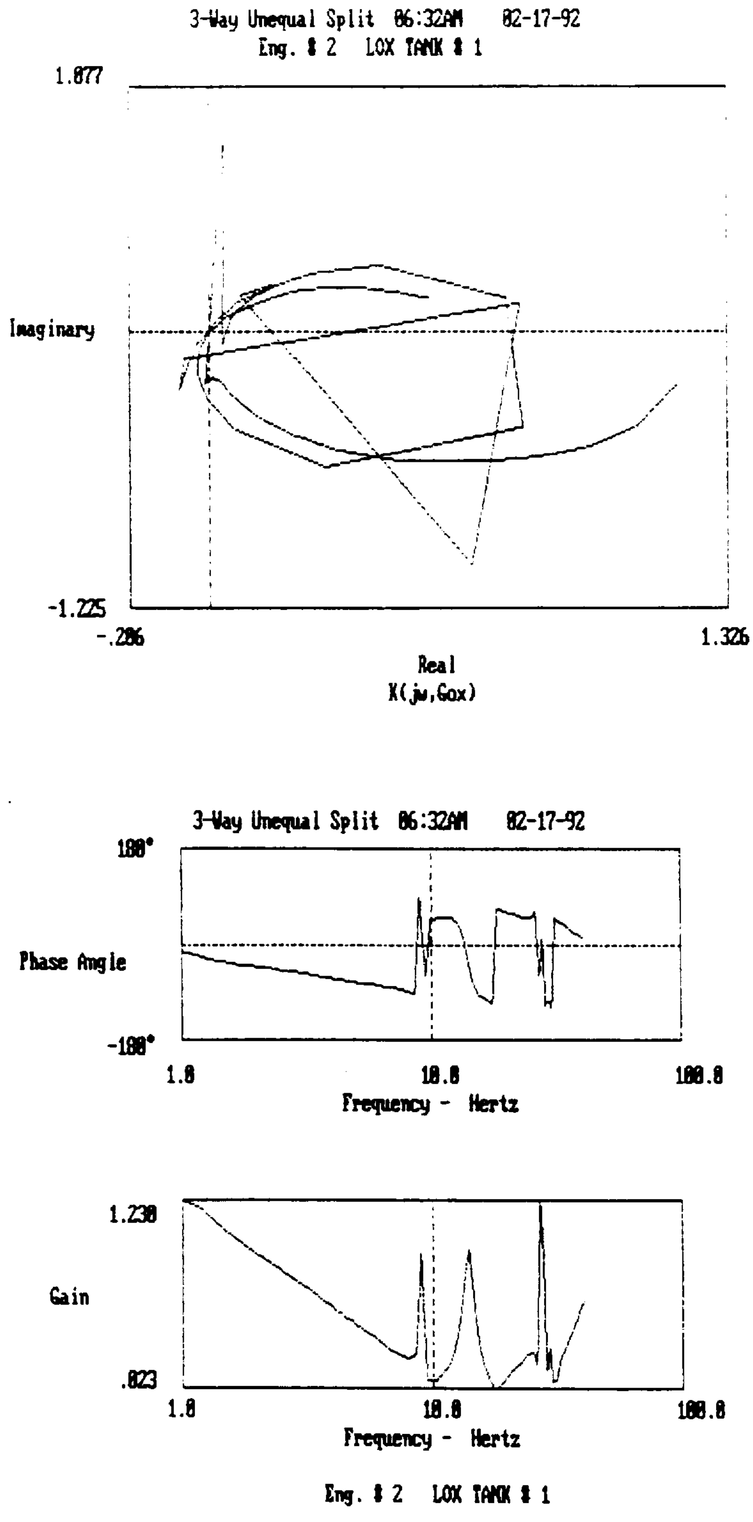
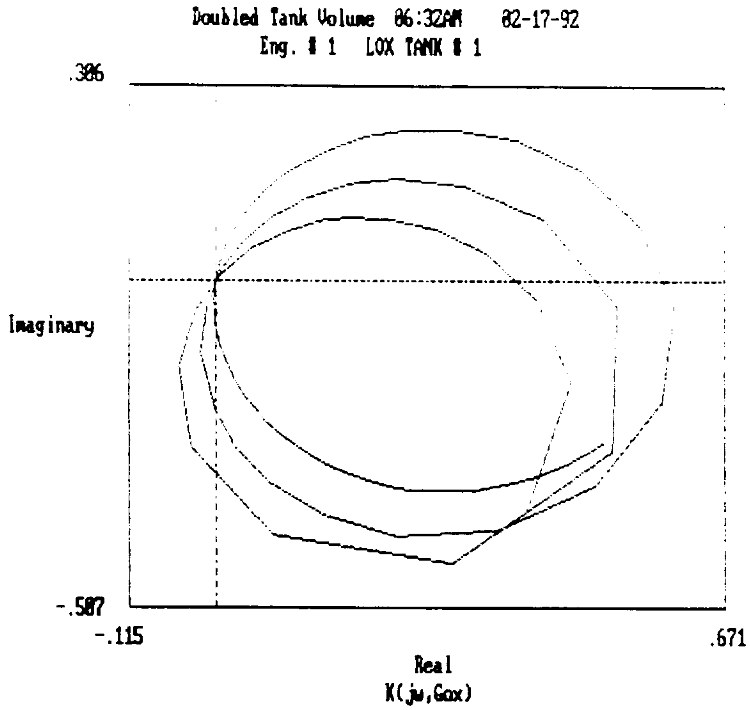
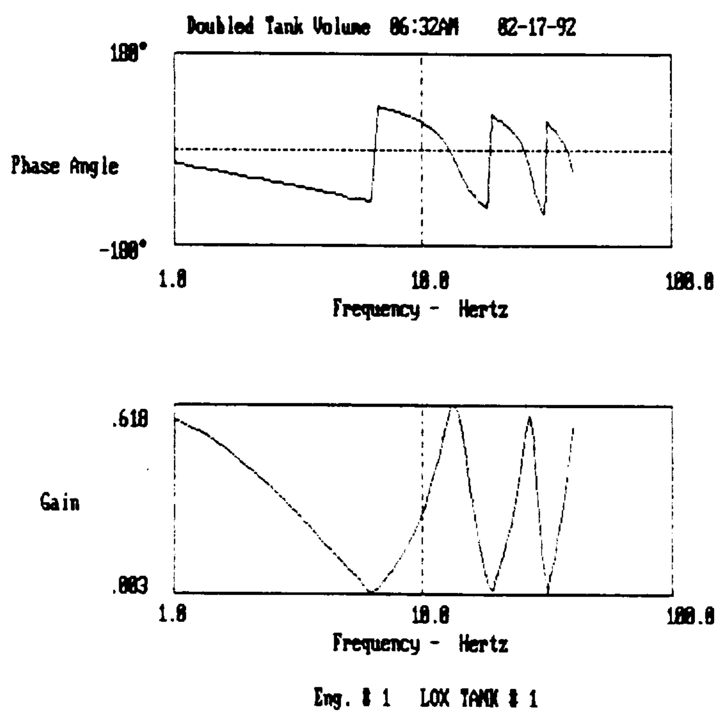

3-Way Unequal Split 06:32AM 02-17-92
Eng. # 2 LOX TANK # 1
1.077
Imaginary
-1.225
-.206
1.326
Real
X(jw,Gox)
3-Way Unequal Split 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
1.230
Gain
.023
1.0
10.0
100.0
Frequency - Hertz
Eng. # 2 LOX TANK # 1

Figure 27



Doubled Tank Volume 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.306
Imaginary
-.587
-.115
.671
Real
K(jw,Gox)



Doubled Tank Volume 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.618
Gain
.003
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 28

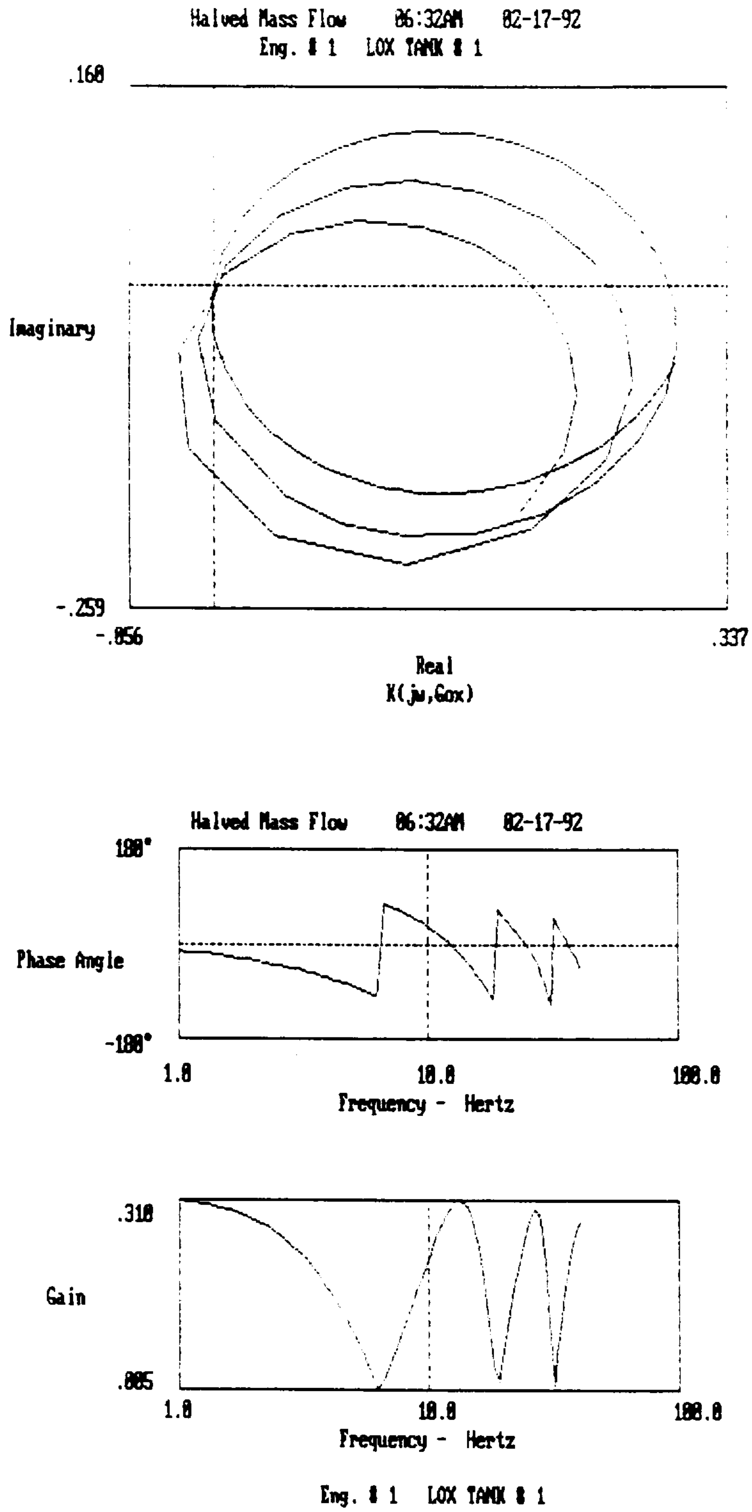
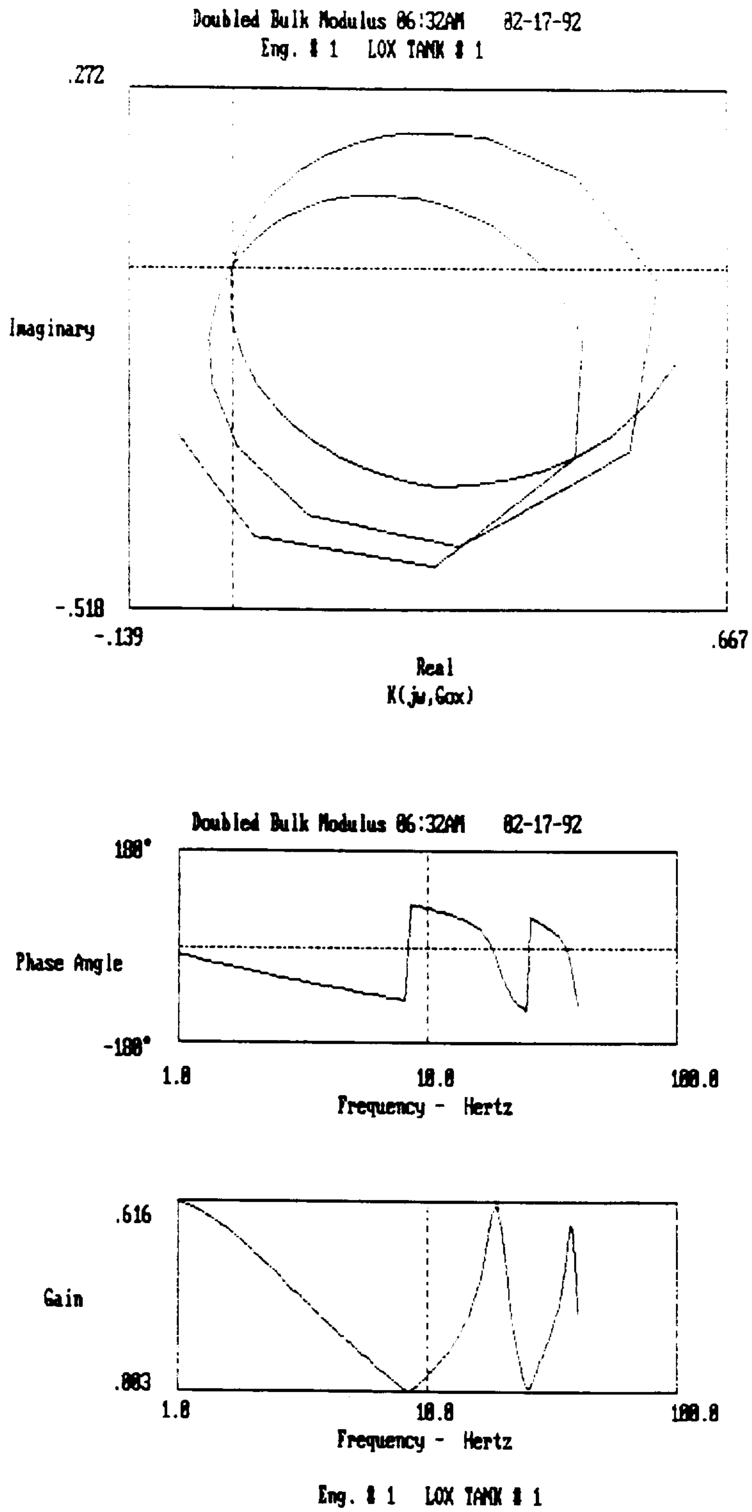
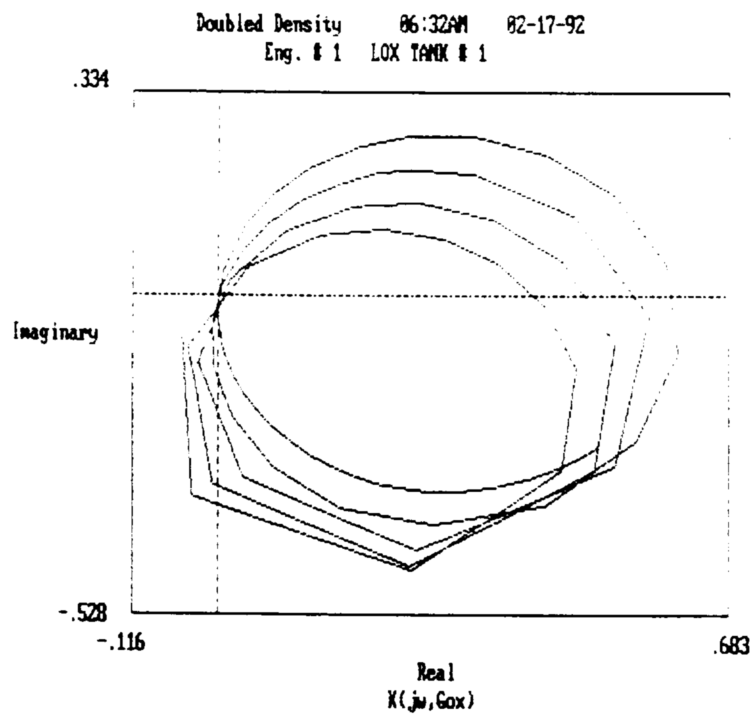

Halved Mass Flow 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.160
Imaginary
-.259
-.056
.337
Real
X(jw,Gox)
Halved Mass Flow 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.310
Gain
.005
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 29



Doubled Bulk Modulus 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.272
Imaginary
-.518
-.139
.667
Real
K(jw,Gox)
Doubled Bulk Modulus 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.616
Gain
.003
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 30


Doubled Density 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.334
Imaginary
-.528
-.116
.683
Real
X(jw,Gox)

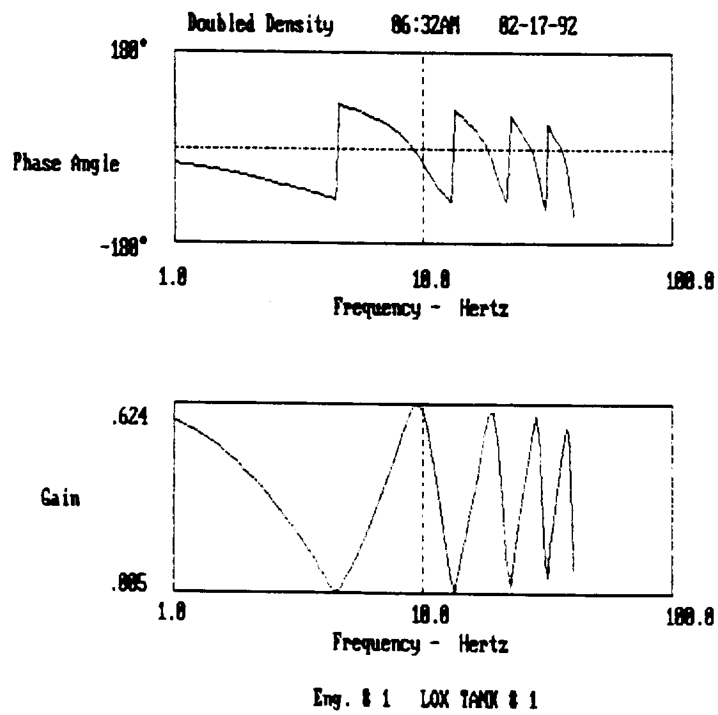

Doubled Density 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.624
Gain
.005
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 31

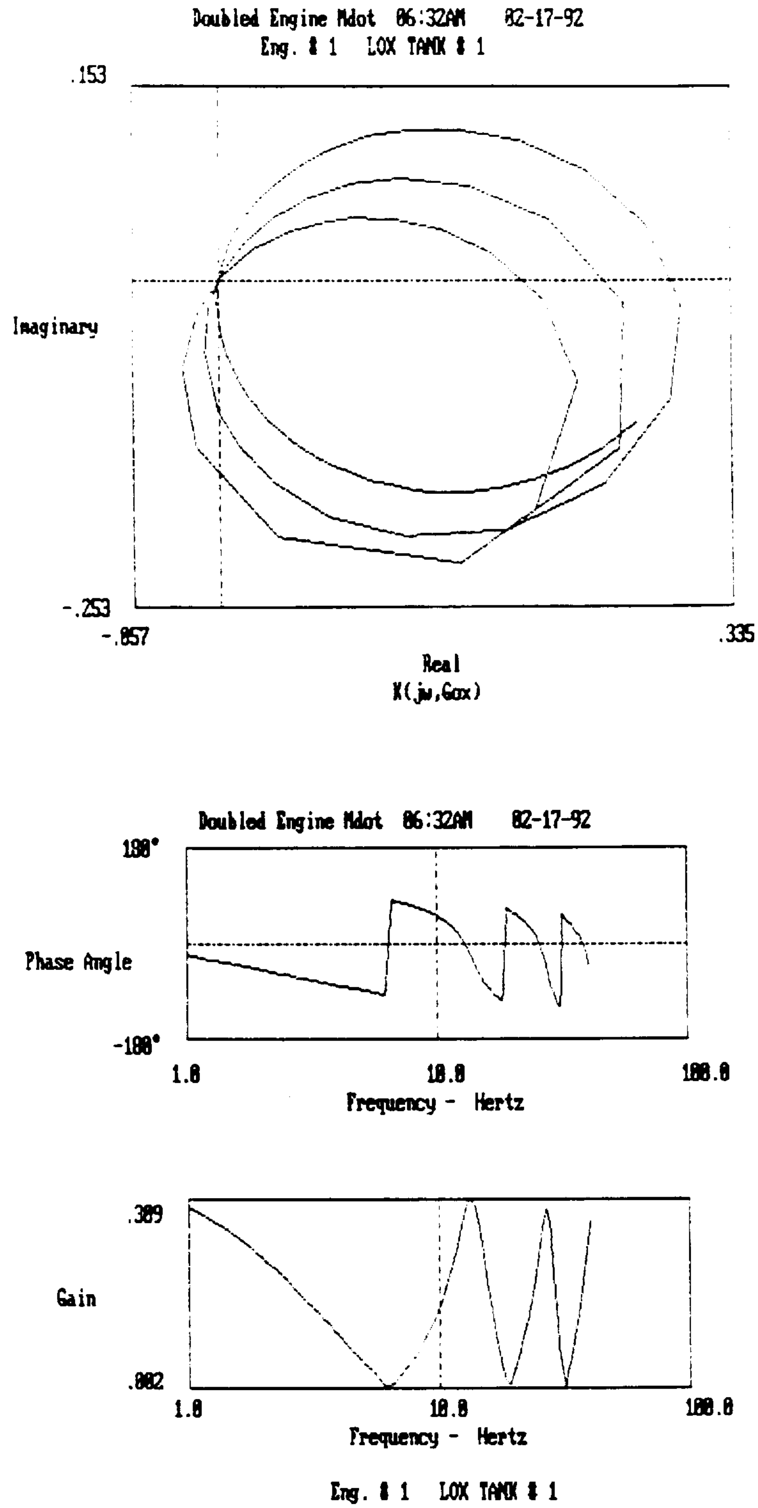

Doubled Engine Mdot 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.153
Imaginary
-.253
-.857
.335
Real
K(jw,Gox)
Doubled Engine Mdot 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.309
Gain
.002
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 32

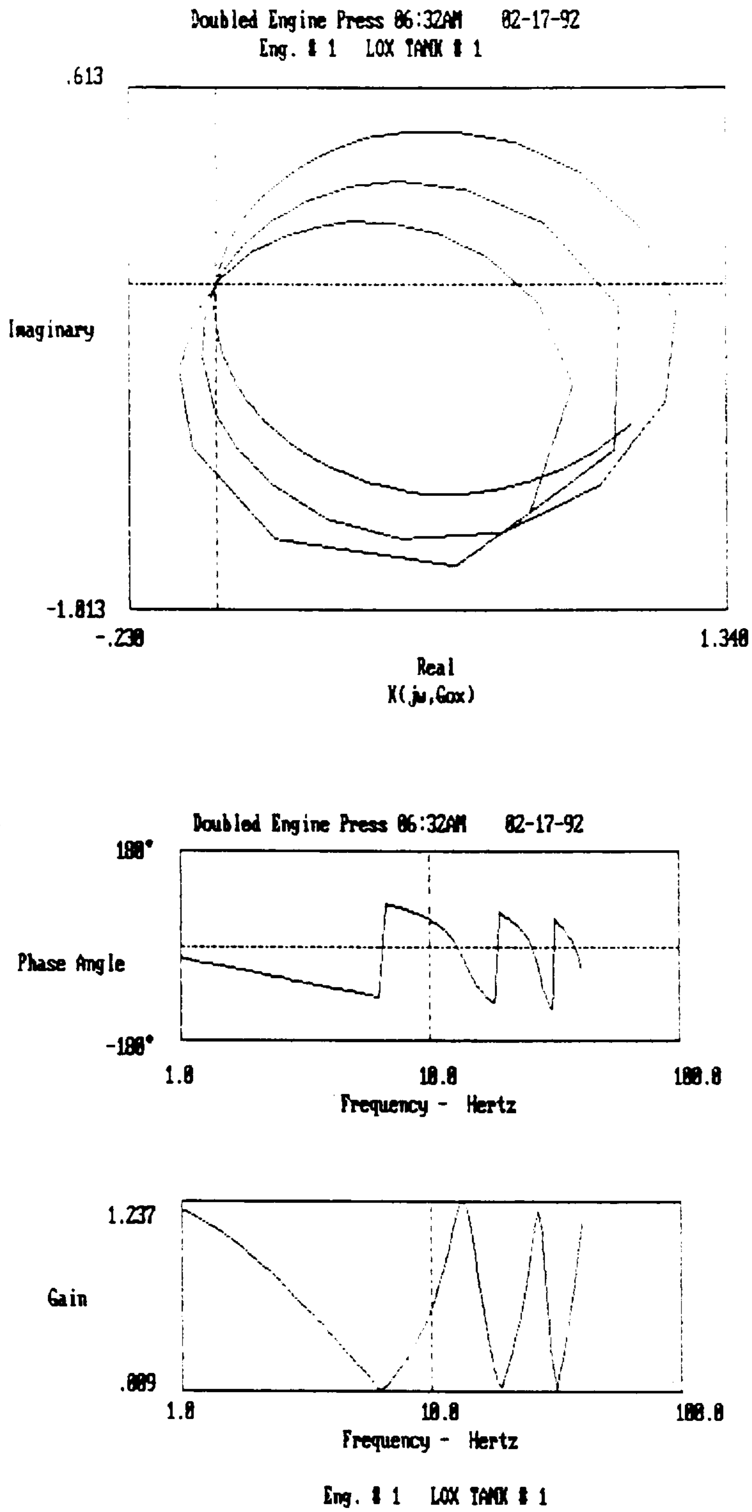
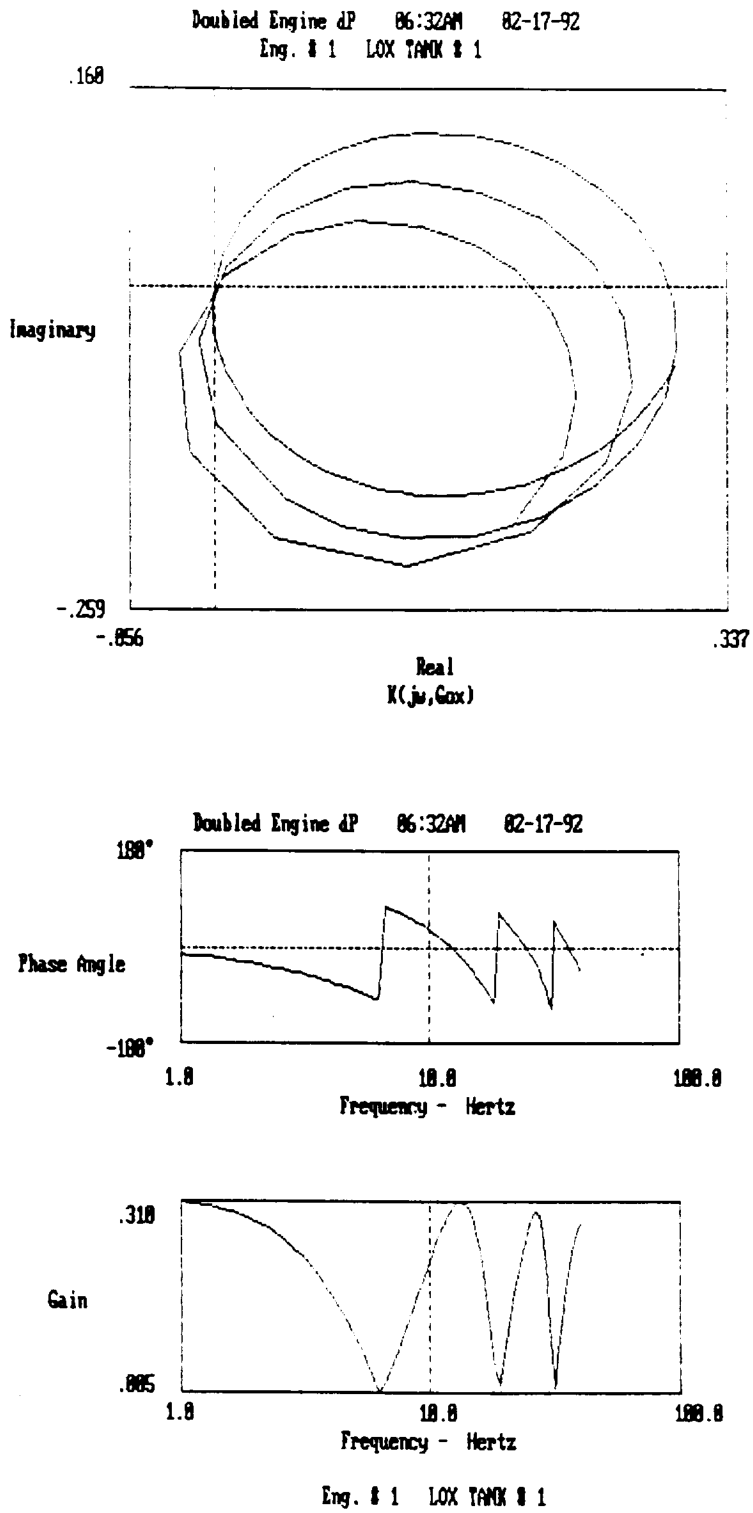

Doubled Engine Press 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.613
Imaginary
-1.013
-.230
1.340
Real
X(jw,Gox)
Doubled Engine Press 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
1.237
Gain
.009
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 33



Doubled Engine dP 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.160
-.259
Imaginary
-.056
.337
Real
K(jw,Gox)
Doubled Engine dP 06:32AM 02-17-92
180°
-180°
Phase Angle
1.0
10.0
100.0
Frequency - Hertz
.310
.005
Gain
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 34

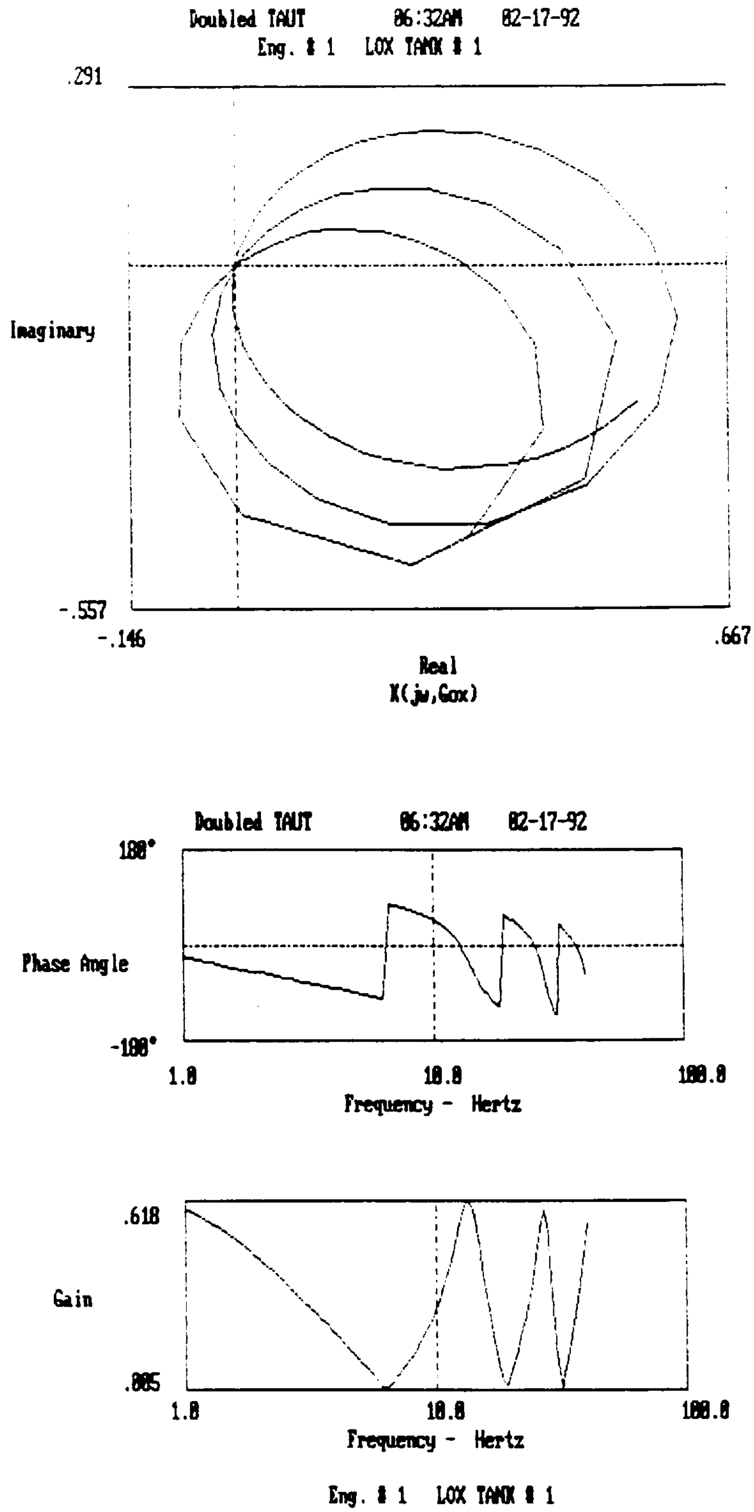

Doubled TAUT 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.291
Imaginary
-.557
-.146
.667
Real
X(jw,Gox)
Doubled TAUT 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.618
Gain
.005
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 35

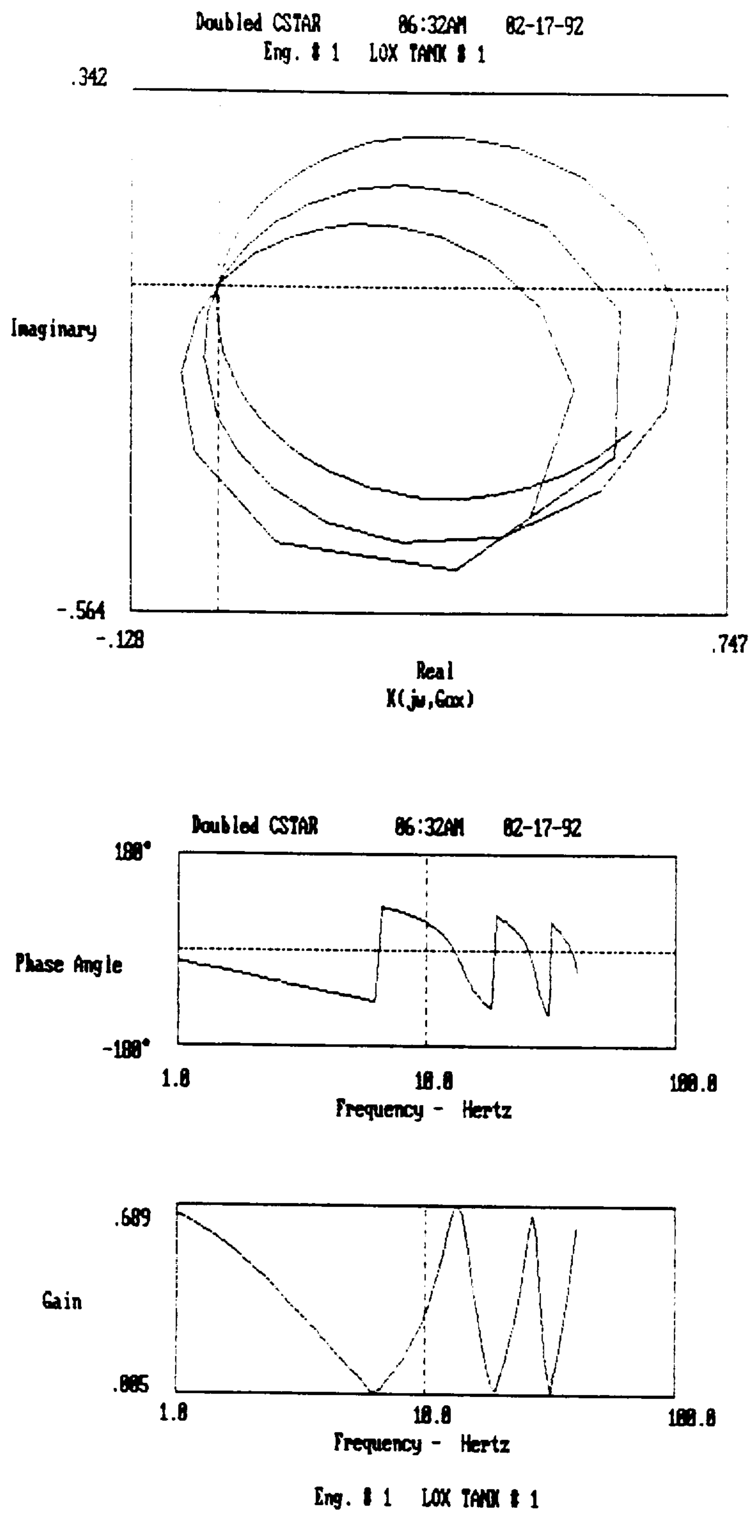

Doubled CSTAR 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.342
Imaginary
-.564
-.128
.747
Real
X(jw,Gox)
Doubled CSTAR 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.689
Gain
.005
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 36

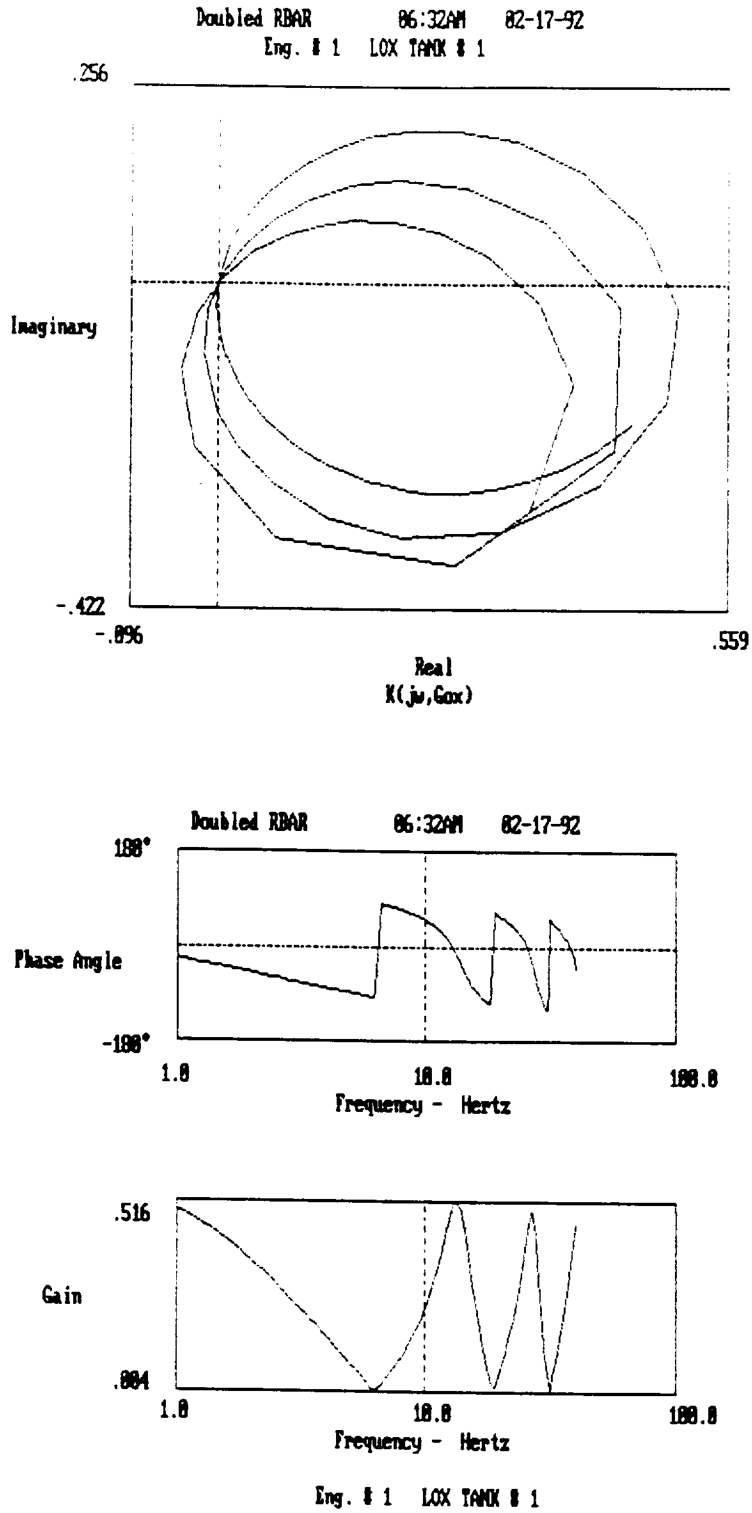

Doubled RBAR 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.256
Imaginary
-.422
-.096
.559
Real
K(jw,Gox)
Doubled RBAR 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.516
Gain
.004
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 37

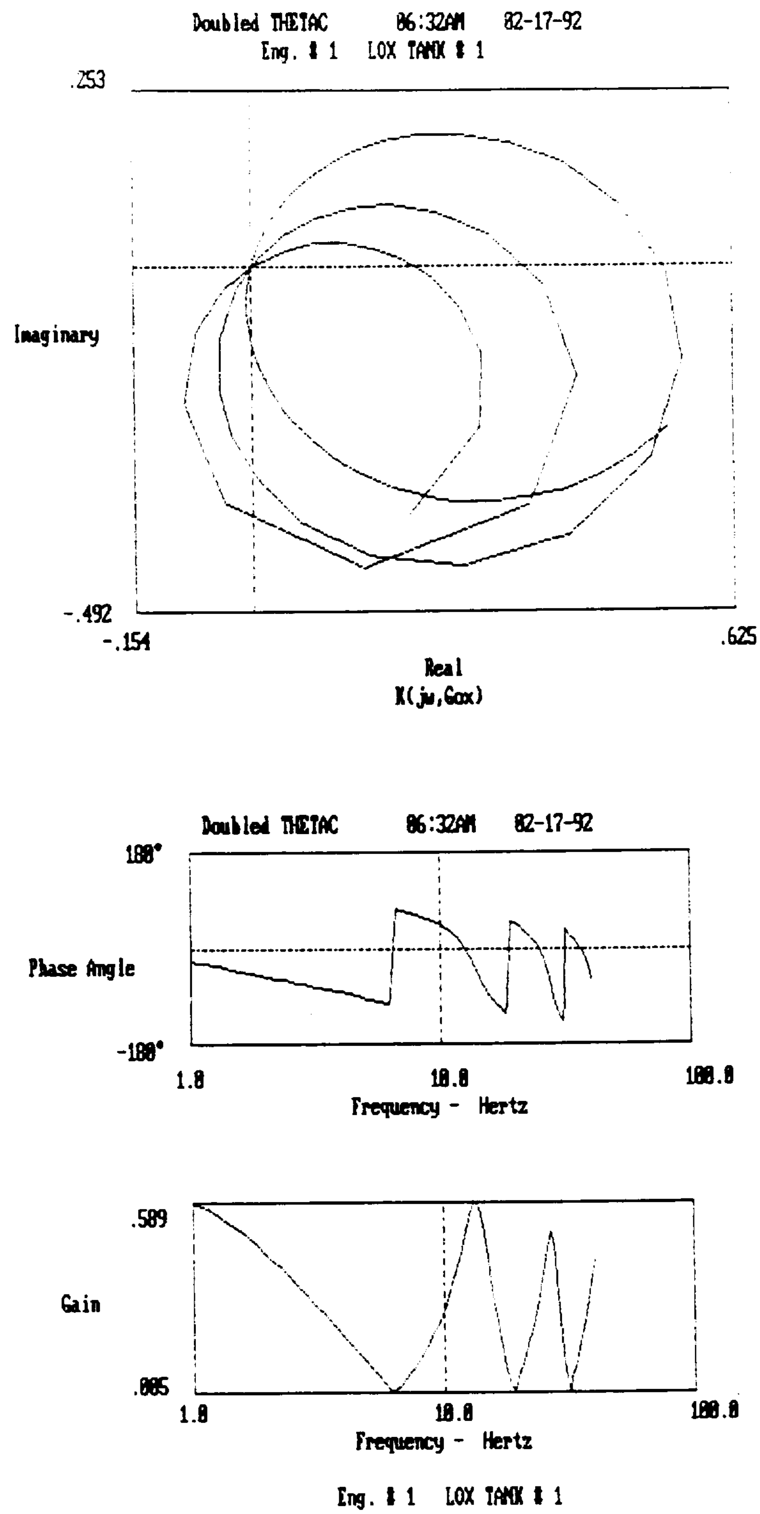
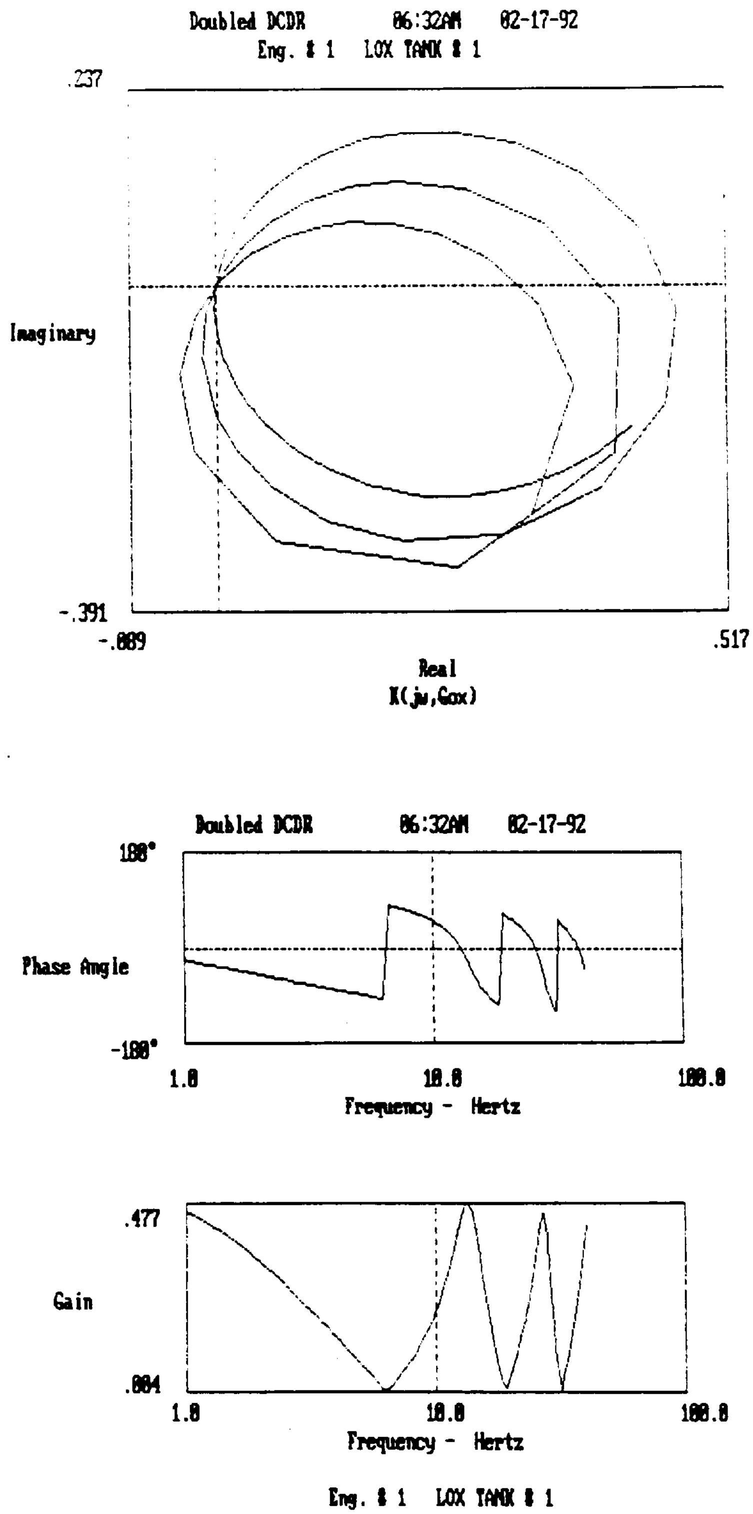

Doubled THETAC 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.253
Imaginary
-.492
-.154
.625
Real
X(jw,Gox)
Doubled THETAC 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.589
Gain
.005
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 38



Doubled DCDR 06:32AM 02-17-92
Eng. # 1 LOX TANK # 1
.237
Imaginary
-.391
-.009
.517
Real
K(jw,Gox)
Doubled DCDR 06:32AM 02-17-92
180°
Phase Angle
-180°
1.0
10.0
100.0
Frequency - Hertz
.477
Gain
.004
1.0
10.0
100.0
Frequency - Hertz
Eng. # 1 LOX TANK # 1

Figure 39

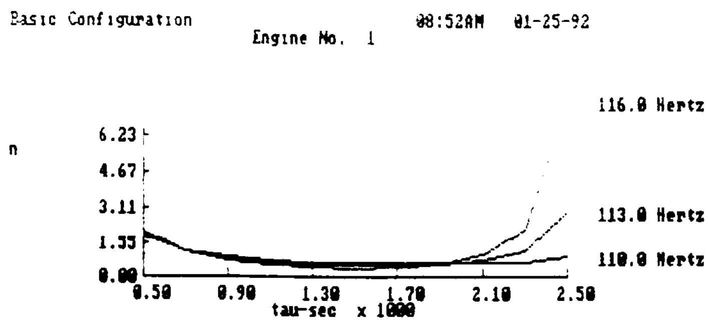


Figure 40

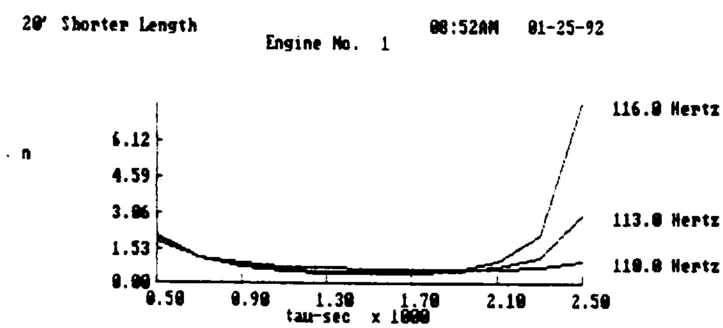


Figure 41

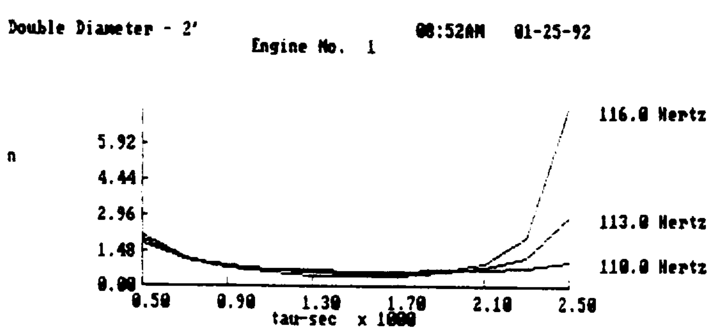


Figure 42

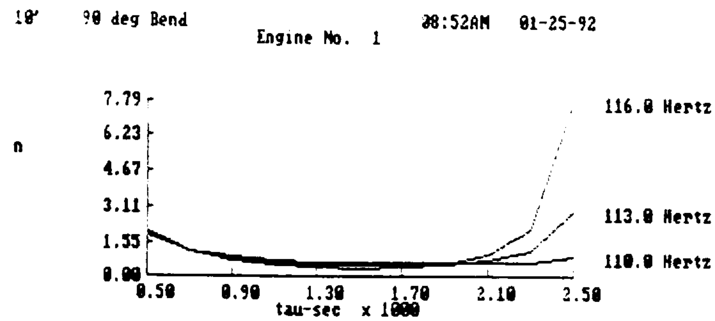


Figure 43

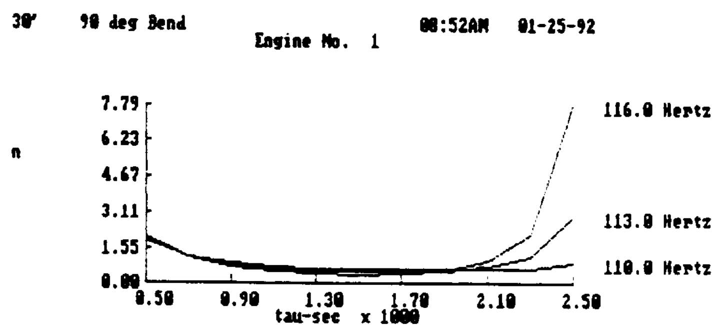


Figure 44

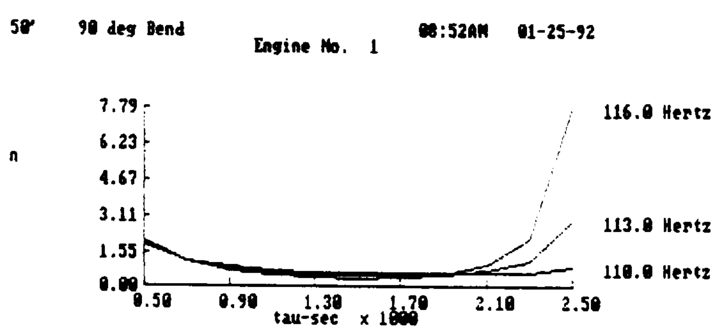


Figure 45

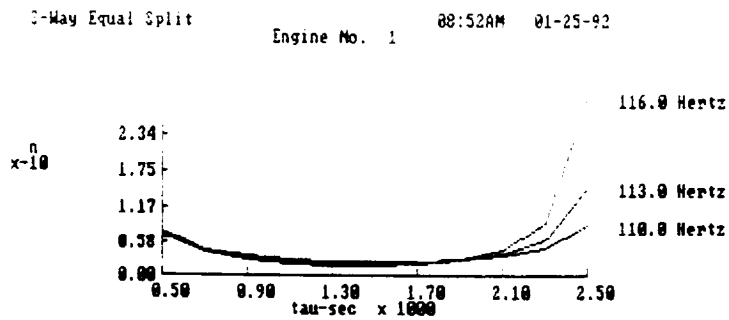


Figure 46

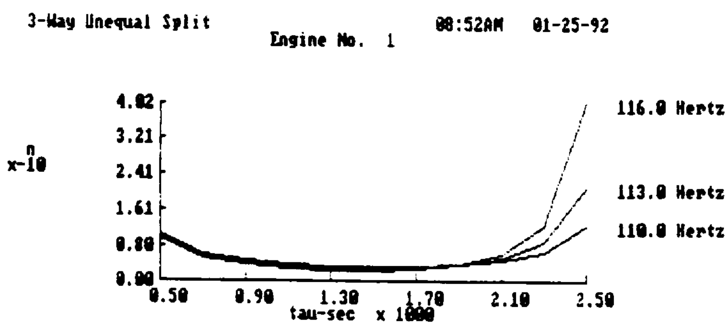


Figure 47

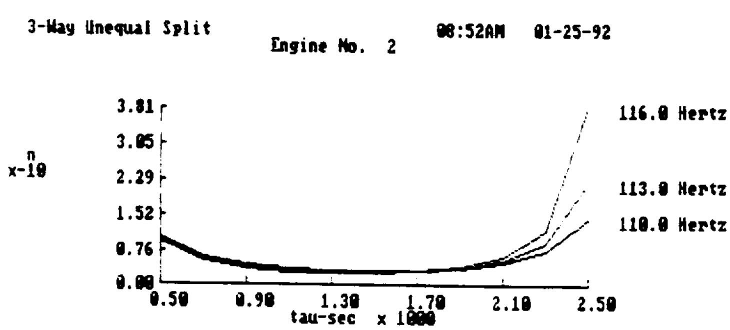


Figure 48

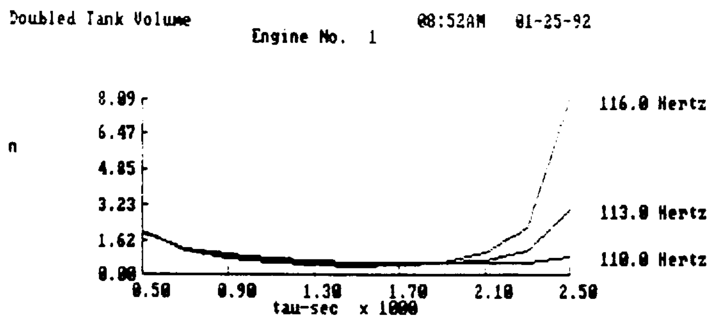


Figure 49

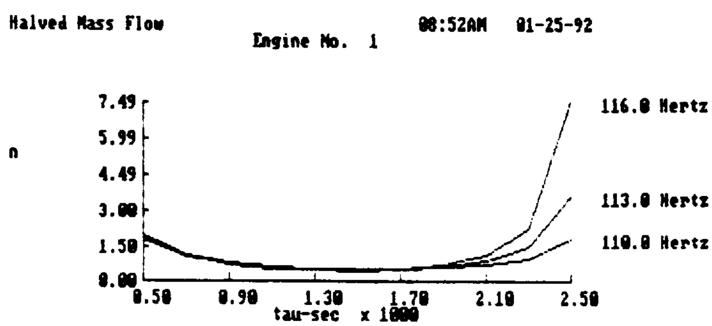


Figure 50

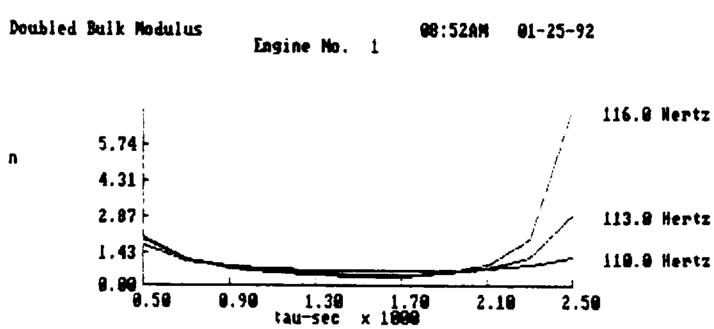


Figure 51

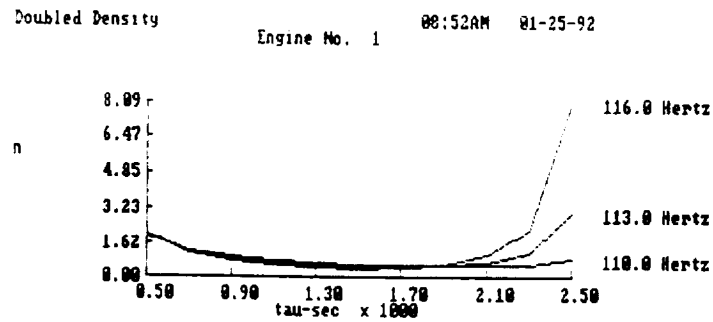


Figure 52

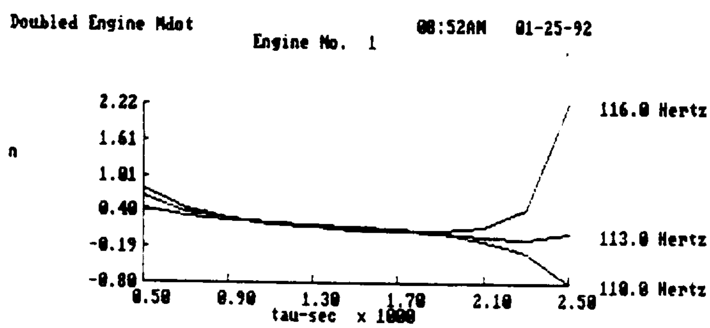


Figure 53

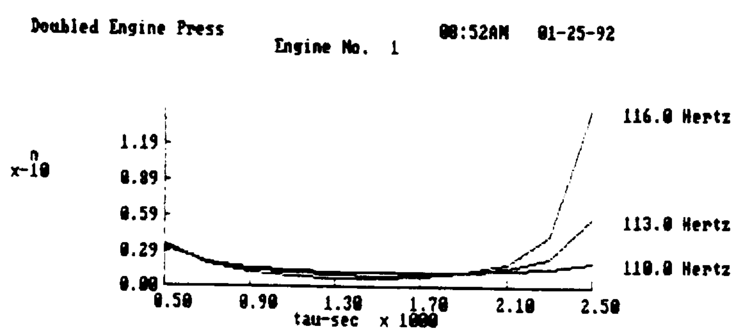


Figure 54

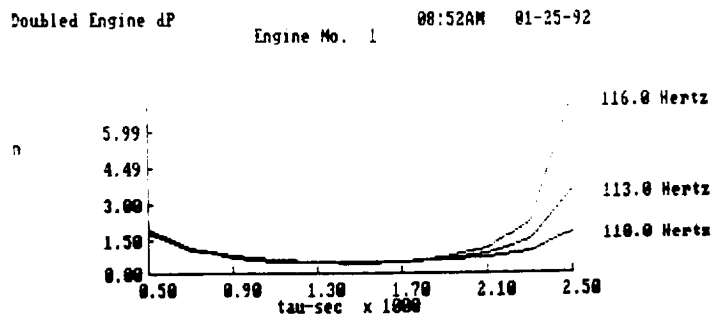


Figure 55

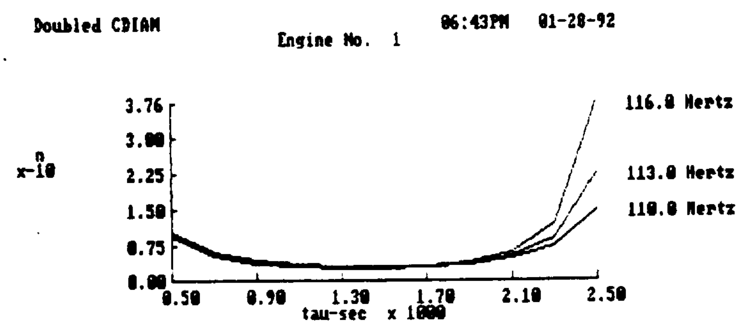


Figure 56

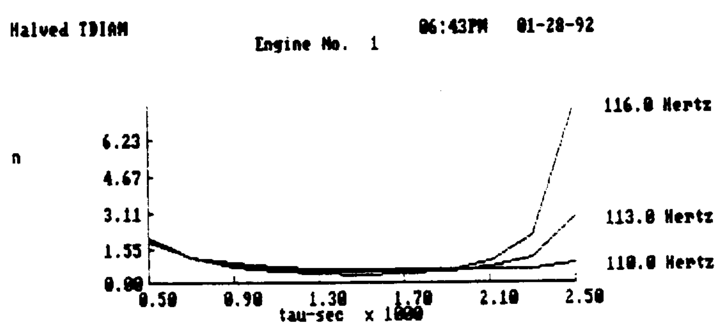


Figure 57

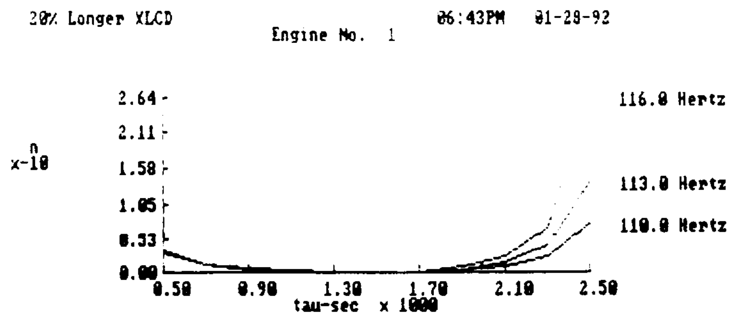


Figure 58

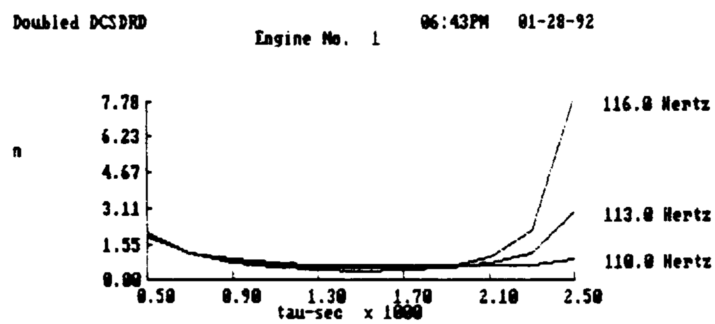


Figure 59

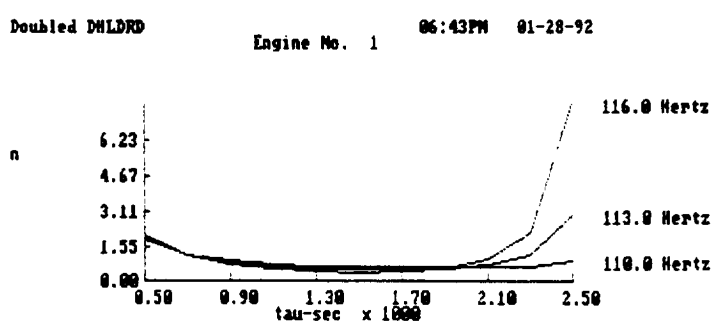


Figure 60

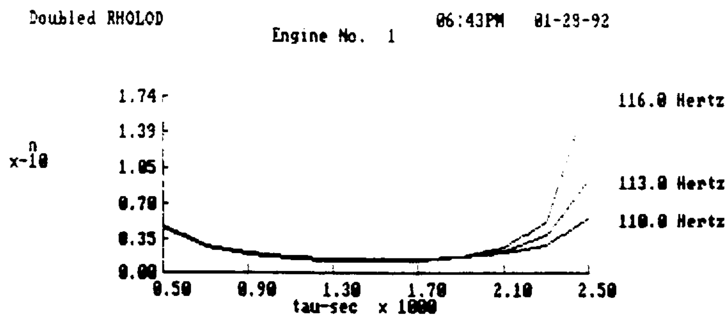


Figure 61

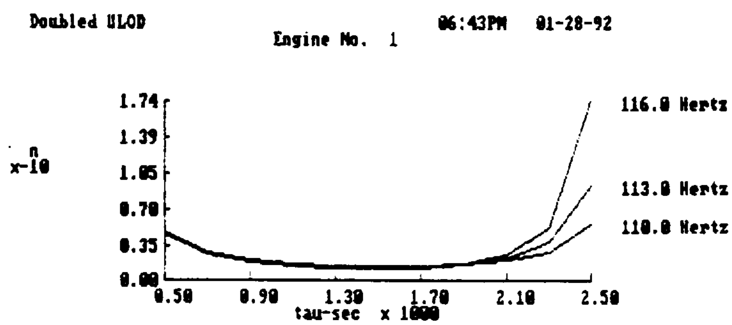


Figure 62