Modal Analysis and Feedback Control of HAM MEPI

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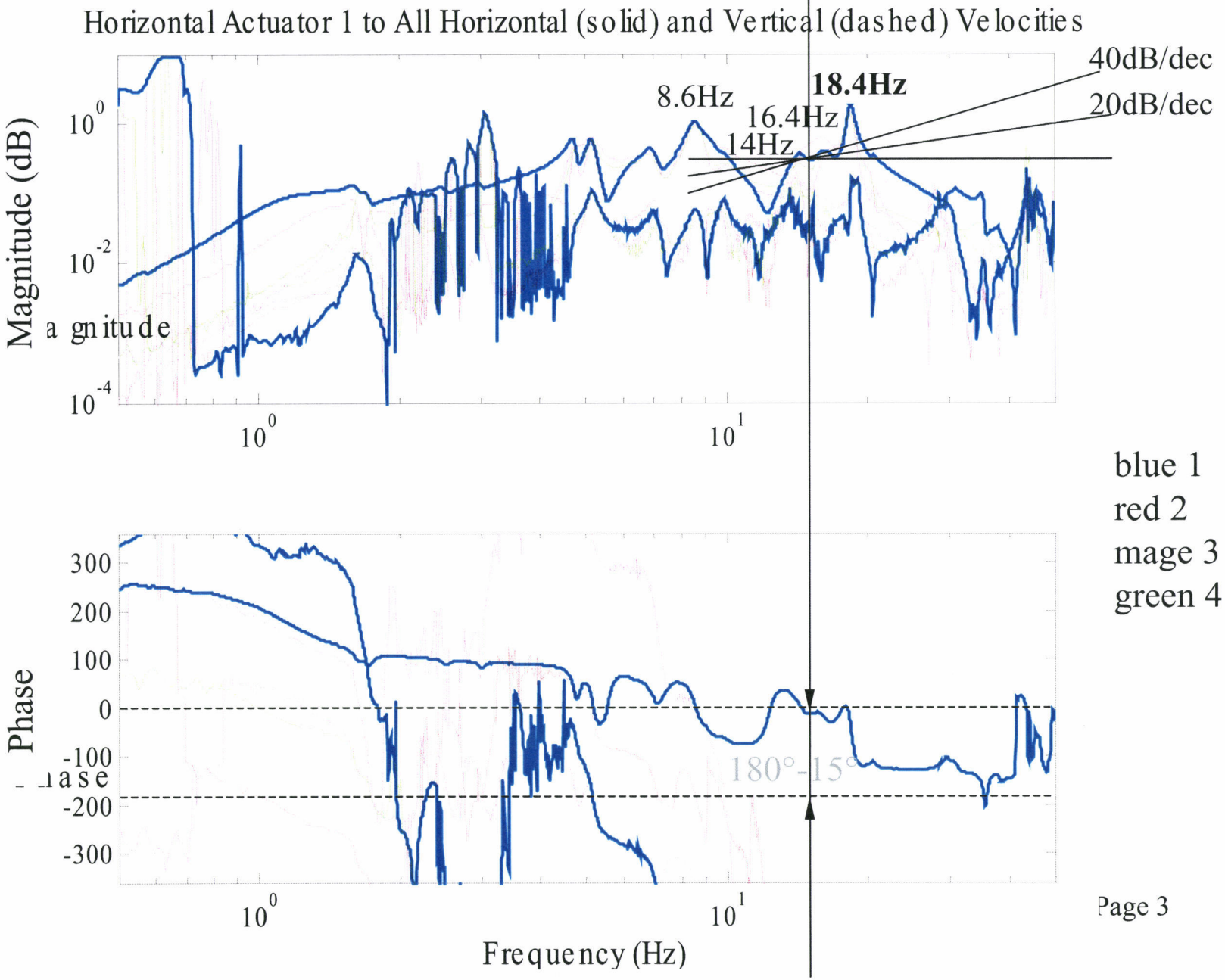
Overview

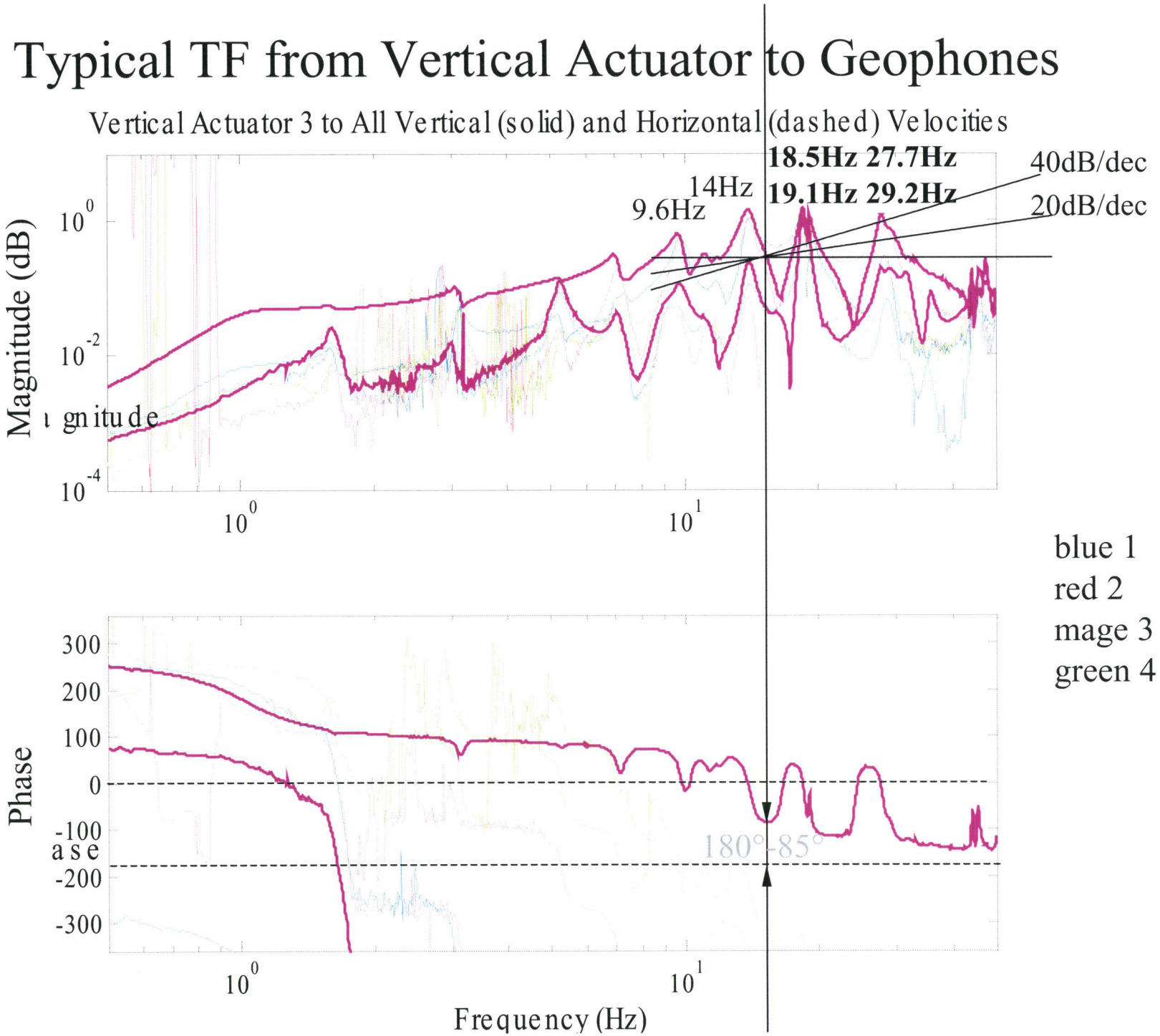
- Review of loop transmissions vs. modal data
- Preliminary look at control
  - Multiple lightly damped modes close to crossover make control difficult
- Approaches
  - Modal control may decrease the relative magnitudes of the flexible modes.
  - Easiest approach to robust performance: structural damping.
  - Optimal MIMO Control can improve the performance, but requires a good model

Typical TF from Horizontal Actuator to Geophones



blue 1
red 2
mage 3
green 4

Typical TF from Vertical Actuator to Geophones



blue 1
red 2
mage 3
green 4

Observation of this two typical TFs

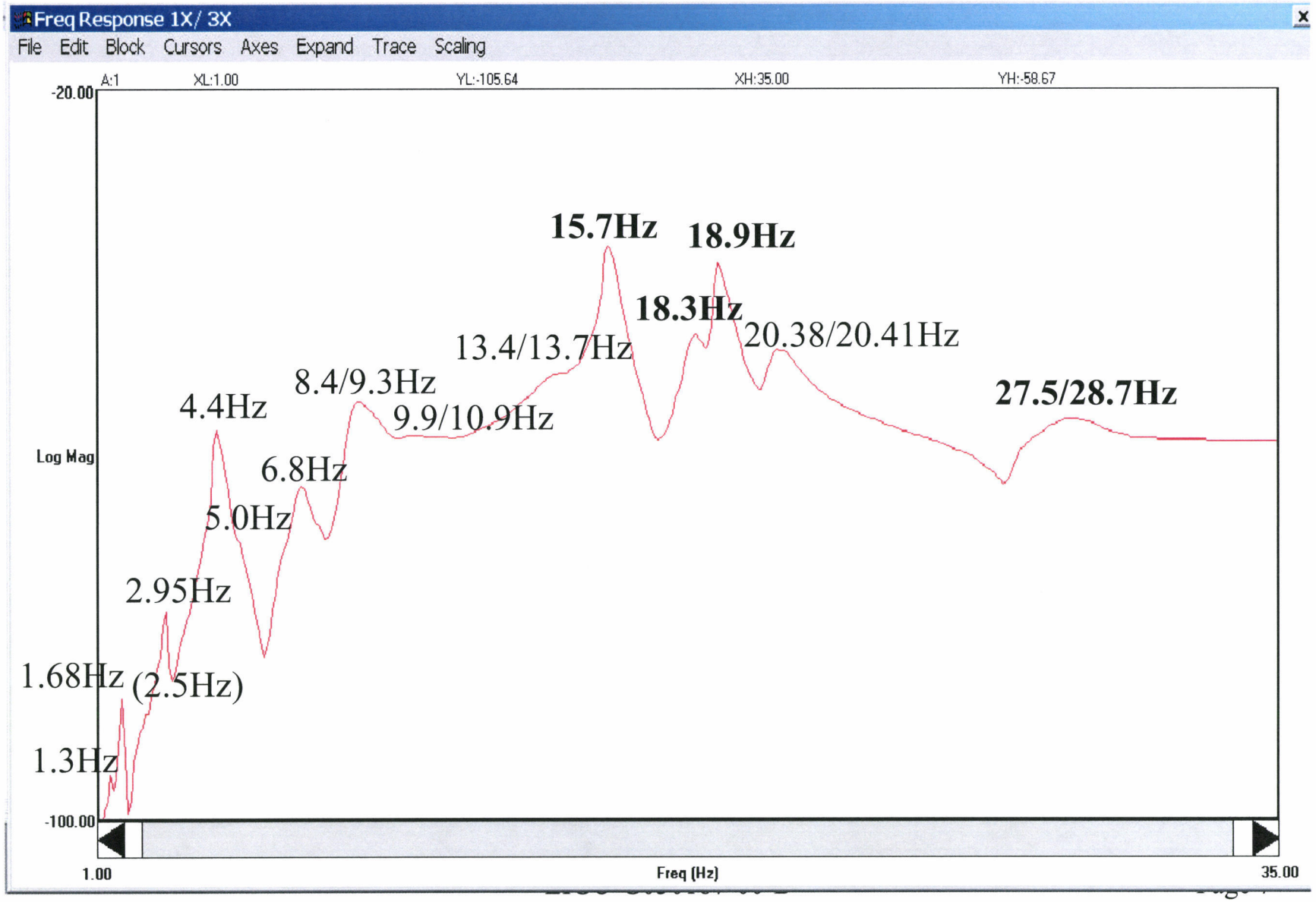
- The horizontal-horizontal **coupling** is very strong, so is vertical-vertical coupling. The vertical -horizontal coupling is very strong at around 3Hz, 19Hz and 28Hz

- The actuator-sensor pairs seems to be **collocated** well

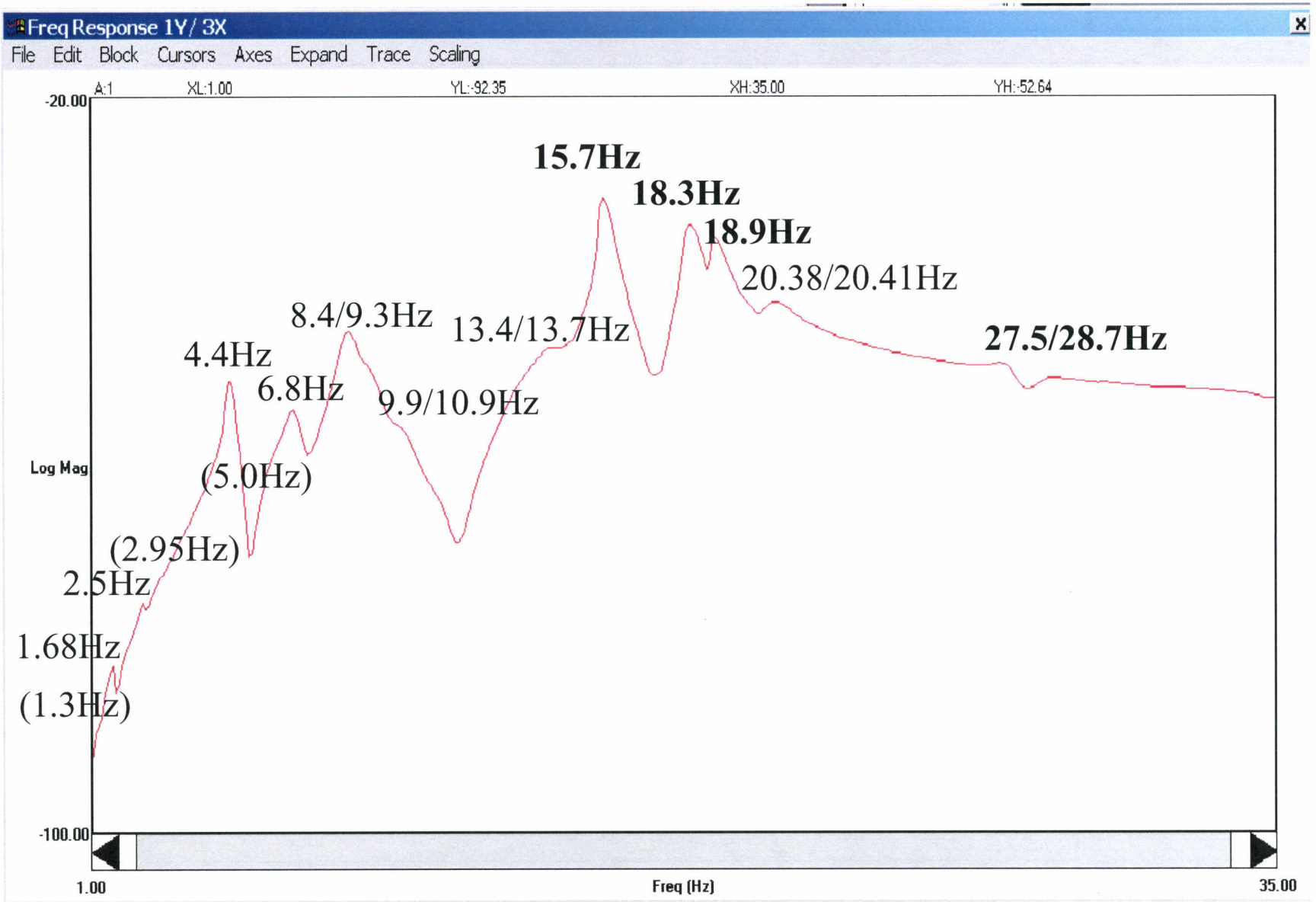
- For control consideration, **the critical modes** are the two modes around 19Hz, and two modes around 28Hz. (The modes around 14Hz are also critical)

Modal Analysis

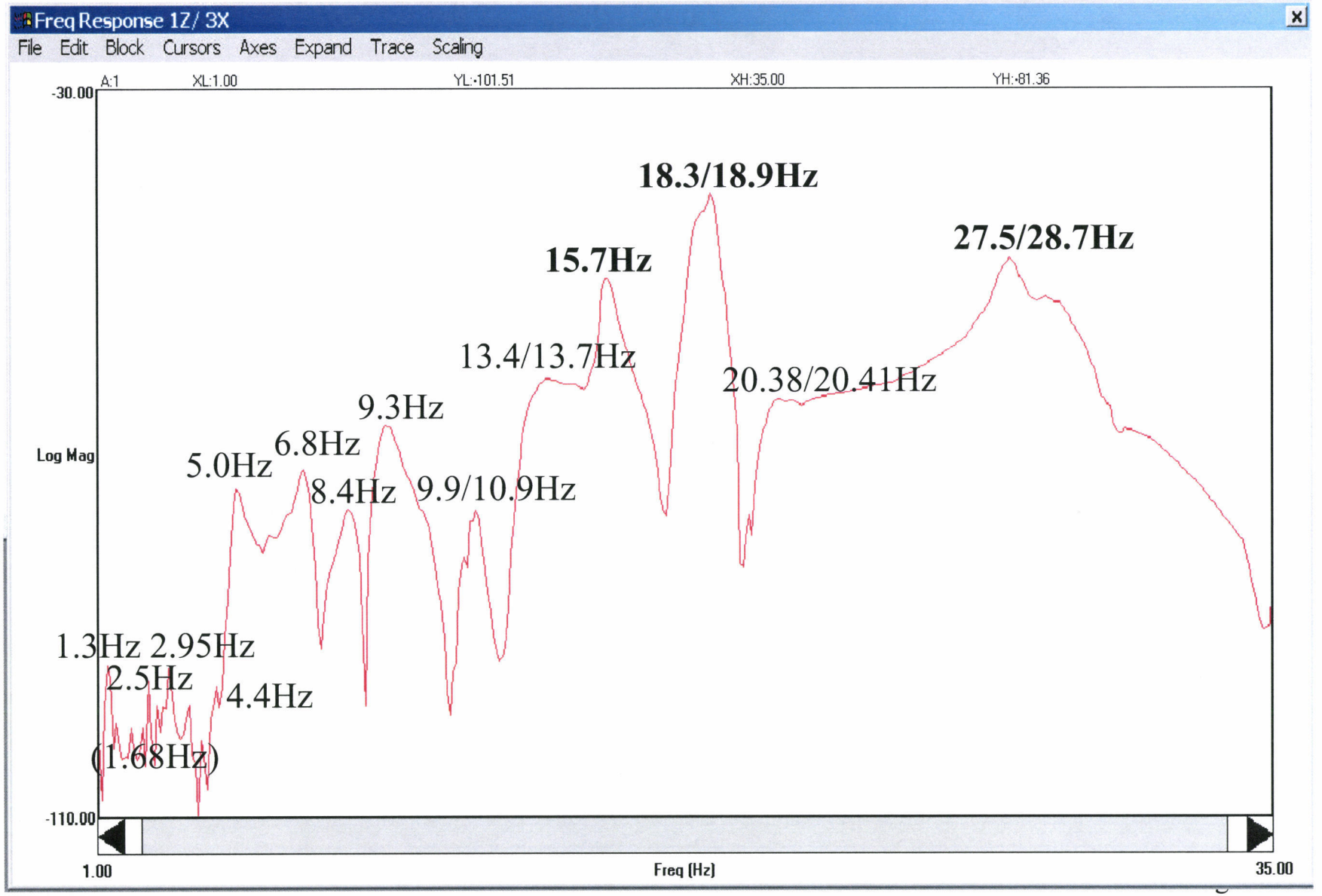
Typical Measurement (x)



Typical Measurement (y)

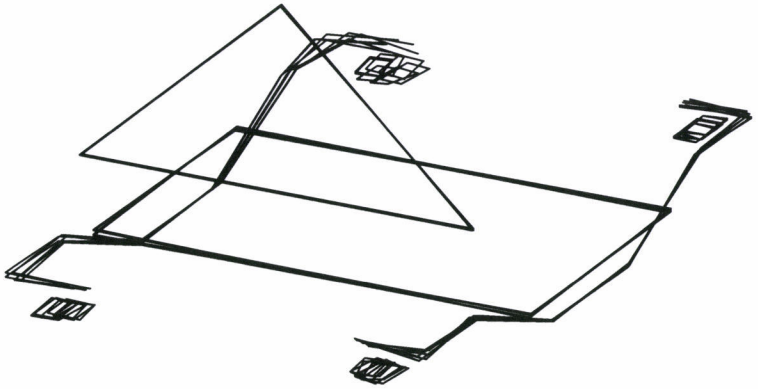


Typical Measurement (z)

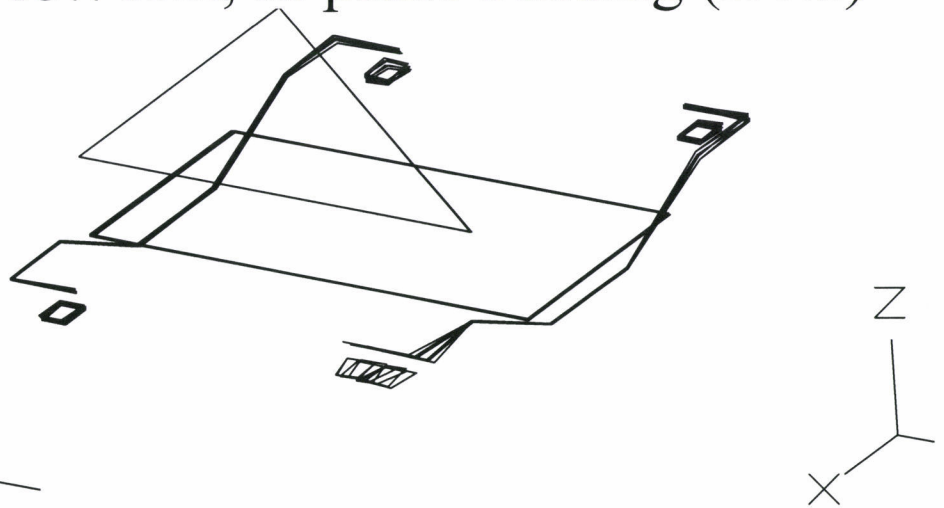


Critical Modes

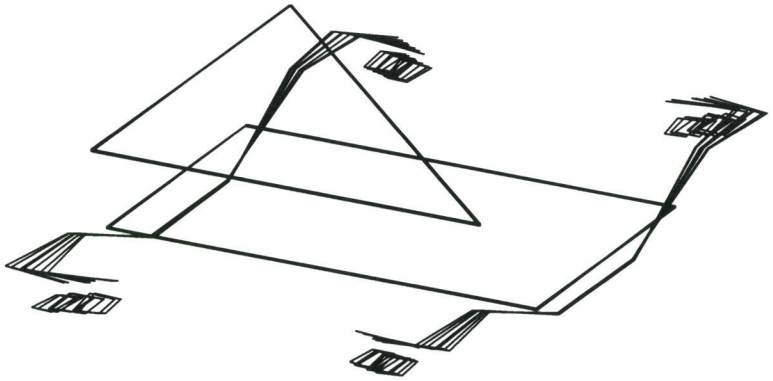
13.37Hz, in-plane bending + twist



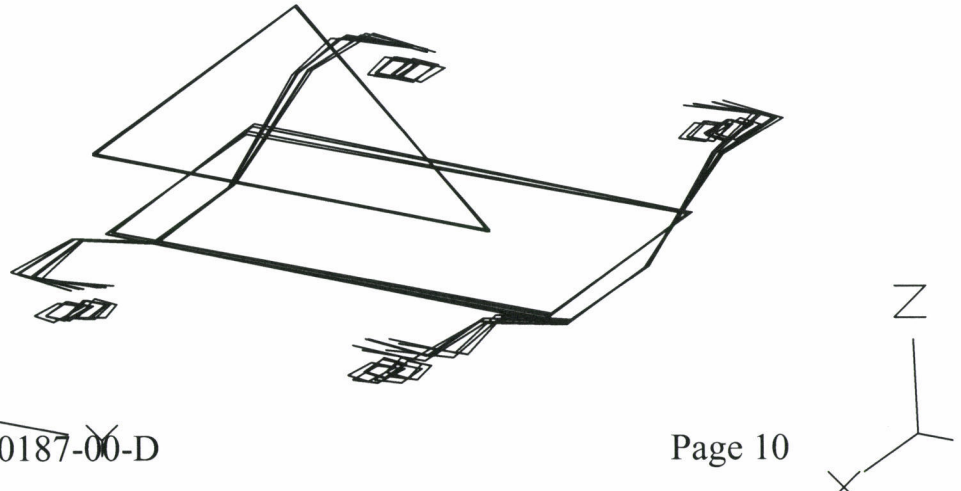
13.71Hz, in-plane bending (local)



15.75Hz, in-plane bending



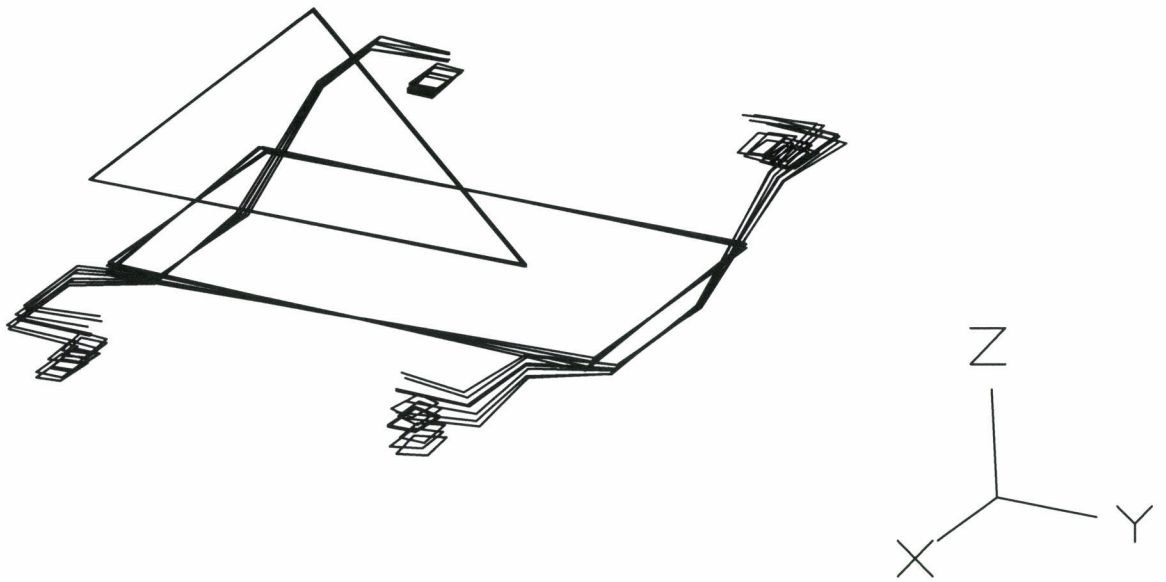
18.32Hz, in-plane bending



In-plane Beam Bending

Critical Modes

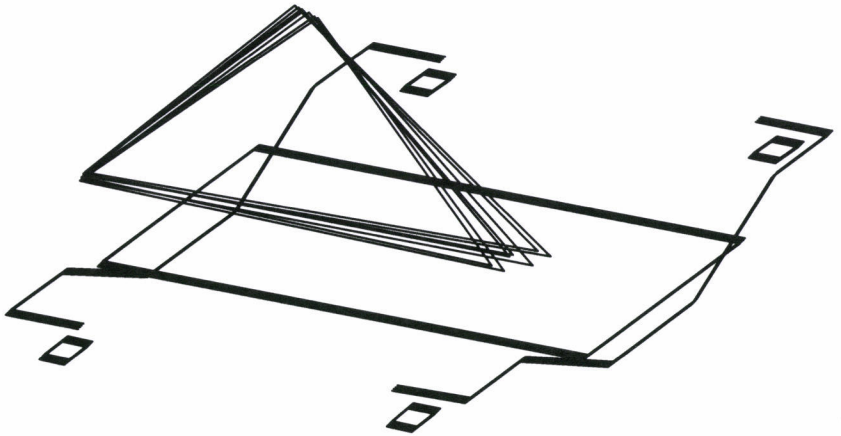
18.85Hz, out-of-plane twist

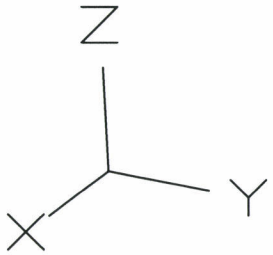


Twist

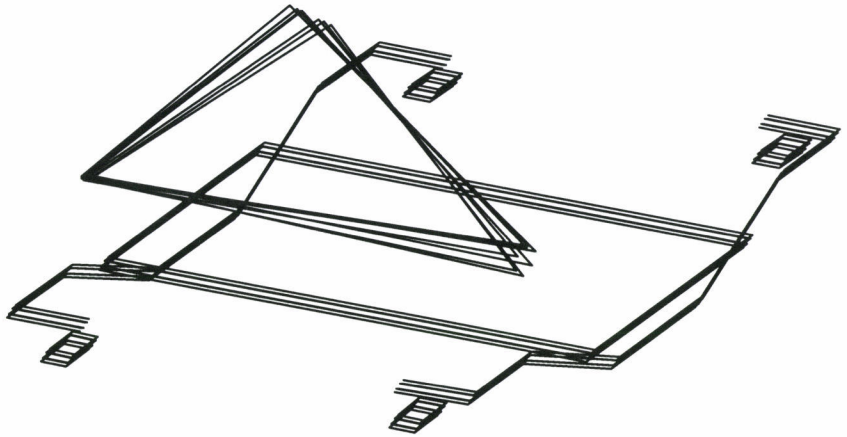
Critical Modes

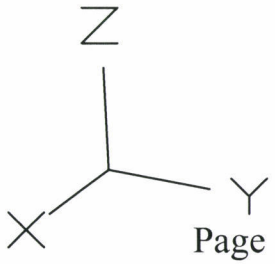
27.45Hz, tank





28.74Hz, tank





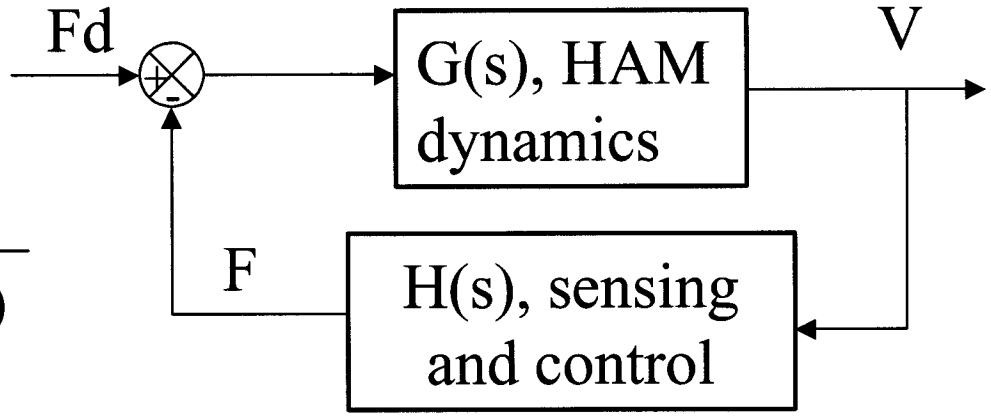
Tank Related

Mode Summary

- Modes at (2.5),3.0, 4.4, 5.0, 6.8, 8.4, and 9.3 Hz are rigid-body modes (compare with Dennis's modeling?)
- Modes at **13.4, 13.7, 15.7 Hz, and 18.3 Hz** are associated with in-plane bending
- Mode at **18.9 Hz** is related to twist
- Modes at **27.5 and 28.7 Hz** are associated with tank motion
- Two modes around 20.4 are out-of-plane (vertical) bending
- Modes at 1.3 and 1.7 Hz seems to be tank motion+frame rigid body (measurements is not so reliable at so low freq)
- Modes at 9.9, 10.9 are rigid-body plus some bending

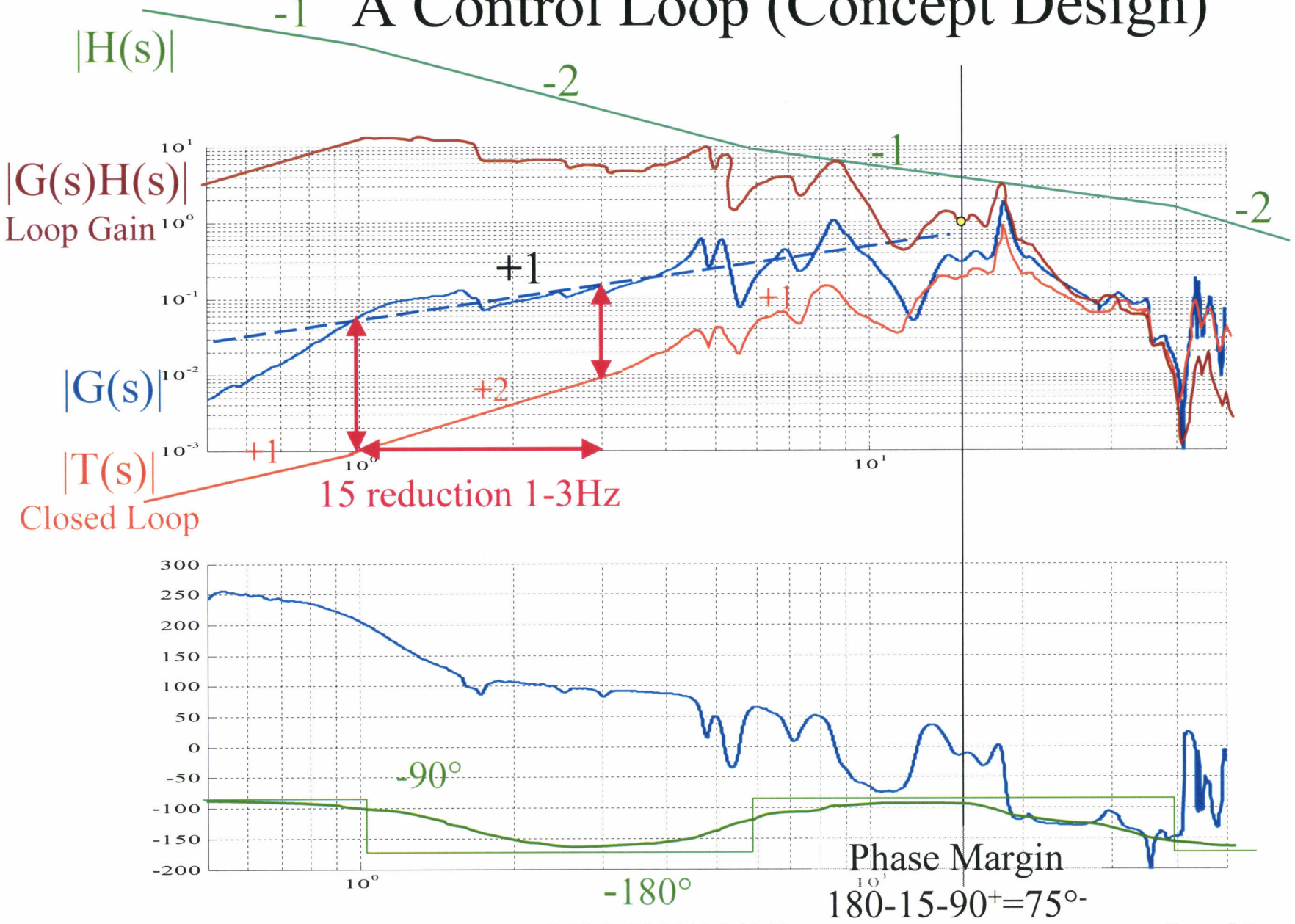
Feedback Control of HAM

$$T(s)=\frac{V}{Fd}=\frac{G(s)}{1+G(s)H(s)}$$



- $|G(jw)H(jw)| >> 1$ at low frequency, $T(jw) \approx 1/H(jw)$
- $|G(jw)H(jw)| << 1$ at high frequency, $T(jw) \approx G(jw)$

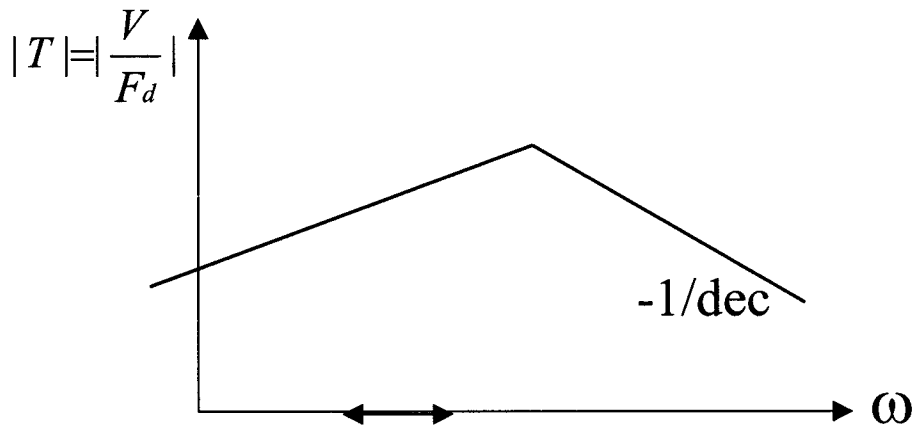
A Control Loop (Concept Design)



(The low-frequency characteristics of geophones is not good ⇒ Position feedback will be used for <0.5Hz)

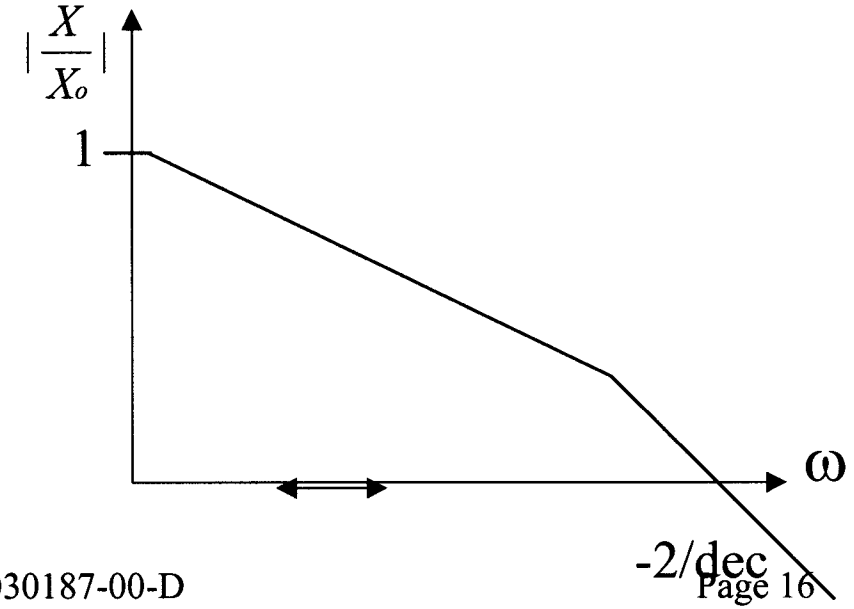
$F_d \rightarrow V$ and $X_0 \rightarrow X$

$$\frac{V}{F_d} = \frac{sX}{k(X - X_o)}$$



$$\Rightarrow$$

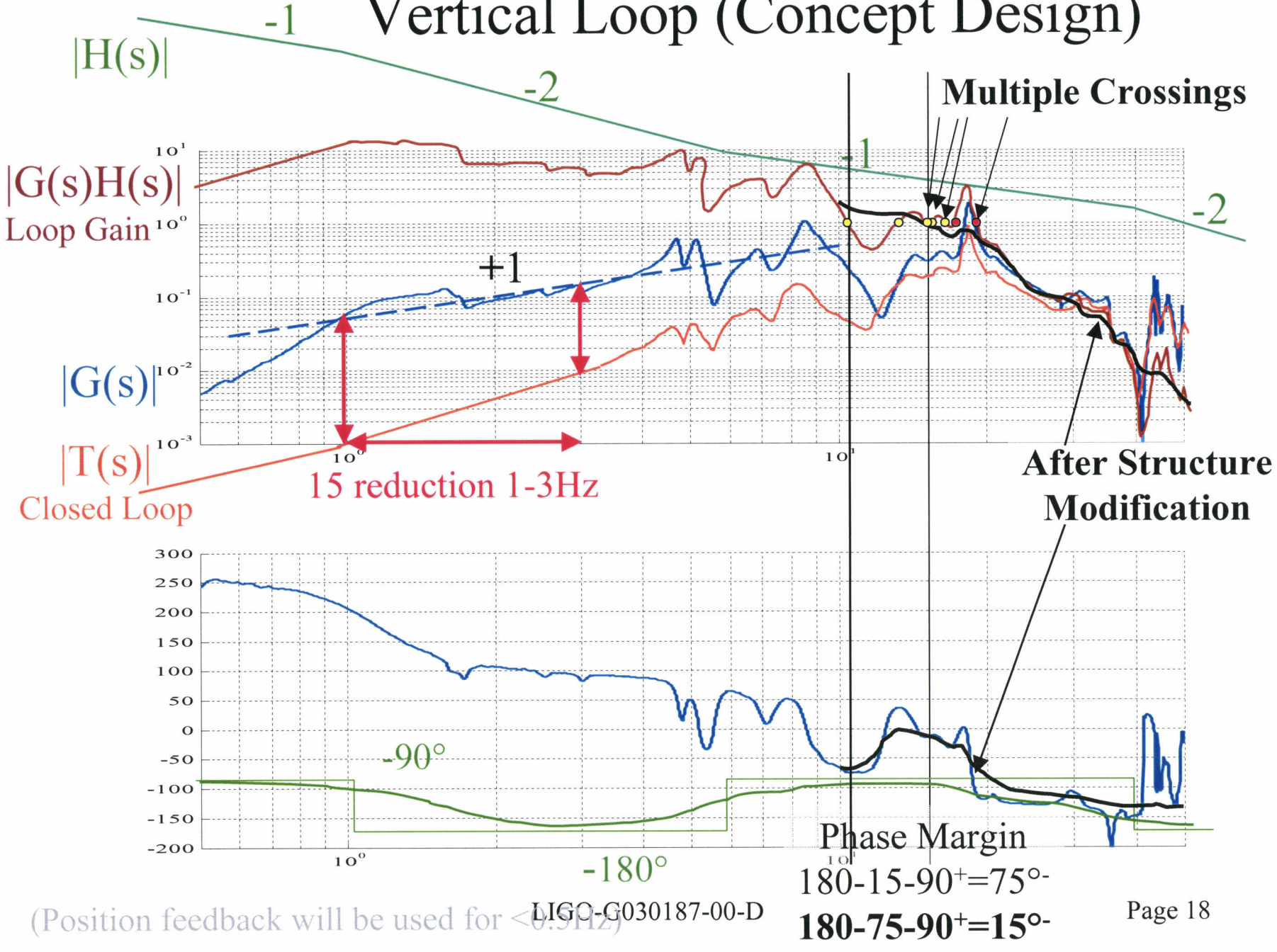
$$\frac{X}{X_o} = \frac{\frac{V}{F_d}}{\frac{V}{F_d} - \frac{s}{k}}$$



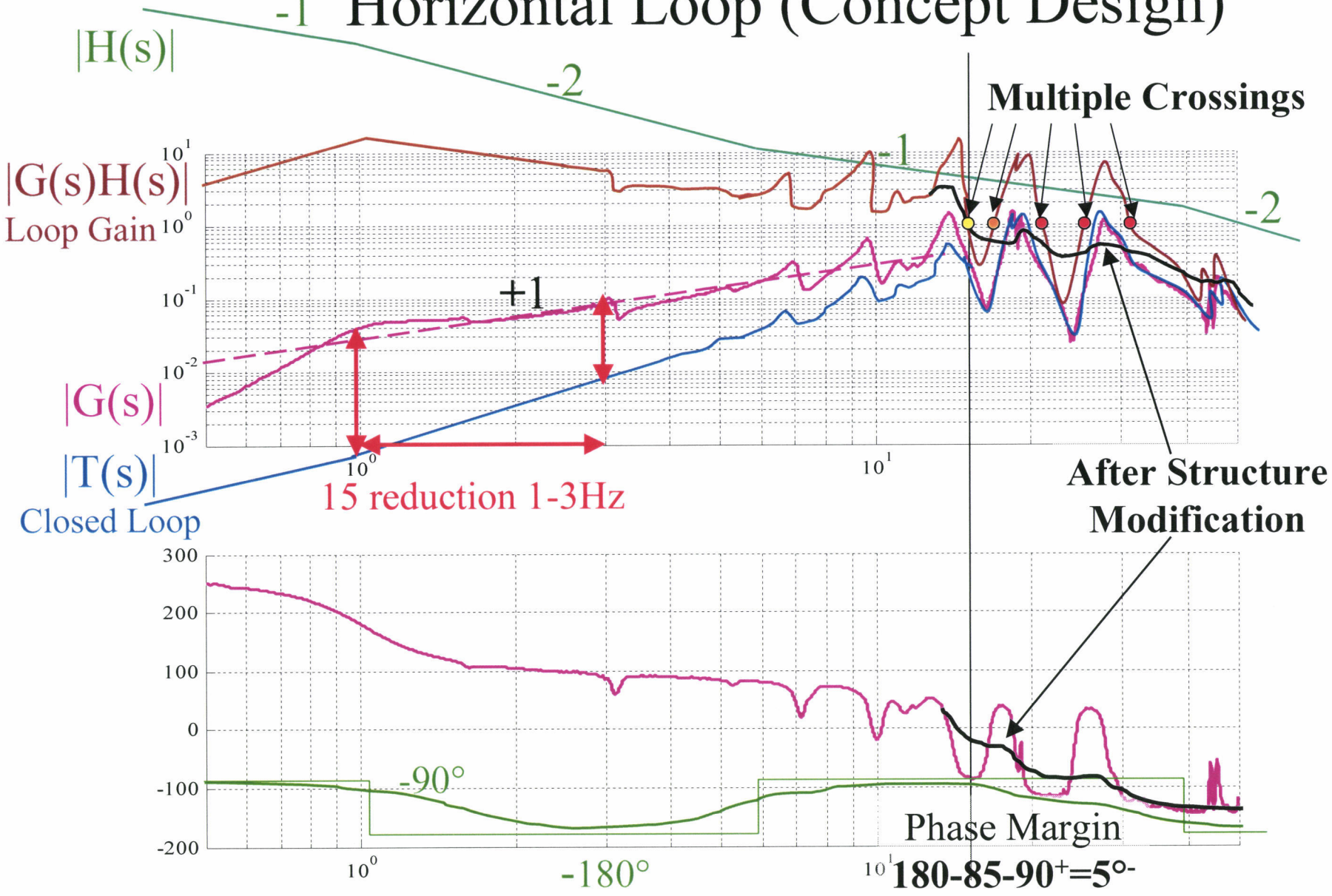
Further Consideration

- The previous concept design is for vertical channels based on the assumption of low plant uncertainties.
- See the previous control loop again:
  * Multiple crossing, not robust (unstable!)
  * PM is 15°, not 75° (add lead? no)
- See horizontal channels
  * Multiple crossing, not robust
  * PM is only 5°

Vertical Loop (Concept Design)



Horizontal Loop (Concept Design)



(Position feedback will be used for <0.5Hz)

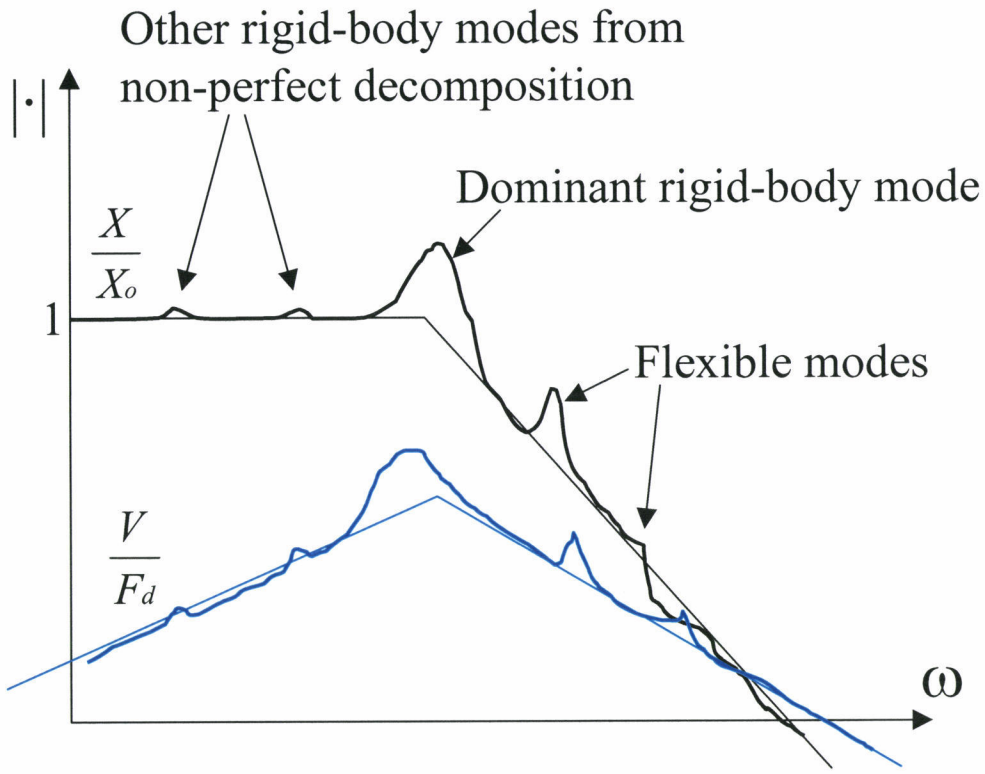
Suggestion for Feedback Control

* Modal Decomposition SISO Control.

Questions (SISO):

1) how good is the decomposition?

2) how large are the peaks of flexible modes?



Suggestions on Structure Modification
(to make control easier)

- Add constrained layer (viscoelastic) damping to the beam structure (to damp the bending modes)
- Make the joints stiffer; add some damping to the joints; or add another beam
- Reduce the coupling between tank and the frame.

Conclusions

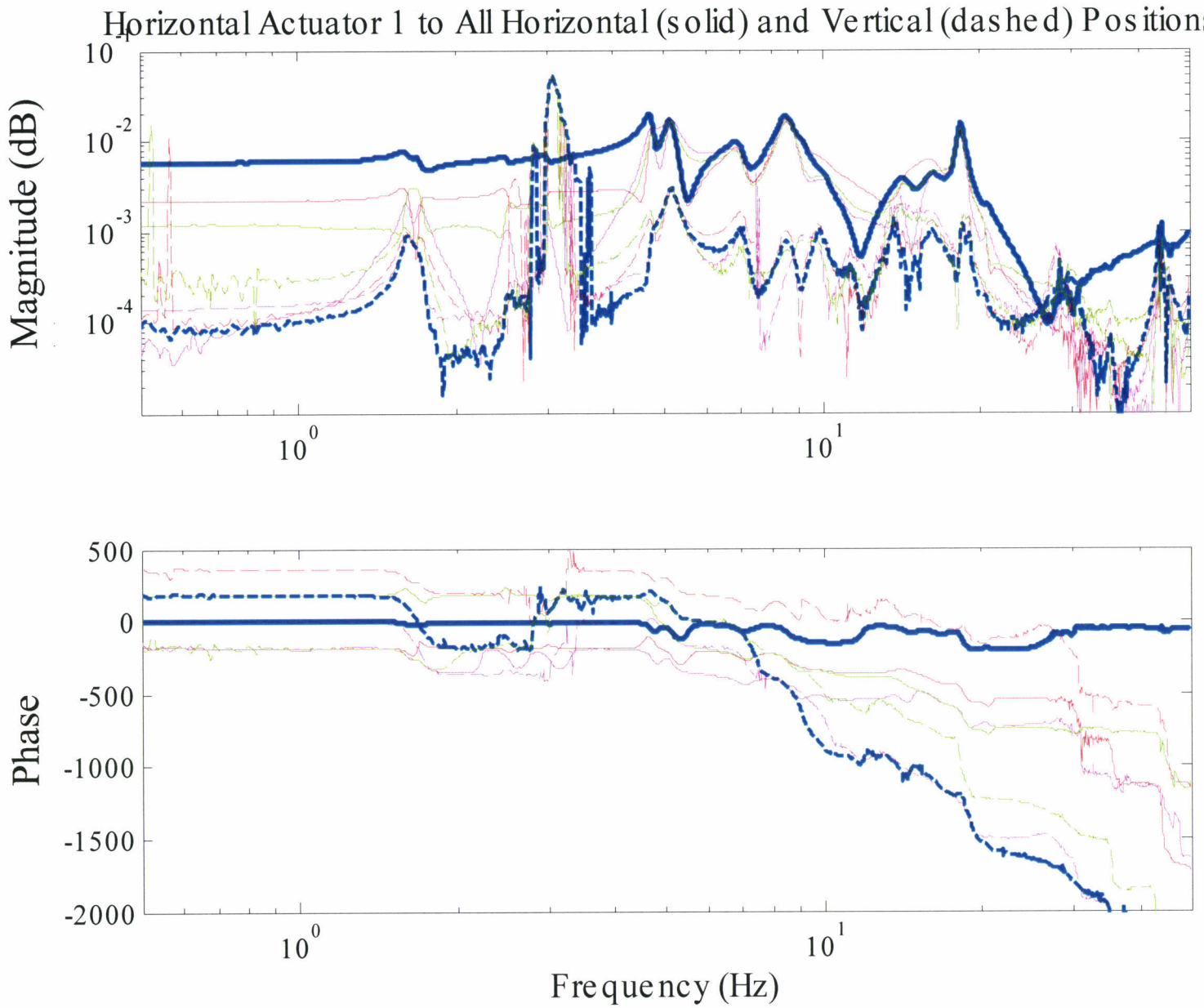
- Multiple lightly damped modes close to crossover make control difficult
  - Instability
  - Amplification of disturbances
- Modal control may decrease their relative magnitudes.
- Easiest approach to robust performance: structural damping.
- Optimal MIMO Control can improve the performance, but requires a good model

Other Control Schedules Discussed

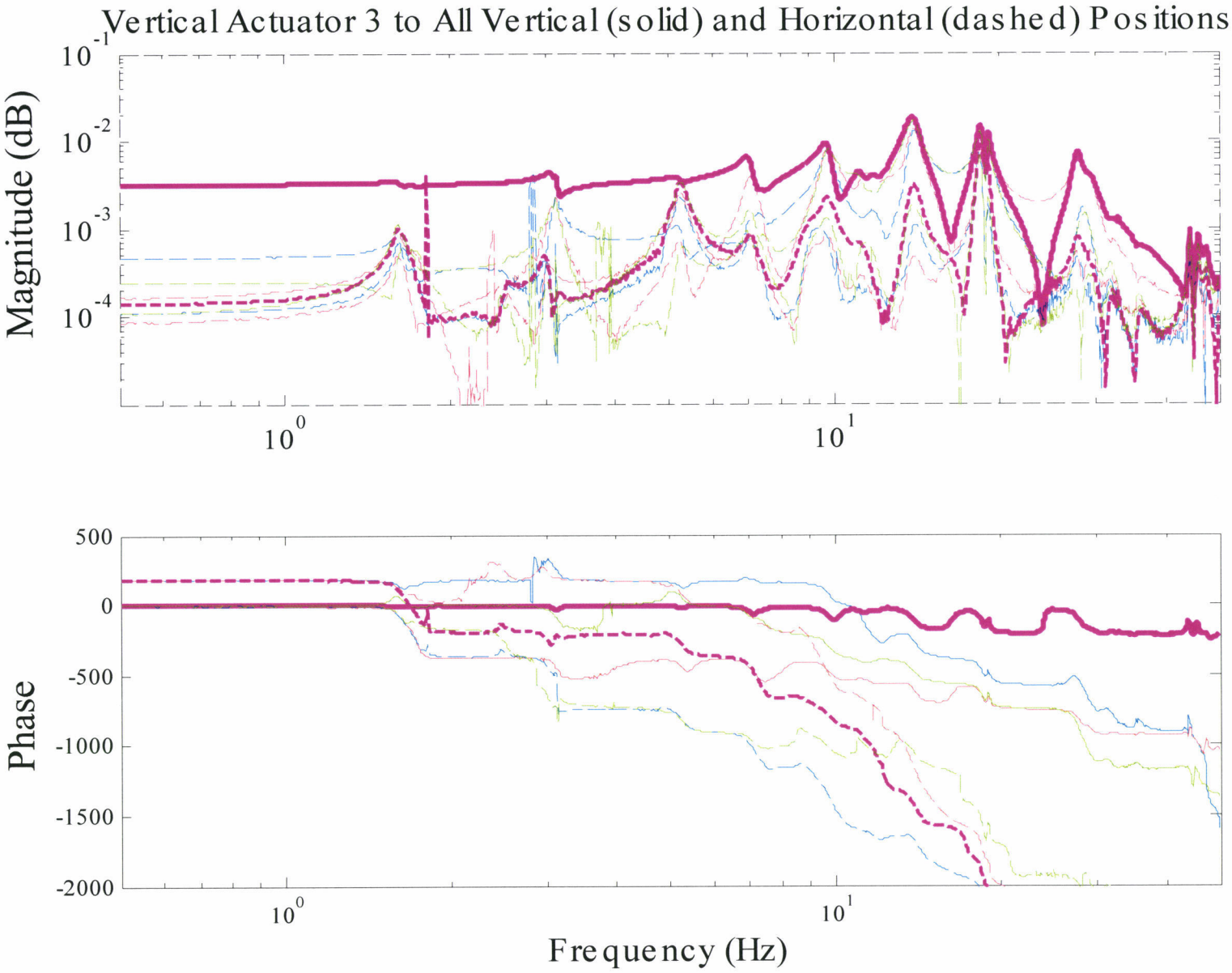
- Osamah: low frequency crossing with high order controller
- Dave: notch filter
- Rich, David and Denis: high frequency crossing

Appendix

Typical TF from Horizontal Actuator to Positions

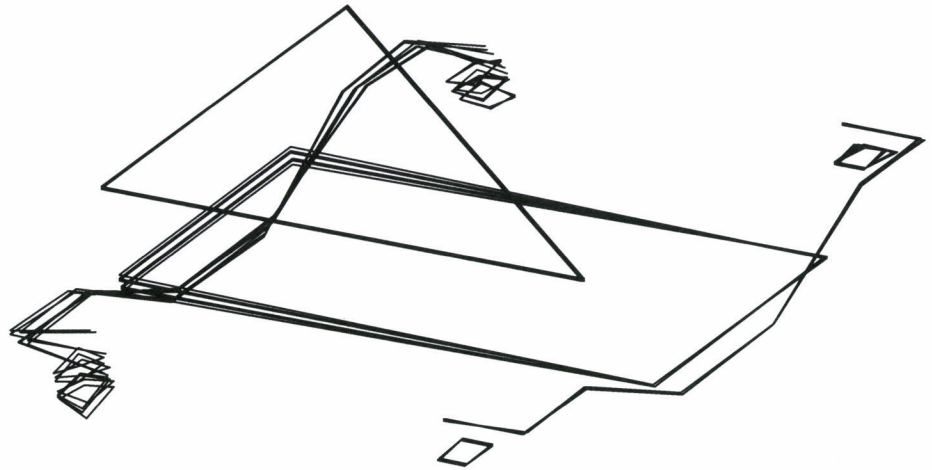


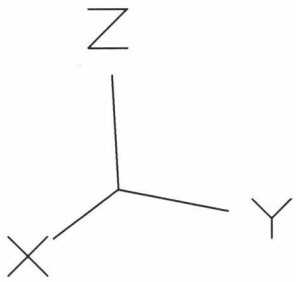
Typical TF from Vertical Actuator to Positions



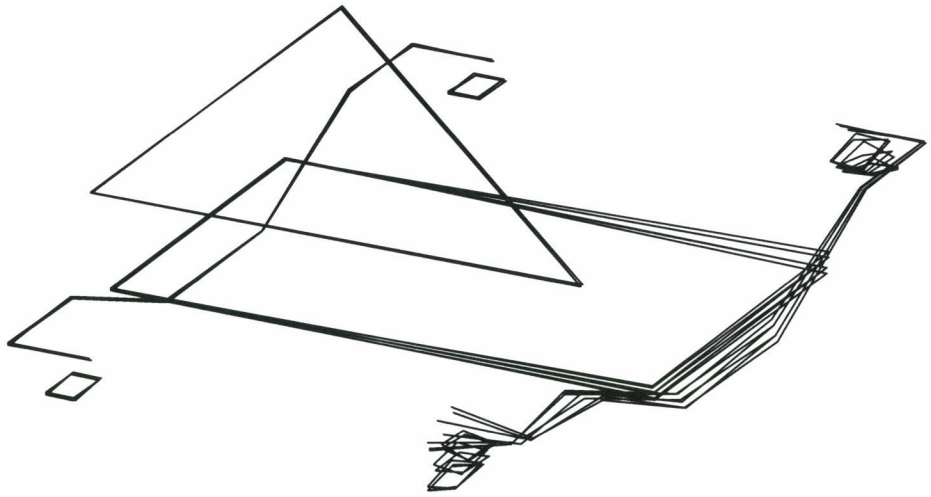
Out-of-Plane Bending Modes

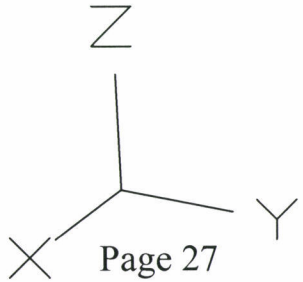
20.38Hz





20.41Hz

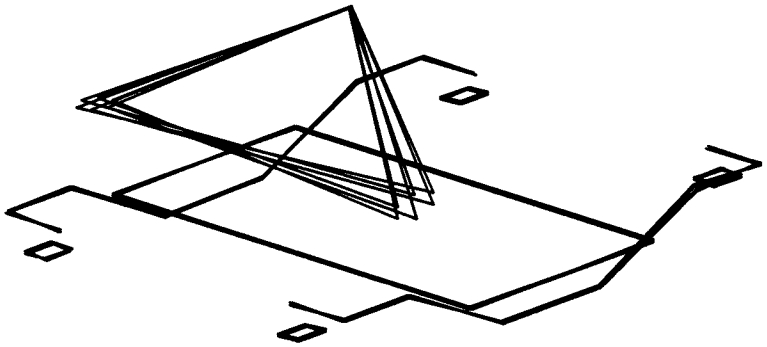




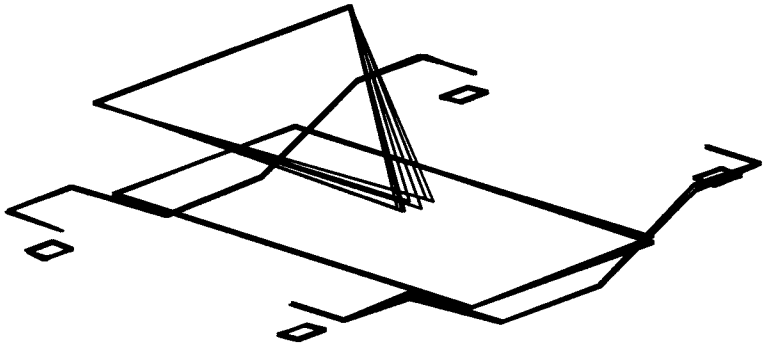
Out-of-Plane Beam Bending Related

Mode Shapes

1.3Hz



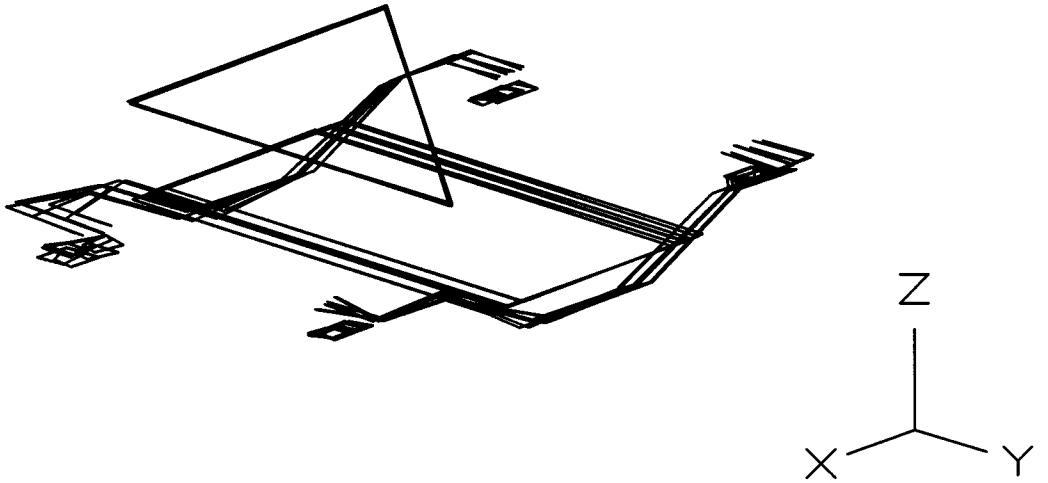
1.7Hz



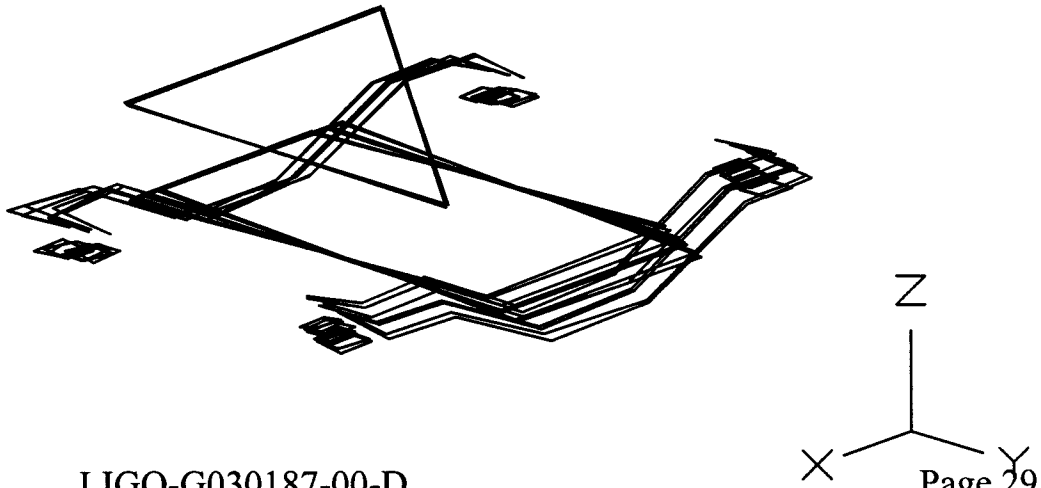
(low-freq, measurement is not reliable)

Mode Shapes

2.50Hz

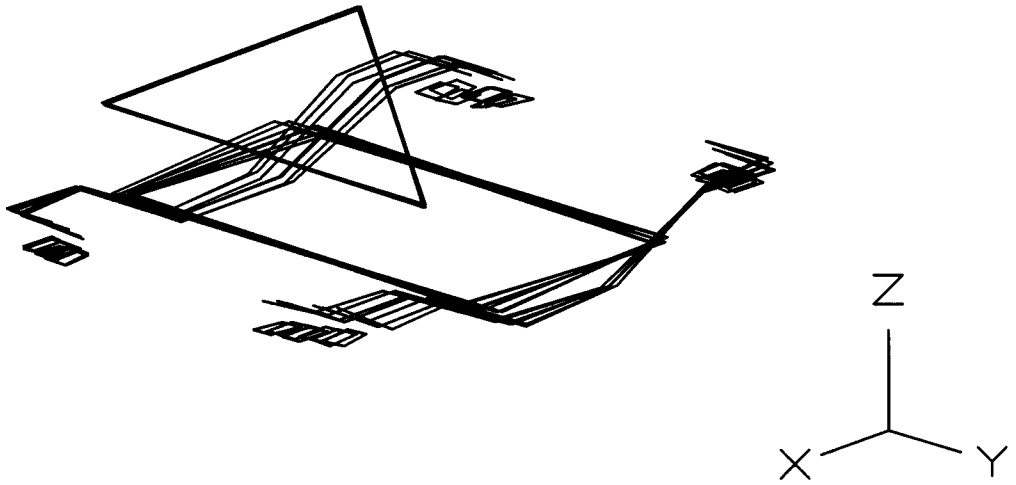


2.97Hz

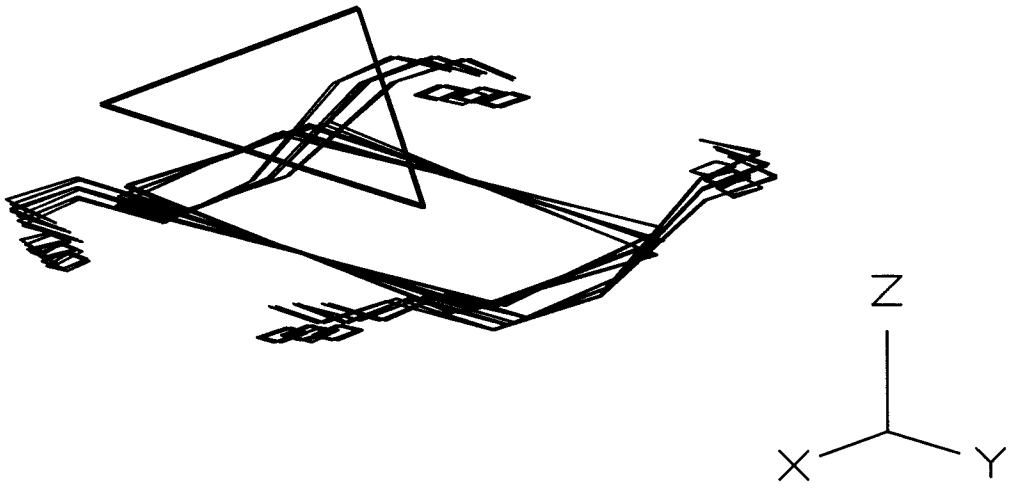


Mode Shapes

4.41Hz

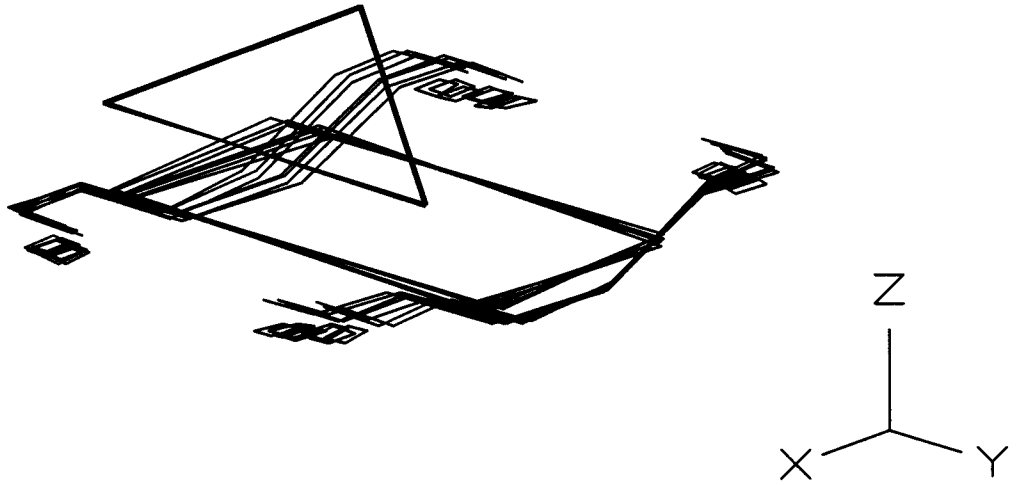


4.99Hz

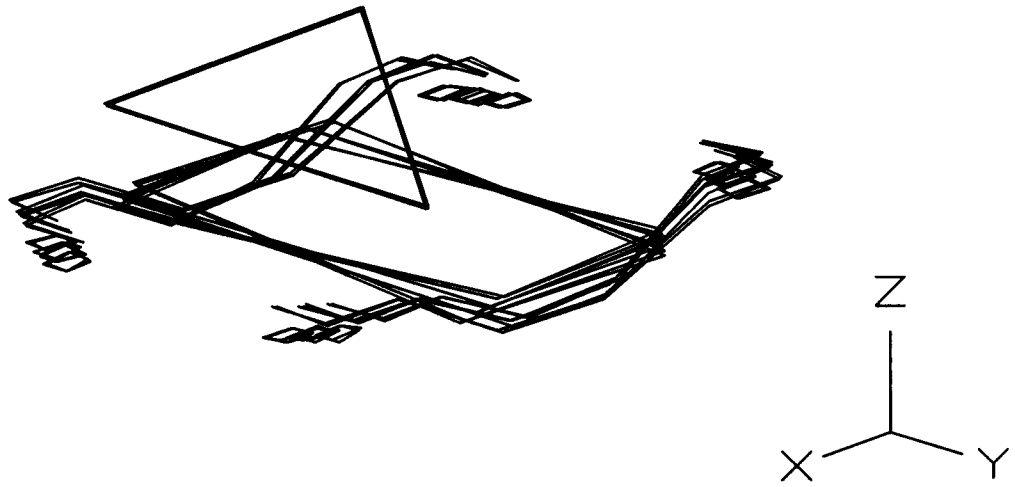


Mode Shapes

6.86Hz

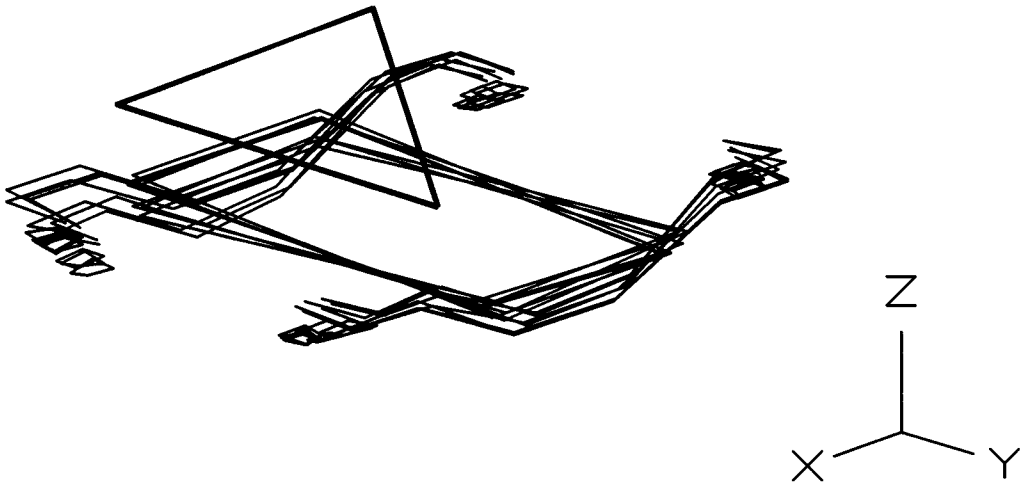


8.33Hz



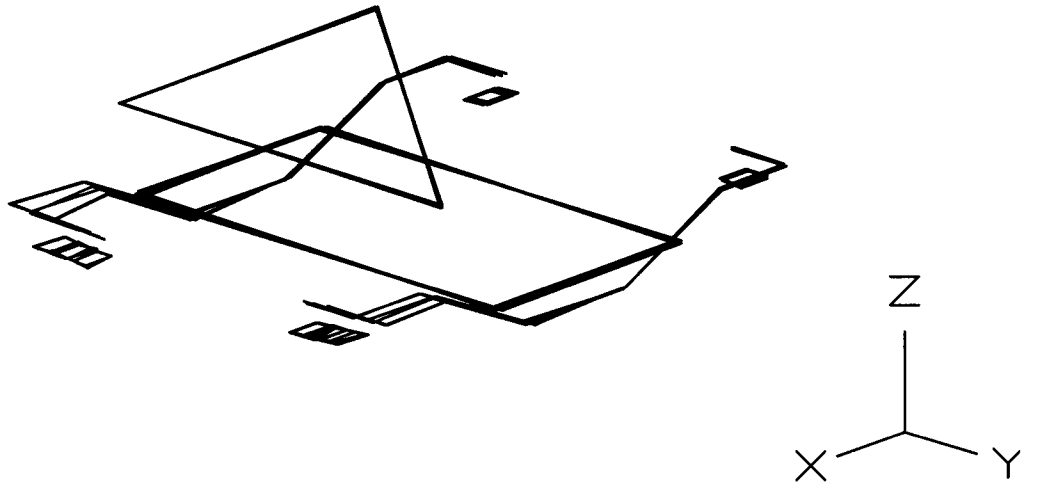
Mode Shapes

9.25Hz



Mode Shapes

9.82Hz



10.9Hz