Experimental Structural Mechanics & Piping Vibration issues at Loviisa NPP

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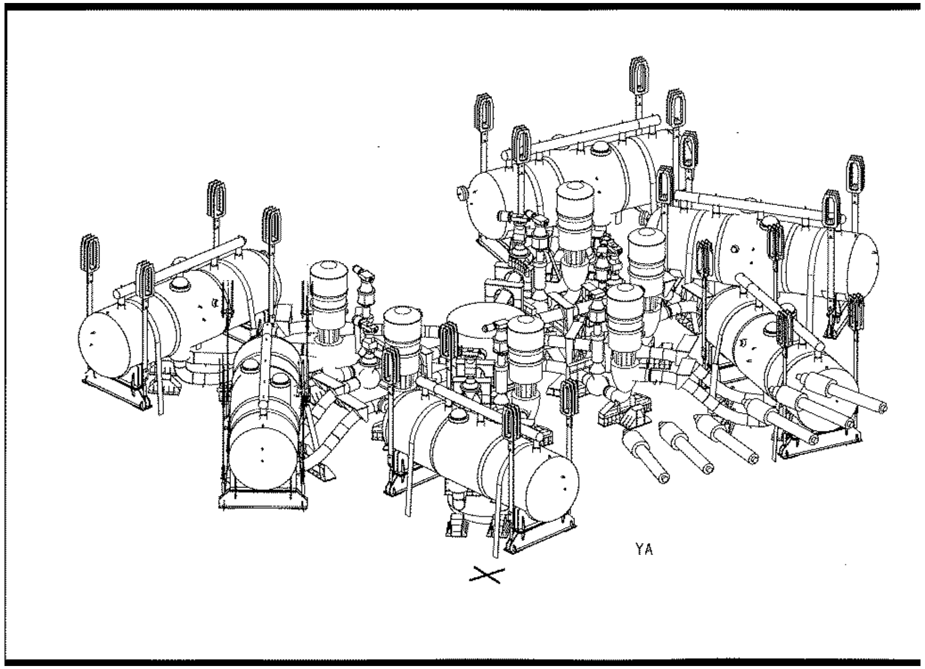
Loviisa Nuclear Power Plant

Loviisa NPP has two reactor units:

- PWR-type plant of VVER-440 type (i.e. VVER-440/213)
- Nominal electrical capacity of 440 MW
- With 6 primary loops
- 6 Horizontal Steam Generator units
- Each of the reactor units is associated with 2 Turbine –Generator units (i.e. 4 TG-sets)
- Some of the core design features are unique:
  - Fuel bundles inside hexagonal "channels"
  - Control rods of the neutron trap design
  - Fuel followers mounted at the bottom of the control rods
  - RPV wall exposed to elevated fast neutron fluence



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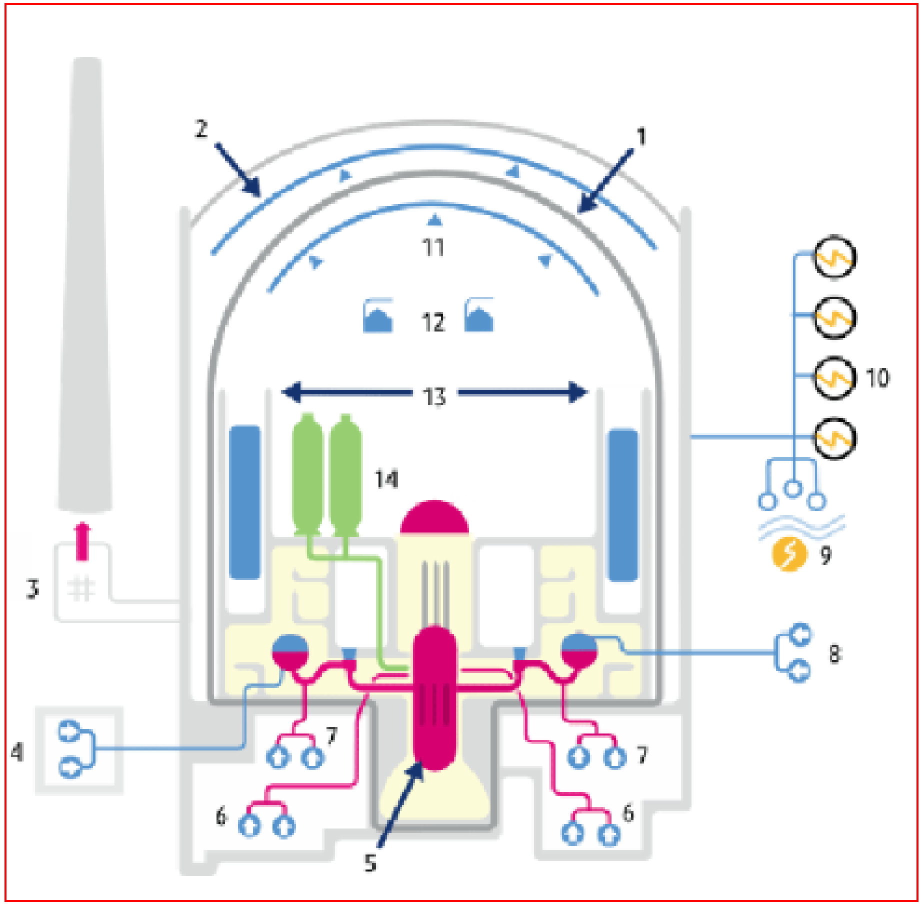
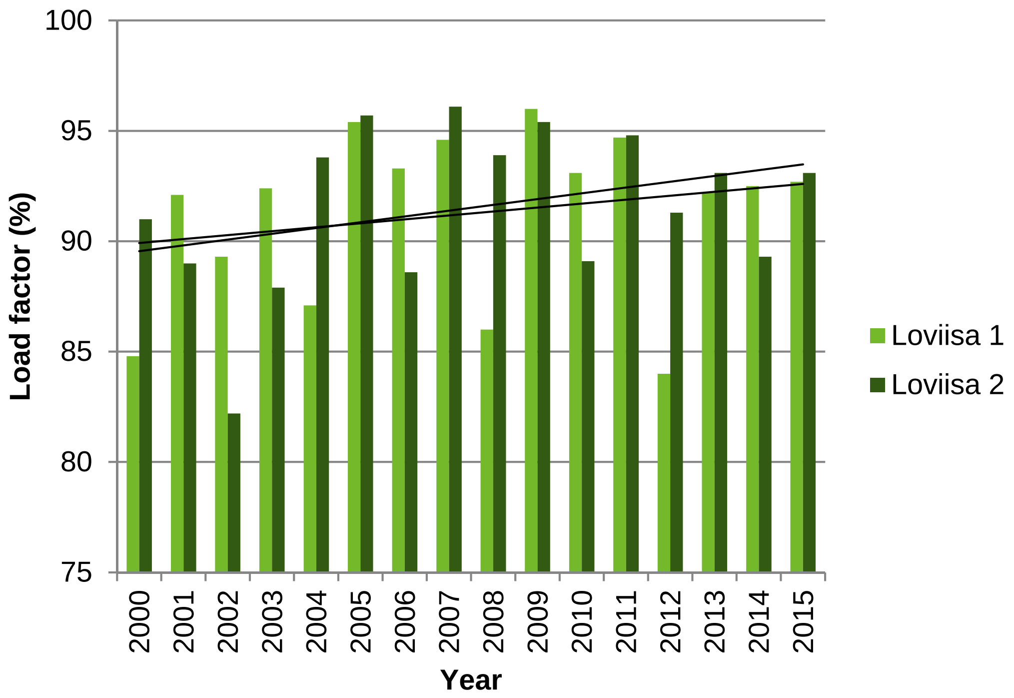
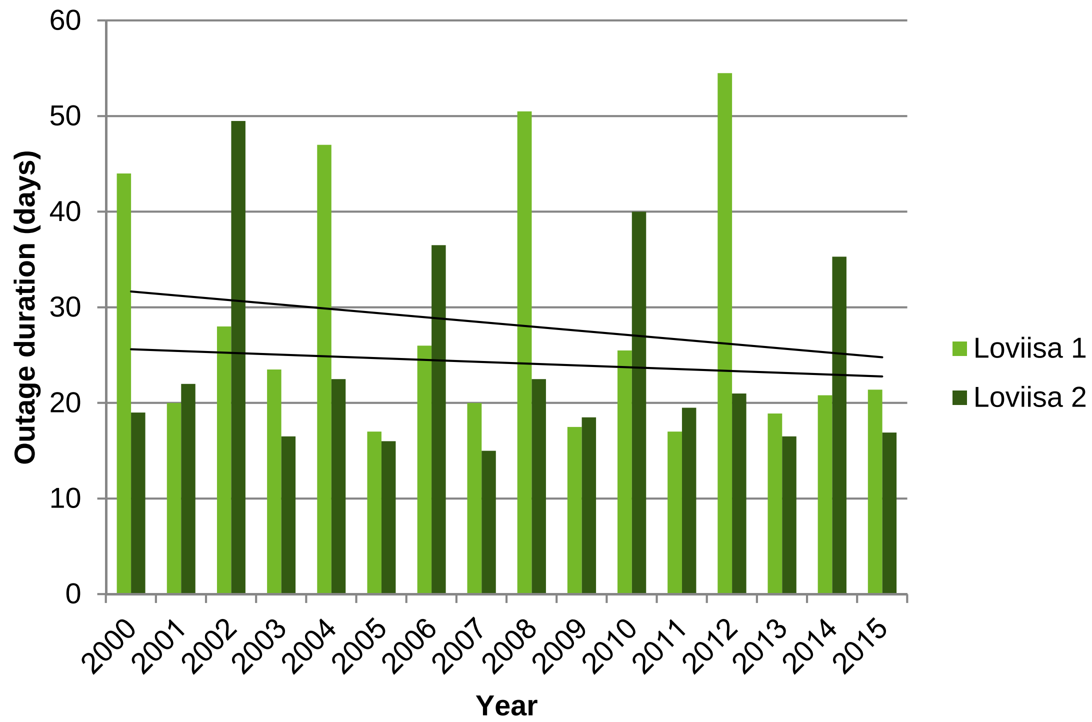
Loviisa Nuclear Power Plant



- **Original VVER-440-design was with no containment (i.e. Greifswald-type design)**
- **Prerequisite of the Finnish regulatory body (i.e. STUK) was that modern western safety features must be implemented (containment etc.) to meet western safety & design principles**
- **Commissioned Loviisa 1 in 1977; Loviisa 2: 1980**
- **Heavily upgraded with current thermal output of 1500+ MW**

Load factor and outage periods at Loviisa





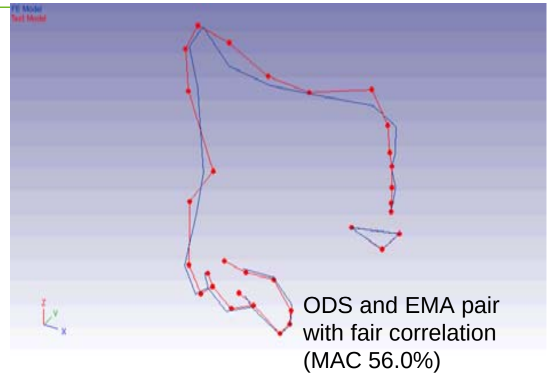
- Loviisa load factors are among the highest and outage periods correspondingly among the shortest in the whole world

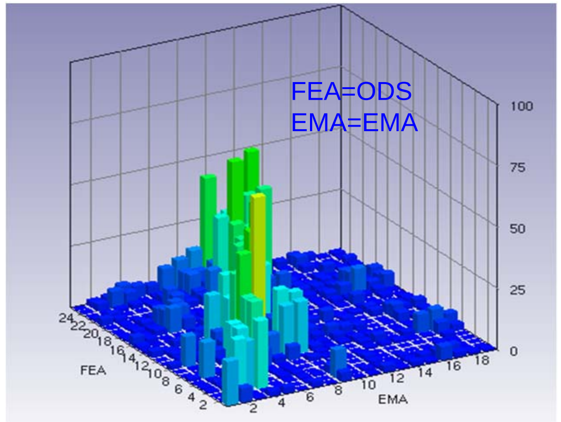
Measurement of structural responses, Measurement & Analysis FRF's and Updating, Estimation of Input Loads and Modifications

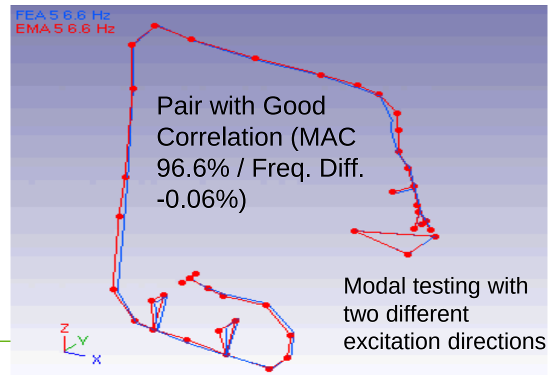
Number of unknowns

- **Measurement and analysis of operational responses**
  - Identification of the most prominent structural response spectral components
  - Identification of Operating Deflection Shapes (i.e. ODS)
- **Measurement of FRF's and analysis of inherent structural properties**
  - SMURF-modification
  - Identification of modal parameters
- **Detailed analysis of the FRF's to yield:**
  - Verified modal model to be used for updating of the theoretical FEM-models
  - Modal parameters used to estimate structural integrity
  - Modification based on the extracted modal parameters
  - Operational excitation loads are extracted

Difficulty in measurement & analysis







Stages of the utilization of Structural Mechanics measurements (i.e. mainly FRF-results (including Operating Deflection Study)

- Detection of dominant frequency components under operational loads
- Estimation of natural frequencies of a structure
- Extraction & animation of ODS-shapes
- Excitation of the structure with artificial excitation Force
- Measurement of Response over Excitation Force-type Frequency Response Functions (i.e. FRF's)
- Analysis of Modal Parameters (natural frequency, damping Value & Mode Shape)
- Detection of the root cause of problematic vibration i.e. detection of lack of stiffness (typically at a poor bolted joint) or natural frequency adjacent to operating forces
- SMURF-modifications
- Correlation analysis with a theoretical model
- Updating of theoretical model
- Estimation of excitation forces
- Prediction of effect of structural modifications

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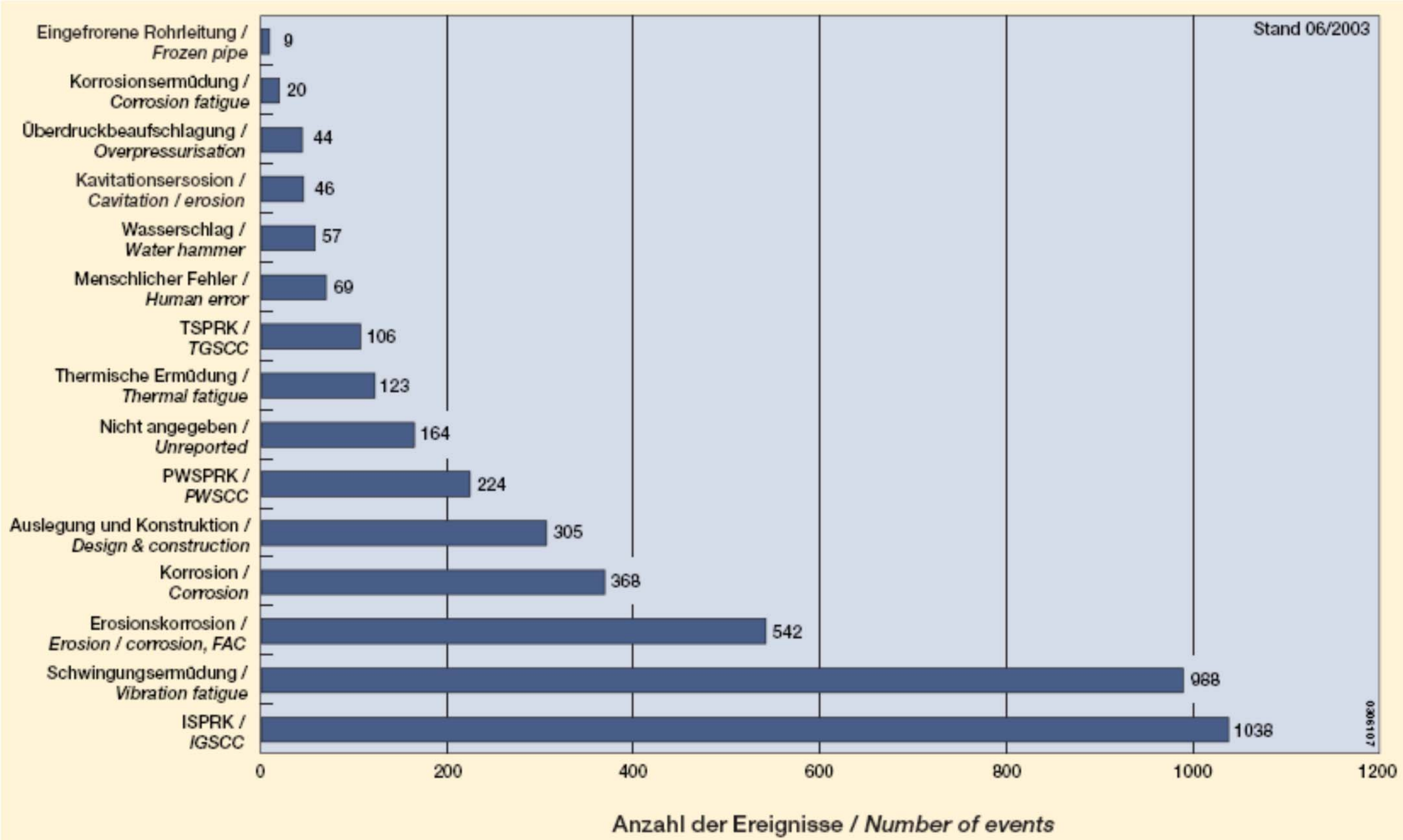
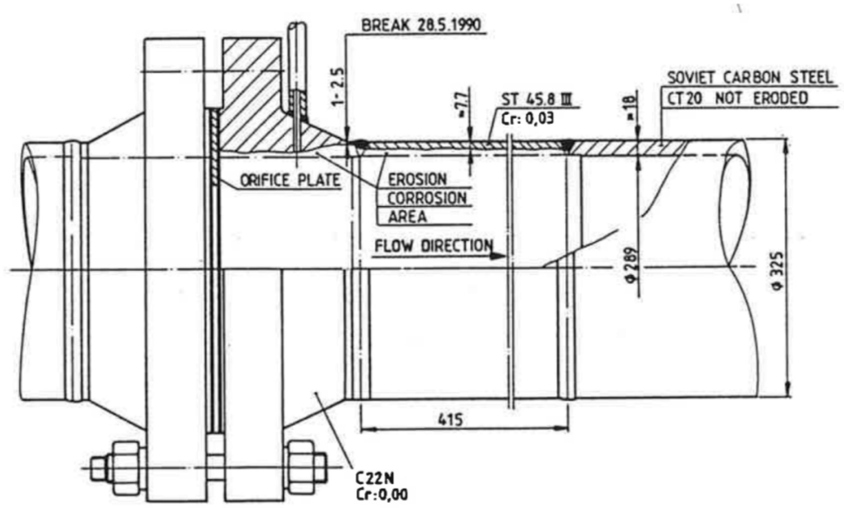
Failure Root Causes at Nuclear Power Plants



The piping failures can be traced to the following factors (according to the American experience at nuclear power plants)

<u>Diameter larger than 2”:</u>

- •Piping vibration 10%
- •Water hammer 18%
- •Corrosion in general 8%
- •Corrosion due to cavitation
- •Erosioncorrosion 60%



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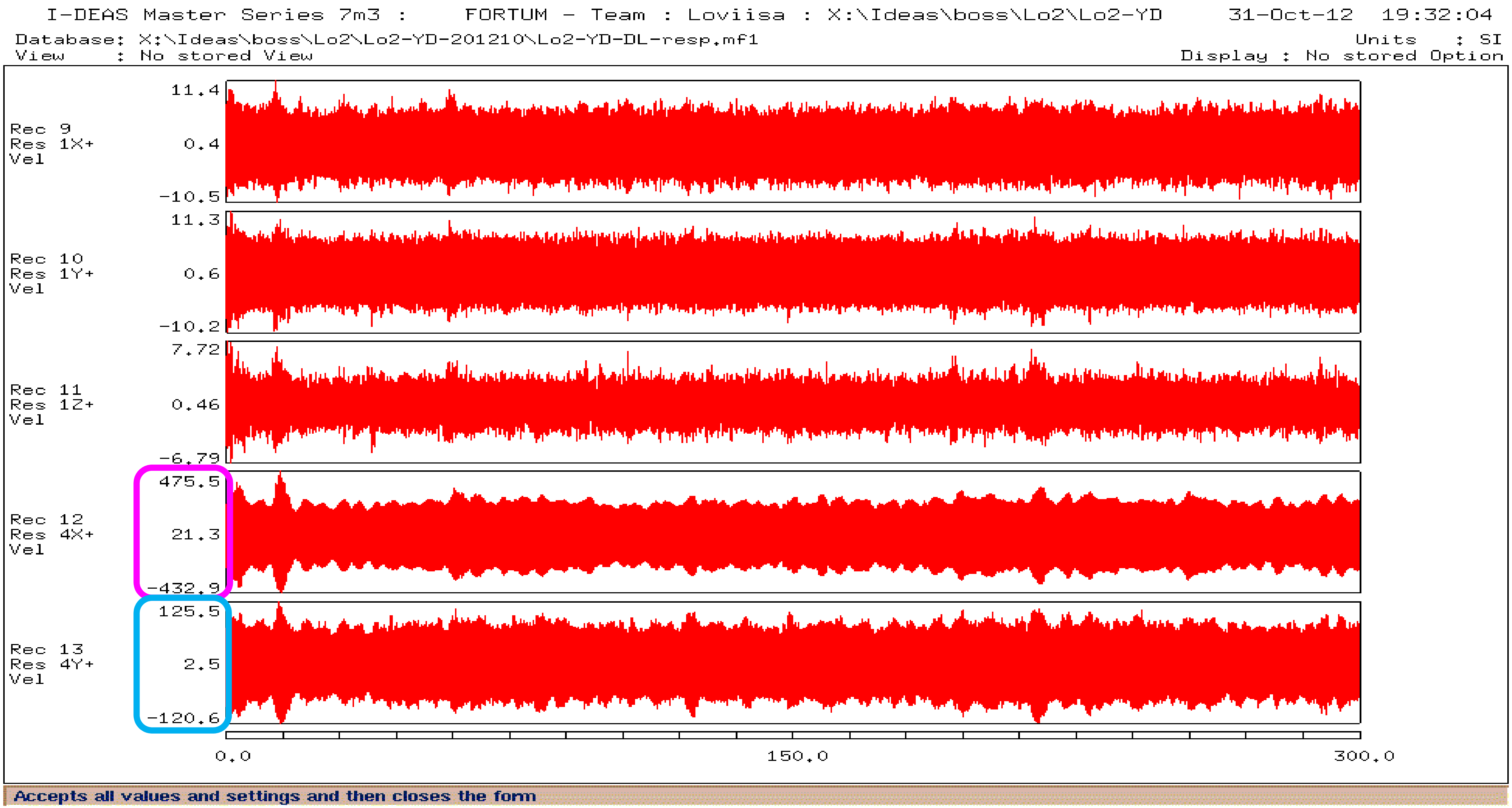
The piping failures can be traced to the following factors (according to the American experience at nuclear power plants)

<u>Diameter larger than 0.5“ but smaller than 2”:</u>

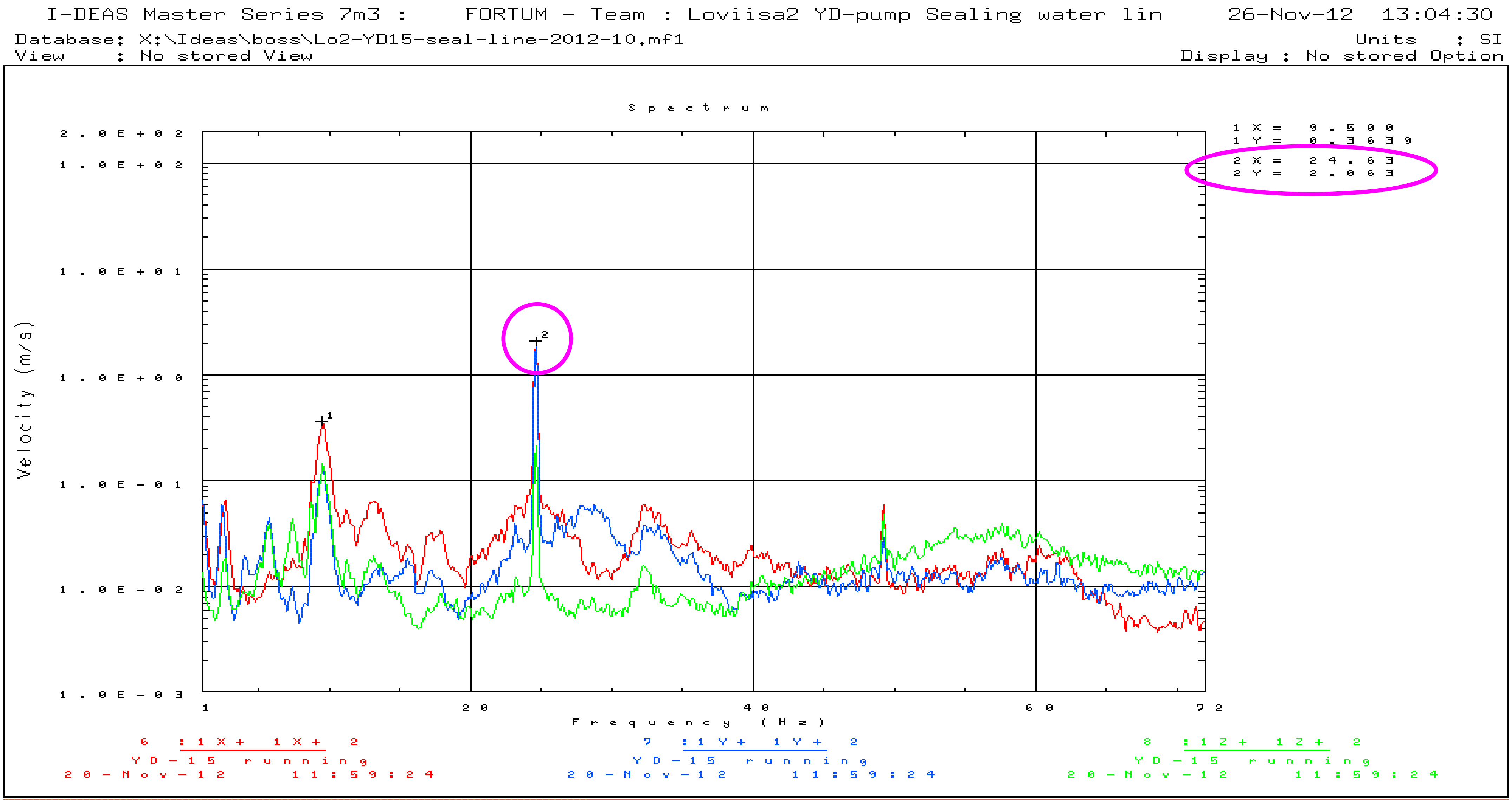
- Piping vibration 45%
- Water hammer 12%
- Failures with maintenance 7%
- Corrosion in general 3%
- Corrosion due to cavitation 12%
- Erosioncorrosion 5%
- Erosioncorrosion + vibration 3%
- Thermal fatigue 3%
- Failures with connections 11%

Vibration analysis of a small diameter PCP injection line

Vibration analysis of a small diameter PCP injection line



Vibration analysis of a small diameter PCP injection line



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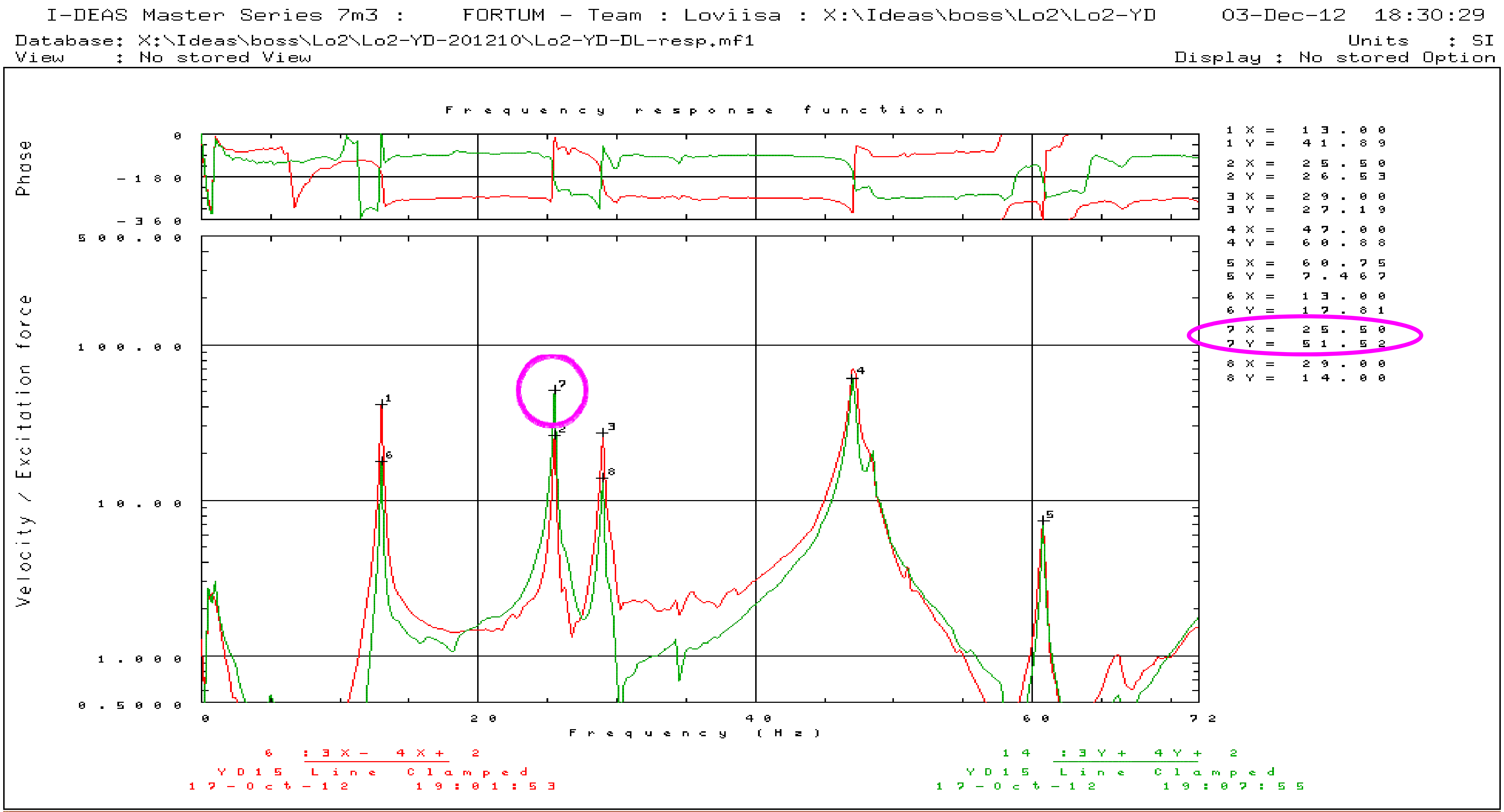

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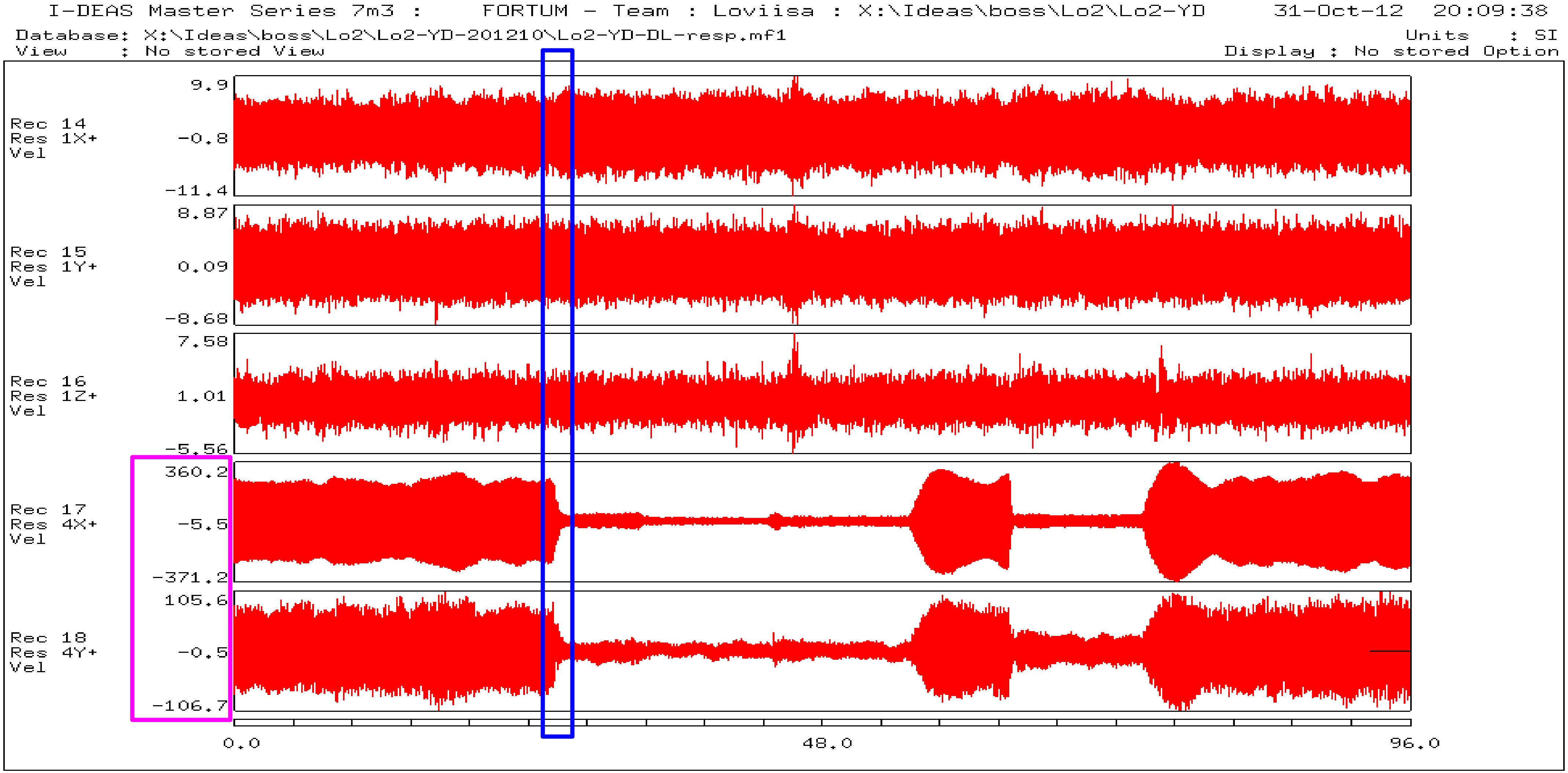
Vibration analysis of a small diameter PCP injection line



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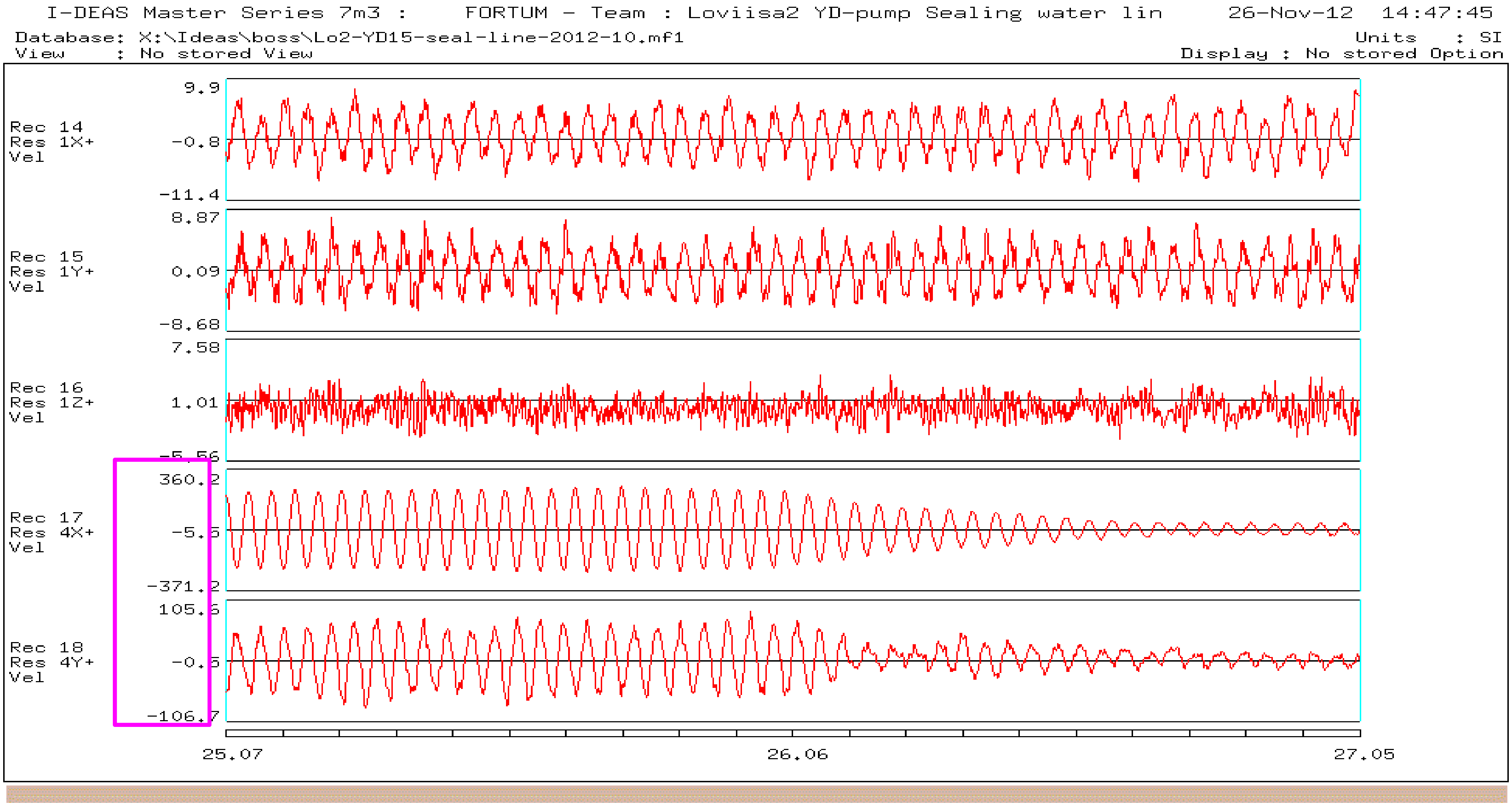
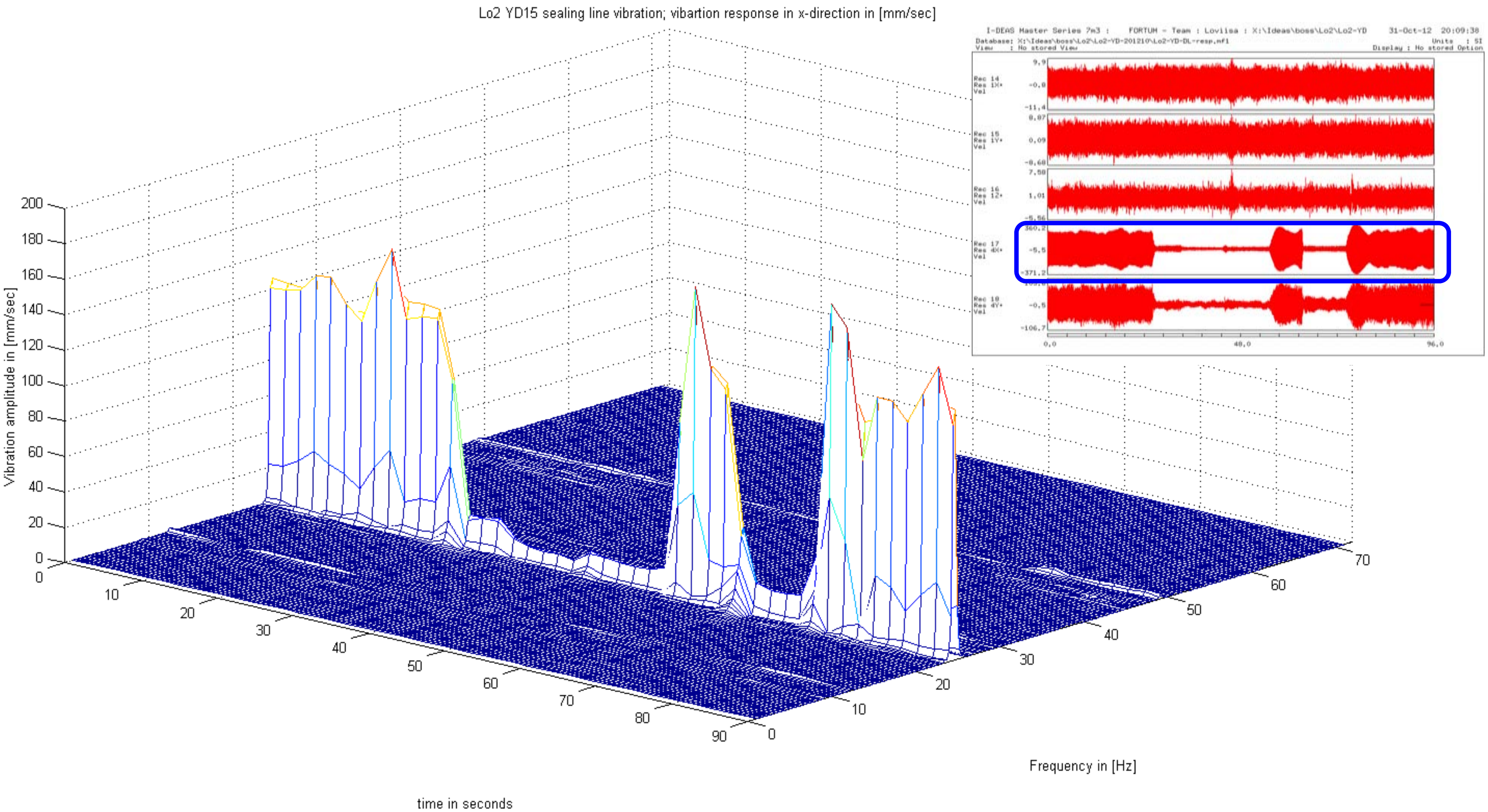
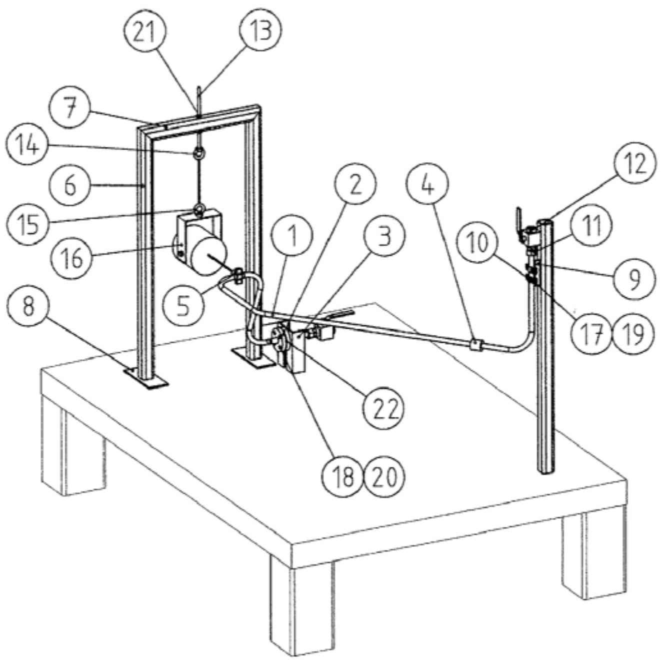
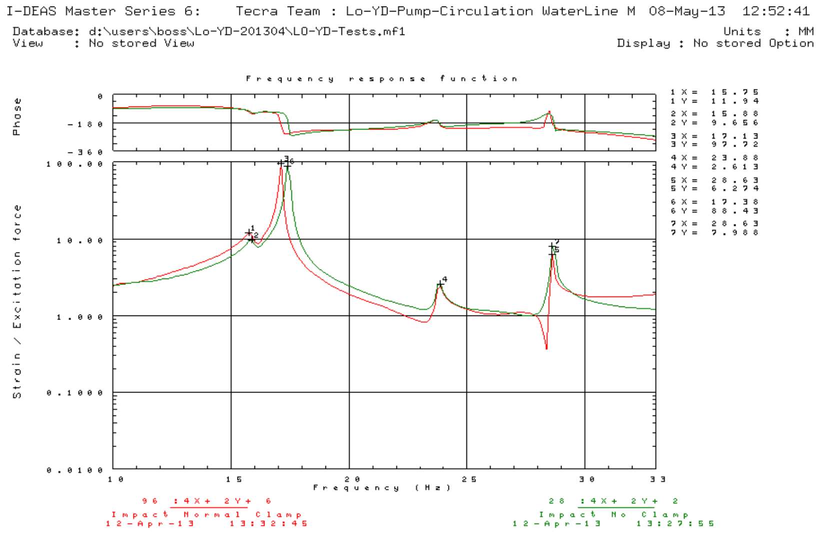


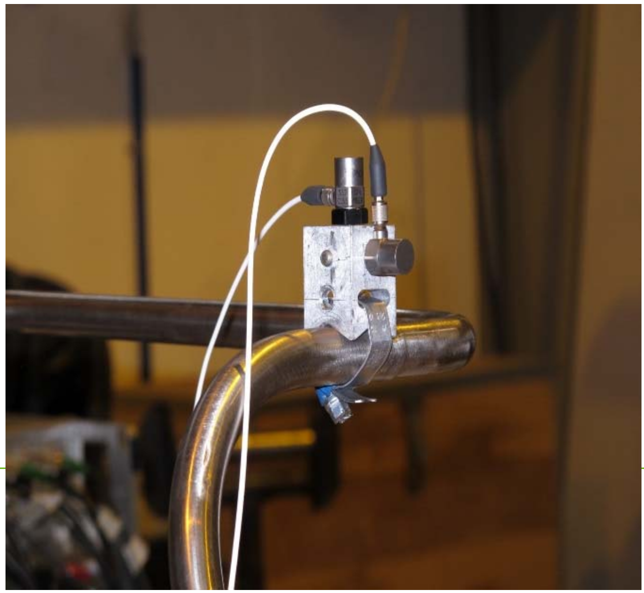
Vibration analysis of a small diameter PCP injection line

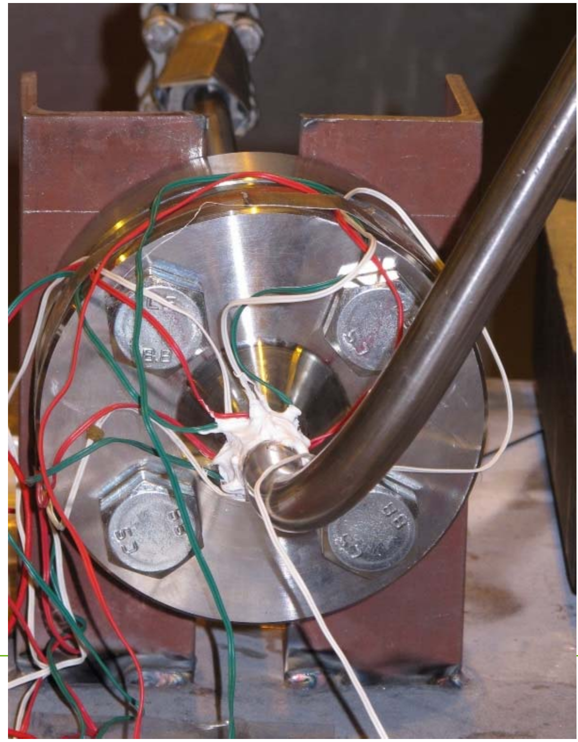


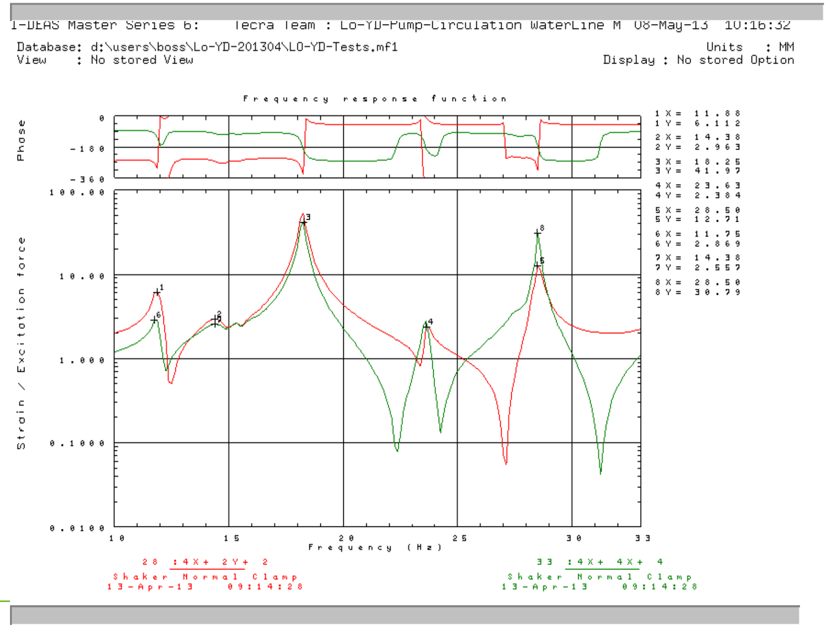
Vibration analysis of a small diameter PCP injection line



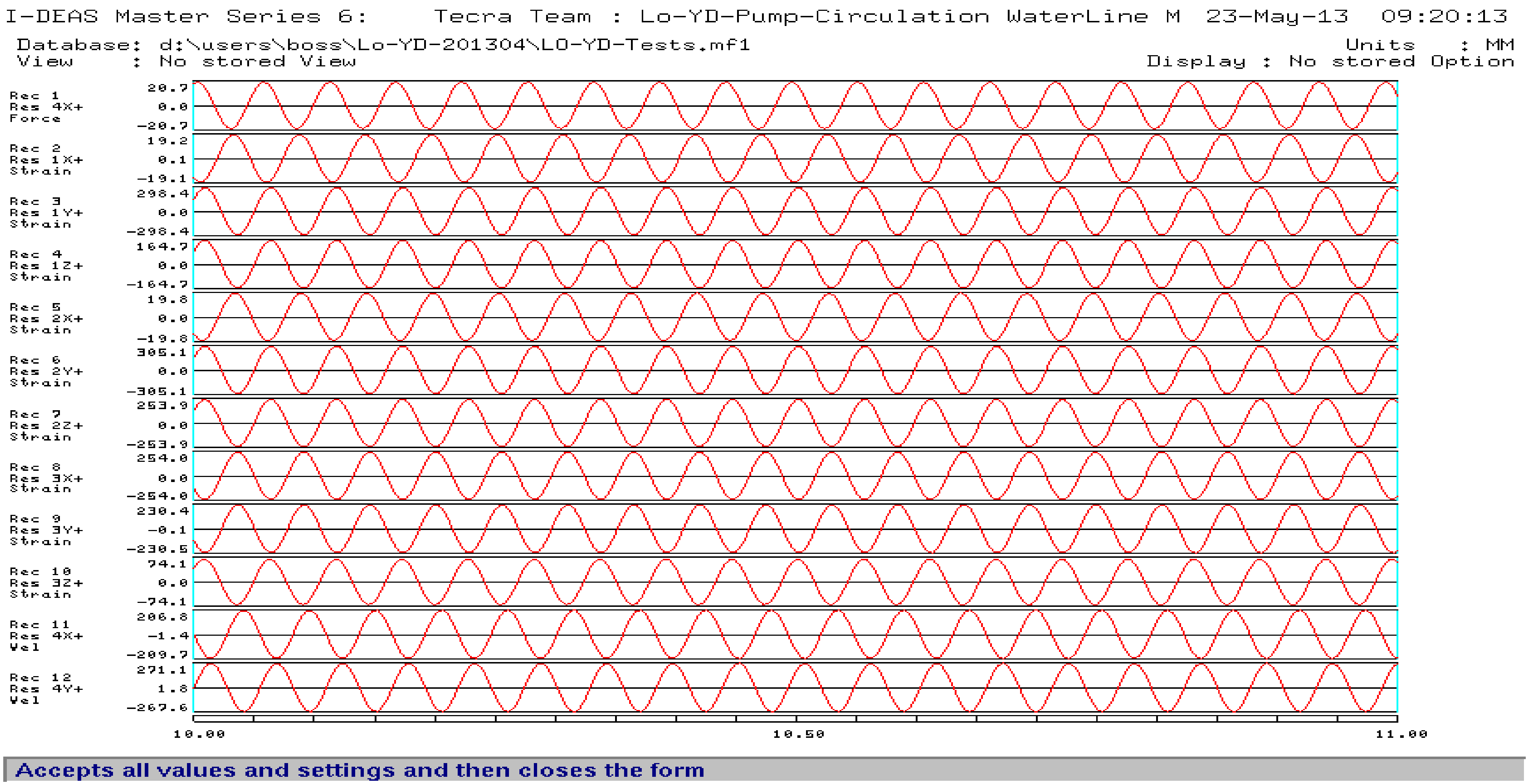






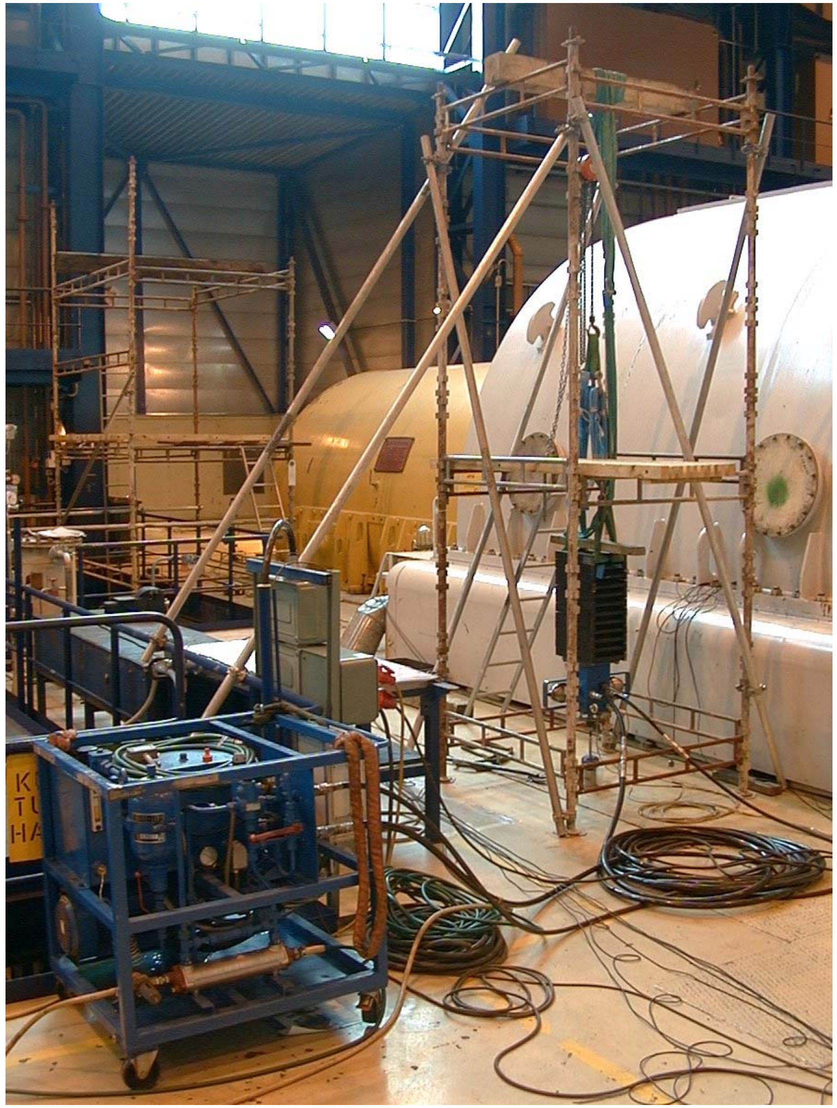


Vibration analysis of a small diameter PCP injection line

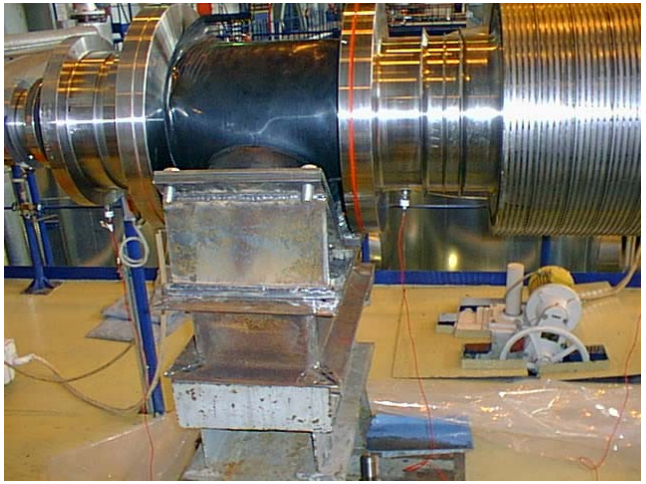


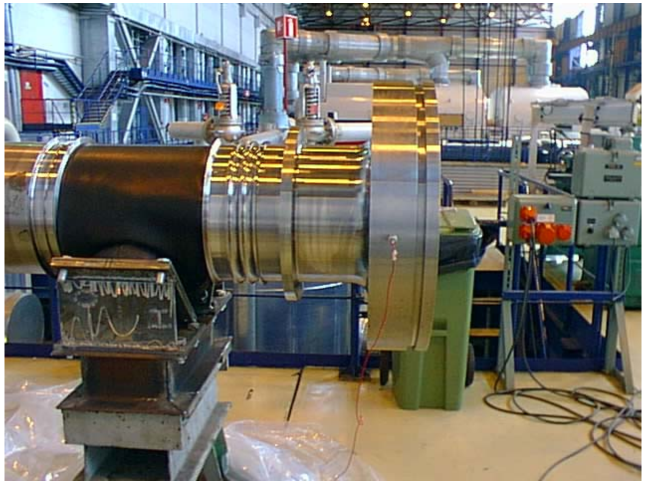
Stages of the Modal Analysis Survey

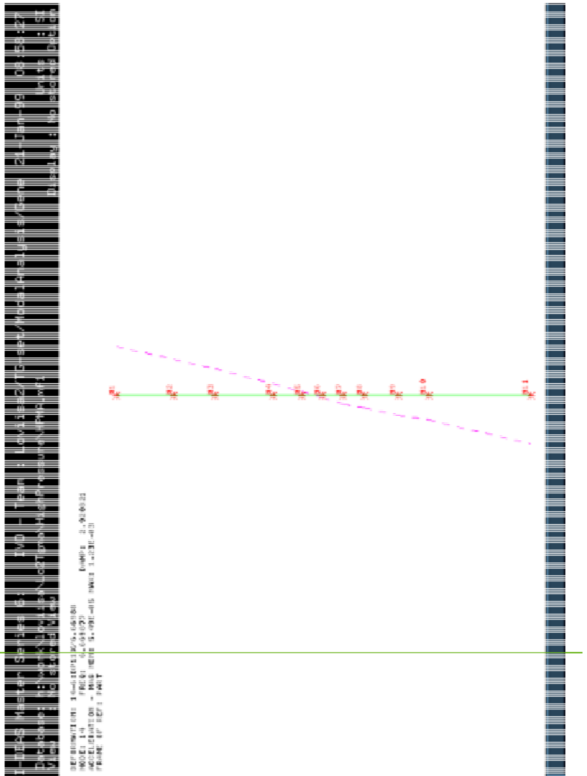
- **Detailed planning of FRF-measurements; Issues:**
  - **boundary conditions**
  - **frequency band**
  - **frequency resolution**
  - **excitation method & excitation force level**
  - **excitation locations and directions and their number**
  - **response locations and their number**
  - **access to the response locations**
  - **Suspension of the shaker unit**
  - **Timing of the testing (with minimal outside/internal excitation signals but with operating boundary conditions faithfully reproduced**

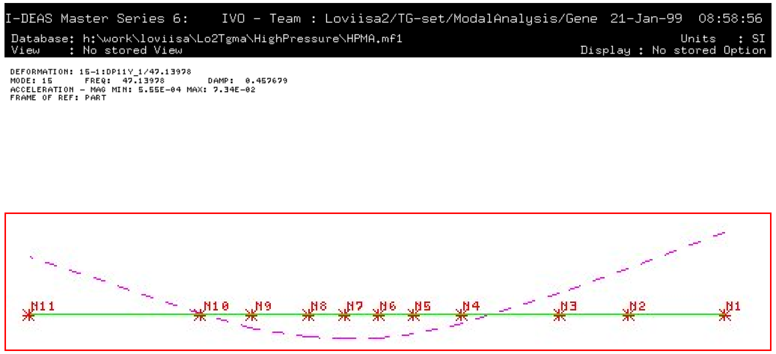


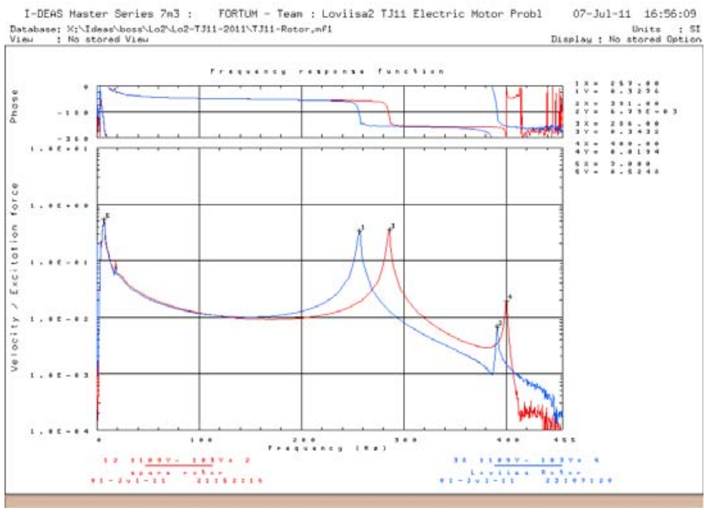
Boundary conditions of structures for FRF-measurements; free-free







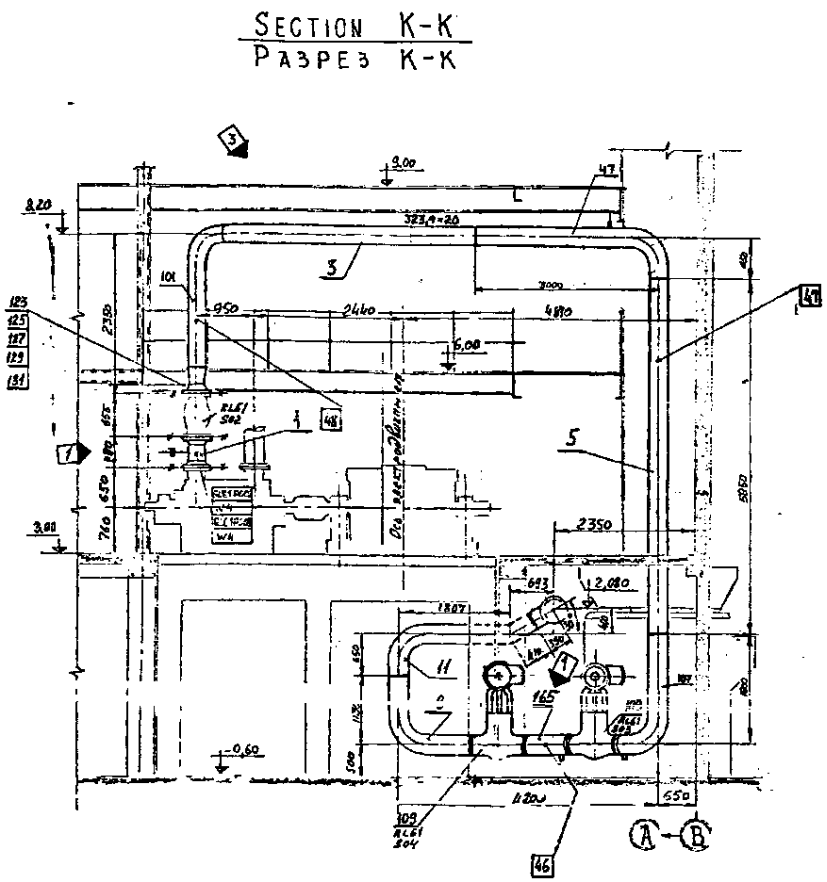


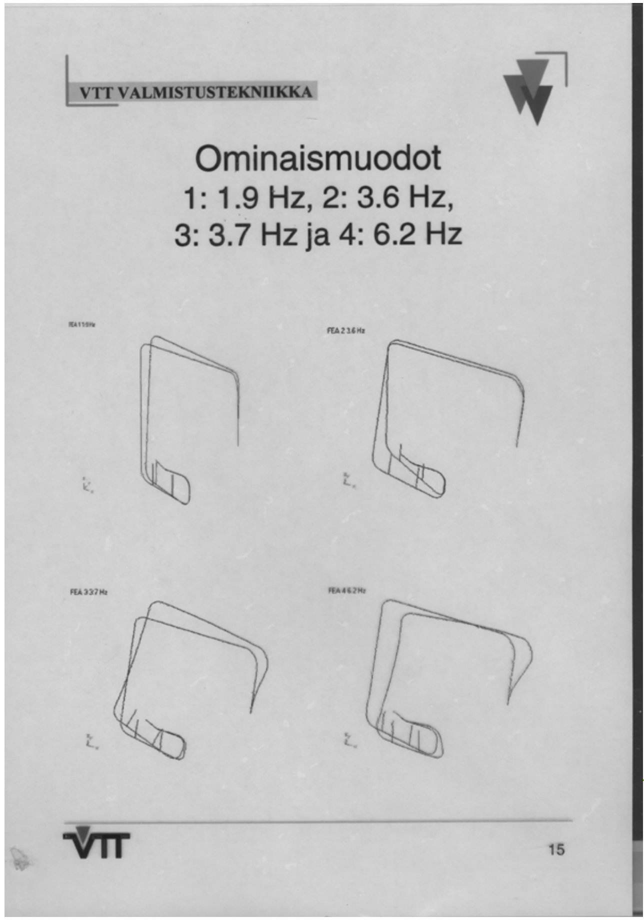


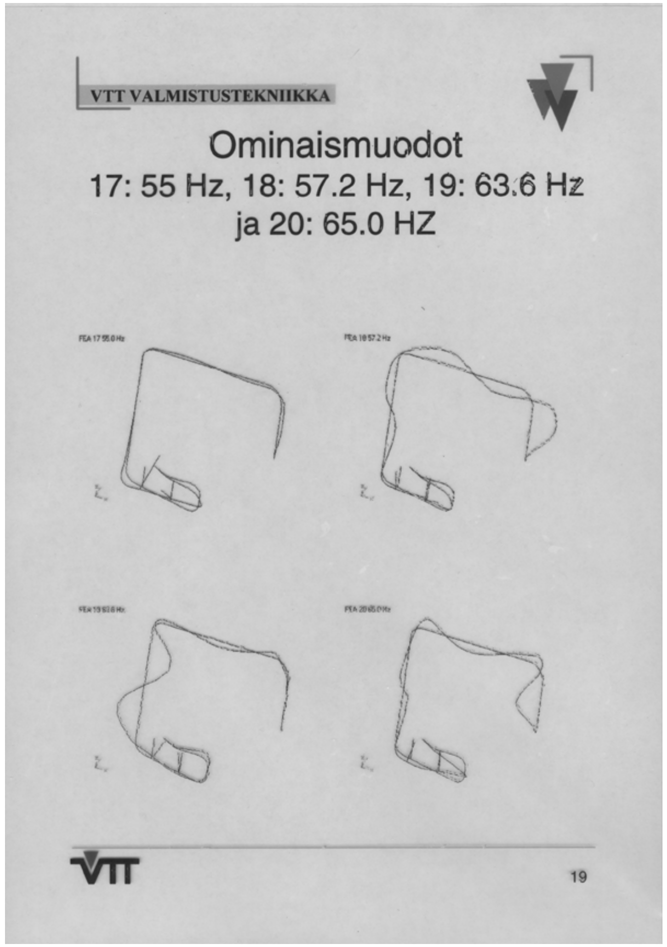
Minimum separation between the 1:st natural frequency vs. rigid body mode frequency; ratio of frequencies > 5:1

Stages of the Modal Analysis Survey

For a seemingly simple structure like the feed water line a comprehensive pre-analysis was however carried to find out answers to the questions as outlined in the previous slide







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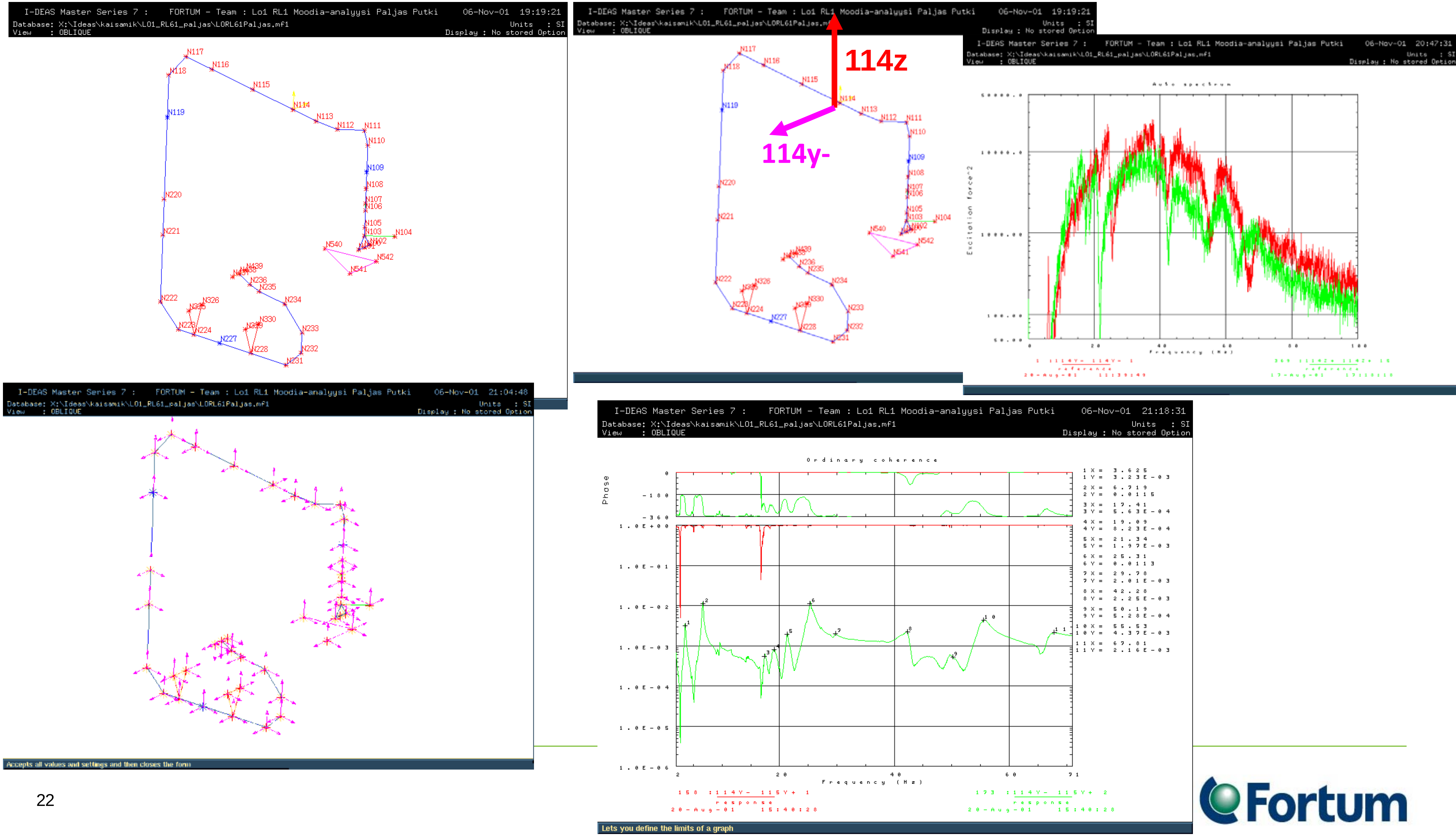
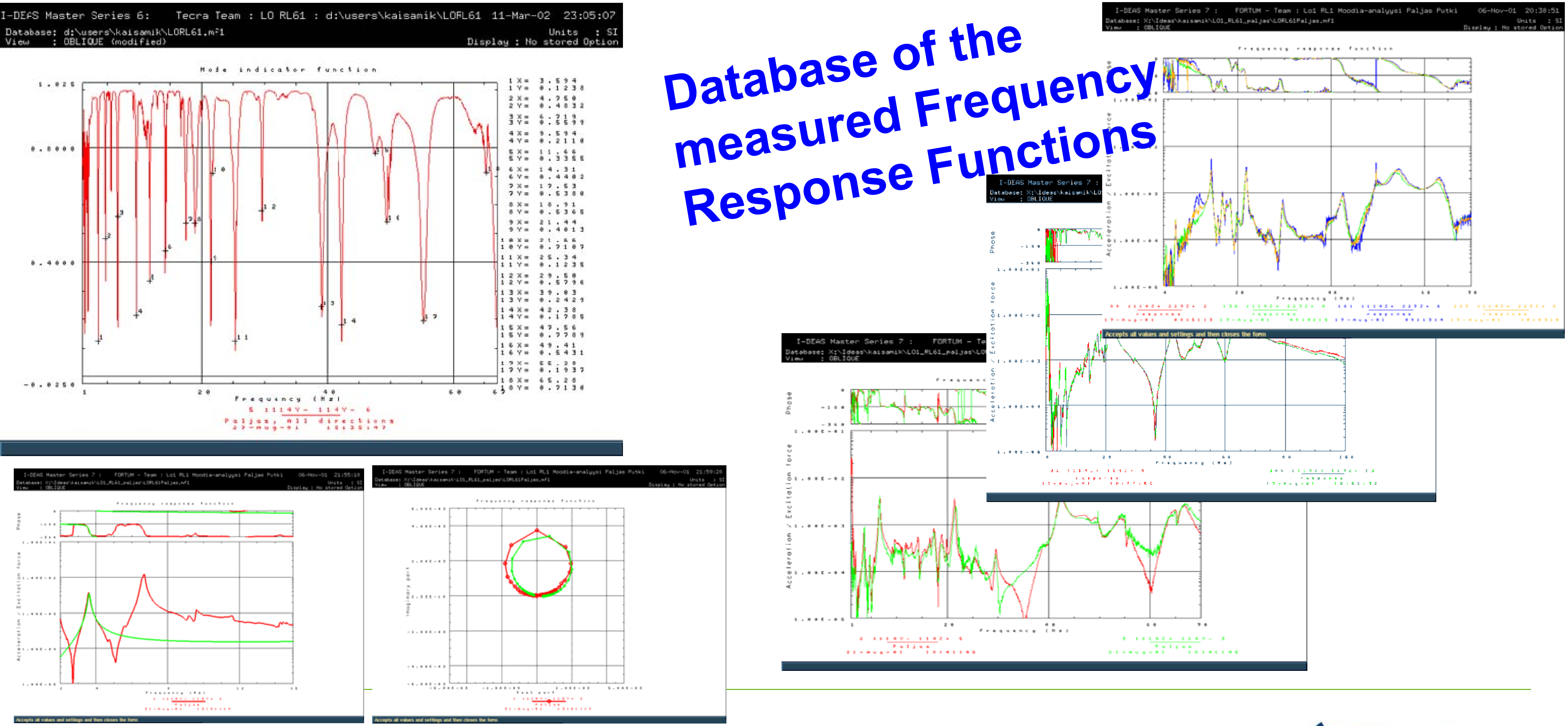
Stages of the Modal Analysis Survey



Stages of the Modal Analysis Survey

- **Measurement of Frequency Response Functions data-base i.e. at each of the locations/ directions where structural mode shape is desired**



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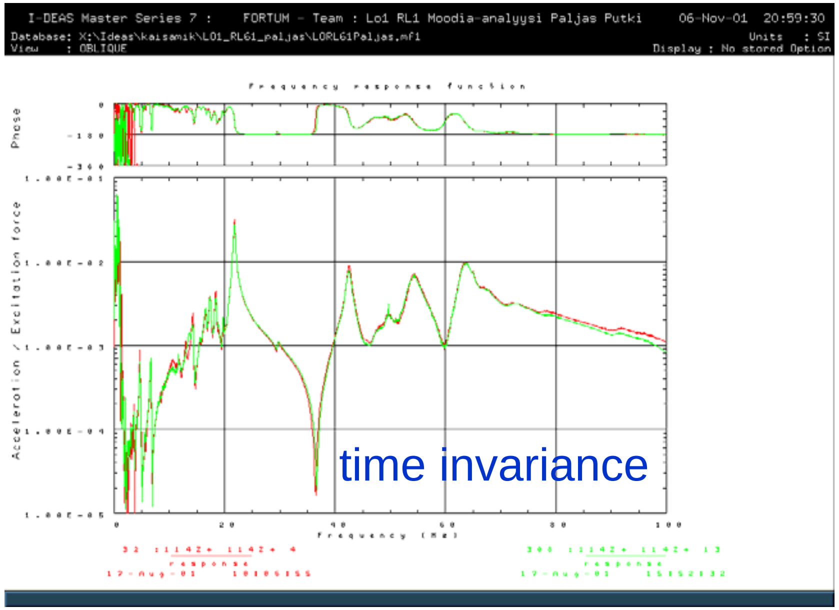
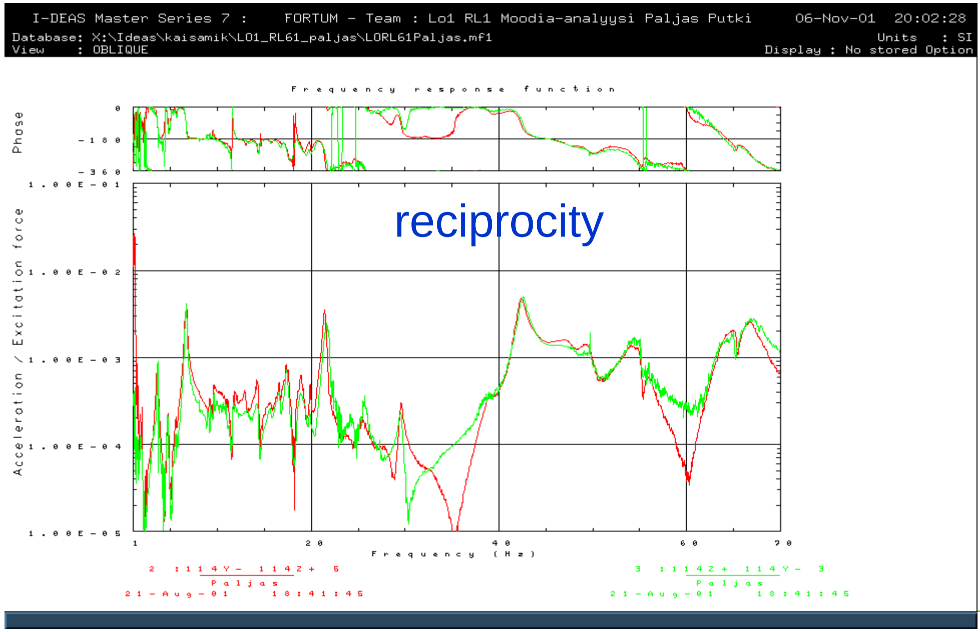
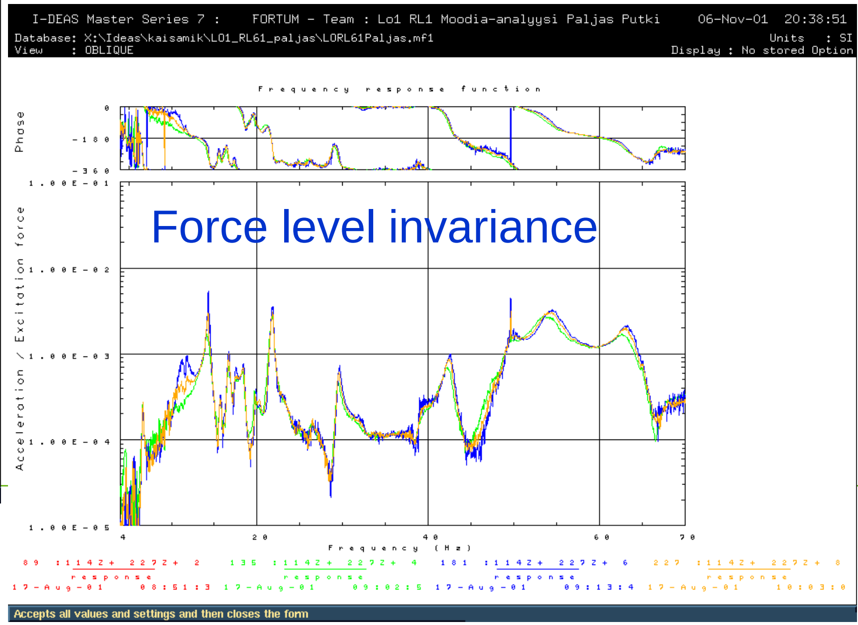
Stages of the Modal Analysis Survey

- **Verification of linearity assumptions for FRF's:**
  - **Time invariance**
  - **Force level invariance**
  - **Reciprocity (Betty-Maxwell-)**

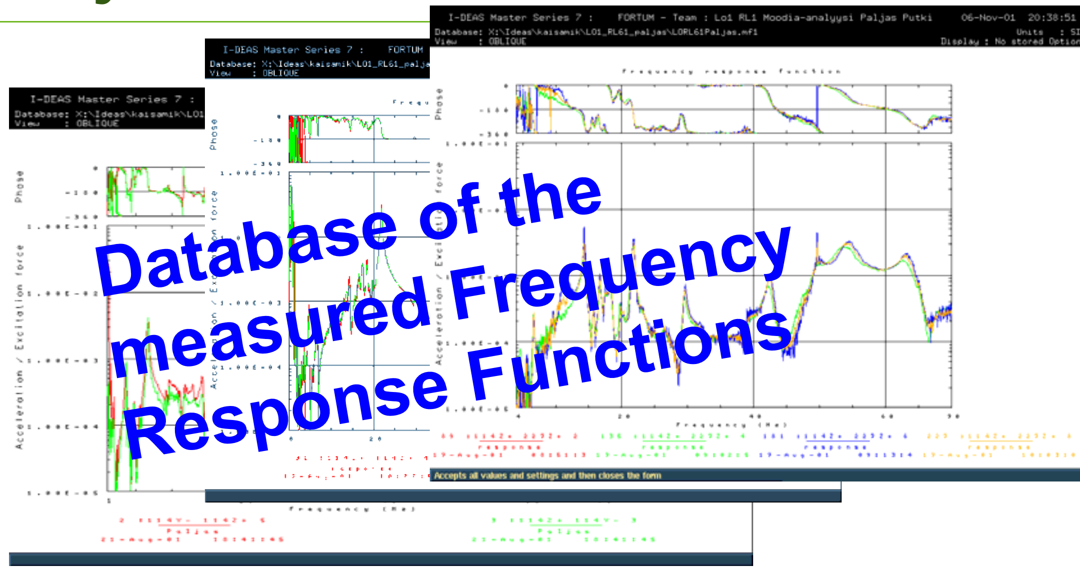




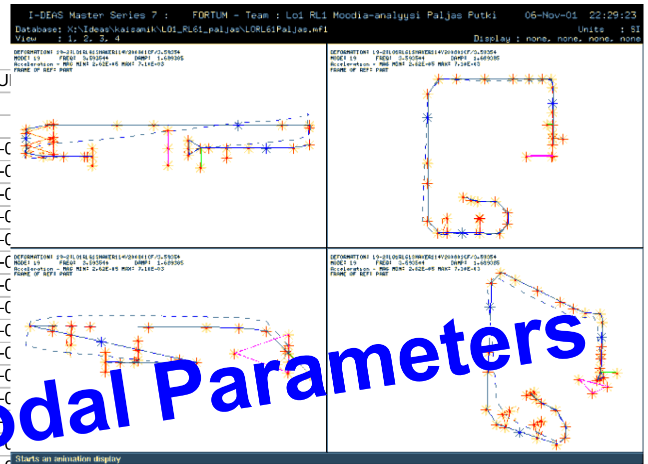


Stages of the Modal Analysis Survey

- The modal parameters are extracted in the analysis phase of a EMA project :
  - Natural frequencies of a structure
  - Damping values associated with each of the natural frequencies
  - Mode shape associated with each the natural frequencies



PARM LABEL	SHAPE REC	FREQUENCY (HERTZ)	DAMPING (%)	AMPLITU			
1	1	1.846	2.605	5.4595E-0			
2	2	3.613	1.650	1.2220E-0			
3	3	4.680	1.000	1.3199E-0			
4	4	5.584	1.327	2.8422E-0			
5	5	6.576	0.975	5.0433E-0			
6	6	6.675	0.688	6.2681E-0			
7	7	11.679	0.669	3.8131E-0			
8	8	11.851	0.327	5.6375E-0			
9	9	14.269	1.426	8.5633E-0			
10	10	15.681	0.986	1.5415E-0			
11	11	16.625	0.942	2.3536E-0			
12	12	17.400	1.035	6.7385E-0			
13	13	19.777	0.488	[illegible]			
14	14	21.459	1.139	[illegible]			
15	15	21.803	0.707	4.5588E-03	0.395	0.000	114Z+,233Y+
16	16	29.542	0.699	1.1327E-03	1.961	0.000	114Z+,118X+
17	17	42.520	0.951	6.4033E-03	1.749	0.000	114Z+,118X+



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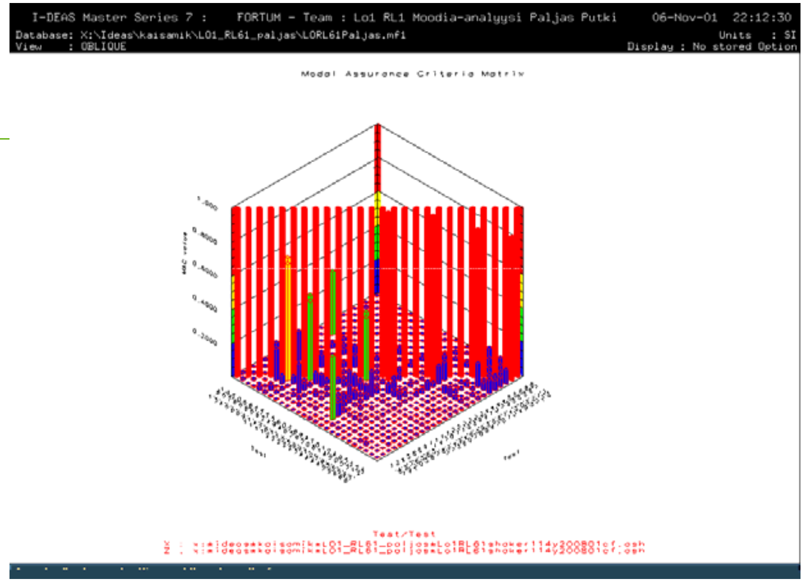
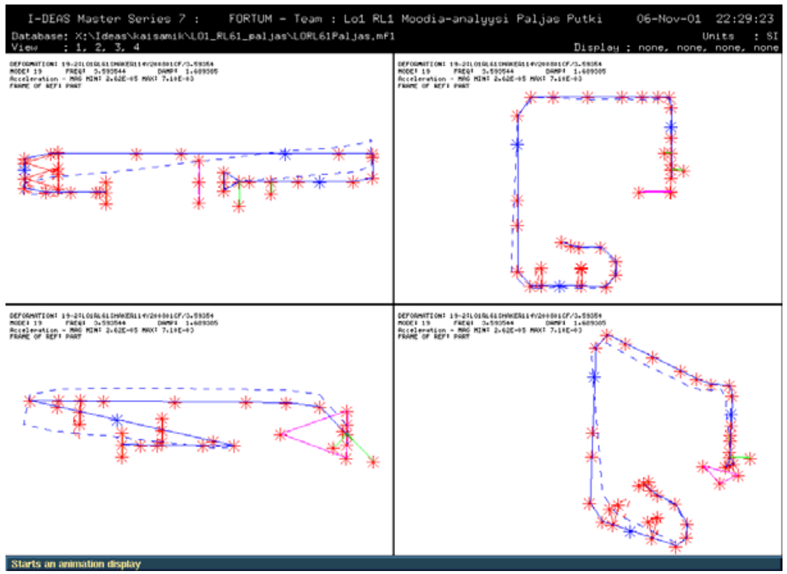
Stages of the Modal Analysis Survey

- **Verification of the Modal analysis data base (Natural frequencies; the associated damping values & associated Mode Shapes)**
  - **Are all the extracted damping values reasonable**
  - **Are all the extracted mode shapes reasonable (animation)**
  - **Are all the extracted mode shapes unique (i.e. orthogonal); MAC-matrix**

PARM LABEL	SHAPE REC	FREQUEN (HERTZ)	DAMPING (%)	AMPLITUD	PHASE (RAD)	MCF	REF,RES
1	1	1.812	2.902	7.7649E-0	1.413	0.000	114Y-,115Y+
2	2	3.594	1.689	1.3634E-0	1.589	0.000	114Y-,115Y+
3	3	4.718	1.055	4.7560E-0	-1.394	0.000	114Y-,115X+
4	4	5.599	1.614	1.2128E-0	-1.499	0.000	114Y-,115X+
5	5	6.551	0.810	5.1011E-0	-1.313	0.000	114Y-,115Z+
6	6	6.680	1.135	1.2936E-0	-1.868	0.000	114Y-,115Z+
7	7	9.572	0.691	8.6647E-0	-1.530	0.000	114Y-,118Y+
8	8	11.670	0.696	2.9975E-0	-1.708	0.000	114Y-,118Y+
9	9	14.272	0.450	8.2677E-0	-1.539	0.000	114Y-,233X+
10	10	17.451	1.387	8.3877E-0	-1.488	0.000	114Y-,118Z+
11	11	18.961	2.661	2.7195E-0	1.352	0.000	114Y-,115Y+
12	12	21.400	0.718	1.7287E-0	1.365	0.000	114Y-,115Y+
13	13	21.672	0.895	5.4451E-0	1.805	0.000	114Y-,115Y+
14	14	25.384	0.970	1.5863E-0	1.488	0.000	114Y-,115Y+
15	15	25.986	1.029	3.1699E-0	0.799	0.000	114Y-,115Y+
16	16	29.544	0.674	9.3260E-0	1.644	0.000	114Y-,115X+
17	17	39.070	1.324	1.4439E-0	-1.782	0.000	114Y-,115Z+
18	18	41.600	2.143	1.8814E-0	-1.942	0.000	114Y-,115Z+
19	19	42.109	0.443	5.1937E-0	2.316	0.000	114Y-,115Z+
20	20	47.418	1.570	9.2088E-0	1.753	0.000	114Y-,115X+
21	21	49.539	1.287	2.1746E-0	1.257	0.000	114Y-,115X+
22	22	55.087	0.512	9.7876E-0	-0.448	0.000	114Y-,115Z+
23	23	55.526	1.520	6.6059E-0	1.573	0.000	114Y-,115Z+
24	24	65.322	0.186	1.6618E-0	0.072	0.000	114Y-,118X+
25	25	66.118	0.076	1.3889E-0	2.016	0.000	114Y-,118X+
26	26	67.255	1.488	6.8410E-0	1.392	0.000	114Y-,118X+





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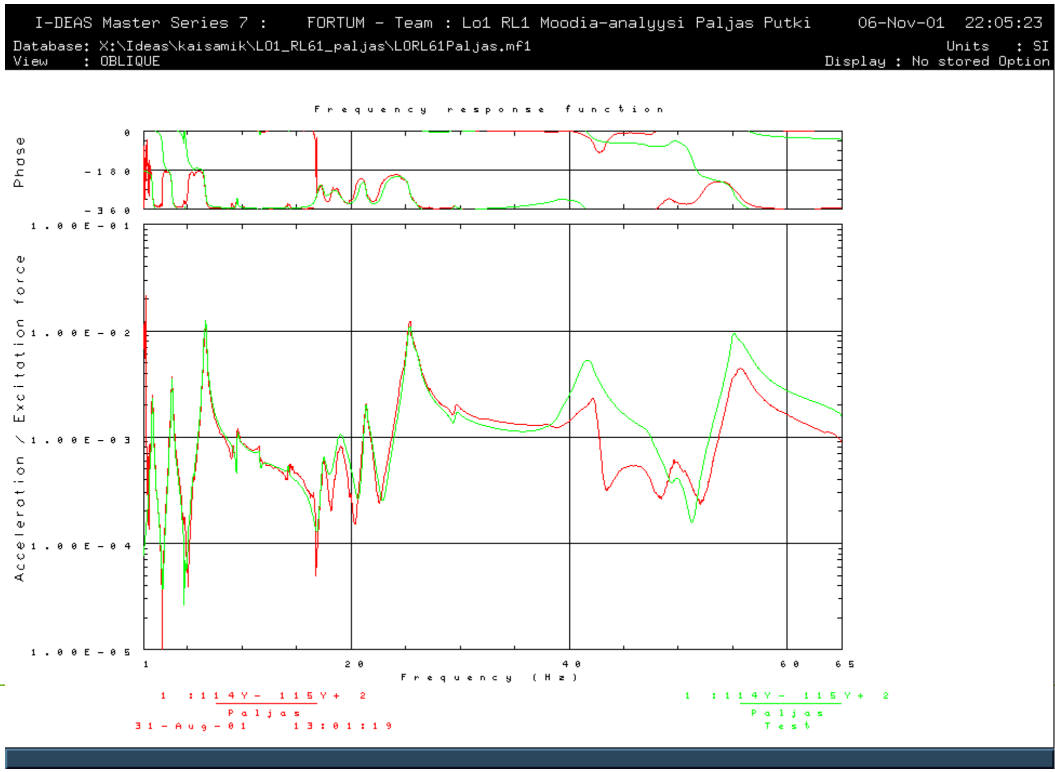
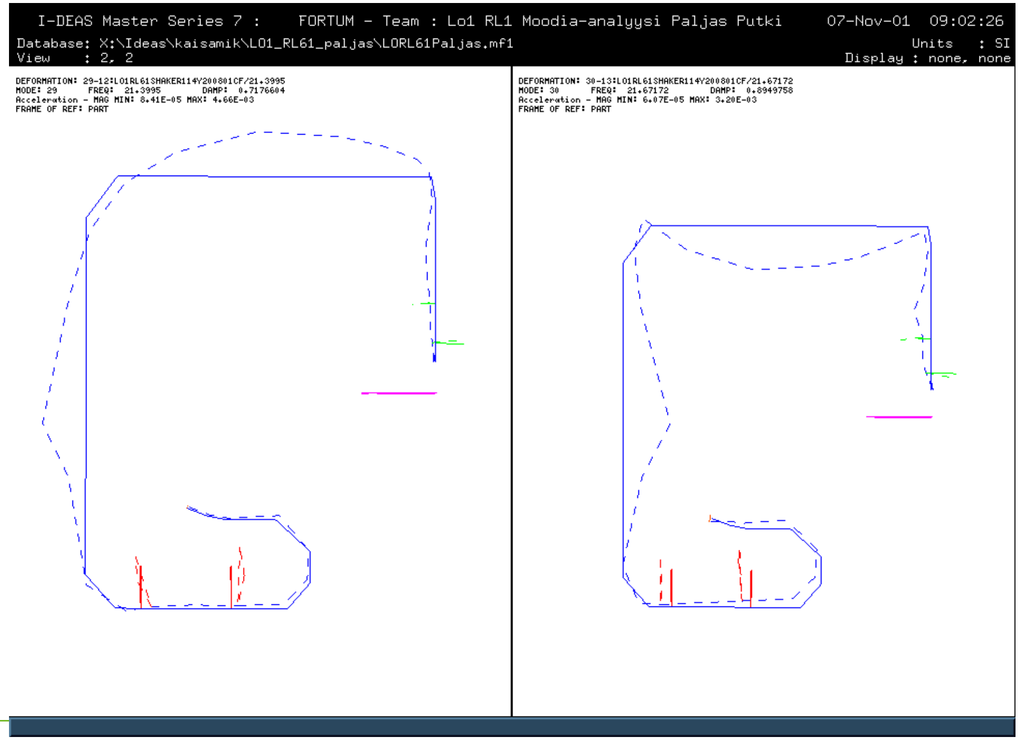
Stages of the Modal Analysis Survey

- **Verification of the Modal analysis data base (Natural frequencies; the associated damping values & associated Mode Shapes)**
  - **Are all the modes of the frequency band of interest detected & analyzed (also the closely spaced ones)?**
  - **synthesis vs. measured FRF’s**





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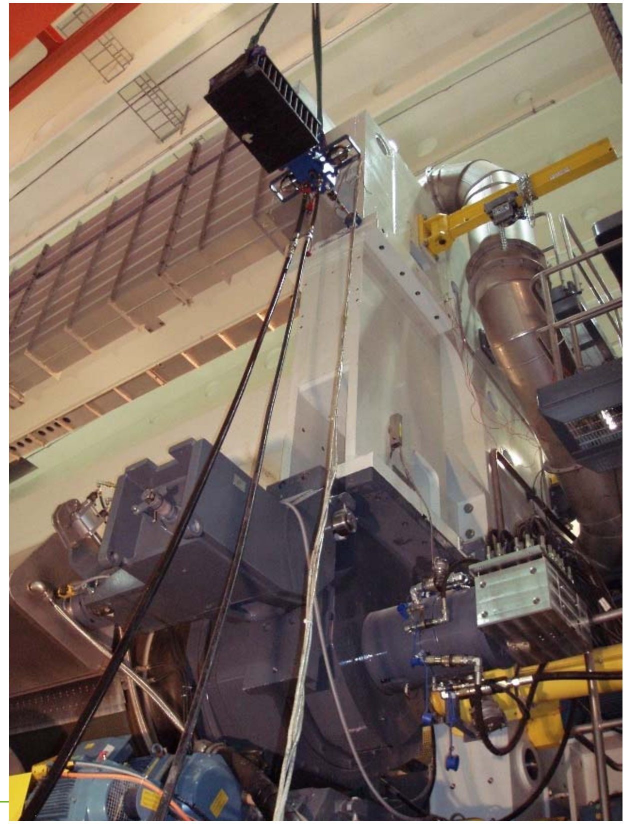
Hydraulic shaker unit as employed at a feed water line of the secondary circuit

Hydraulic shaker unit employed for generating excitation force for modal testing

- Turbine pedestal
- Turbine bearing pedestal
- Flue gas fan
- Various heavy paper machinery components



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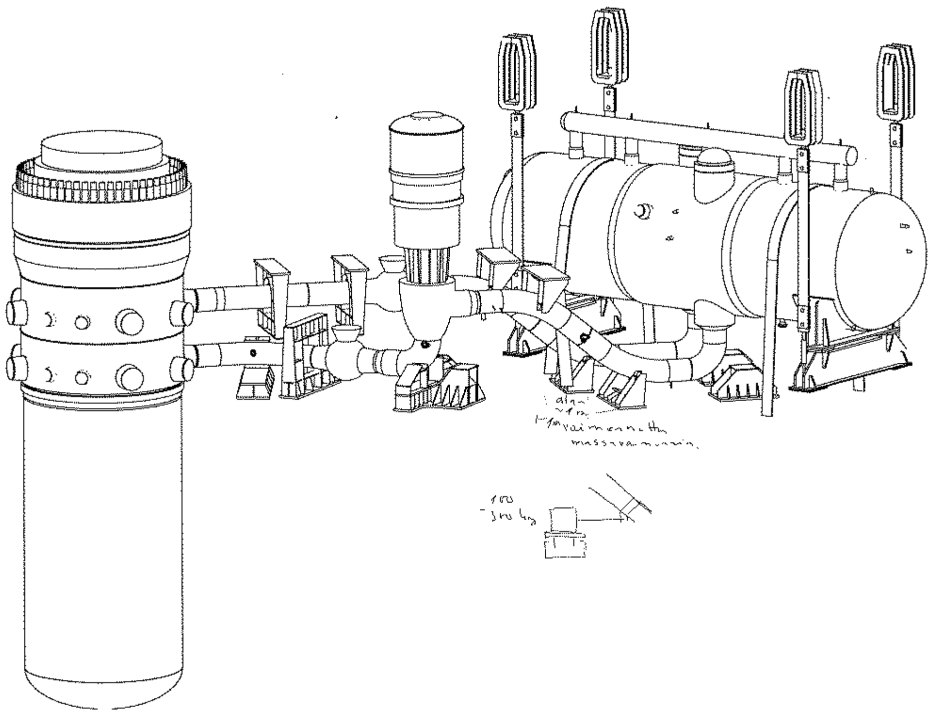
Primary Circulation Pump (i.e. PCP) issue: vibration at 60+ Hz

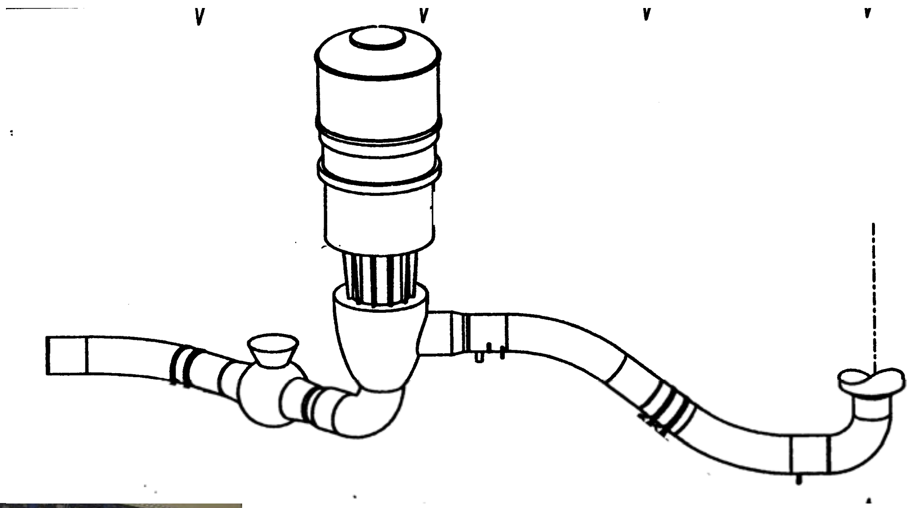


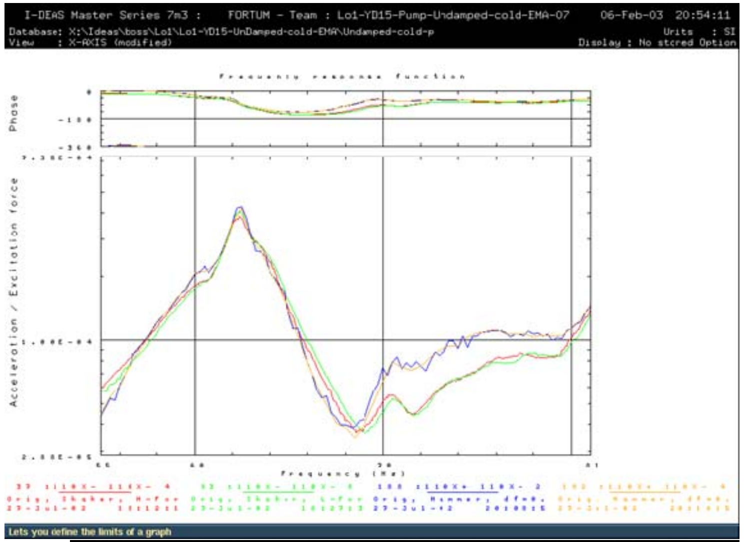
- The PCP is of unique design with mixed axial-radial-flow pattern
- Long standing vibration issue at 60+ Hz
- No satisfactory root cause for the vibration problem has been found out over the years
- The PCP-problem has been compounded by natural frequency of the loops and other components occurring at adjacent frequencies
- A typical PCP-vibration issue manifests itself in the starting sequence of the various PCP-units

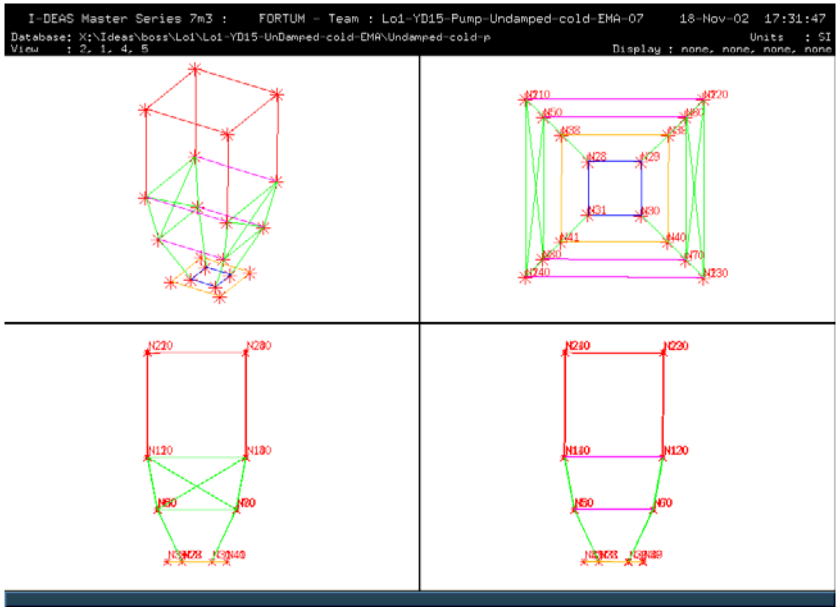
Two different remedies were envisioned and tested:

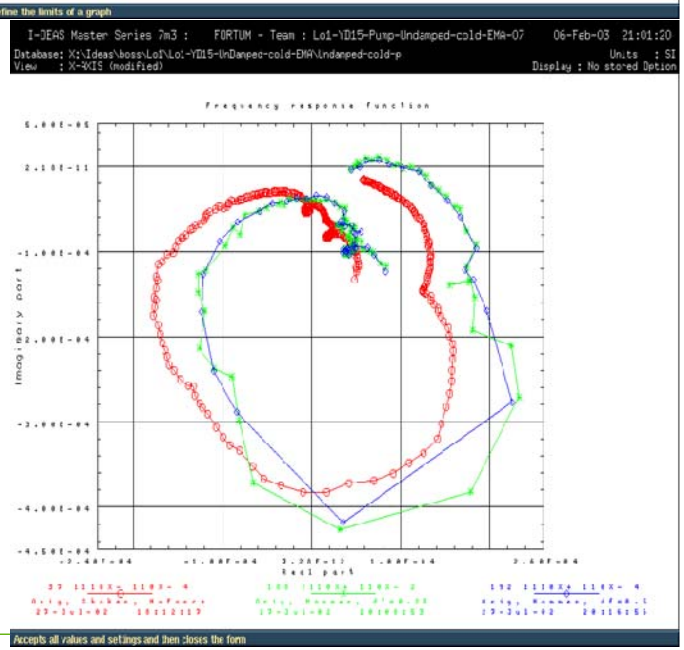
- **Reduction of vibration response by Tuned Mass Absorber i.e. TMA**
- **Reduction of vibration response by viscous absorber units**

Testing of a loop filled with water, pump not running and in cold state:





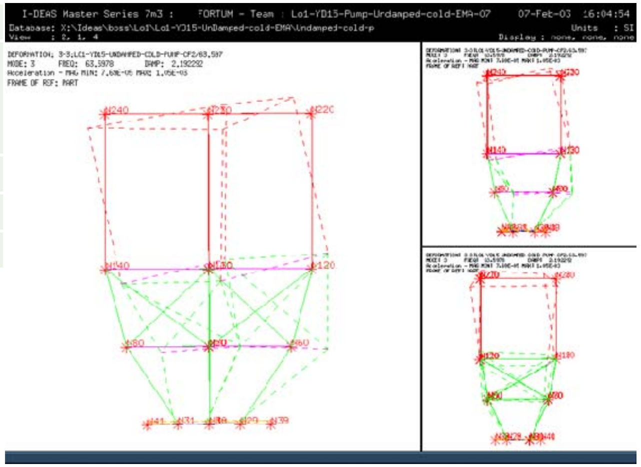


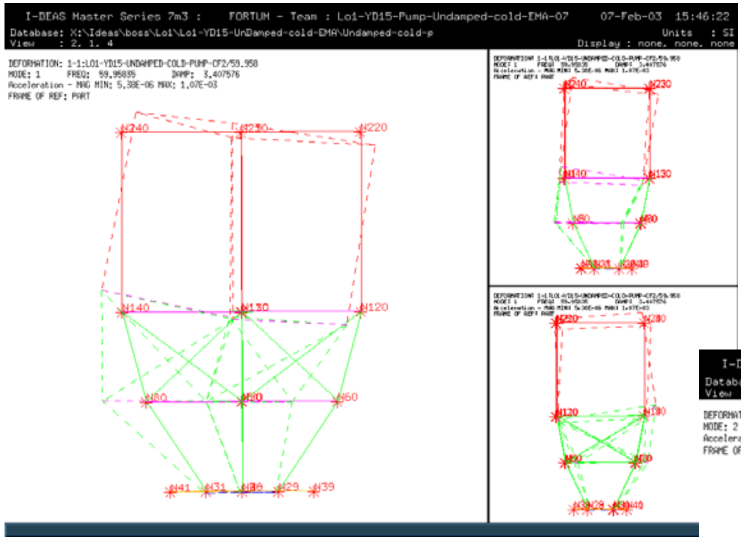


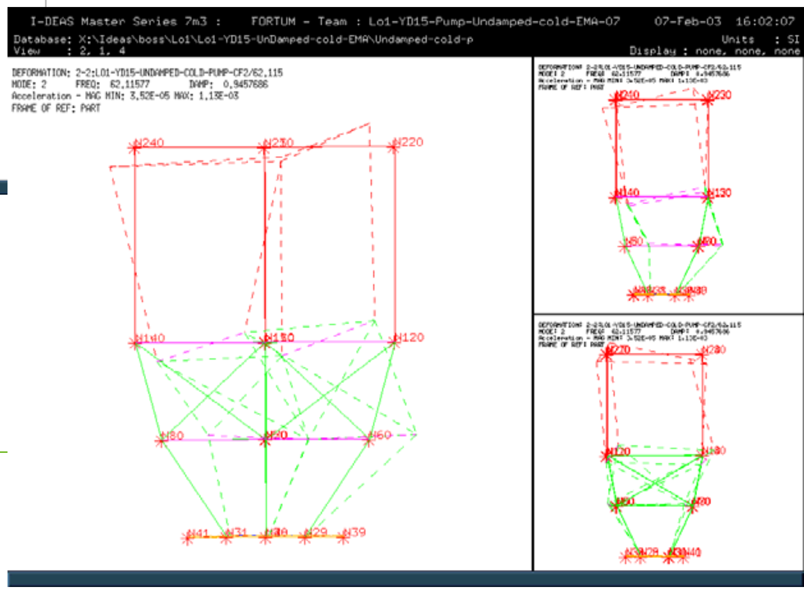
Fortum

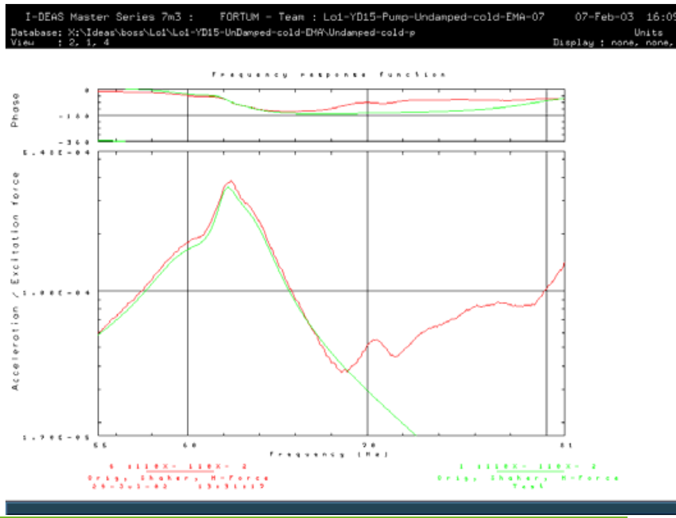
Modal Parameters for the Cold Leg

	Circle-Fit			Complex Exponential			Direct parameter		
Natural frequency #	Freq-value [Hz]	Relative Damping value[%]	Phase Angle [Rad]	Freq-value [Hz]	Relative Damping value[%]	Phase Angle [Rad]	Freq-value [Hz]	Relative Damping value[%]	Phase Angle [Rad]
1	59.49	4.975	0.149	59.95	3.408	-0.715	60.34	3.172	-1.406
2	62.31	1.073	-1.384	62.11	0.946	-0.952	62.14	1.486	-0.764
3	64.07	3.296	2.982	63.59	2.192	-2.608	63.58	3.753	2.768



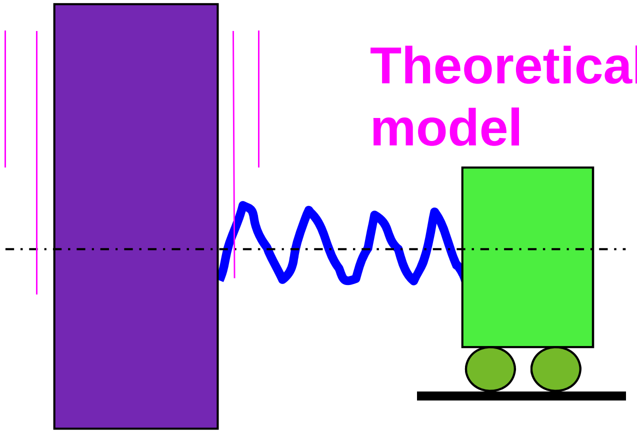




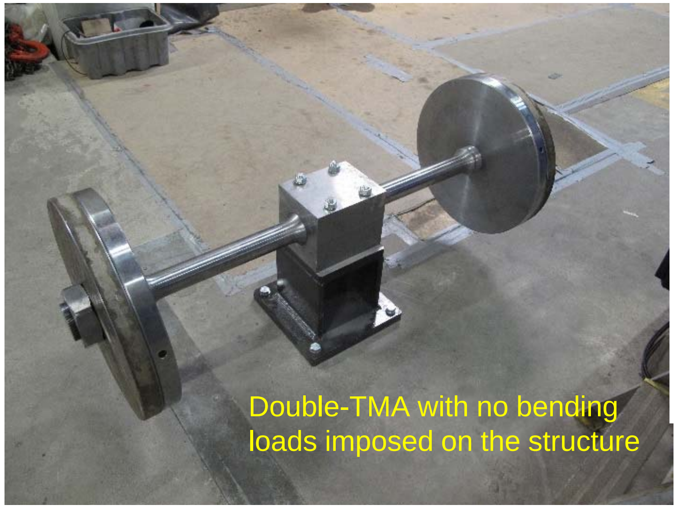


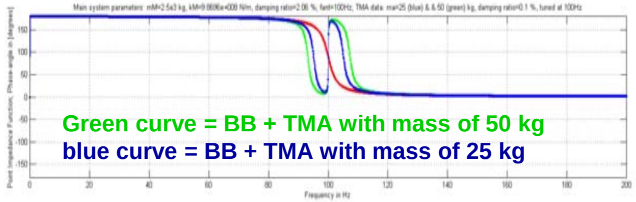
Fortum

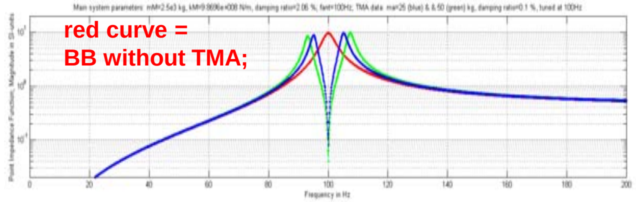
Tuned Mass Absorber (i.e. TMA) as tested on a PCP at Loviisa NPP

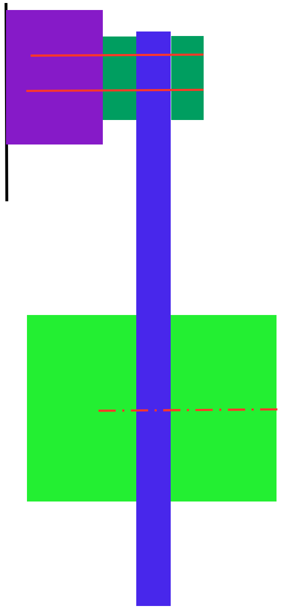


Theoretical model

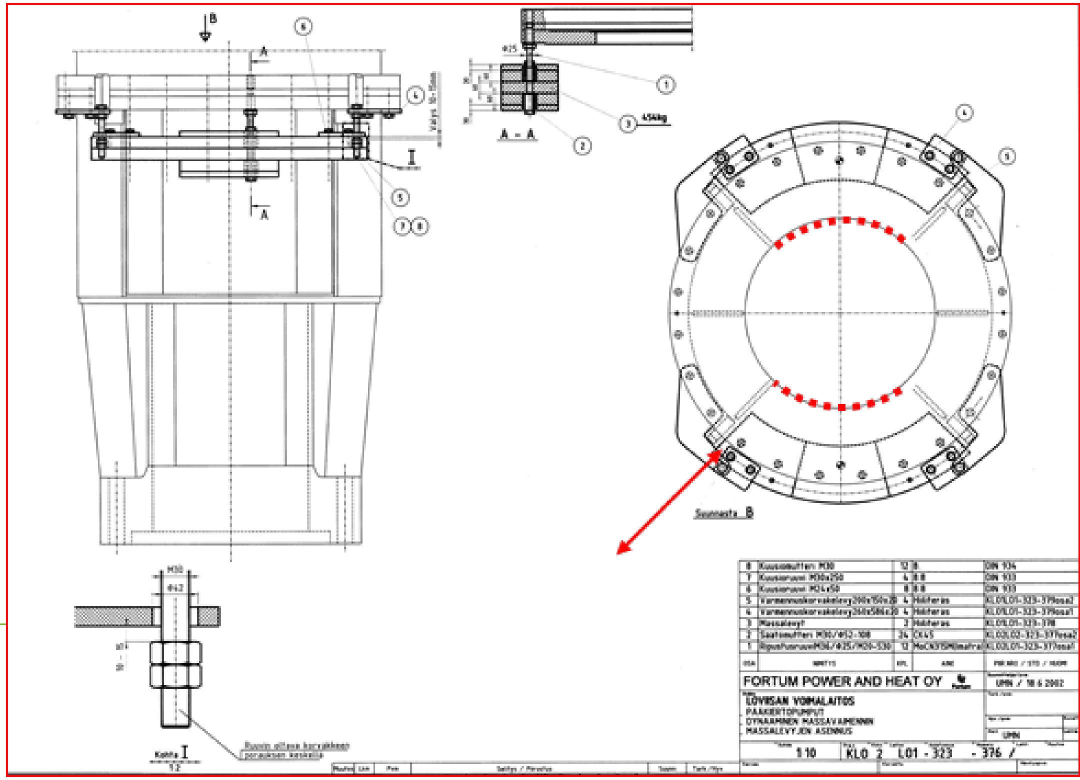


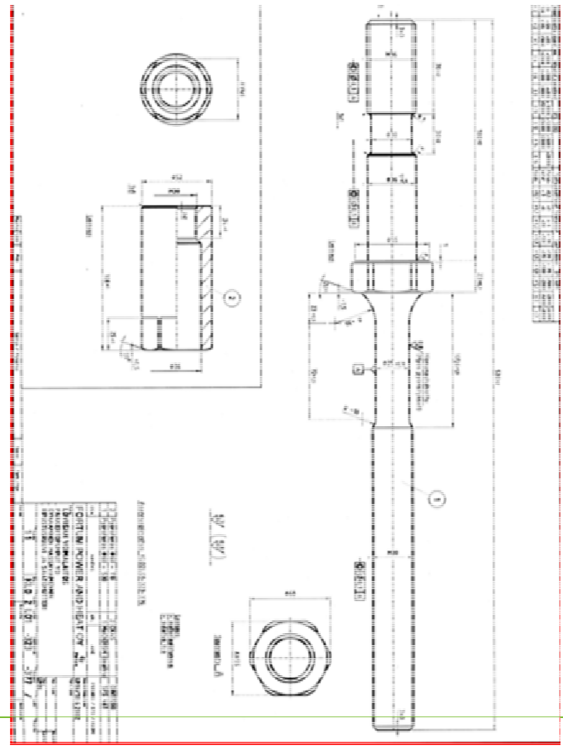




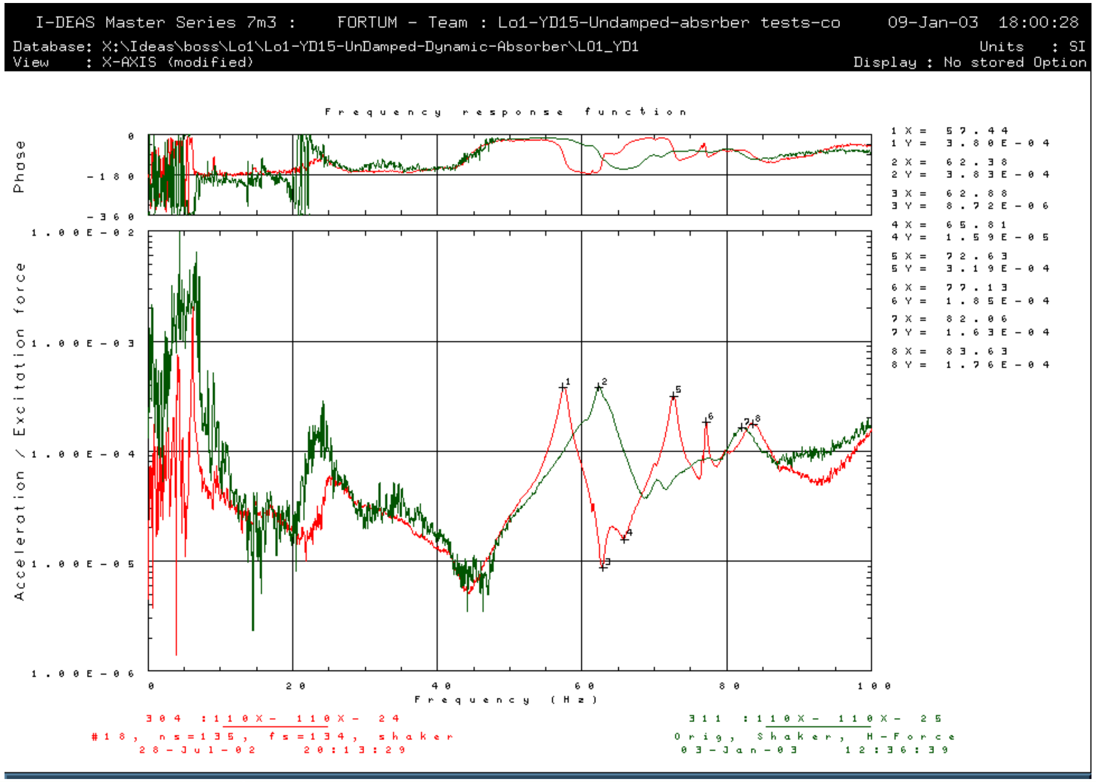


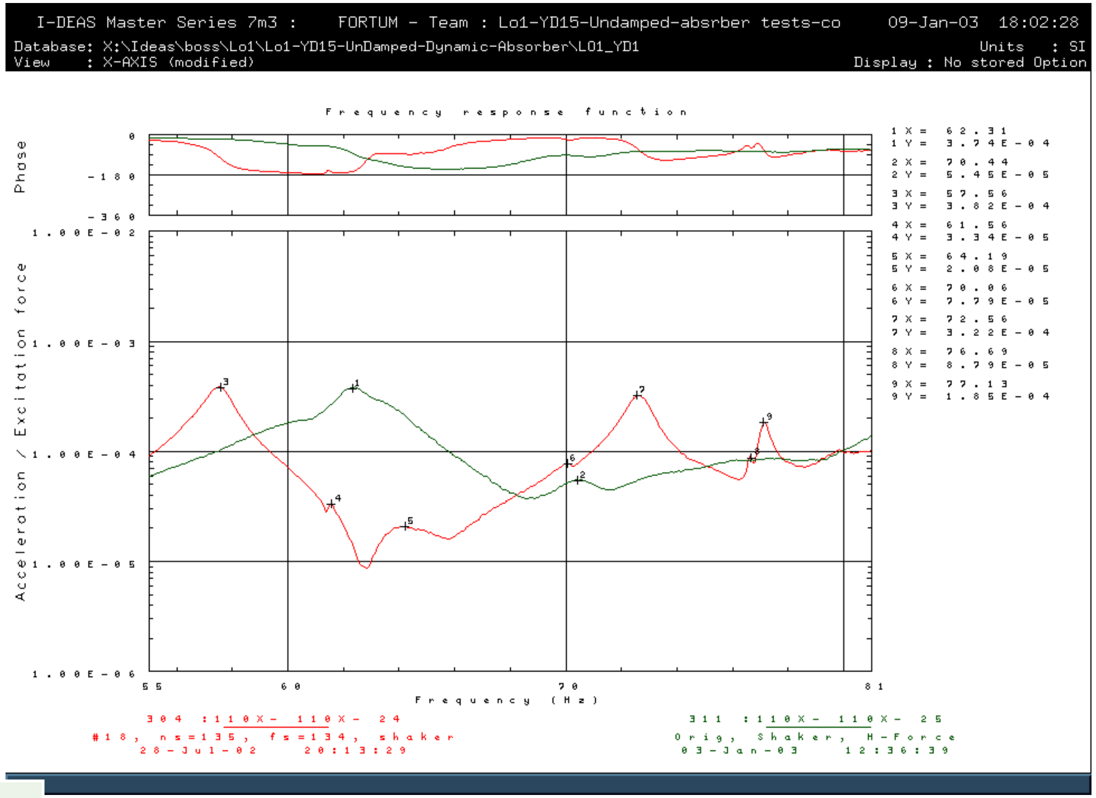
Practical implementation



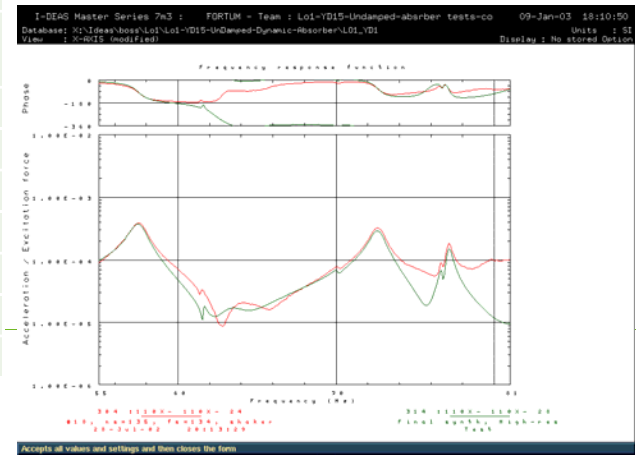


Tuned Mass Absorber as tested on a PCP at Loviisa NPP



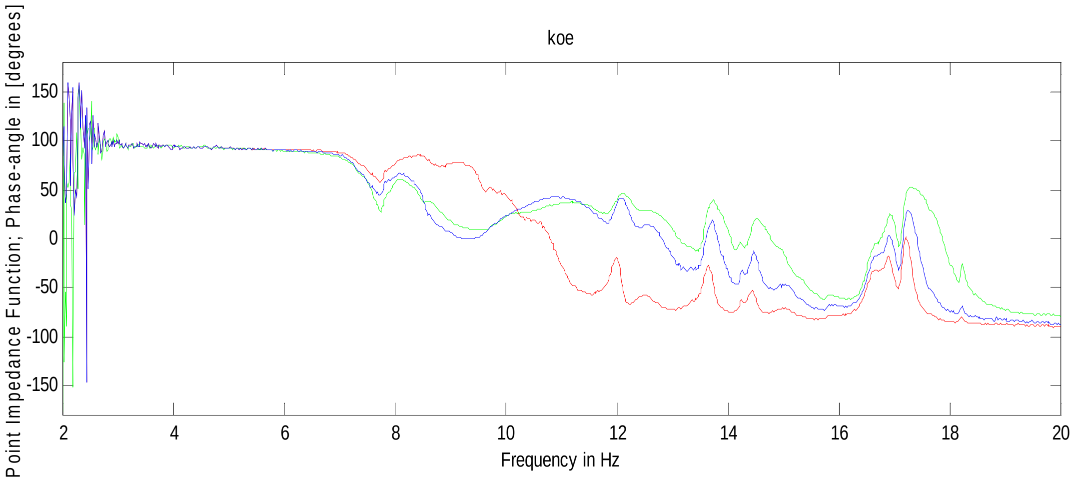


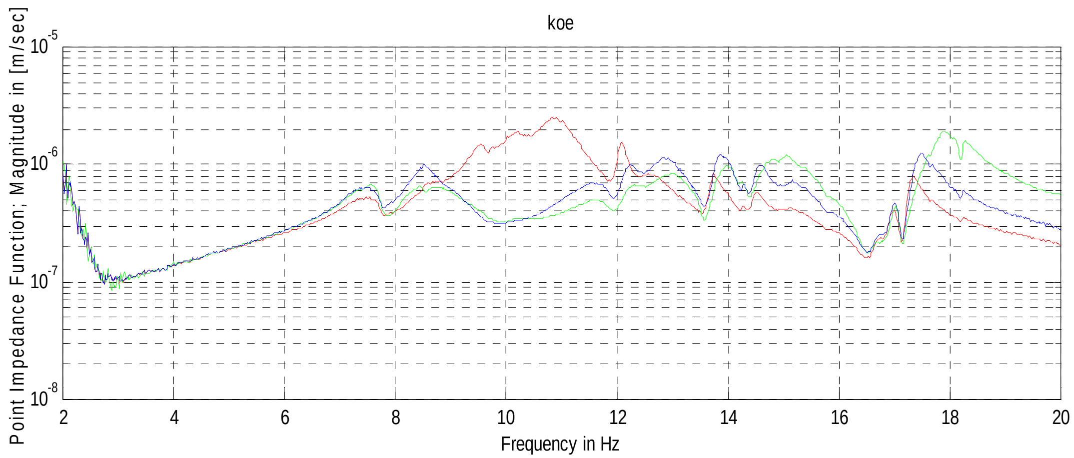
110x; 110x	Complex Exponential		
Natural frequency #	Freq-value [Hz]	Relative Damping value [%]	Phase Angle [Rad]
1	57.506	0.93	-1.762
2	61.604	0.117	-1.972
3	63.288	1.812	-0.269
4	70.079	0.263	-1.547
5	72.643	0.667	-1.273
6	76.696	0.16	-2.192
7	77.121	0.267	-1.153

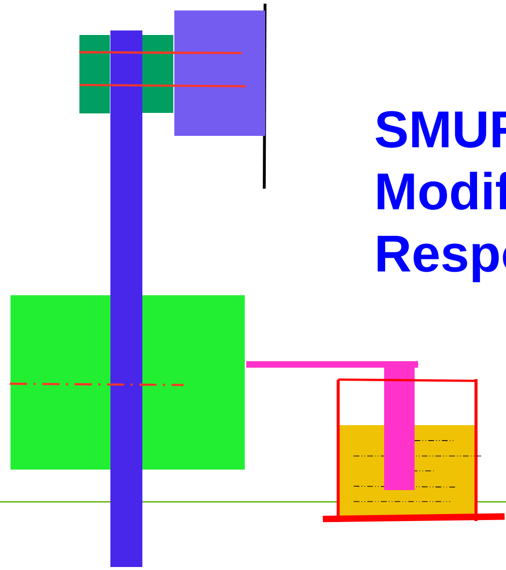


Fortum

Patented design of a Damped Tuned Mass Absorber







SMURF = Structural Modification Using Response Functions

SMURF-prediction & Measured results

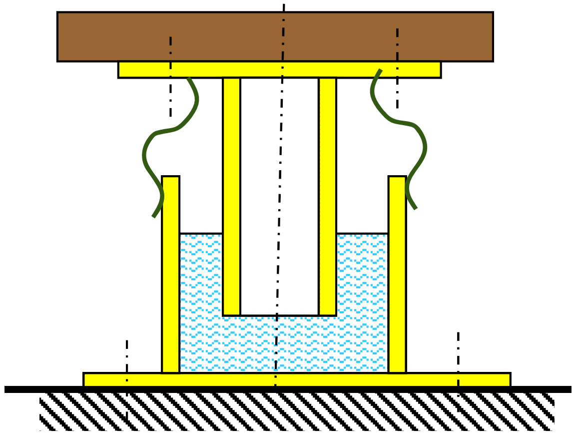
Red curve= measured; original structure

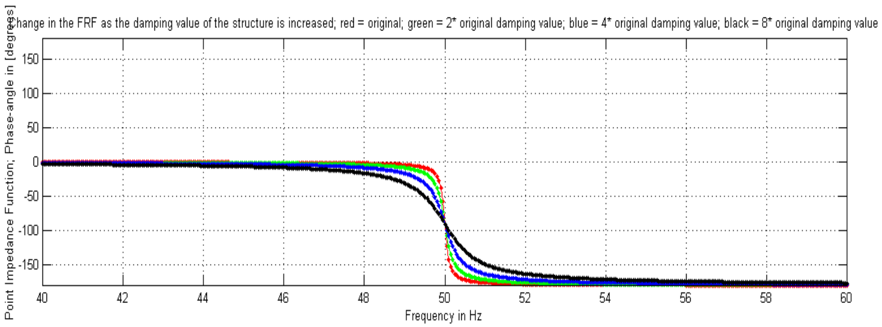
Green curve = measured with absorber

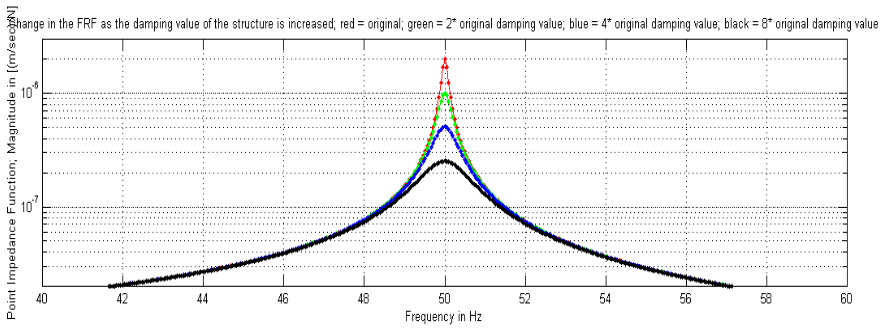
Blue curve = SMURF-prediction

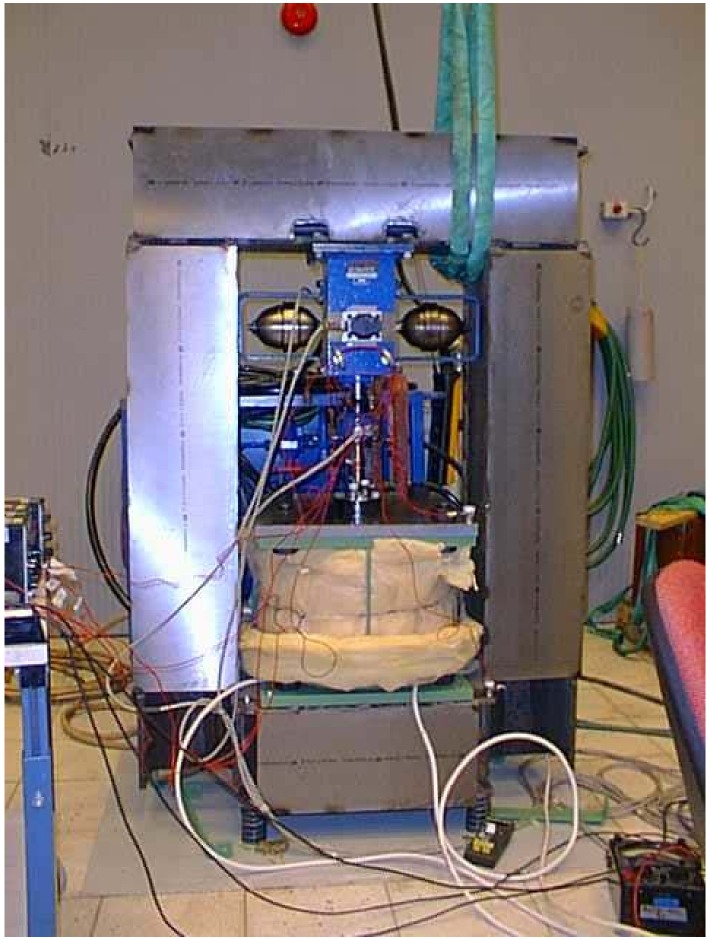
Fortum

Viscous absorber element (GERB)

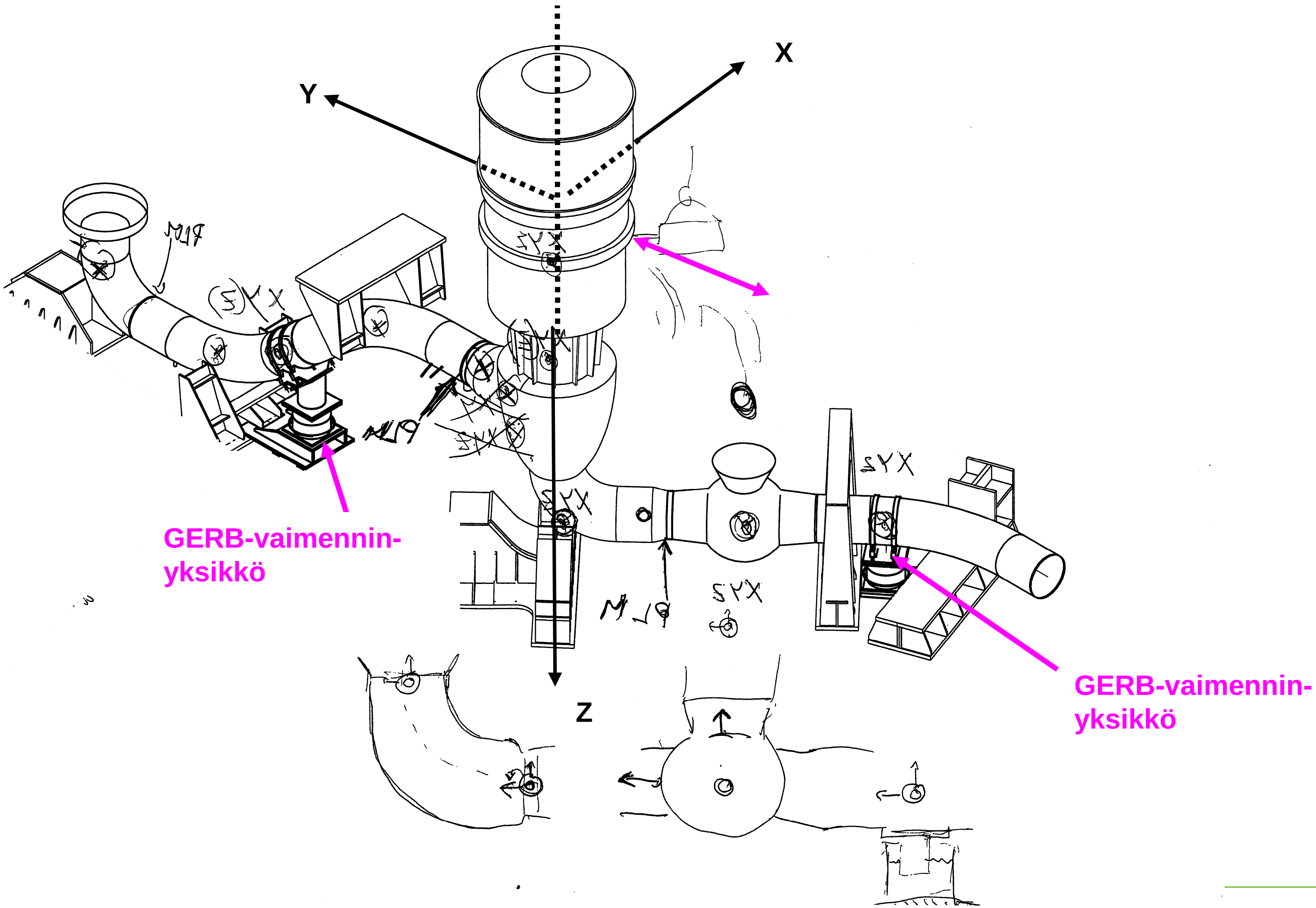






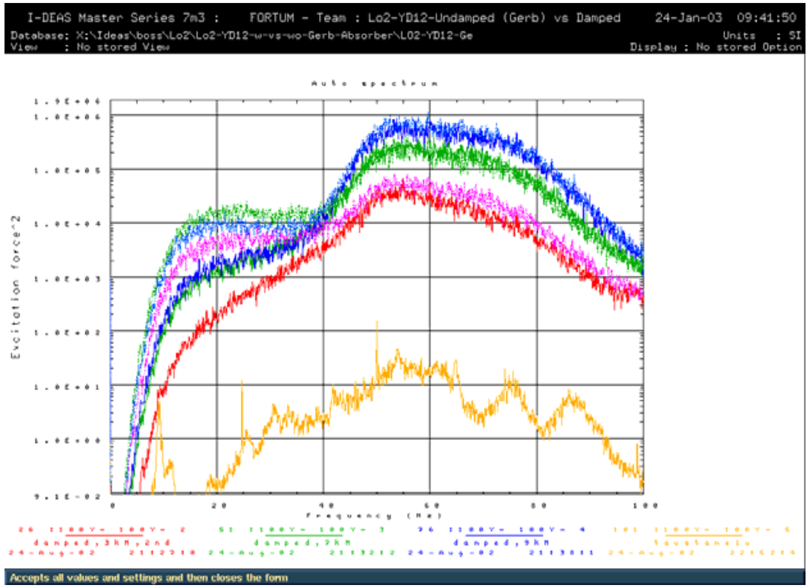


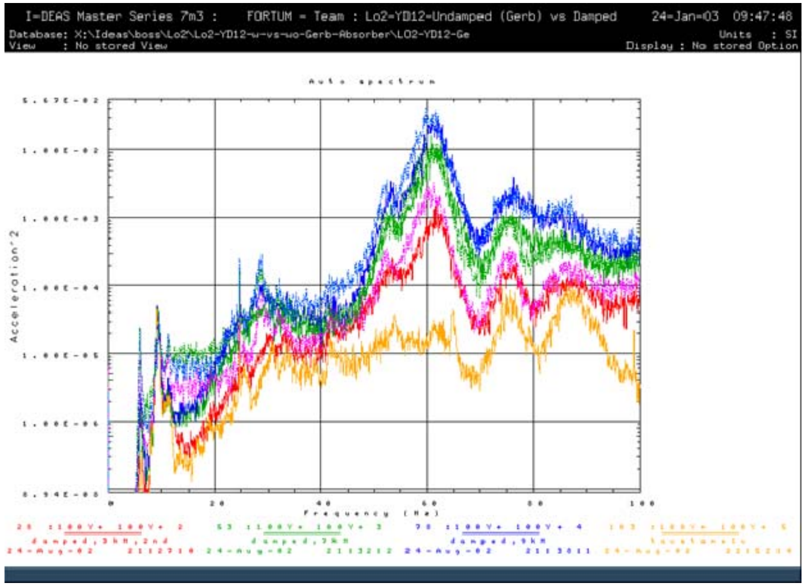
Mounting of two GERB viscous absorber units on the Cold Leg

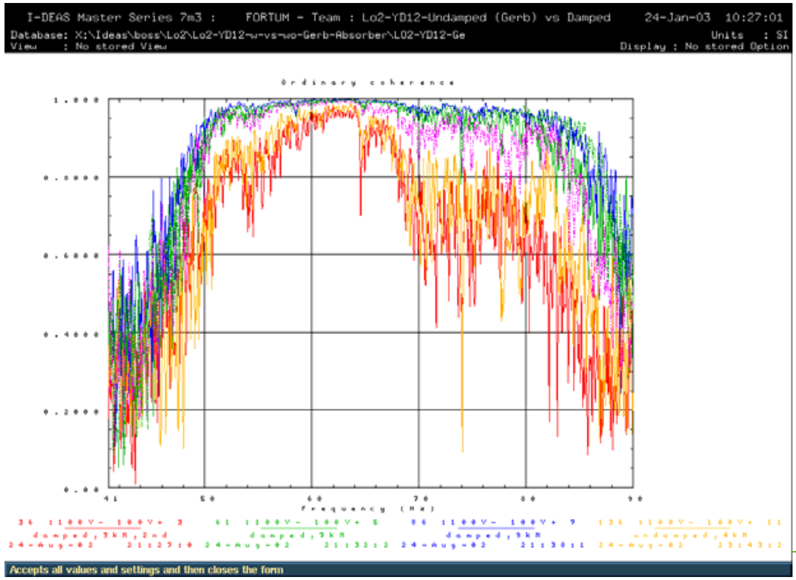


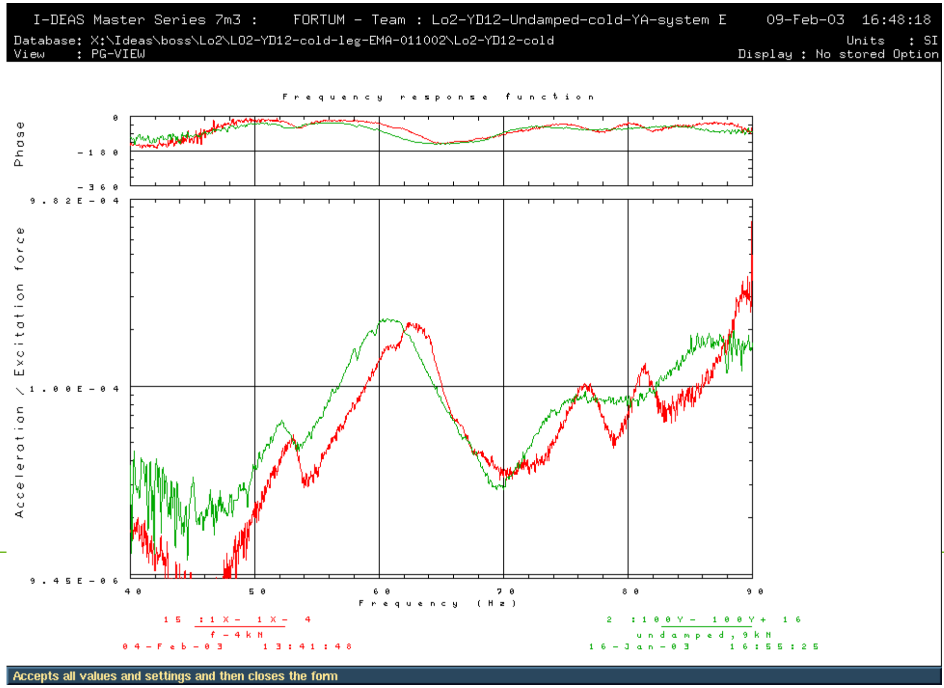
Fortum

Mounting of two GERB viscous absorber units on the Cold Leg

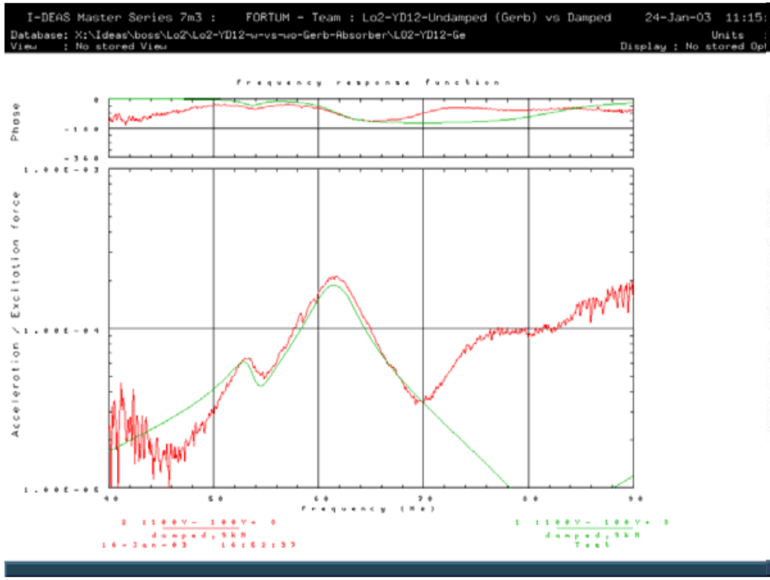


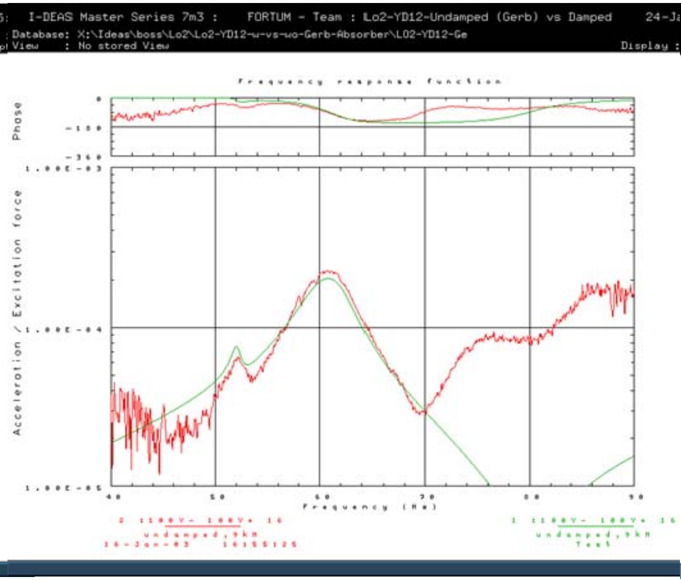


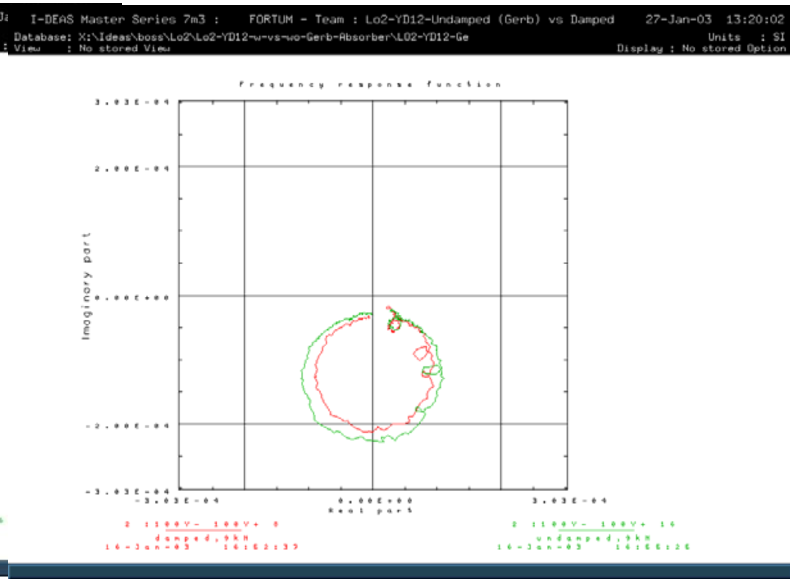




Mounting of two GERB viscous absorber units on the Cold Leg







	Viscous Absorber Mounted/Complex Exponential			No Viscous Absorber/Complex Exponential		
Natural frequency #	Frequency [Hz]	Relative damping value %]	Phase angle [Rad]	Frequency [Hz]	Relative damping value %]	Phase angle [Rad]
1	53.41	2.07	-1.637	52.514	1.797	-1.708
2	61.38	3.237	-1.445	61.471	3.316	-2.205
3	62.65	1.414	-1.872	62.681	0.699	-1.567

Fortum

The problems encountered when carrying out Modal Analysis on Nuclear Power Plant pipelines:

1) Heavy piping systems with insulation => Highly damped systems => Impact response decays rapidly
2) Closely spaced modes => good frequency resolution=> long measurement time => continuous excitation
3) High level of damping => coupled modes => good frequency resolution => long measurement time => continuous excitation
4) Excitation only in one direction/at one location is often not sufficient to excite all the modes => minimum of two excitation directions/locations
5) Suspension of the shaker may require special arrangements
6) Change of excitation location/direction may require special arrangements
7) Access to response locations => scaffolding to be erected and dismantling of the insulation to gain access to the pipe-line material
8) When carrying out conventional Modal Testing with a operating plant the background noise tends to be extensive => Excitation force has to be sufficient to raise the response level above background level => High Capacity Hydraulic shaker
9) The test article has to be taken out of service vs. simulate operating conditions without excessive noise
10) The choice of excitation location dictated by limited availability of space for the shaker and possible suspension locations
11) Special arrangements for introducing the exciation force into the structure
12) Careful planning when dealing with pressurized primary circuit components
13) Special arrangements with cooling of the hydraulic power supply and removal of the shaker equipment from the site after testing