HELSINKI UNIVERSITY OF TECHNOLOGY

Numerical Simulation of Ice-Induced Vibrations in Offshore Structures

by

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- Ice Mechanics
- Dynamic Ice-Structure Interaction
- Self-Excited Model
- Application Examples
- Wind Turbine Foundations
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- Conclusion

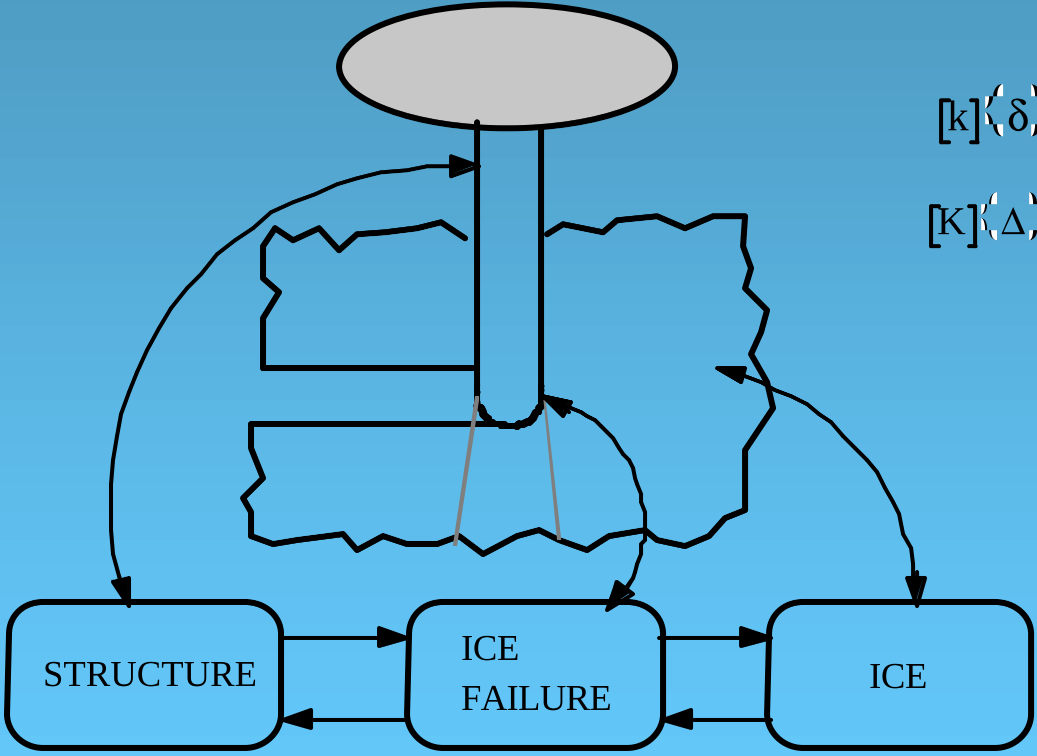
Ice mechanics background

- Moving ice
- Observed ice-induced vibrations
- Ice properties
- Energy interchange
- Numerical model requirements
- Different model approaches

Ice properties

- Homologous temperature >0.95
- Salinity and temperature effects
- Elastic, creep, damage, cracking
- Nonhomogeneous or orthotropic
- Grain size, aspect ratio and size effects

Ice-Structure Dynamic Interaction



STRUCTURE

ICE FAILURE

ICE

$$[k]\{\delta\}+[d]\{\dot{\delta}\}+[m]\{\ddot{\delta}\}=\{f(\delta, \dot{\delta}, \ddot{\delta}, \Delta, \dot{\Delta}, \ddot{\Delta}, t, V)\}$$

$$[K]\{\Delta\}+[D]\{\dot{\Delta}\}+[M]\{\ddot{\Delta}\}=\{F(\delta, \dot{\delta}, \ddot{\delta}, \Delta, \dot{\Delta}, \ddot{\Delta}, t, V)\}$$

Ice-induced vibration

- Dynamic ice-structure interaction
- Response of structure significant
- Ice strength vs. loading rate
- Frequency lock-in
- Synchronisation
- In-field experience

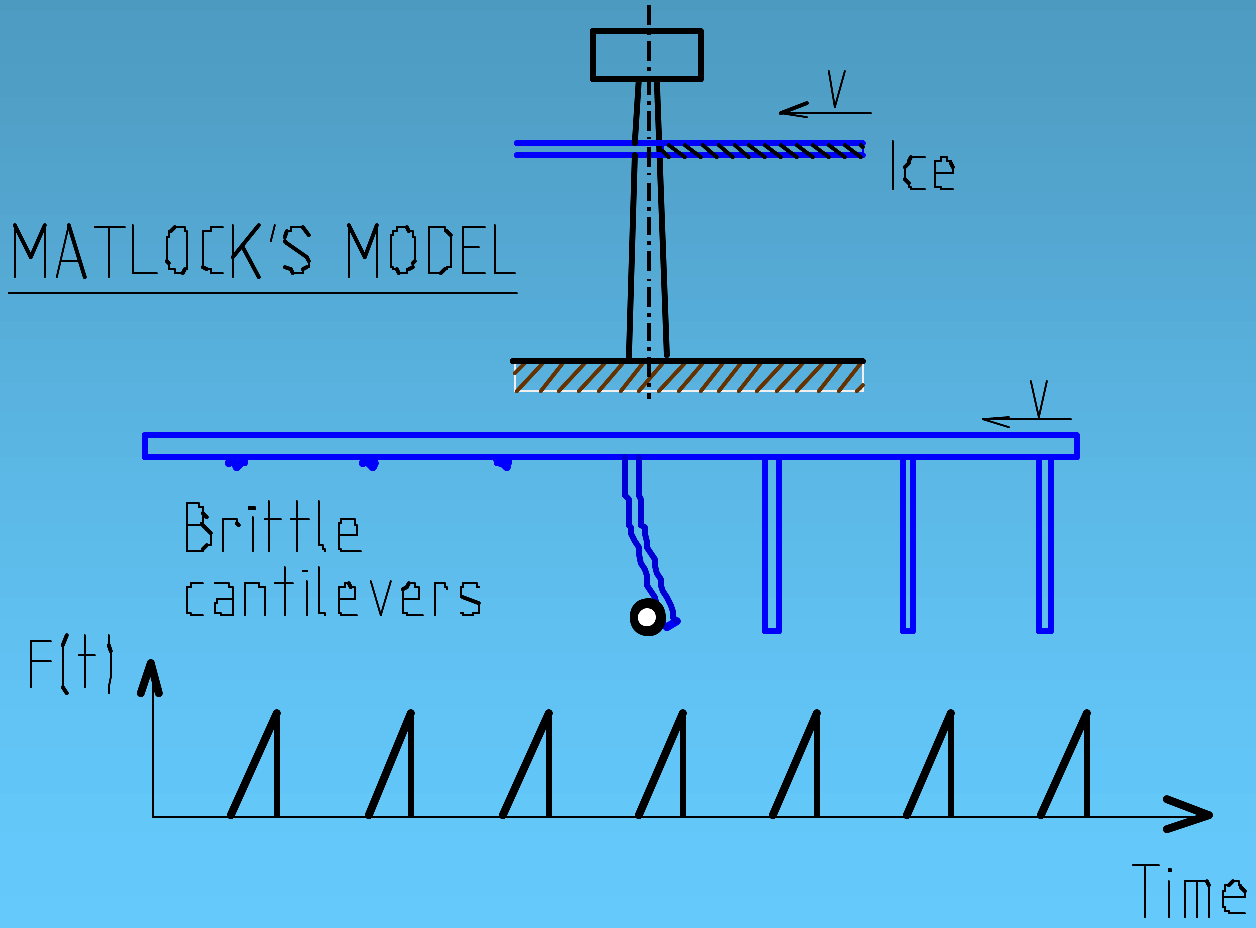
Model Requirements

- Simulate real structural response
- Saw tooth response, low ice velocity.
- Random response, high ice velocity.
- Frequency lock-in and resonance.
- Synchronization, wide or multi-legged.

Different model approaches

- Ice having a characteristic failure frequency
- Characteristic ice failure length
- Matlock's model
- Self-excited model (displ. & velocity control)
- Extrusion of crushed ice
- Contact line (hot-spot) models
- Ice damage evolution models (μ-mechanics)

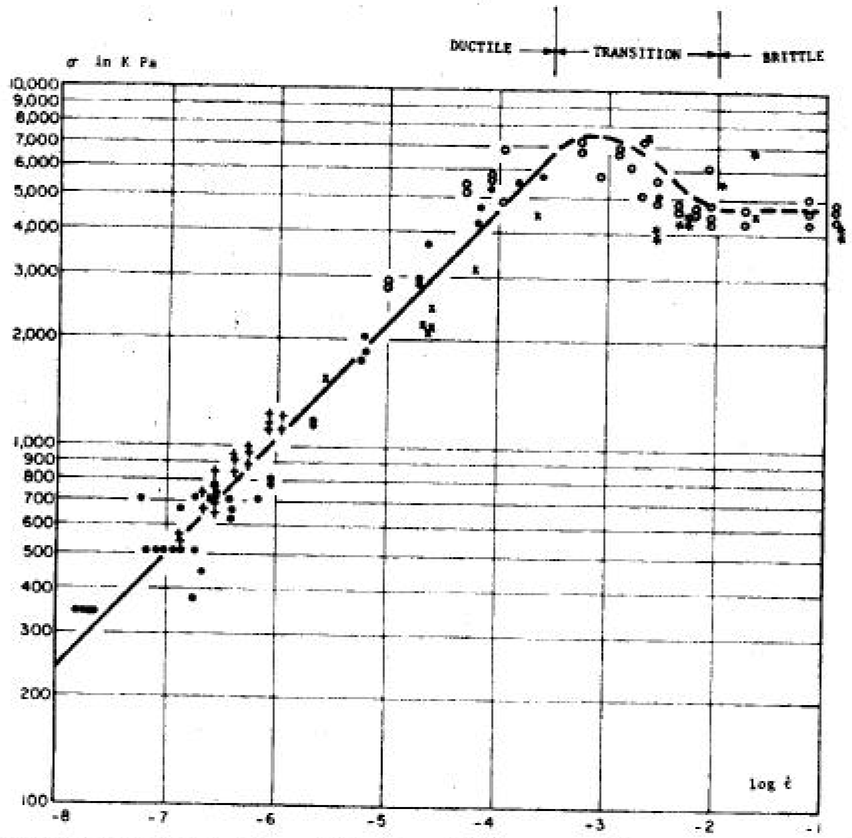
Matlock's model



Self-Excited Model

- Ice strength vs. stress rate.
- Response displacement and velocity coupling.
- Self-excited autonomous model
- Independent multi-point excitation.
- Any structure, principal modes.
- Numerical time integration.
- Steady state limit cycles.

Crushing strength vs. strain rate



ig. 10. *Universal curve for uniaxial crushing and indentation of S_2 ice at −10°C: ○—— Michel and Paradis (1976), uniaxial; ○– – – Carter and Michel (1972), uniaxial; † Frederking and Gold (1975), indentation; * Hirayama and others (1974), indentation; × present study, indentation.*

Crushing strength vs. strain rate

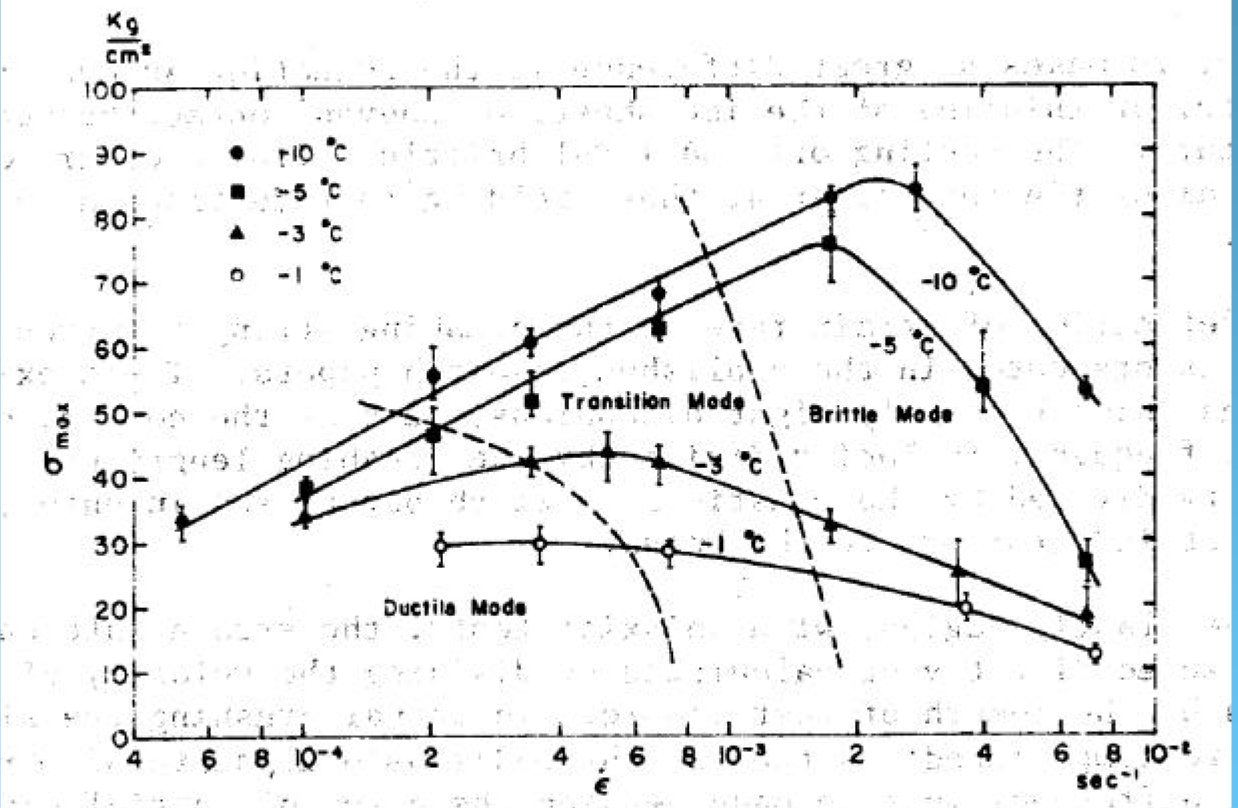
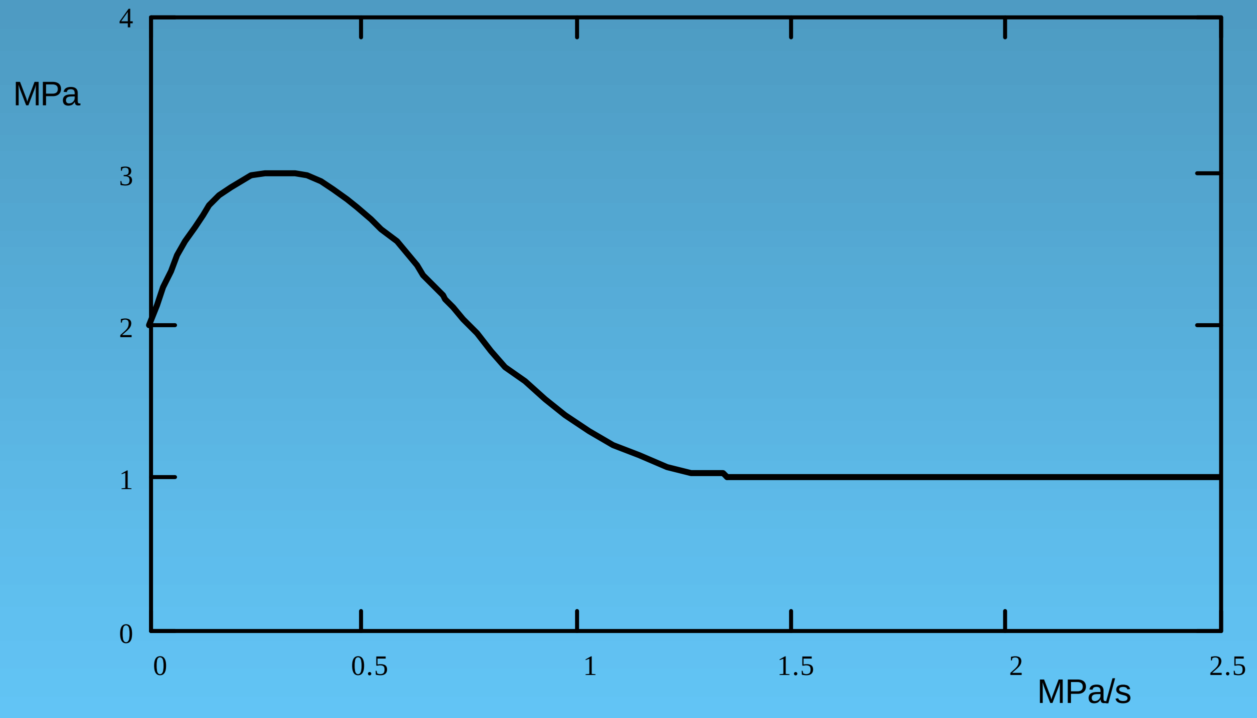


Figure 3.5 Ice crushing strength vs. strain rate and temperature, Wu et al. (58).

Crushing strength vs. stress rate



$$\sigma_c = (2.00 + 7.80\dot{\sigma} - 18.57\dot{\sigma}^2 + 13.00\dot{\sigma}^3 - 2.91\dot{\sigma}^4)\sqrt{\frac{A_0}{A}}\ MPa$$

Equations of motion

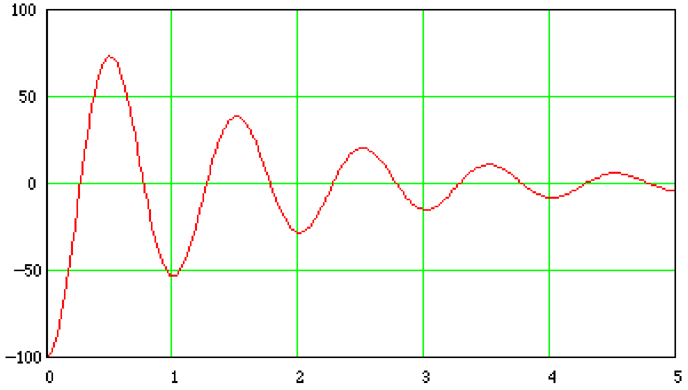
$$F_i = A_i \cdot s_c(\dot{s}) \cdot \sqrt{\frac{A_0}{A_i}}$$

$$\dot{s} = (v - \dot{u})\frac{8s_0}{pD}$$

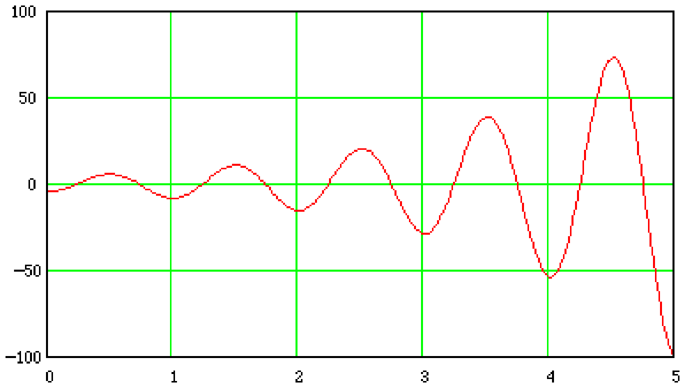
$$[k]\{u\} + [d]\{\dot{u}\} + [m]\{\ddot{u}\} = \left\{F\left(v, \{u\}, \{\dot{u}\}\right)\right\}$$

Complex roots, $\lambda=a\pm i\omega$, of a mode

- $a<0$
- Stable mode

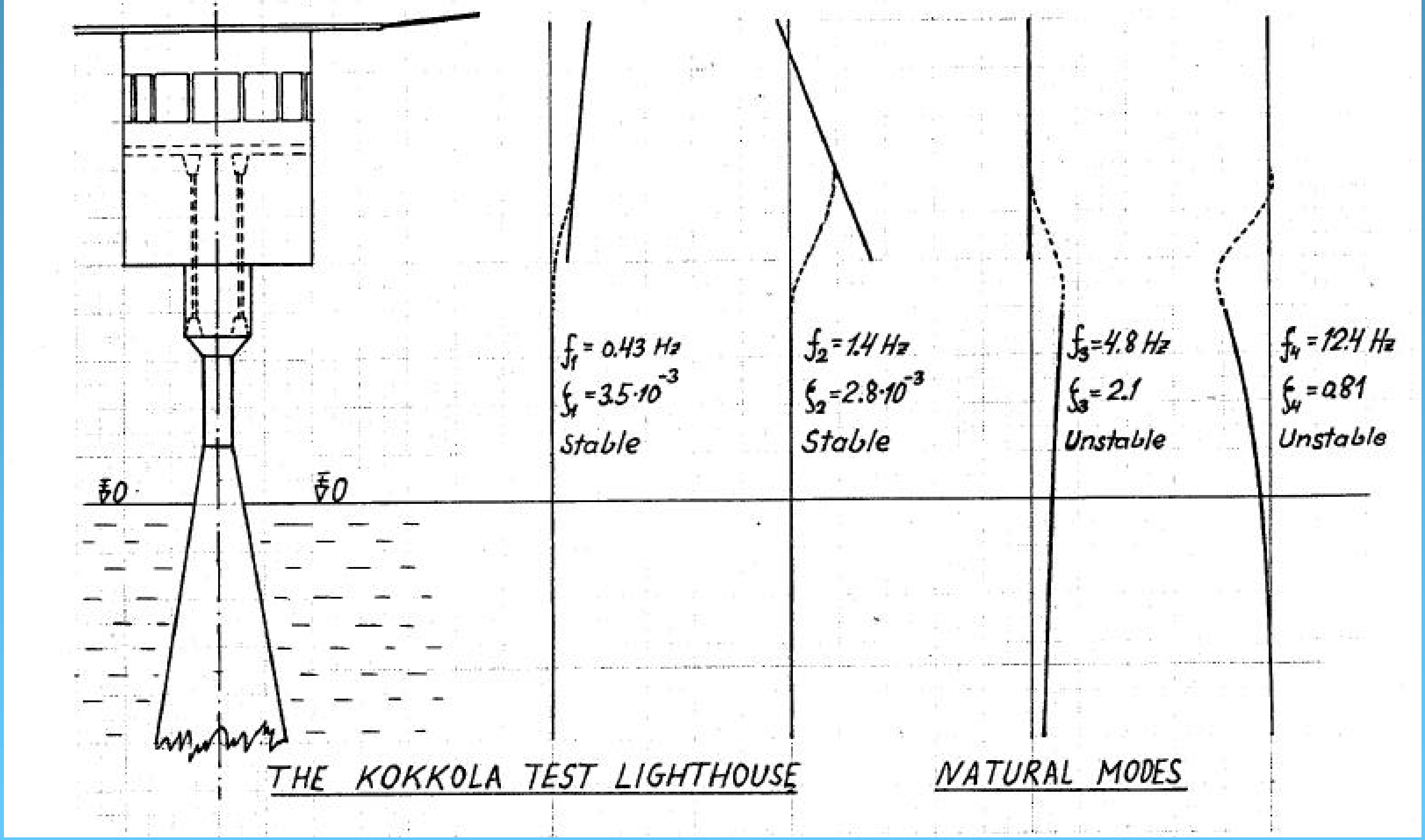


- $a>0$
- Unstable mode



- real part ˜ sensitivity to ice-induced vibrations

First application 1997



Kemi-2 Lighthouse 1981

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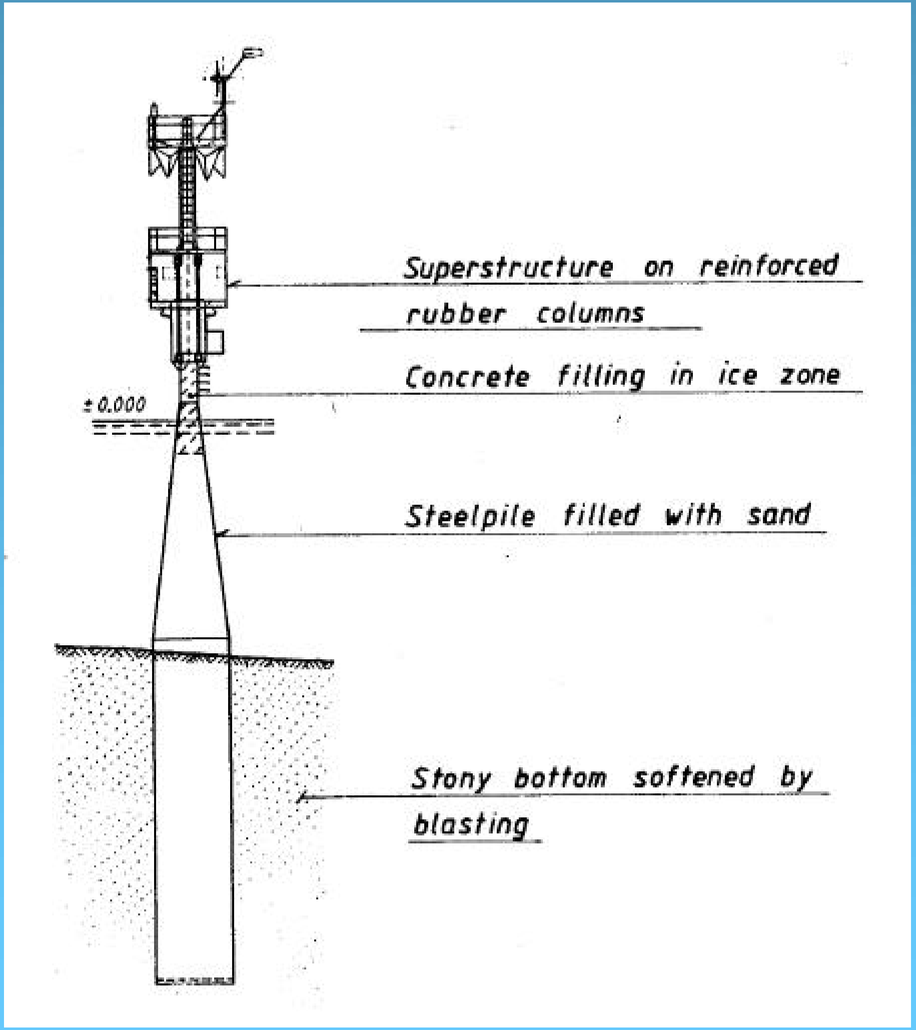
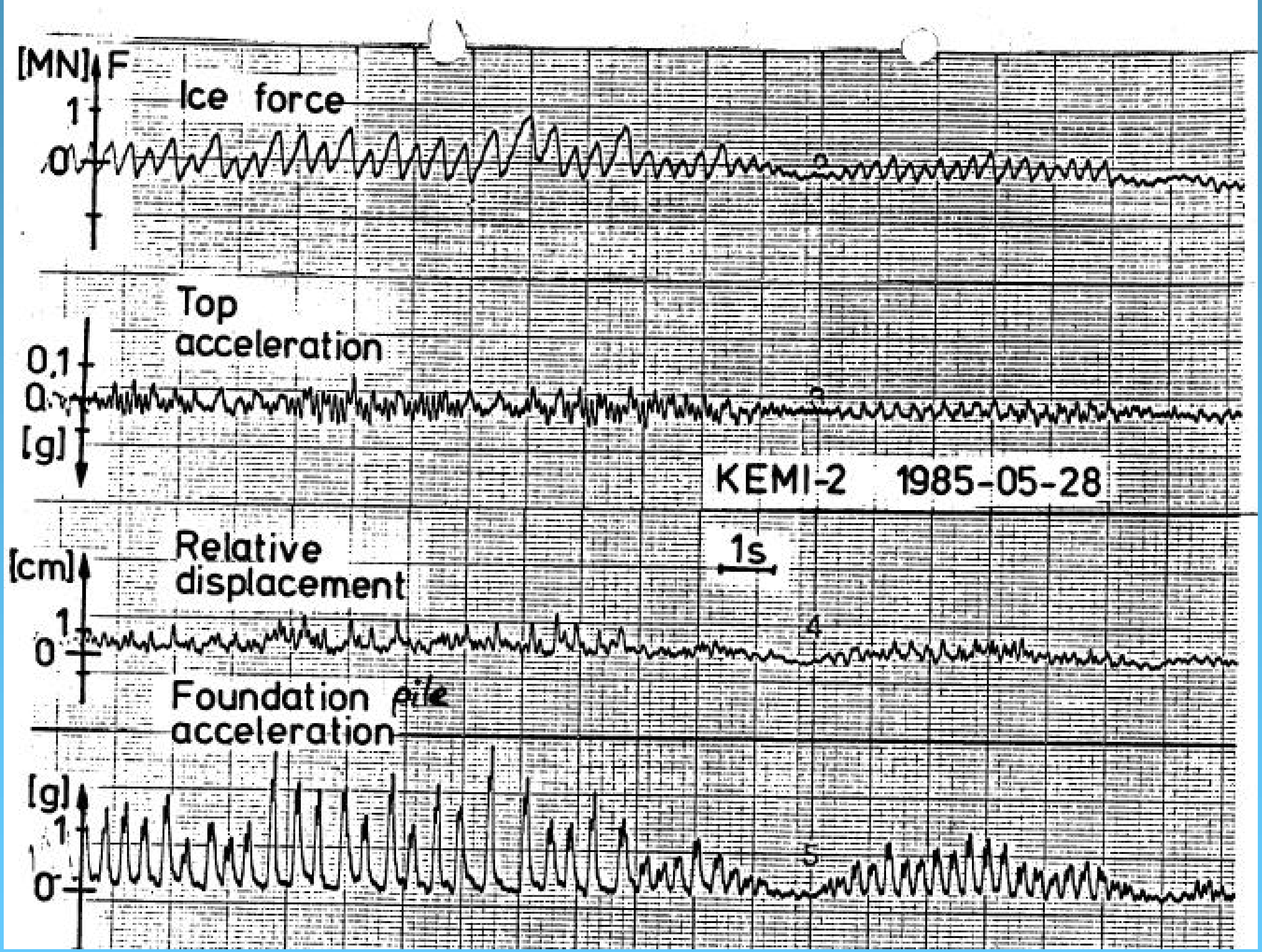
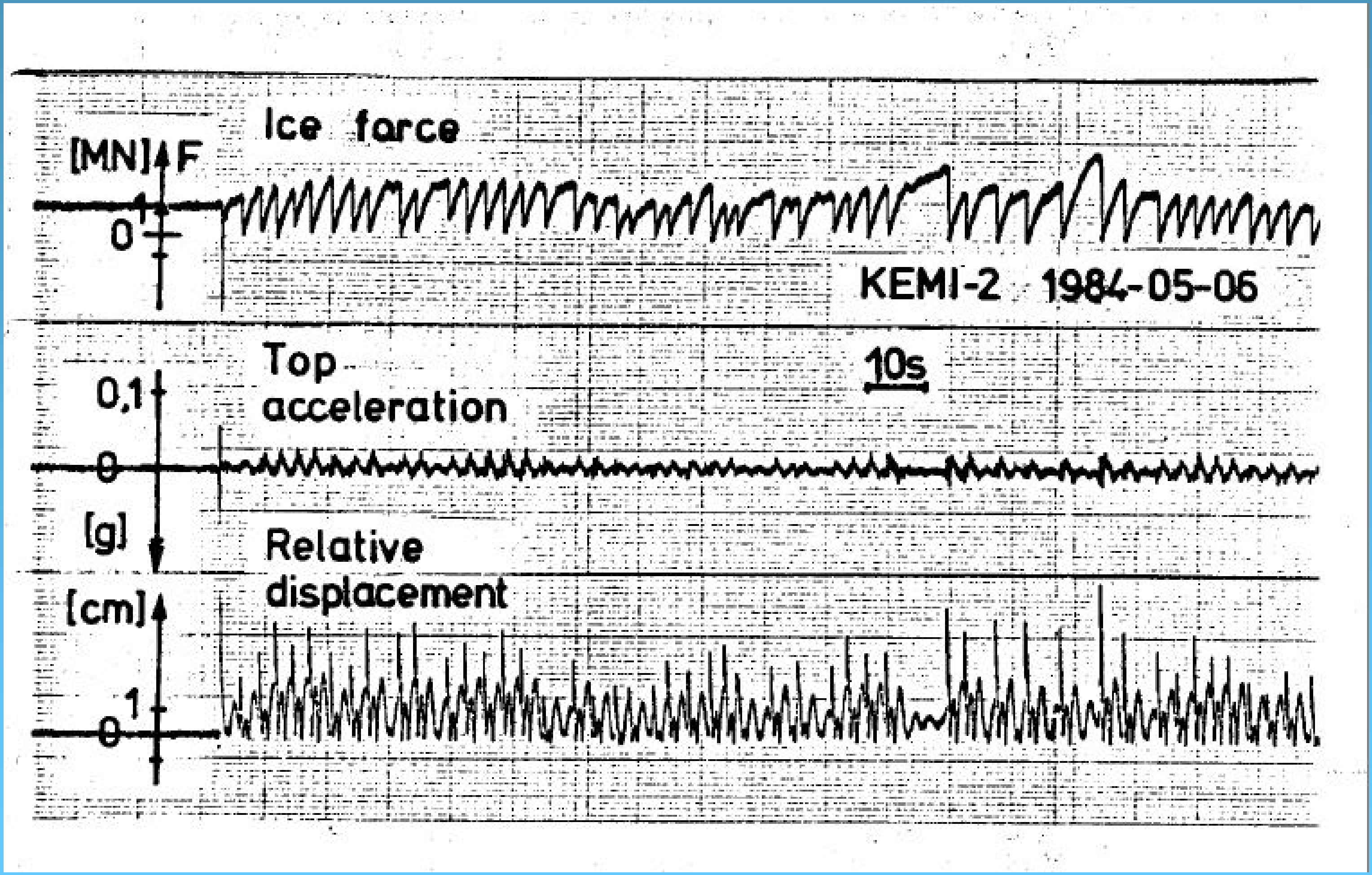


Mode	Freq Hz	ζ %
1	0.32	0.33 stable
2	0.93	0.36 stable
3	7.6	530 unstable
4	12.3	0,0 stable

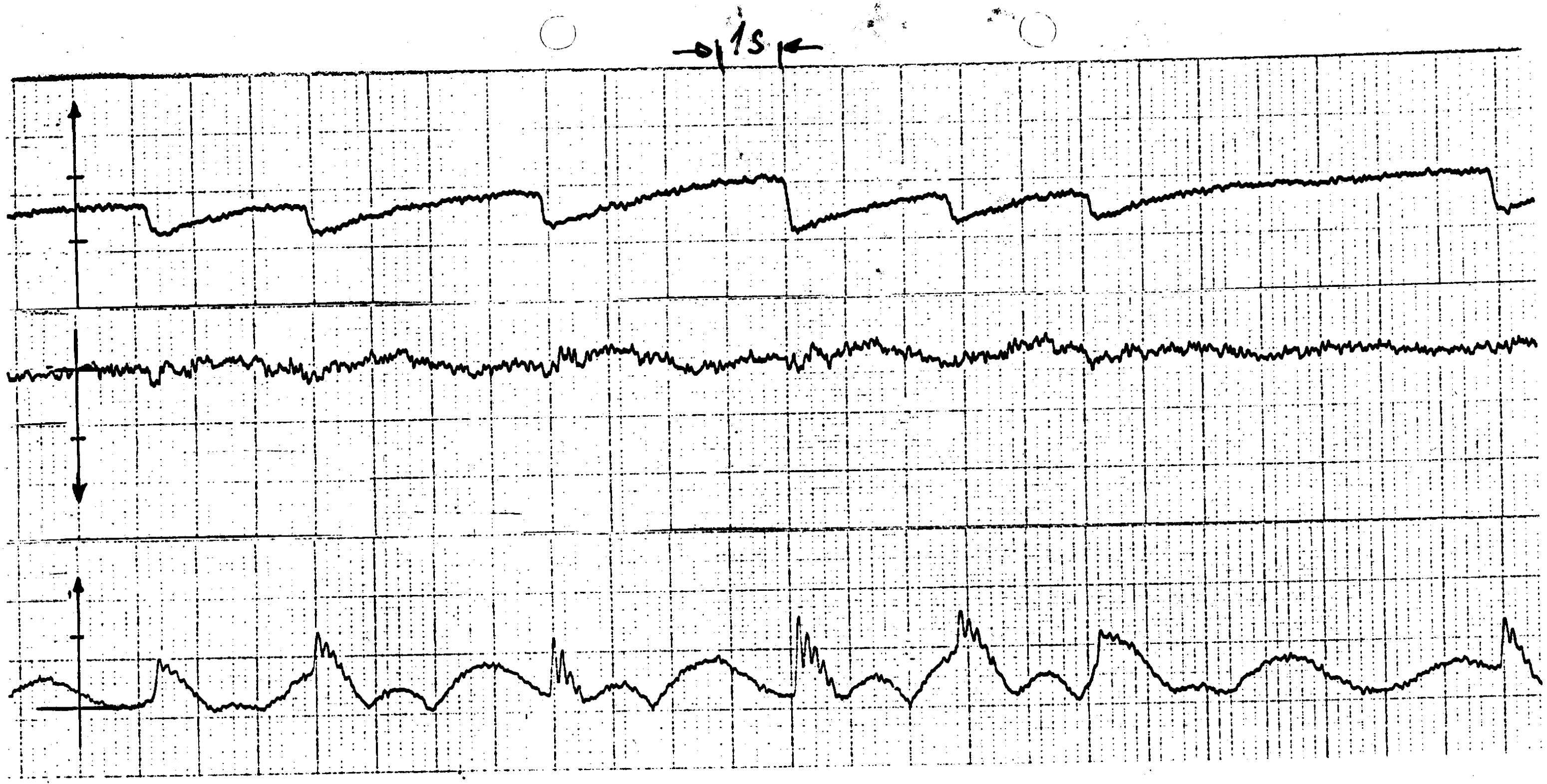
Kemi-2 Measurement data



Kemi-2 Measurement data



Kemi-2 Measurement data

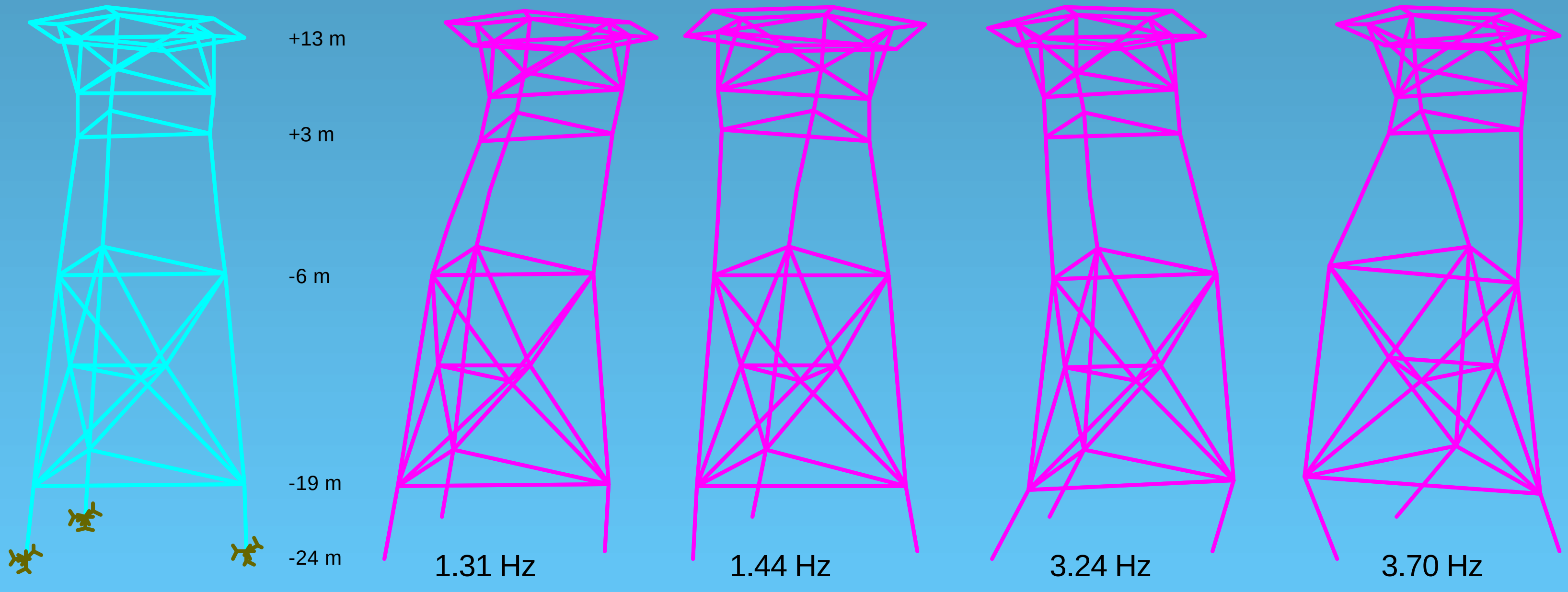


$f_1 \simeq 0{,}32$ Hz
$\zeta = 15\,\%$
Dynamically stable natural mode

Application structures

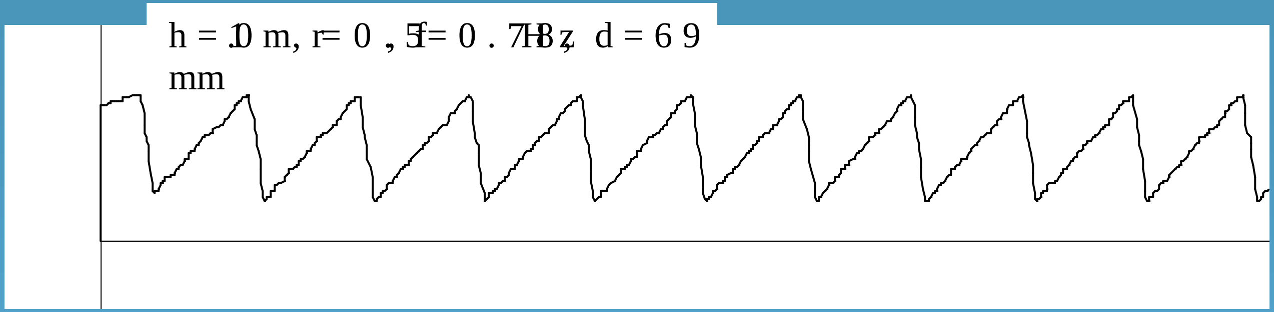
- **Three-legged jacket platform**
  - Relatively flexible structure
  - Narrow legs under ice action
  - Sensitive to ice-induced vibrations
- **Caisson retained island**
  - Relatively stiff structure
  - Wide area under ice action
  - Generally unsensitive to ice induced vibrations

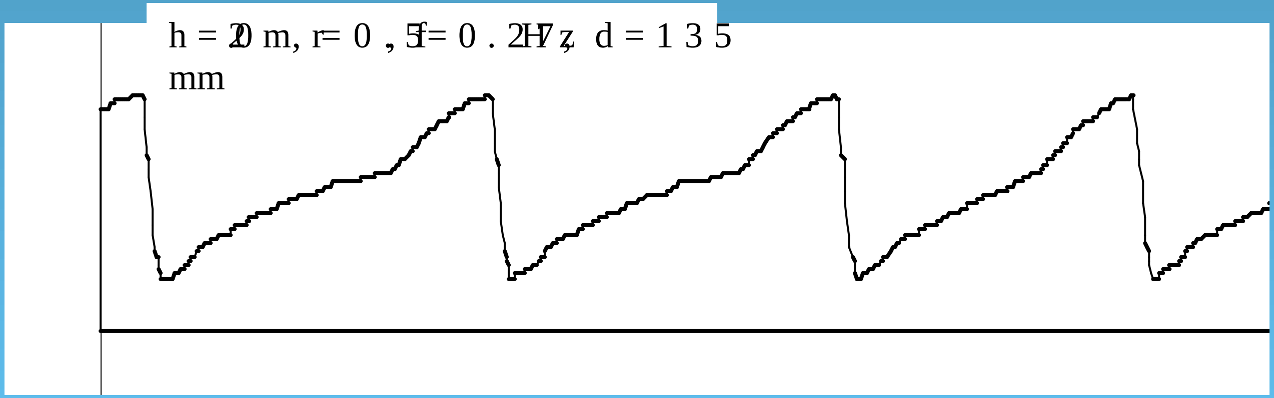
THREE LEGGED PLATFORM NATURAL MODES

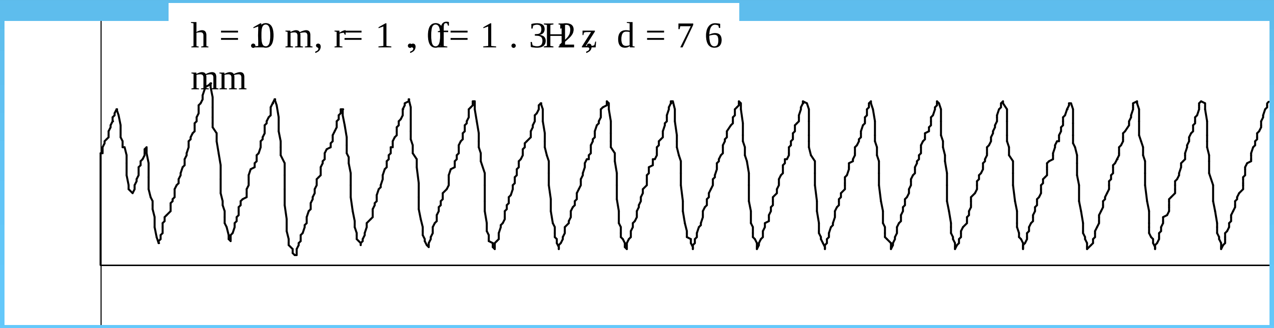


Application results

- Three
- legged
- platform

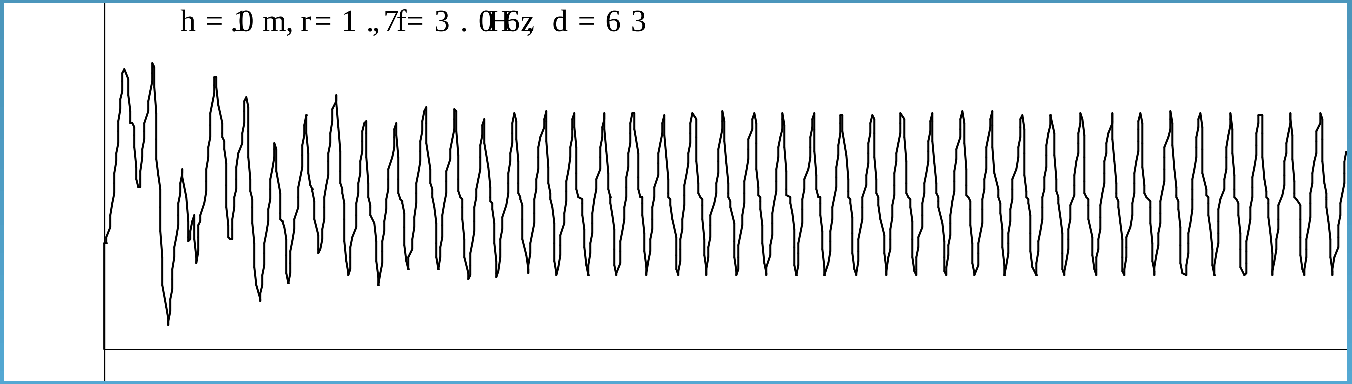


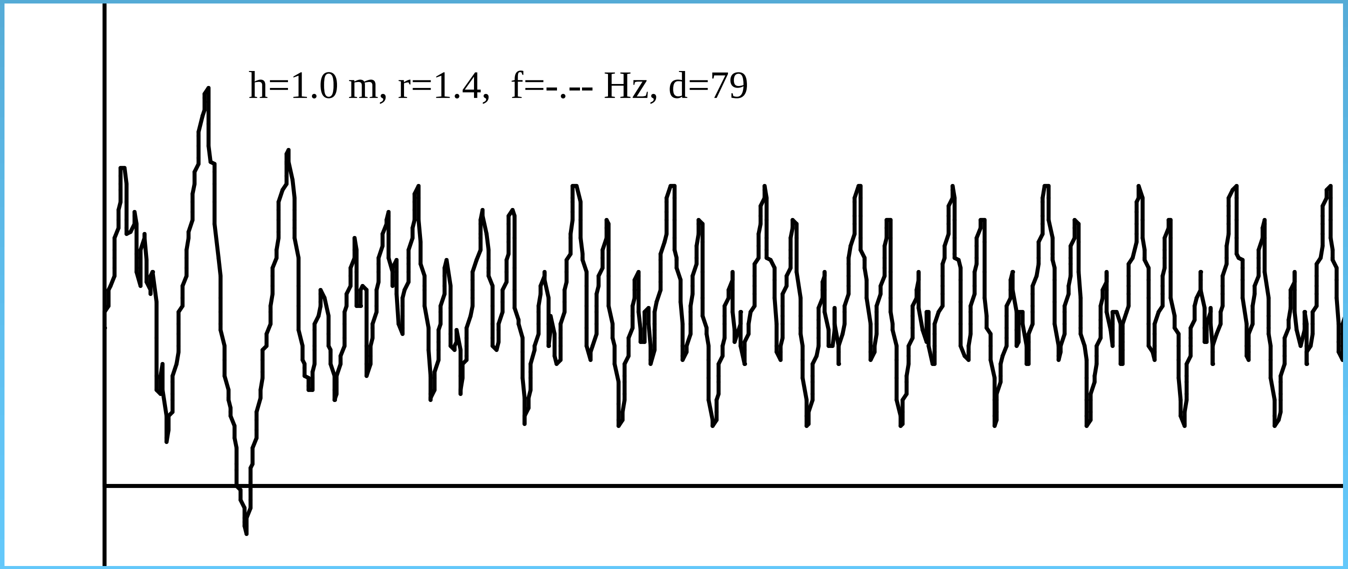




Application results, cont

- Three
- legged
- platform

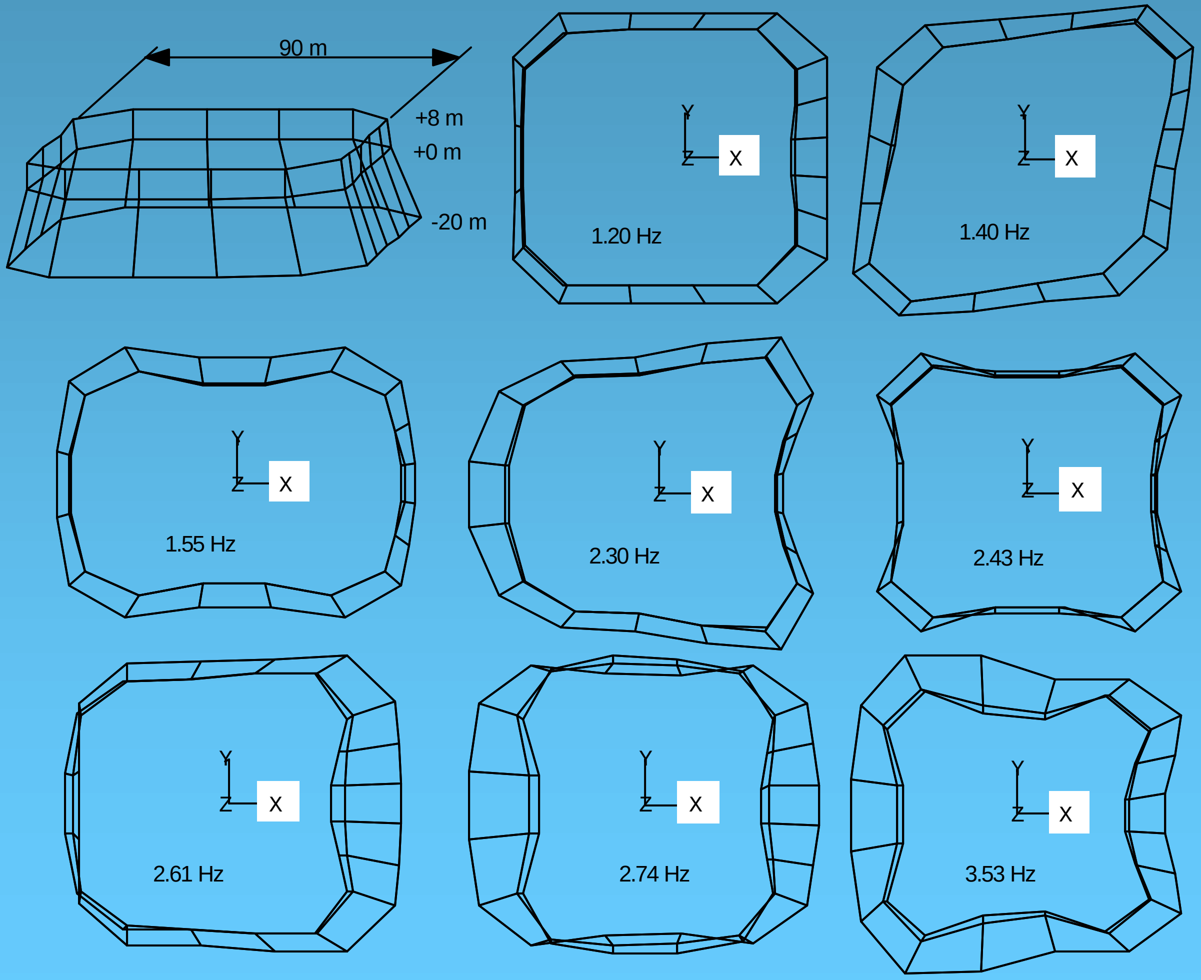




Application results:
Three legged structure

- Predicts correctly velocity dependence:
  - Saw tooth, random and frequency lock-in.
- Very sensitive to ice-induced vibrations:
  - Limit cycles develop fast.
- Frequency lock-in with different modes.
- Synchronization at different legs prevails
- Vibrations cannot be suppressed by increasing structural damping.
- Results agree well with lighthouse measurements

CAISSON RETAINED ISLAND NATURAL MODES

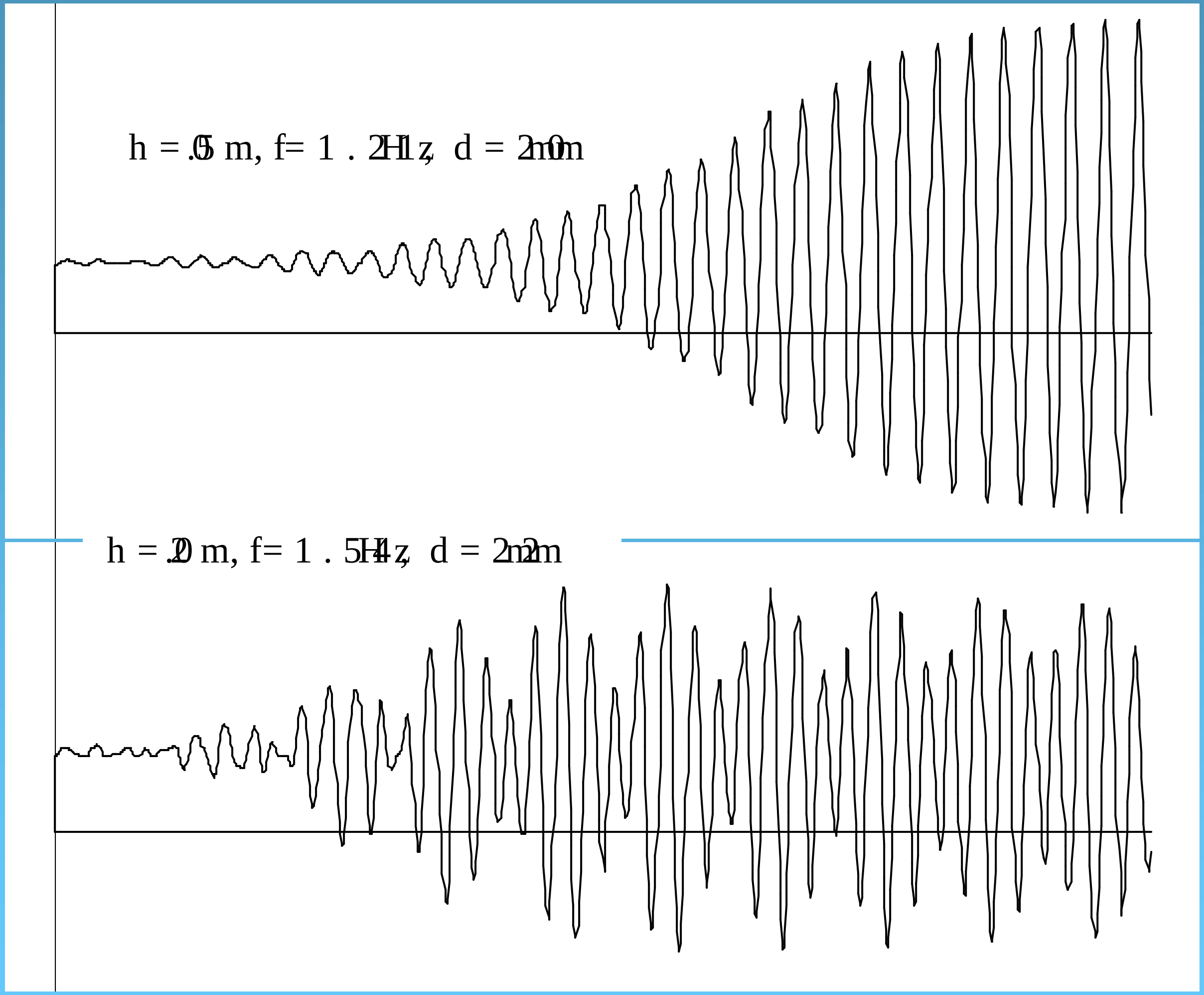


Application results:

Caisson

retained

- island

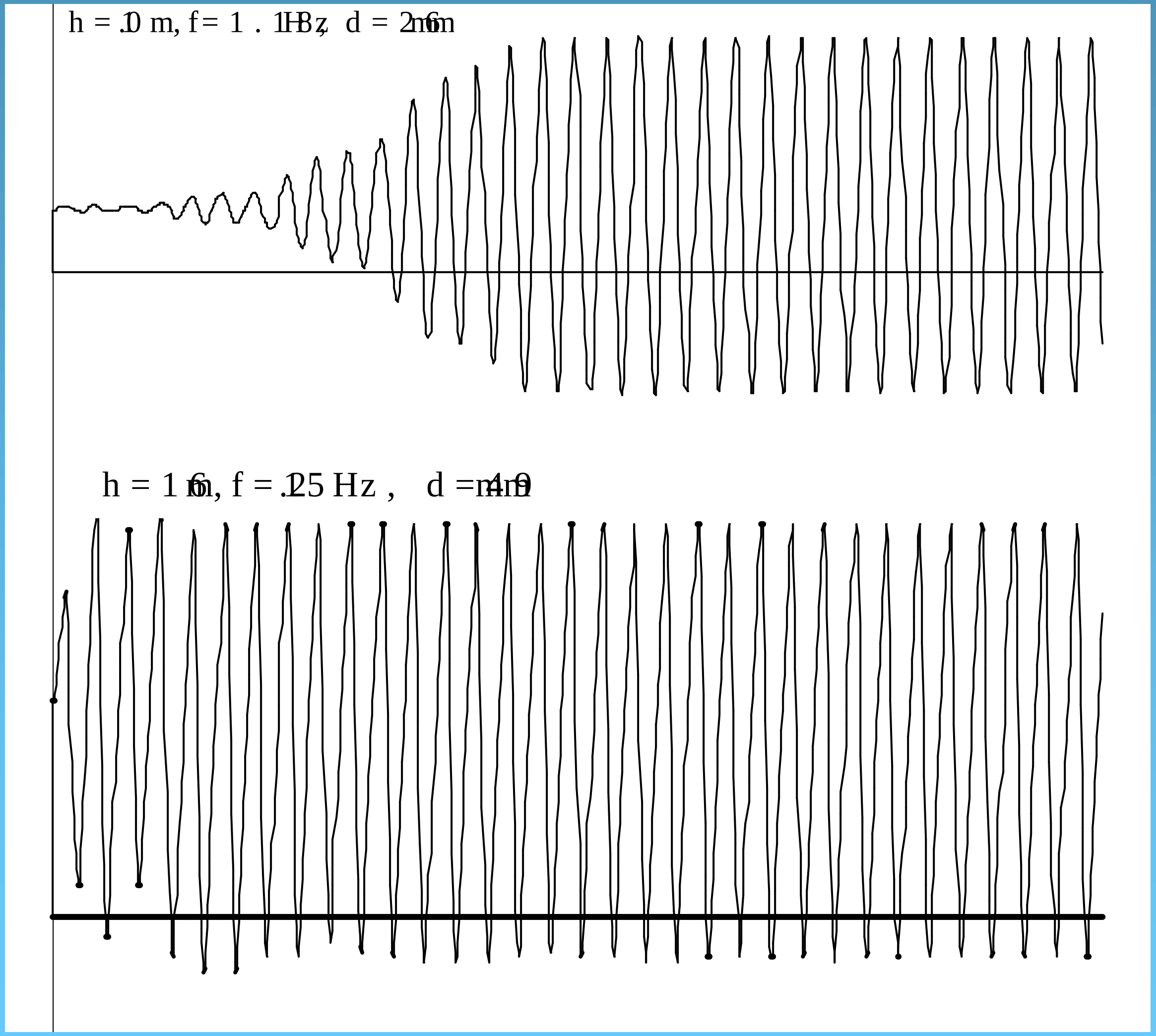


Application results, cont.

Caisson

retained

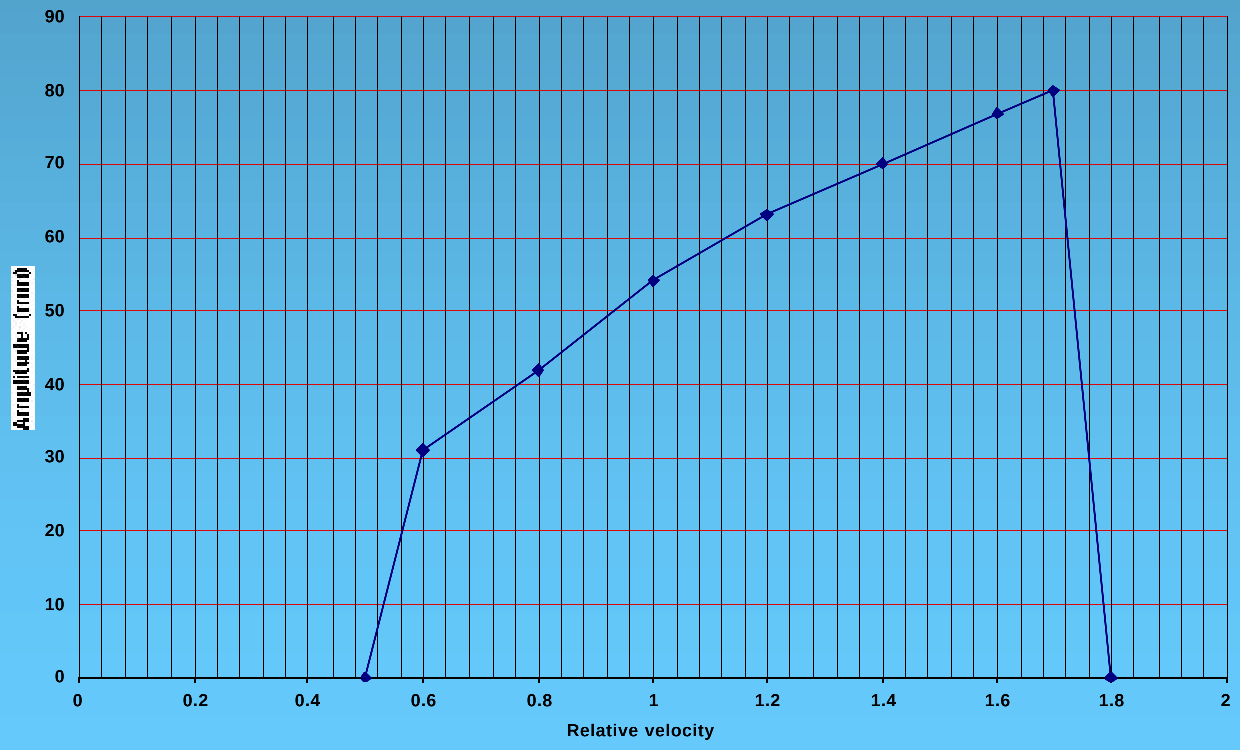
- island



Application results:
Caisson retained island

- Predicts correctly velocity dependence:
- Low sensitivity to ice-induced vibrations:
    - Limit cycles develop slowly.
- Frequency lock-in mainly with the first mode.
- Synchronization at whole contact width prevails
- Vibrations could be easily suppressed by increasing structural damping.
- Results in agreement with full-scale observations

CRI vibration amplitude vs. ice relative velocity

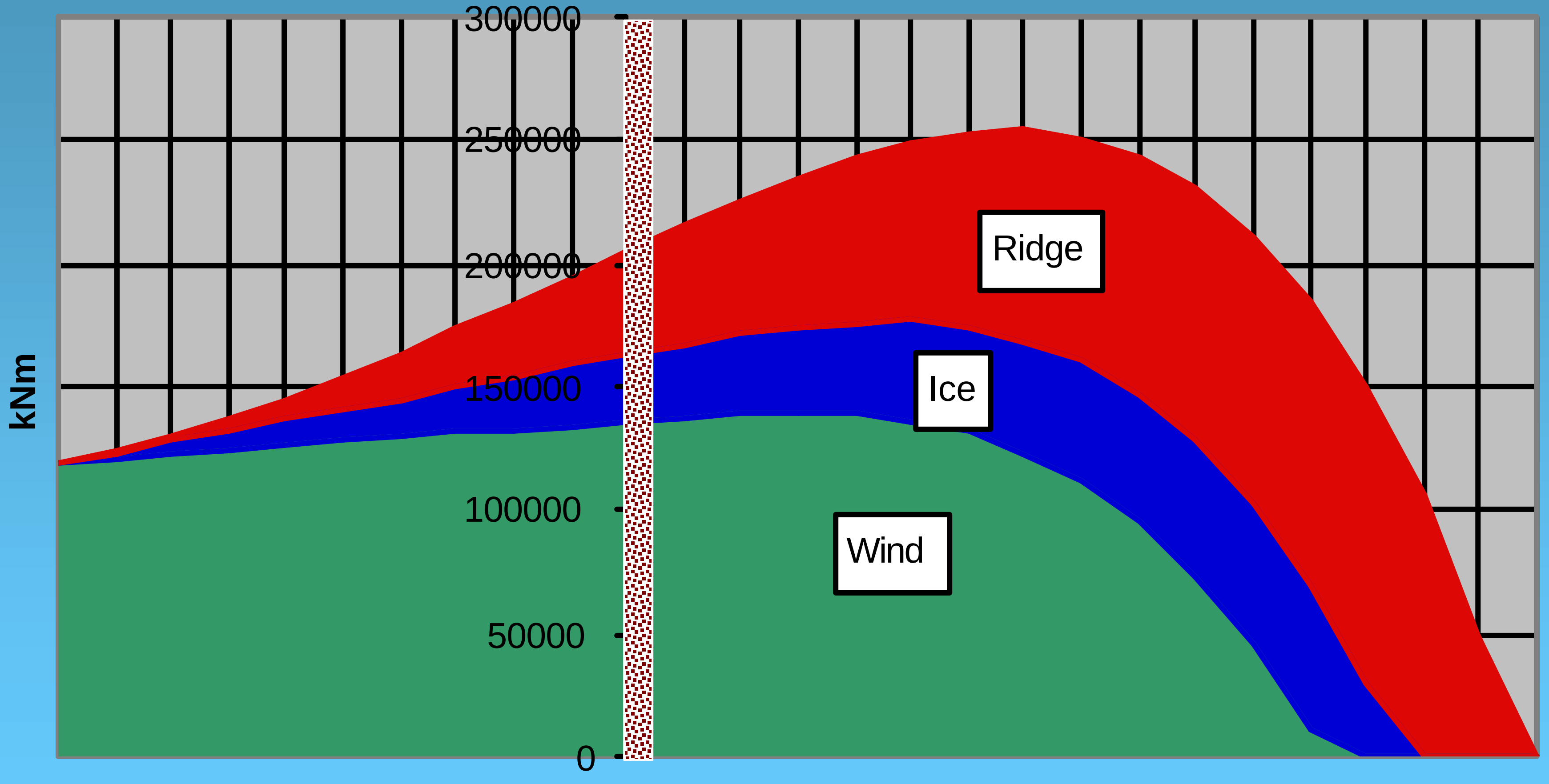


EC Offshore wind energy goal

- 2010 » 5 GW (about 1000…2000 units)
- 2020 » 50 GW (about 10000 units)
- Present projects:

Middelgrunden	2000/2001	20*2 MW	40 MW
Horns Rev	2002	80*2 MW	160 MW
Umeå	2002		60 MW
Rødsand	2002		150 MW +
Germany	2002-20??		12 GW

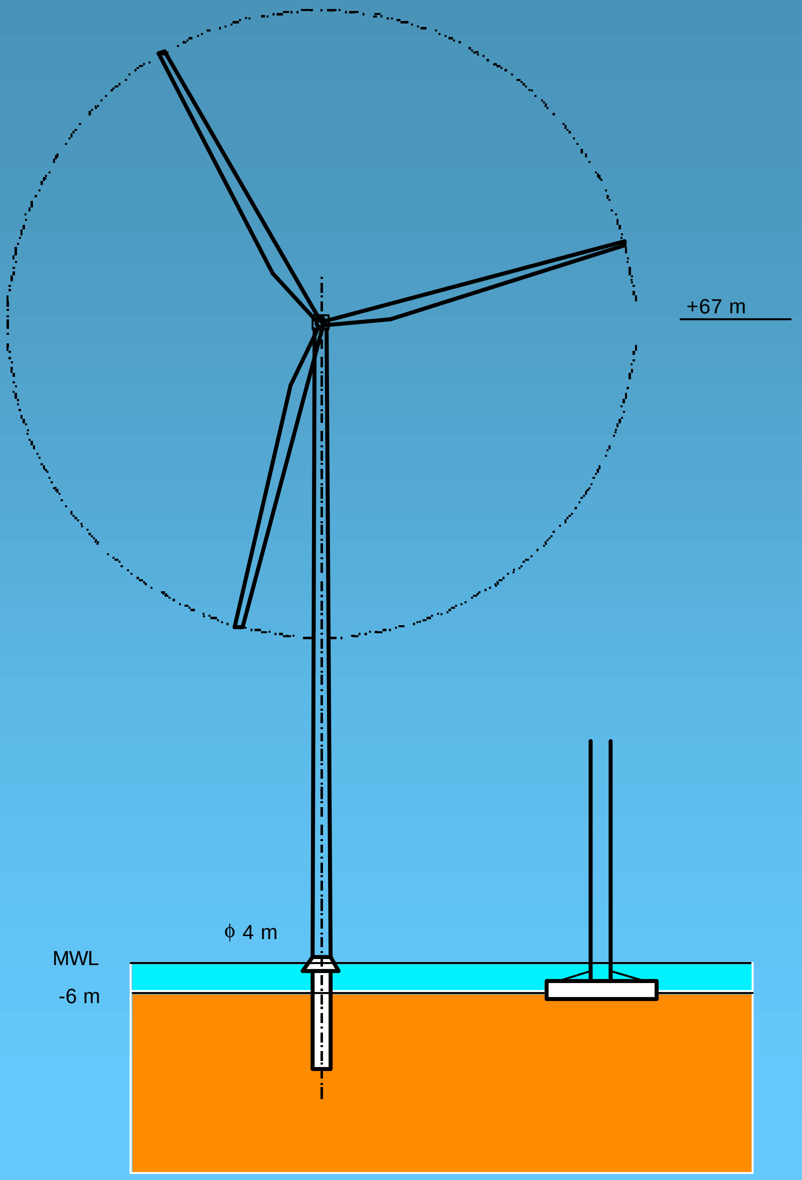
Foundation moment, 5 MW 10 m water depth



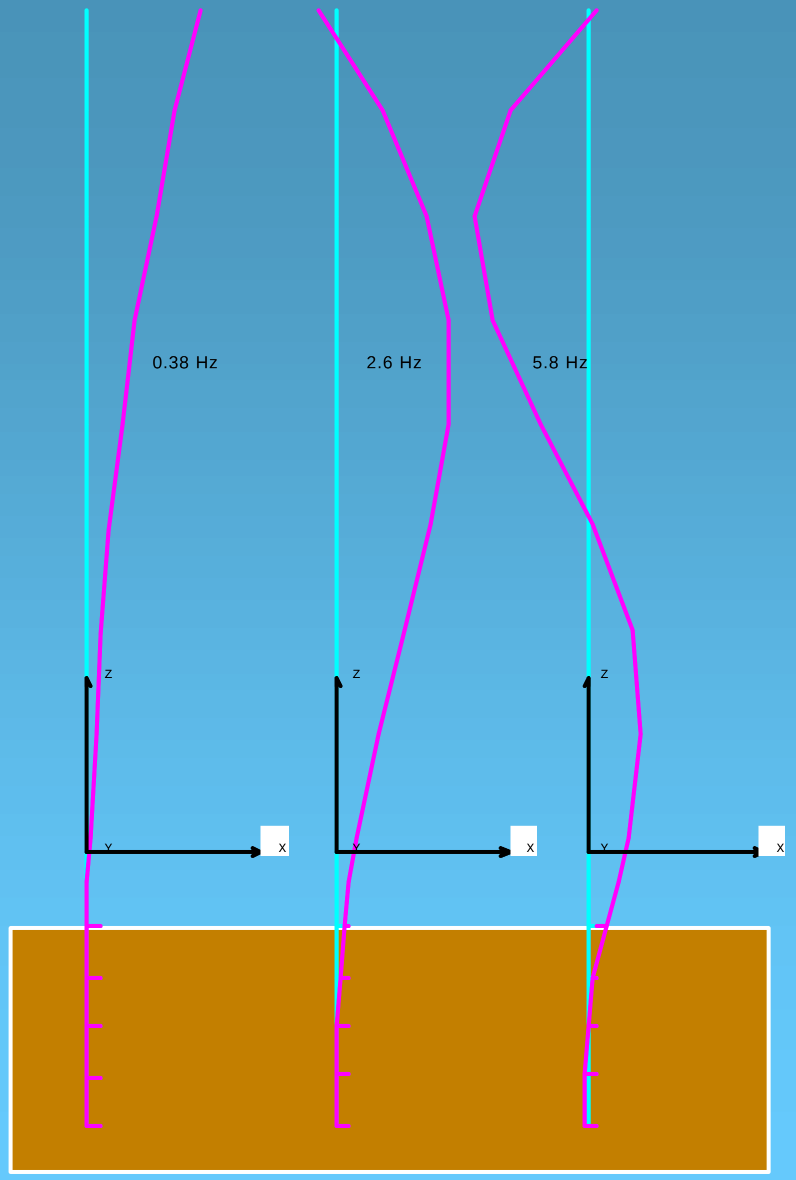
Wind turbine examples

- **Tower 67 m, pile foundation**
  - Relatively flexible structure
  - Sensitive to ice-induced vibrations
  - Acceptable vibration level
- **Tower 67 m, caisson foundation**
  - Relatively stiff structure
  - Generally unsensitive to ice induced vibrations
  - Low vibration level

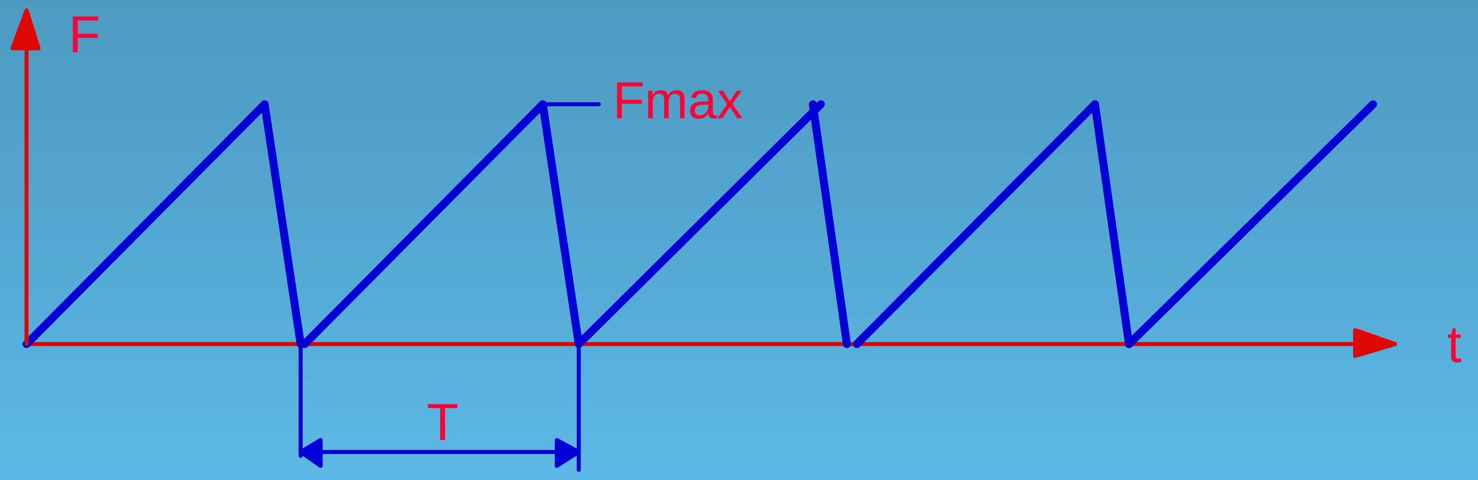
Wind turbine pile and caisson foundations



PILE FOUNDATION NATURAL MODES

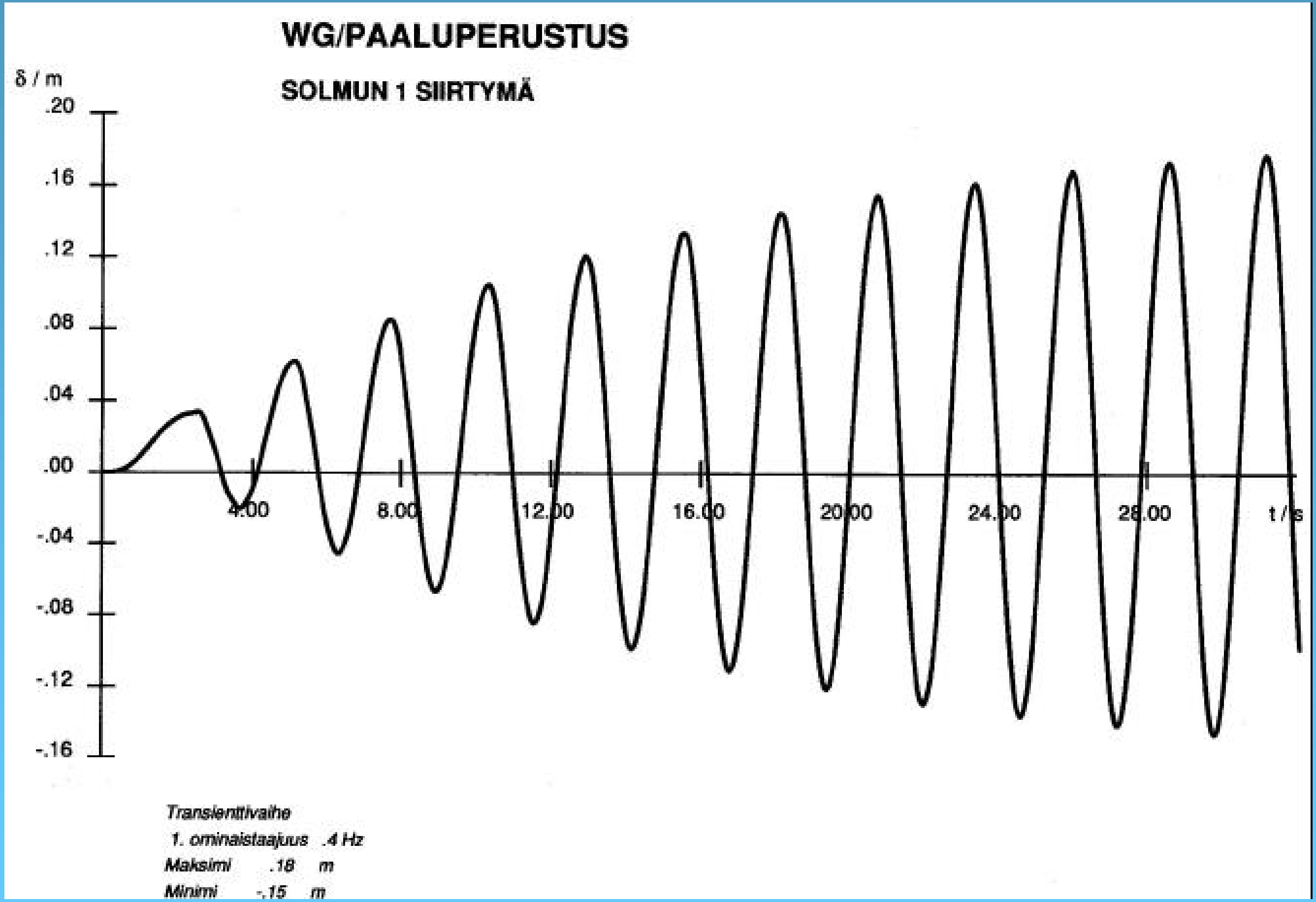


Assumed ice forcing function

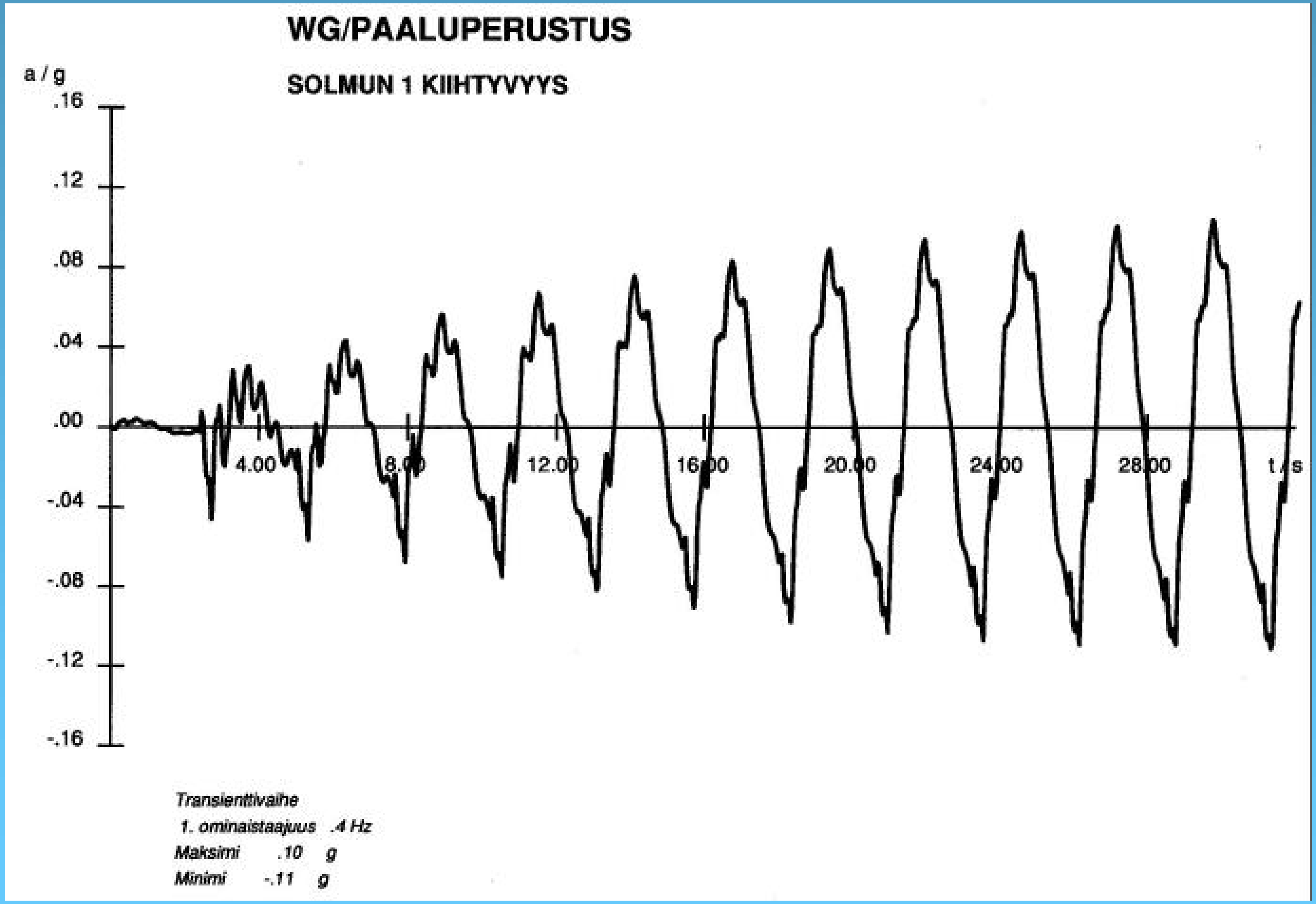


- Assumed saw-tooth ice load function:
  - Resonance with lowest modes
  - Simple
  - Conservative

Nacelle displacement vs. time



Nacelle acceleration vs. time



WG/PAALUPERUSTUS

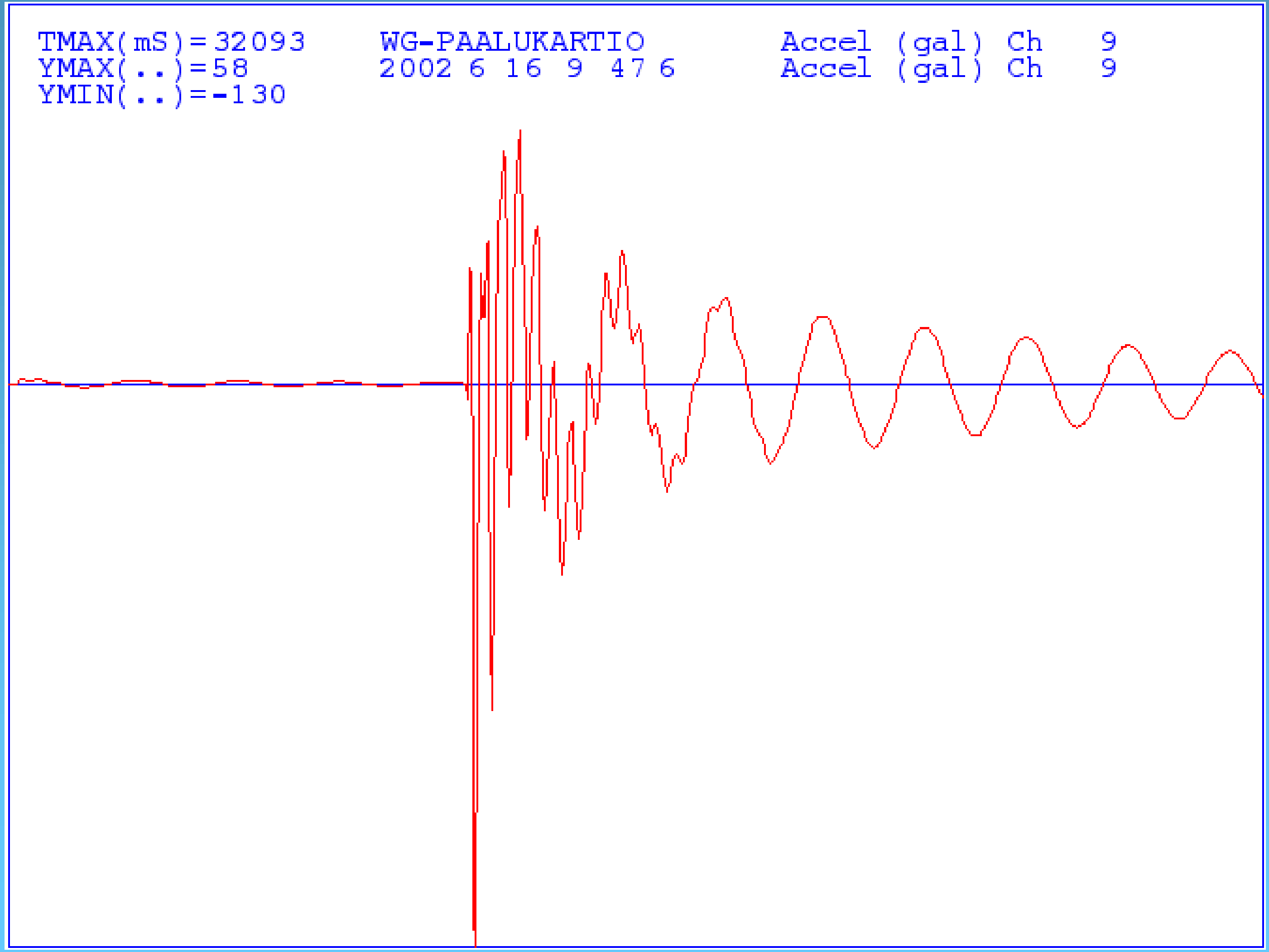
SOLMUN 1 KIIHTYVYYS

Transienttivaihe
1. ominaistaajuus .4 Hz
Maksimi .10 g
Minimi -.11 g

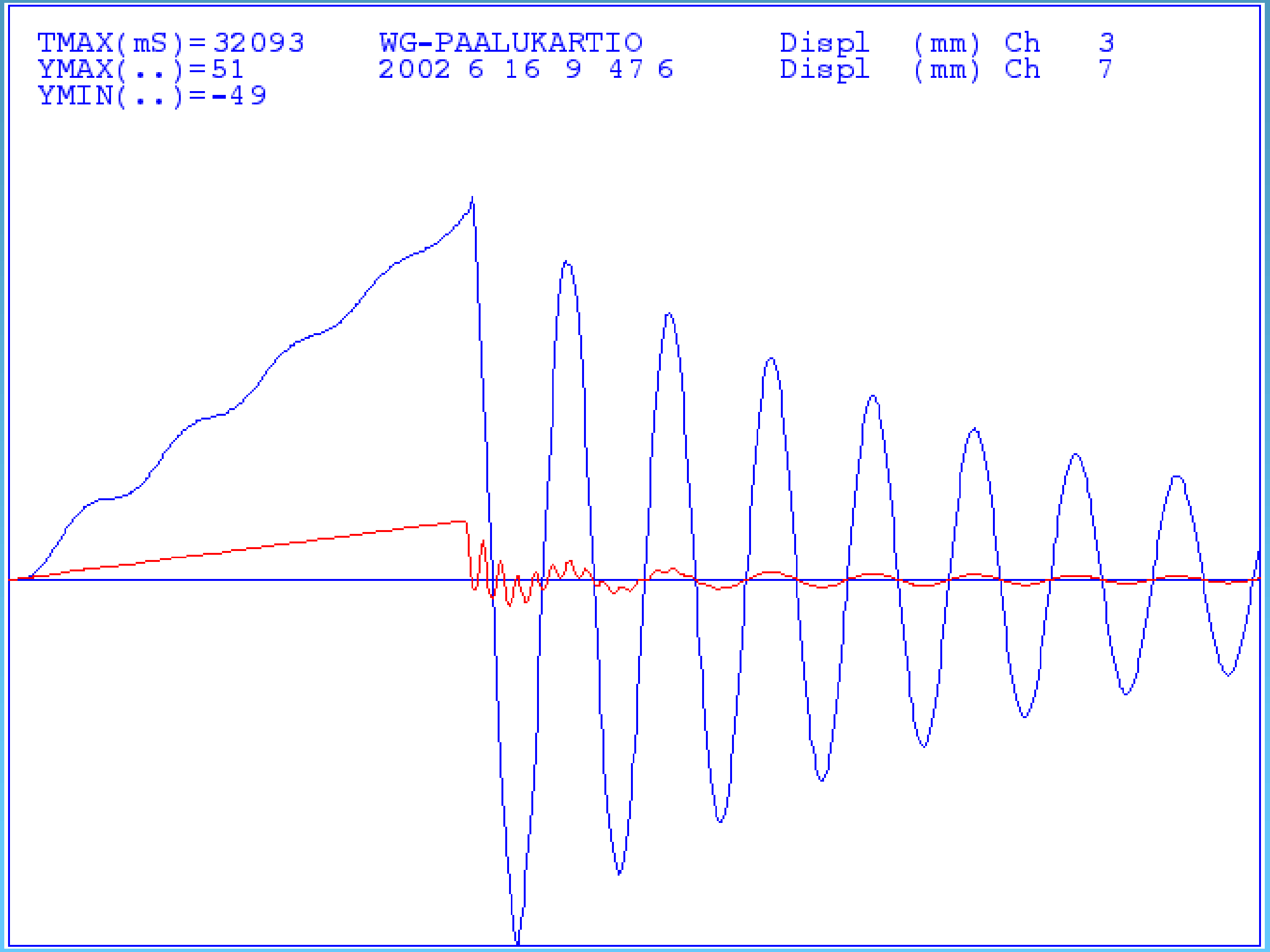
Foundation comparison

	Caisson	**Pile**
1. mode	0.41 Hz	0.38 Hz
2. mode	0.90 Hz	2.50 Hz
3. mode	3.06 Hz	6.4 Hz
4. mode	8.34 Hz	11.3 Hz
Max. displ. p.p.	37 mm	324 mm
Max acceleration	16 gal	111 gal
Static deflection	0.78 m	0.96 m

Nacelle acceleration ΔF=1.2 MN



Top and w.l. displacement ΔF=1.2 MN



Ice induced vibration mitigation

	Tran-sient	Conti-nuous	Multi-modes	Techn. feasible	Cost
Add stiffness	+	+/-	+/-	+	-
Increase mass	+	+/-	+/-	+	+/-
Add damping	≈+	+	+	-	-
Isolation	+	+	+	+	+
Mass damper	-	+	-	+	+
TLD	-	+	-	+	+
Active damping	+	+	+	-	-
Conical W.L.	+	+	+	+	-
Ice breaker	+	+	+	+	-

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Conclusions

- Versatile numerical ice-structure dynamic interaction simulation model presented.
- Ice strength vs. stress rate approach predicts similar response as measured in full-scale.
- Frequency lock-in and synchronization phenomena captured.
- Gives means to design offshore structures insensitive to ice-induced vibration