SEES 2023

Simulation and physical correlation of humidity impact on modal behavior of polymeric parts under dynamic load

2023-10-18, Filip Stenlund & Kevin Hartelius, Husqvarna, PDSL

Agenda

- Introduction – who are we?
- Problem description
- Investigation and results
- Conclusion
- Questions

Husqvarna Group in brief

World-leader in outdoor products for forest, park and garden care, as well as equipment and diamond tools for the light construction industry.

- 334 years in business
- 14,400 employees, 28 production sites
- Sales in more than 130 countries
- Net sales SEK 54bn, EBIT-margin 9%
  Market capitalization of SEK 52bn

SALES DISTRIBUTION

North America

Europe

Rest of the world

Strong brand portfolio

CORE BRANDS

Husqvarna

GARDENA

SUPPORTING BRANDS

Orbit

Flymo

Jonsered

RedMax

néta

ZENOAH

Strong, market-leading divisions

Husqvarna Forest & Garden Division

- Global leader in robotic mowers
- Global no. 2 in handheld products

Share of Group net sales LTM

SEKm 32,082

Share of Group operating income

Operating margin: 10%

Gardena Division

- Global leader in residential watering and smart garden systems
- Strong position in garden tools

Share of Group net sales LTM

SEKm 13,606

Share of Group operating income

Operating margin: 8.6%

Husqvarna Construction Division

- Global leader in power cutters
- Leader in concrete surface and floors
- Significant aftermarket and recurring business, incl. parts and diamond tools

Share of Group net sales LTM

SEKm 8,232

Share of Group operating income

Operating margin: 10.4%

Global presence

Major production facilities

Sales offices or distributors

Sales by geographical area

Europe **51%**

North America **35%**

Rest of the world **14%**

Husqvarna Group

Physical & Durability Specialist Lab (PDSL)
Shared R&D

Areas of expertise – Physical & Durability Specialist lab

- Acoustic & Noise
- Structural Dynamics
- Component test and verification
- Packaging testing
- Durability testing
- Development of accelerated test signals
- Field data measurements
- Root cause analysis
- EMC lab capacity and competence
- OND measurement and certification coordination

Centralized competence and infrastructure in specialist areas. Supports product development organization and other internal costumers.

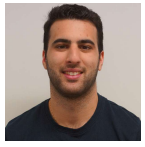
Enabling: Agility, Quality, Cost efficiency and process robustness

Sound & Noise investigations Competence Leader: Fredrik Wibling

Certifications and TC based verification Competence Leader: Henrik Karlsson

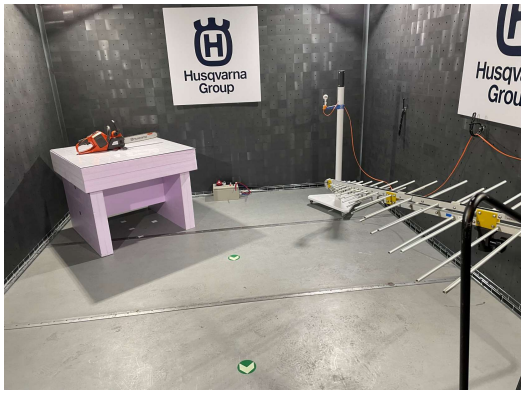
Structural dynamics and mechanics, investigation Competence Leader: Jonas Rolfart

EMC – Under development.



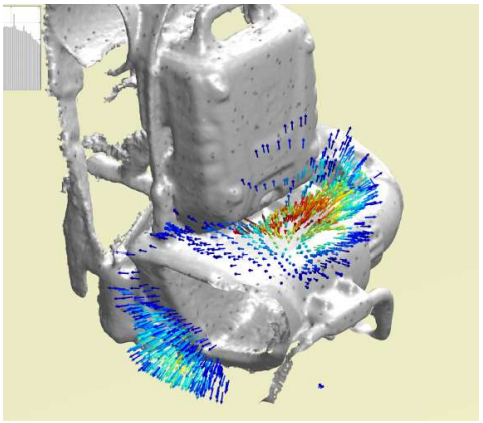
Operational Coordination
Manager Physical & Durability Specialist Lab:
Patrik Zander

Toolbox / infrastructure



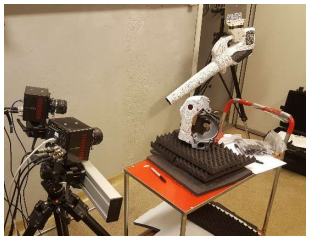
SOUND LOCALIZATION SYSTEMS

SCAN&PAINT 3D



m+p VibPilot

NI Hardware



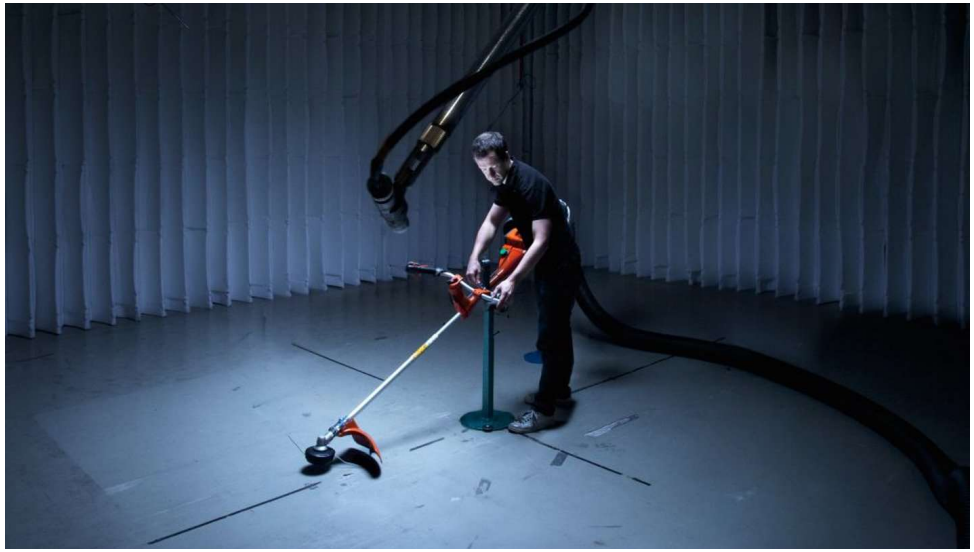
GRAS Sound & Vibration

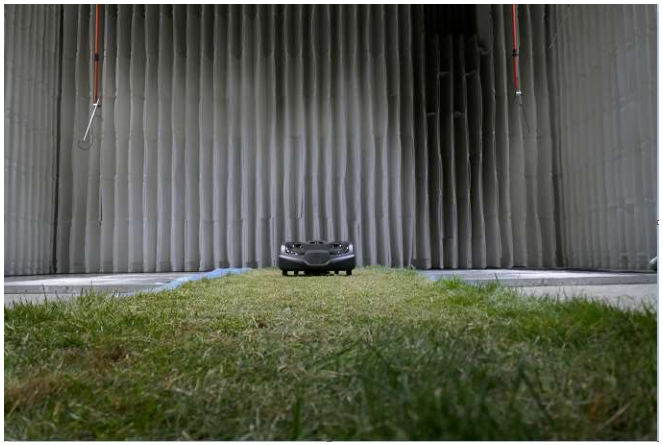
nCode

Brüel & Kjær an HBK company

Husqvarna

Toolbox / infrastructure





Toolbox / infrastructure

Problem description and background

- A recent chainsaw NPD project (New Product Development)
- At an early prototype stage, the Product Quality team complained on high vibrations at the front handle during limbing
- Request from the project:
  - Investigate this with simulation and measurements
    - Root of cause?
    - Is it going to be a problem later in the project?
    - Improvements?

Investigation process

We will briefly go through each of the 7 steps in the investigation

Initial measurement and simulation on complete product with SLS-tank (running saw)

Measurements on complete product with more sensors under SLS-tank and more simulations (running saw)

Measurements on complete product with stiffened SLS-tank (running saw)

Measurements on single SLS-tank (impact testing)

Measurements on single SLS- and PA6-tanks (impact testing, dry and conditioned)

Measurements on complete product with PA6-tank (running saw and impact test)

Measurements on complete conditioned product with PA6-tank (running saw and impact test)

Husqvarna

HUSQVARNA CHAINSAWS

WHY Husqvarna chainsaws

X-Torq®

Delivers lower fuel consumption and reduced exhaust emission levels in accordance with the world´s most stringent environmental regulations.

Air Injection®

Centrifugal air cleaning system removes larger dust and debris particles before reaching the air filter. This results in reduced air filter cleanings and improved engine life.

Husqvarna Group

X-CUT®

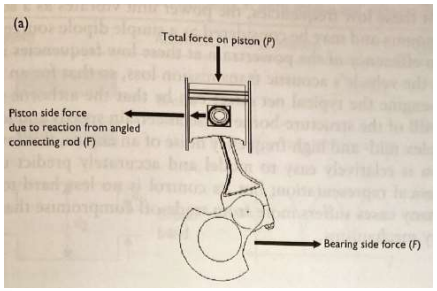
AutoTune

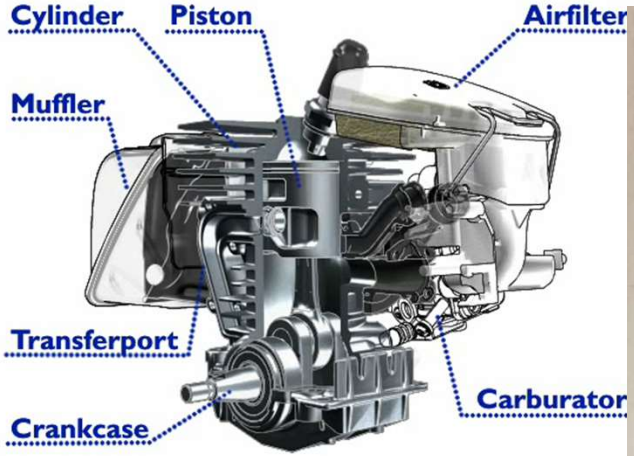
AutoTune gives optimal engine performance throughout automatic engine setting.
No time spent on carburetor adjustments. It compensates for
different fuels, altitude, humidity, temperature and clogged air filter.

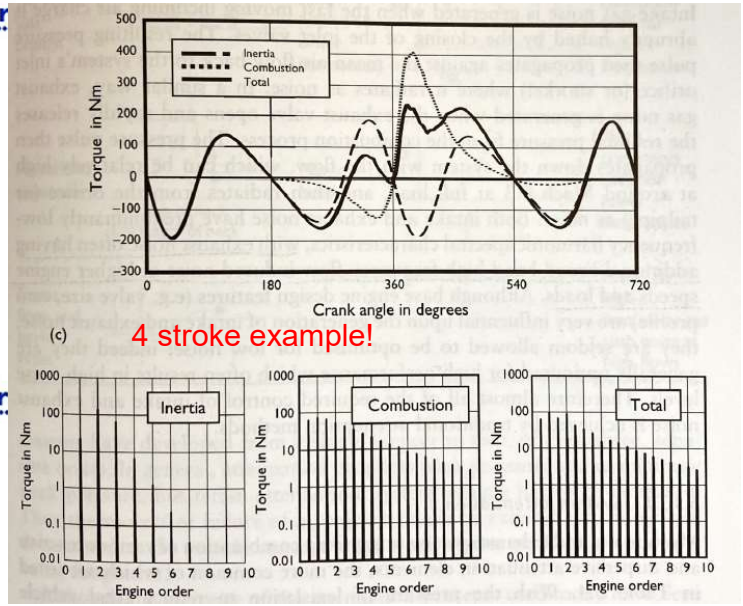
LowVib®

System designed to reduce vibration levels to the operator, which lessens fatigue.

Chainsaw – Two stroke engine



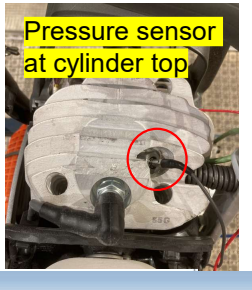


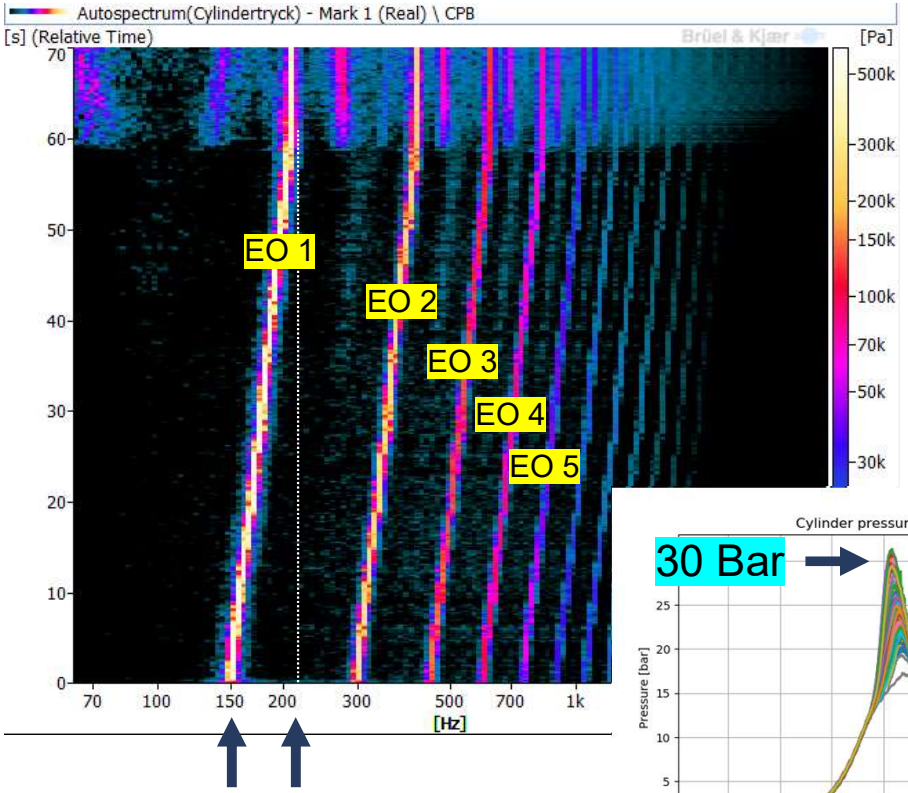


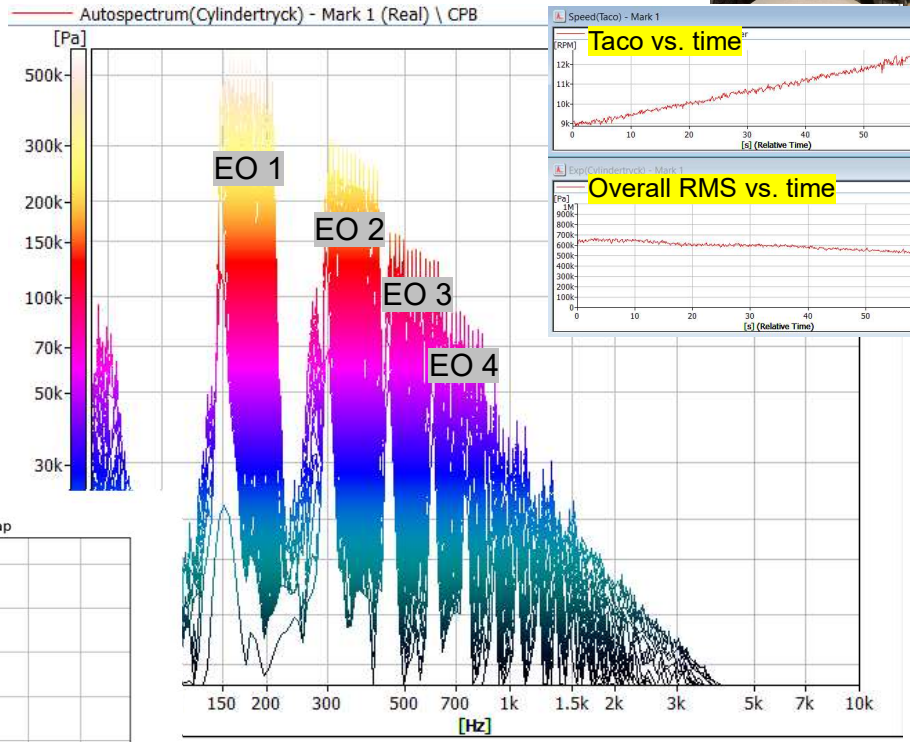
- The piston goes up and down about 230 times per second at max speed
- Strong time varying forces at the rotational speed and its overtones (engine orders) that induce vibrations
  - Frequency = number of events per unit time
  - Order = number of events per revolution
- We hold our hands on the front and rear handle at about 1 dm from the cylinder!
- AV-elements are needed to reduce the vibrations at the handles

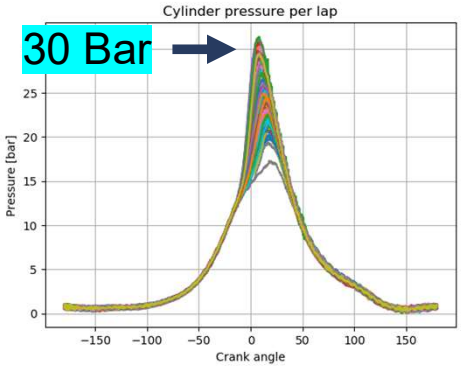
Chainsaw – Two stroke engine

Cylinder pressure during sweep (RMS-values)







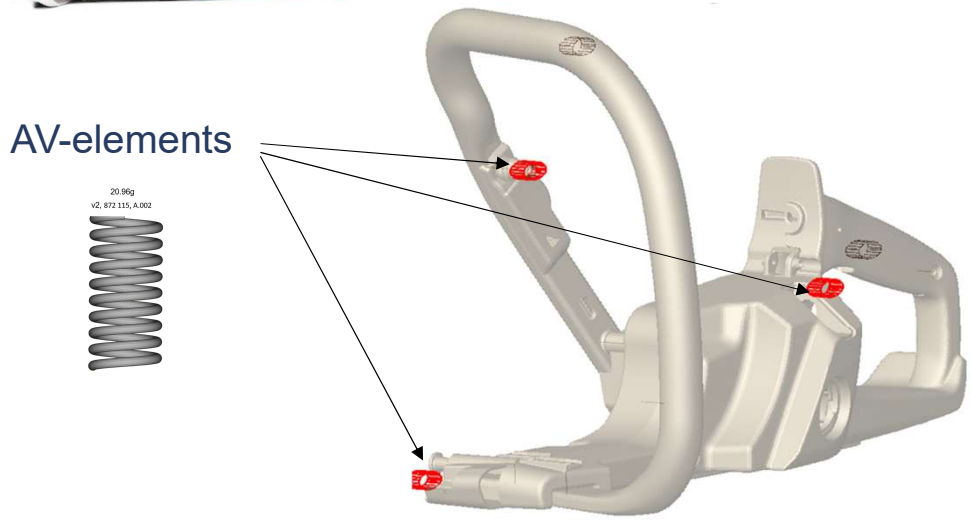


Start:
150 rps
(9000 rpm)

End:
210 rps
(12600 rpm)

Temperatures up to about 1200K in the muffler!

Chainsaw – Handle system



- The handle system is integrated with the tank
- Up to about 3000 m/s^2 (300 g) momentarily (unfiltered) on the crank case at max speed
- The handle system is isolated from the crank case with 3 AV-elements (anti vibration elements)
- The AV-elements are tuned and optimized to reduce the vibrations at the handle

Hand-arm vibrations

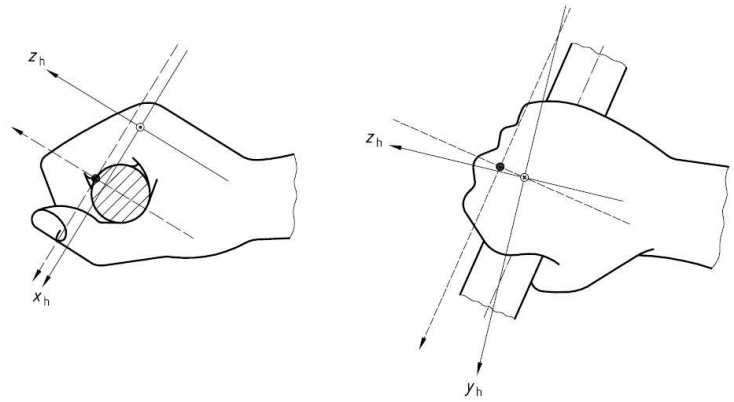
Frequency-weighted acceleration sum:

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2}$$

Daily vibration exposure (T_0=8h):

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}}$$

ISO 5349-1:2001(E)



a) "Handgrip" position (In this position, the hand adopts a standardized grip on a cylindrical bar)

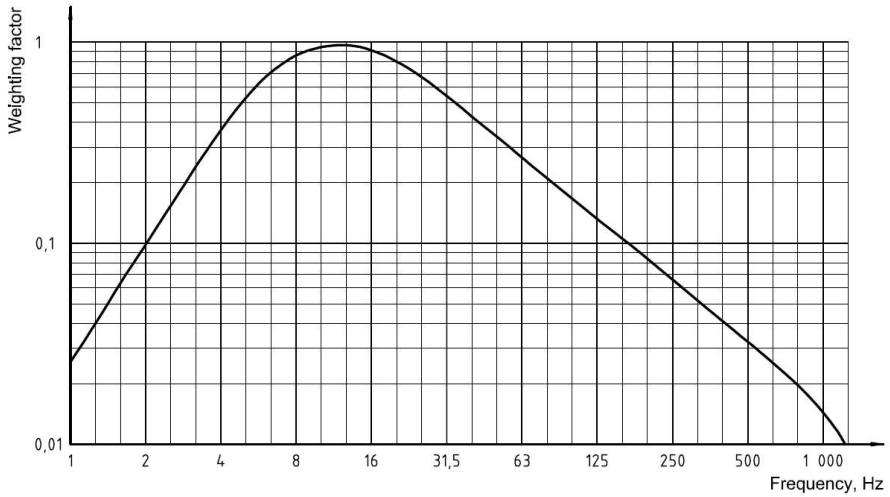


Figure A.1 — Frequency-weighting curve W_h for hand-transmitted vibration, band-limiting included

Requirements, for the employer

Directive 2002/44/EC - vibration

Latest update: 19/03/2021

of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (sixteenth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)

Objective

The Directive aims at ensuring health and safety of each worker and at creating a minimum basis of protection for all Community workers by timely detection of adverse health effects arising or likely to arise from exposure to mechanical vibration, especially musculo-skeletal disorders.

Definitions

The Directive distinguishes between vibration affecting the hand-arm-system and vibration being transmitted to the whole body.

The Directive defines exposure limit values for hand-arm-vibrations and whole-body-vibrations, respectively on basis of a standardised eight hour reference period, simulating a work day.

Additionally it defines exposure action values for both kinds of vibration, on basis of an eight hour reference period.

Article 3

Exposure limit values and action values

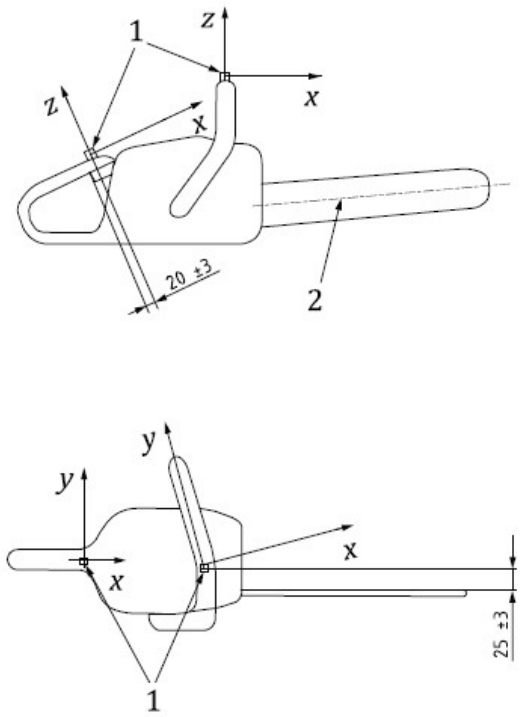
1. For hand-arm vibration:

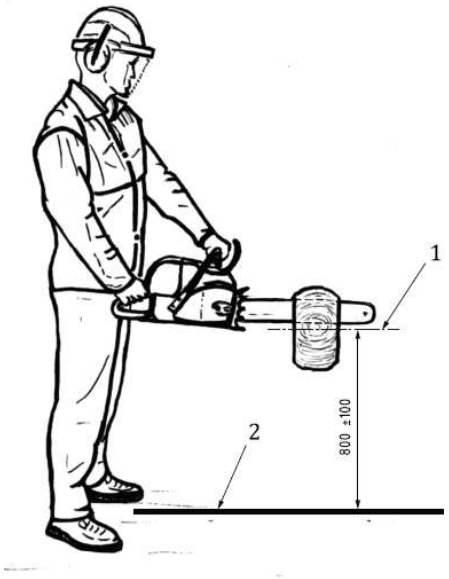
(a) the daily exposure limit value standardised to an eight-hour reference period shall be 5 m/s^2;

(b) the daily exposure action value standardised to an eight-hour reference period shall be 2,5 m/s^2.

Measurement positions and test procedure for chainsaws

EN ISO 22867:2021





A.3 Test procedure

A.3.1 General

The tests shall be carried out in the following operating modes:

a) for machines with an engine displacement of < 80 cm^3 idling, full load and racing;

b) for machines with an engine displacement of ≥ 80 cm^3 idling and full load.

During operation, the chain-saw shall be held with the guide bar centreline horizontal and the guide bar plane vertical.

A.4 Calculation of equivalent vibration total values

A.4.1 General

The equivalent vibration total values are determined by means of work cycles. These are composed of components of equal time duration where the components for chain-saws with an engine displacement <80 cm^3 are the idling, full load and racing modes and, for chain-saws with an engine displacement ≥80 cm^3, the idling and full load modes.

A.4.2 Chain-saws with an engine displacement < 80 cm^3

The equivalent vibration total value, $a_{hv,eq}$, shall be determined by Formula (A.1)

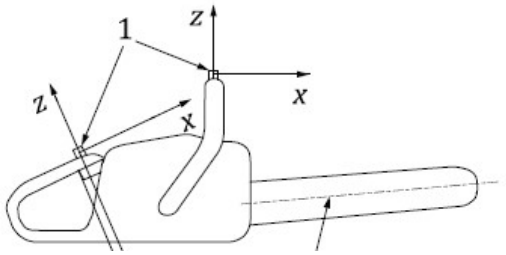
$$a_{hv,eq} = \left[\frac{1}{3}\left(\overline{a}^2_{hv,Id} + \overline{a}^2_{hv,Fl} + \overline{a}^2_{hv,Ra}\right)\right]^{1/2} \quad \text{(A.1)}$$

A.4.3 Chain-saws with an engine displacement ≥ 80 cm^3

The equivalent vibration total value, $a_{hv,eq}$, shall be determined by Formula (A.2)

$$a_{hv,eq} = \left[\frac{1}{2}\left(\overline{a}^2_{hv,Id} + \overline{a}^2_{hv,Fl}\right)\right]^{1/2} \quad \text{(A.2)}$$

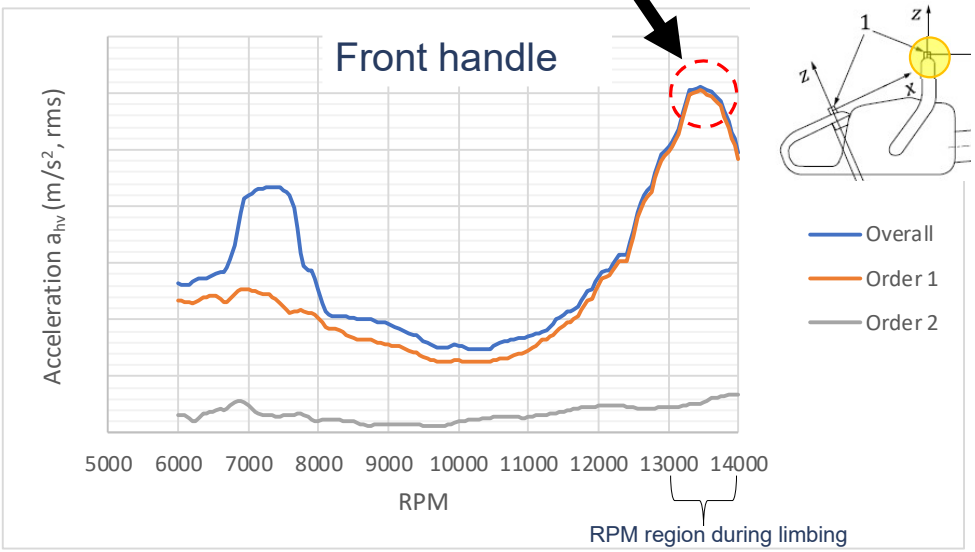
Measurement #1 – Complete product with SLS-tank, handles

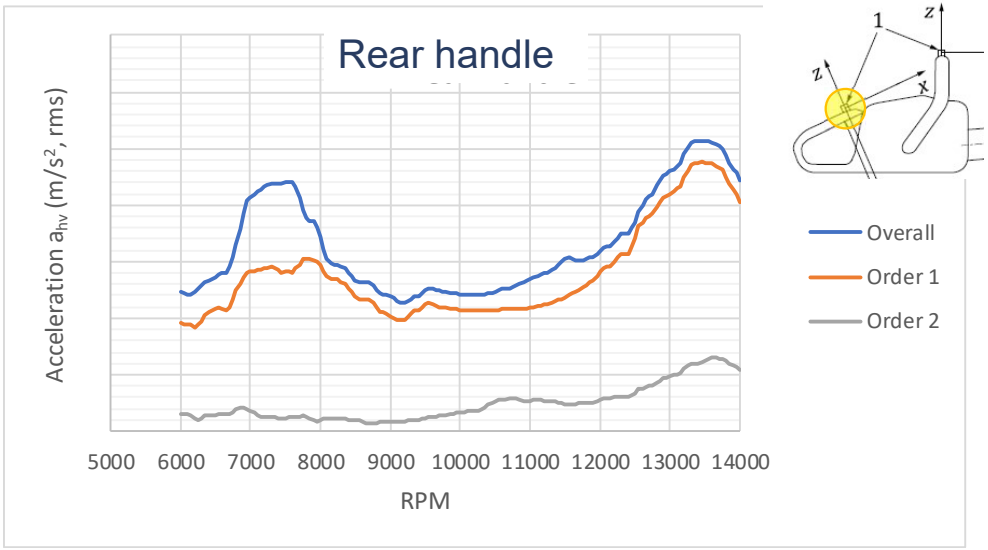


- Tank / rear handle
  - **SLS (PA 3200 GF)**
- Front handle
  - Aluminum
- Crank case / cylinder
  - Magnesium

- Relatively high vibrations on the front handle around 13500 rpm (limbing typically between 13000-14000 rpm)
- Confirms the complaints from PQ
- Engine order 1 is dominating
- Why so steep hill > 11000 rpm? SLS?

Unloaded rpm-sweep





Material data SLS (PA 3200 GF)

Glasfylld finpolyamid PA 3200 GF för EOSINT P

Användning:

PA 3200 GF är lämpligt för bearbetning i alla EOSINT P-anläggningar med finpolyamidtillval. Delar som byggs med detta material kännetecknas av ypperliga mekaniska egenskaper, mycket släta ytor och hög precision. Den rekommenderade skikttjockleken är 0,15 mm. Obestrålat pulver kan återanvändas och måste beroende på konstruktionstiden blandas med färskt pulver med fårhållandet 1:1 - 2:1 (nytt : gammalt) för konstanta bearbetningsparametrar och jämn konstruktionskvalitet.

Typiska användningsområden är kåpdelar och värmebelastade delar.

Allmänna materialdata:

Genomsnittlig grynstorlek	Laserdiffraktion	60	µm
Skrymdensitet	DIN 53466	0,59 – 0,62	g/cm³
Densitet lasersintrat	EOS-metod	1,23 - 1,28	g/cm³

Mekaniska fakta:*

Drag-E-modul	DIN EN ISO 527	3200 ± 200	N/mm²
Draghållfasthet	DIN EN ISO 527	48 ± 3	N/mm²
Dragexpansion	DIN EN ISO 527	6 ± 3	%
Böjnings-E-modul	DIN EN ISO 178	2100 ± 150	N/mm²
Charpy-slaghållfasthet	DIN EN ISO 179	35 ± 6	kJ/m²
Charpy-slaghållfasthet skårad	DIN EN ISO 179	5,4 ± 0,6	kJ/m²
Izod-slaghållfasthet	DIN EN ISO 180	21,3 ± 1,7	kJ/m²
Izod-slaghållfasthet skårad	DIN EN ISO 180	4,2 ± 0,3	kJ/m²
Kultryckshårdhet	DIN EN ISO 2039	98	
Shore D-hårdhet	DIN 53505	80 ± 2	

50% GF

Cond
2.5 GPa

Dry
3.2 GPa

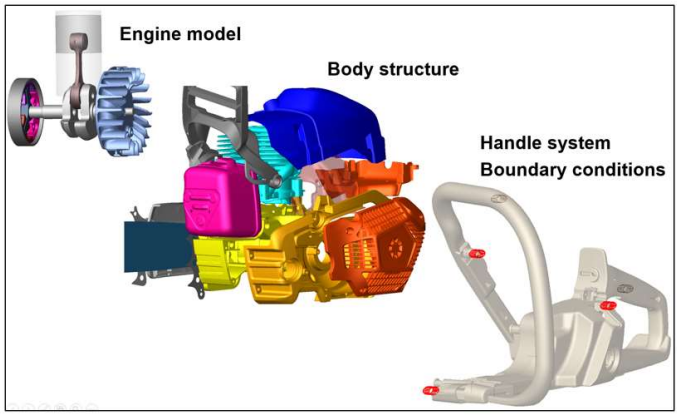
PROPERTY	VALUE
MODULUS OF ELASTICITY	2.5 – 3.2 GPa
FLEXURAL MODULUS	2.9 GPa
DENSITY	1.22 kg/dm³
HEAT DEFLECTION TEMPERATURE (HDT)	96 – 157 °C
MELTING TEMPERATURE	176 °C
VICAT SOFTENING TEMPERATURE	166 – 179 °C

Simulation

Model description

The structure dynamics model consists of a rotating crank system, all parts modelled as flexible bodies with connections and the handle system connected to ground by a simplification of the operator's hands.

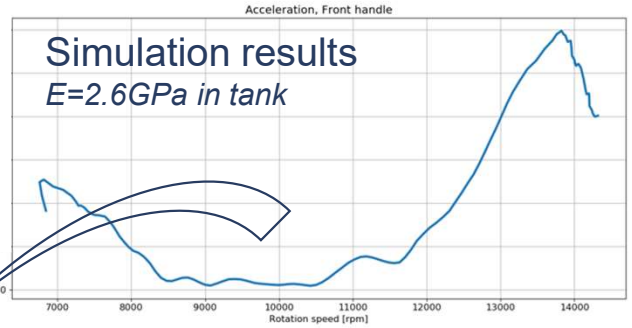
Input is cylinder pressure curves, and the model is adjusted to physical power curves.

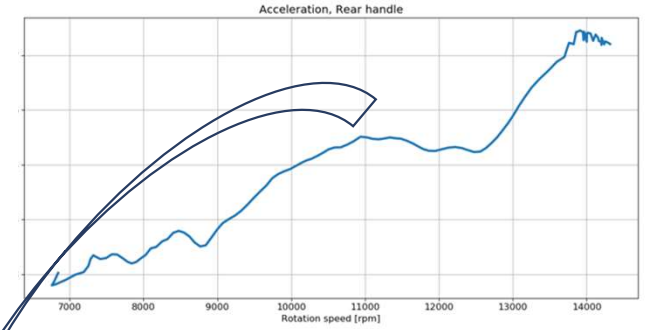


- The model is built in MSC Adams (multibody simulation) with rotating system and ignition as load where we describe a running rpm-sweep
- AV-elements and a theoretical hand-arm model is included as boundary conditions
- Calculations are made in MSC Nastran (FEM) and a simple modal analysis of the handle system
- One challenge is always the E-module, damping and describing the connections correctly

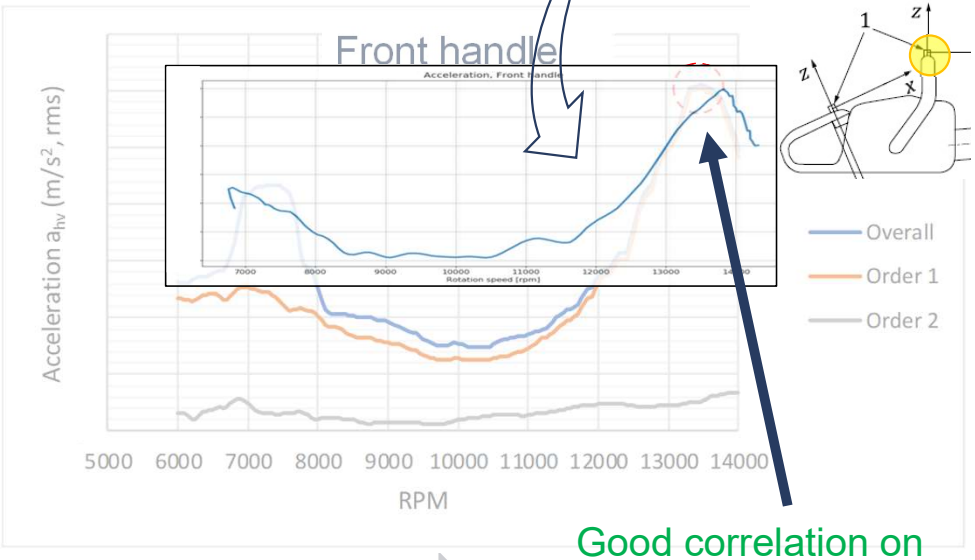
Simulation vs. measurement

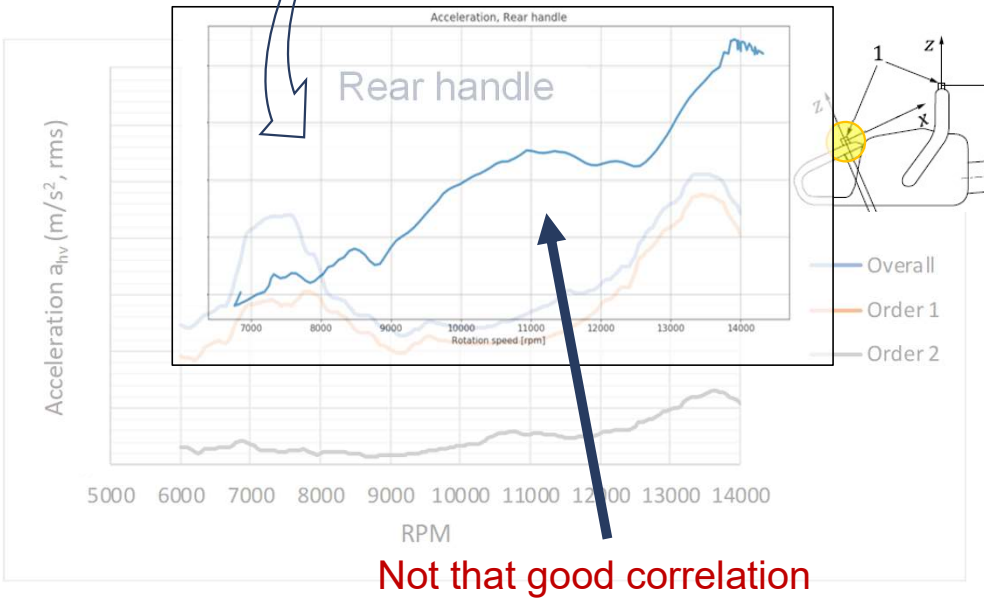
Move on with more measurements





Unloaded rpm-sweep

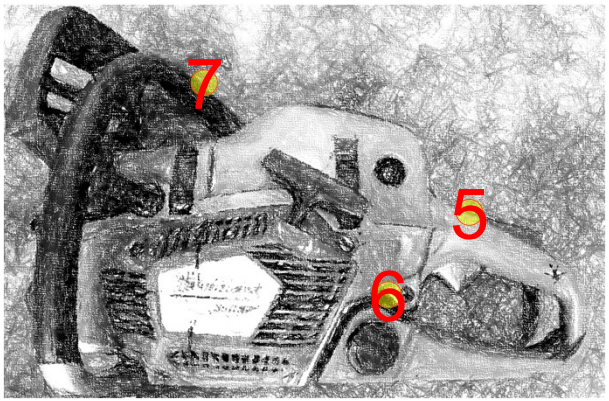


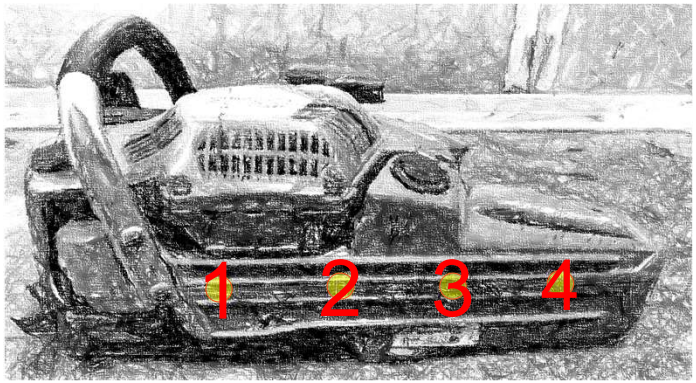


Good correlation on front handle at high rpm

Not that good correlation on rear handle

Measurement #2 – Complete product with SLS-tank, additional accelerometer under the SLS-tank

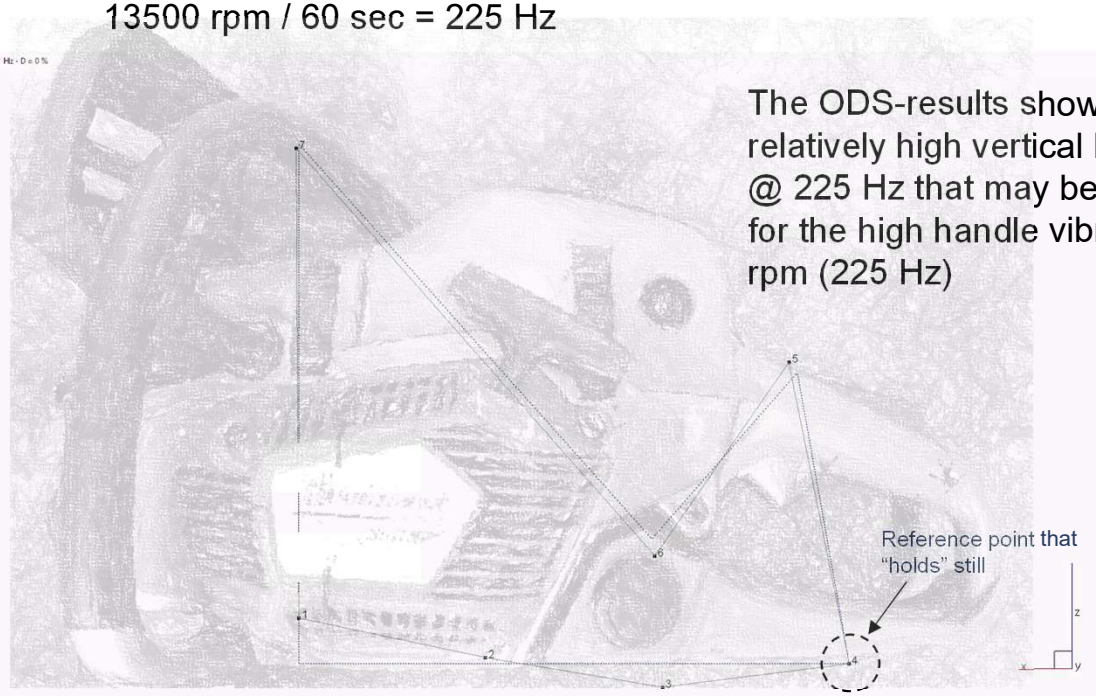




- Added more accelerometers under the tank in two directions (vertical and transversal)
- Want to see the Operational Deflection Shape (ODS) at higher speeds

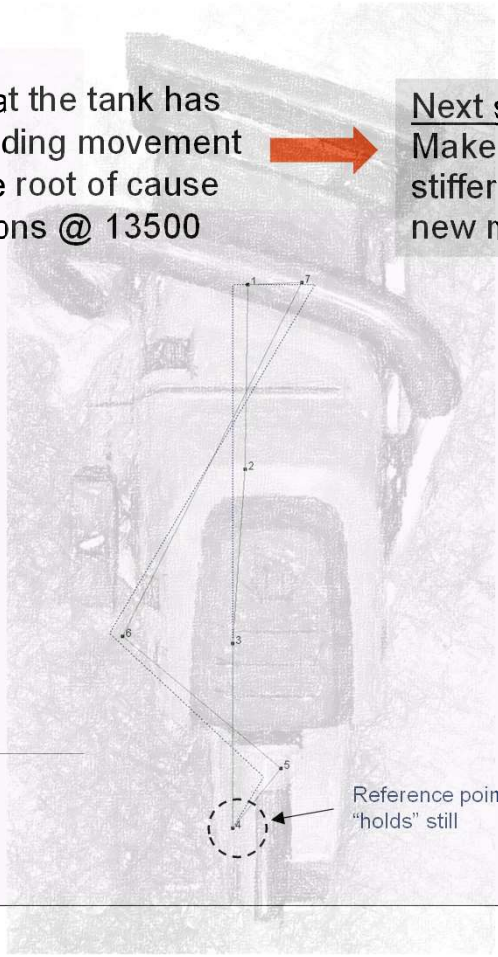
Measurement #2 – ODS @ 13500 rpm

13500 rpm / 60 sec = 225 Hz



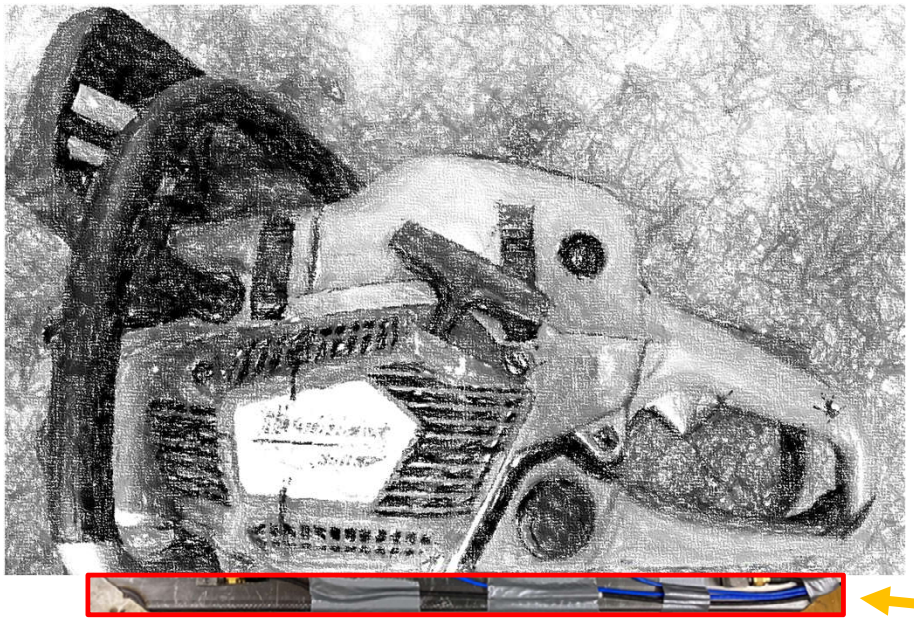
The ODS-results show that the tank has relatively high vertical bending movement @ 225 Hz that may be the root of cause for the high handle vibrations @ 13500 rpm (225 Hz)

Next step:
Make the tank much stiffer and perform new measurements



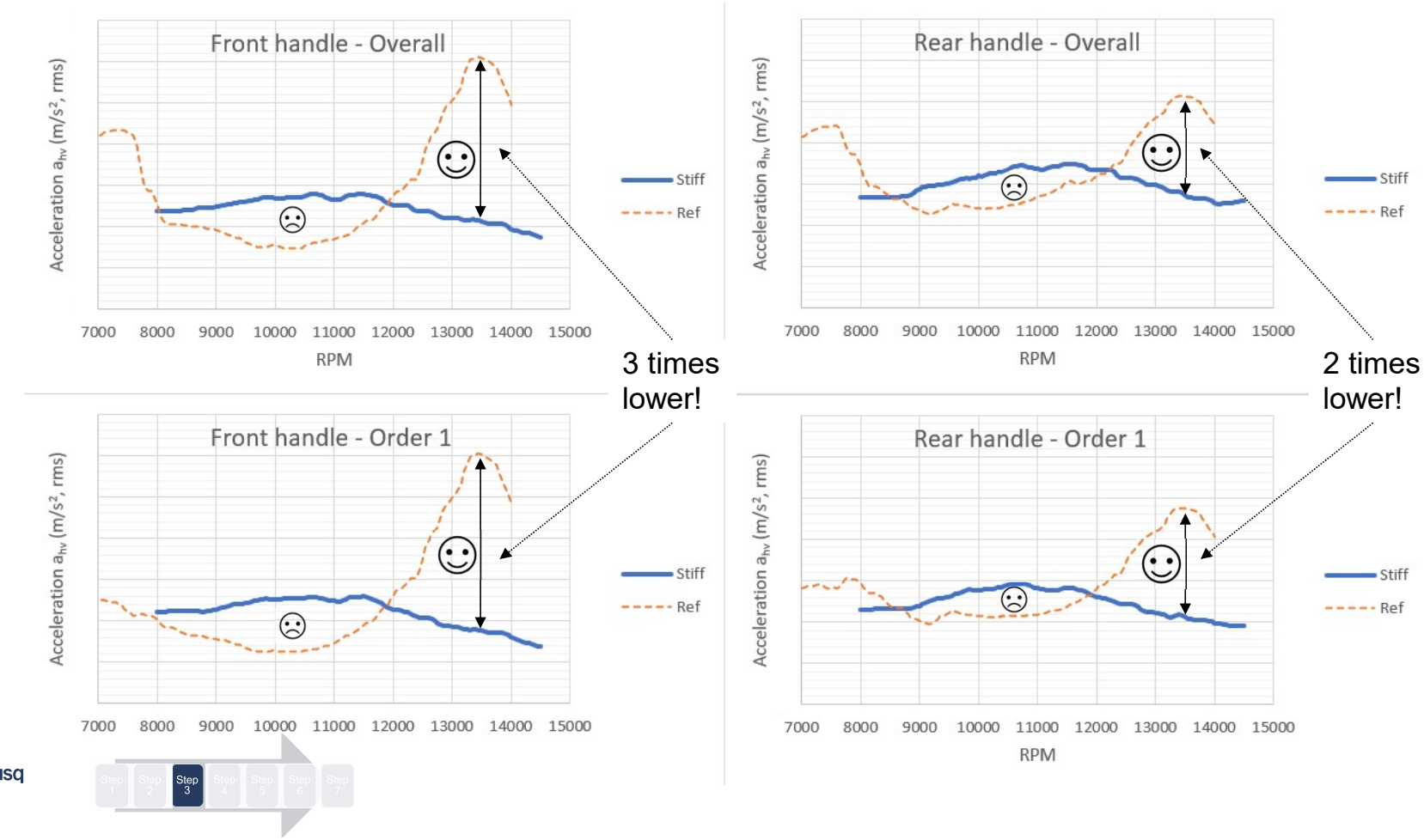
Simulation – Mode shape of the 1st vertical bending resonance

Measurement #3 – Complete product with stiffened SLS-tank



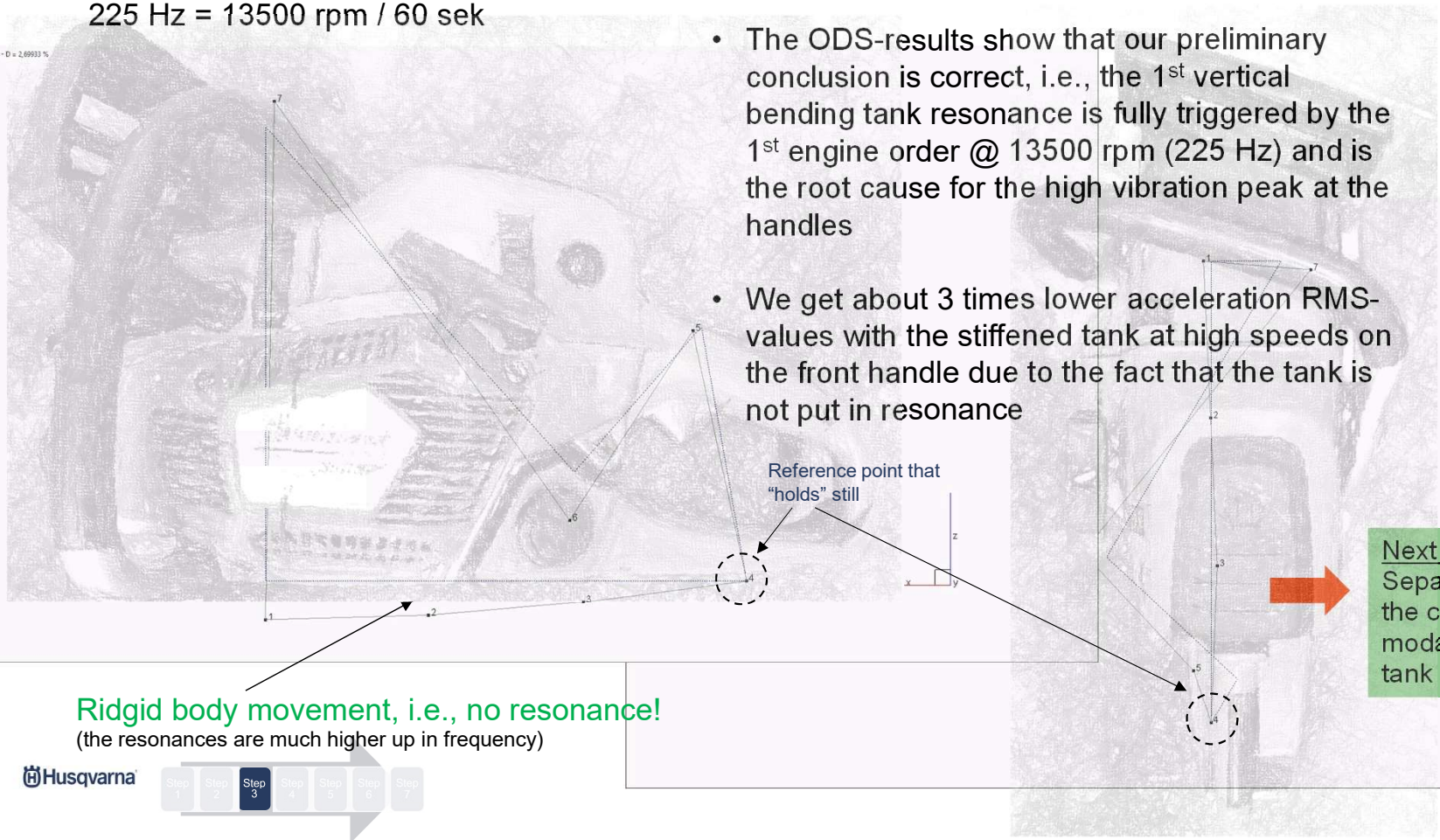
- Same accelerometer setup as measurements #2
- Steel bar (box girder) glued and screwed under the tank (extreme stiff case)

Measurements #3 – Stiffened (stiff) vs. reference (ref)



Measurement #3 – ODS @ 225 Hz, stiffened

225 Hz = 13500 rpm / 60 sek



- The ODS-results show that our preliminary conclusion is correct, i.e., the 1st vertical bending tank resonance is fully triggered by the 1st engine order @ 13500 rpm (225 Hz) and is the root cause for the high vibration peak at the handles
- We get about 3 times lower acceleration RMS-values with the stiffened tank at high speeds on the front handle due to the fact that the tank is not put in resonance

Reference point that "holds" still

Ridgid body movement, i.e., no resonance!
(the resonances are much higher up in frequency)

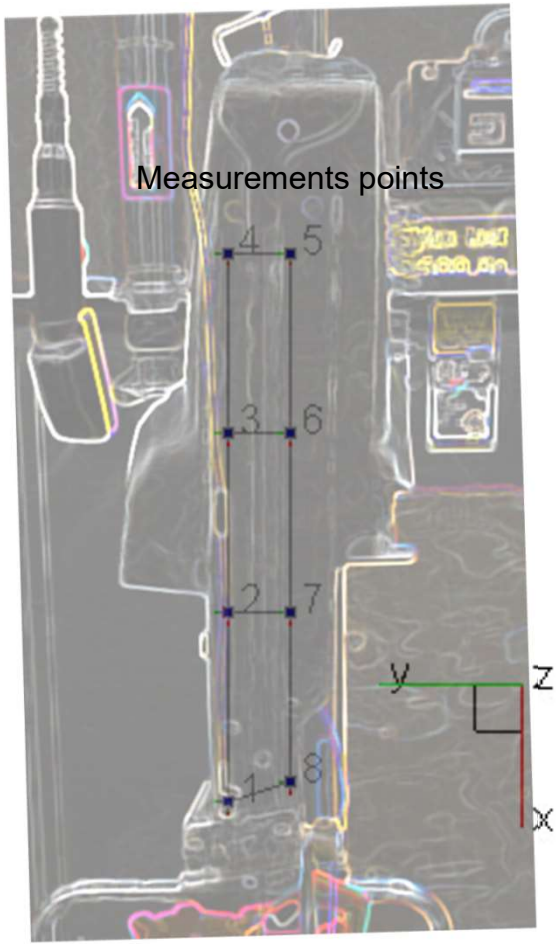
Next steg:
Separate the SLS-tank from the chainsaw and make a modal analysis on the SLS-tank alone

Husqvarna

Step 1 | Step 2 | Step 3 | Step 4 | Step 5 | Step 6 | Step 7

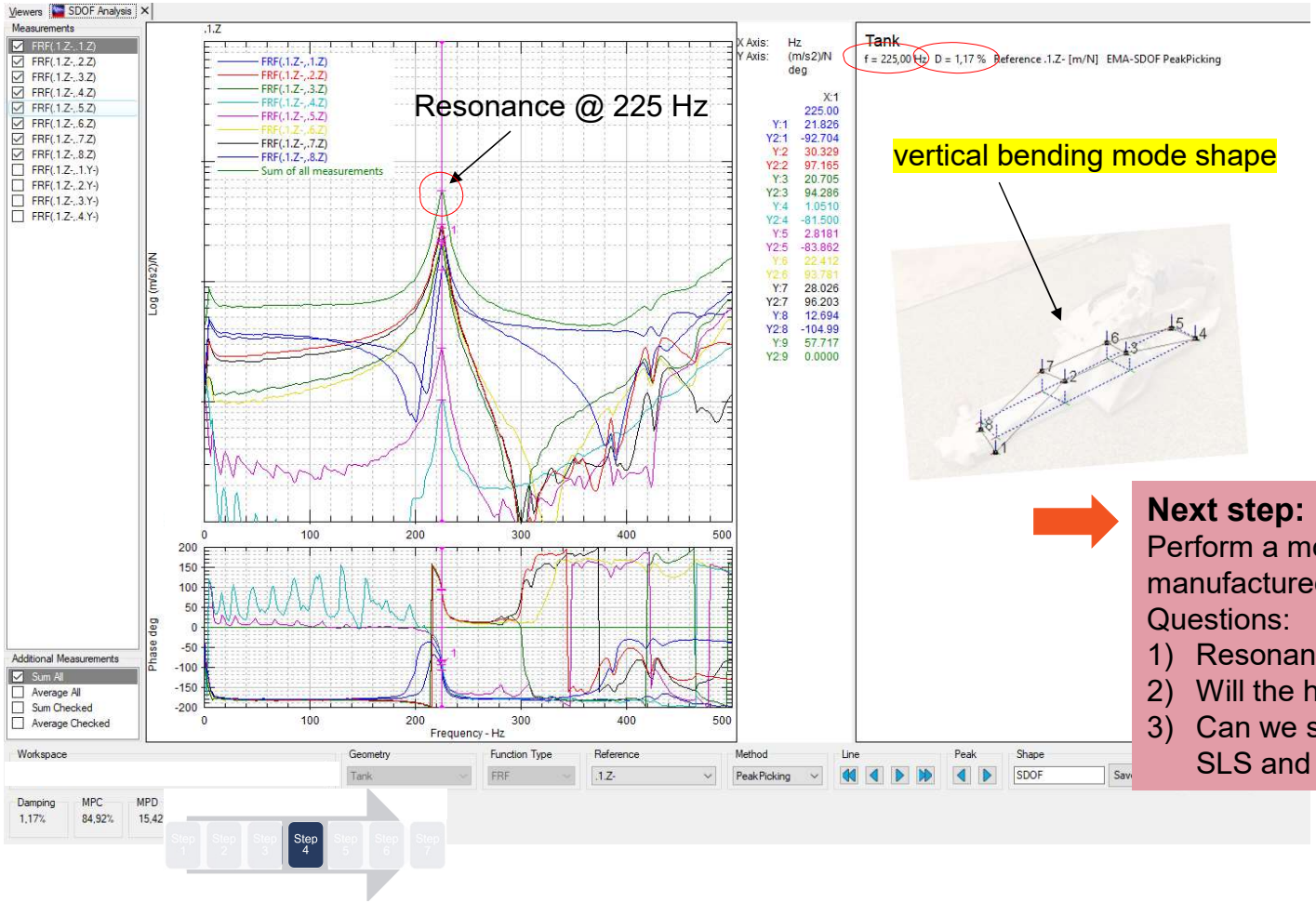
Measurement #4 – single SLS-tank

Freely suspended with spring and rubber bands (≈ 4 Hz)



- Impact testing on single SLS-tank
- Transient impacts with force hammer in each measurement points
- Accelerometer in point 1
- Force and response in Z-dir och Y-dir

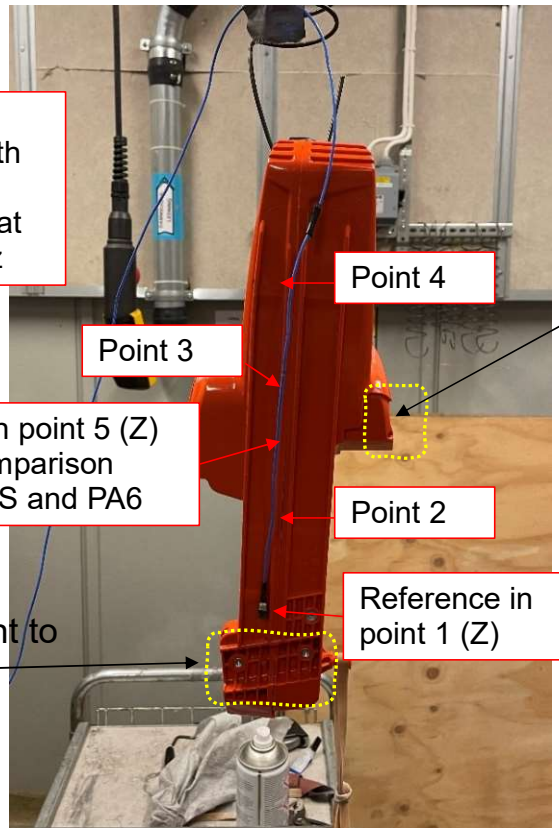
Measurement #4 – FRF and mode shape (single SLS-tank)



- Vertical bending resonance @ 225 Hz
  - Same resonance frequency identified earlier with running chainsaw!
    - The tank seem to be unaffected by other connected chainsaw parts at 225 Hz (uncoupled by the AV-elements…)

Next step:
Perform a modal analysis on the first manufactured tank in PA6
Questions:
1) Resonance frequency and damping?
2) Will the handle vibrations be lower?
3) Can we see general differences between SLS and PA6?

Measurement #5 – single PA6-tanks



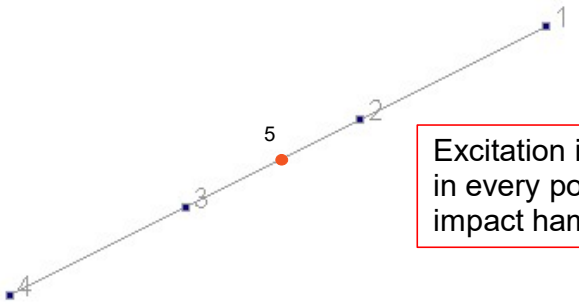
Free-free condition with highest rigid body mode at around 5 Hz

Reference in point 5 (Z) used for comparison between SLS and PA6

Connection point to front handle

Connection point to front handle in the middle of the tank where the movement at resonance is the strongest…

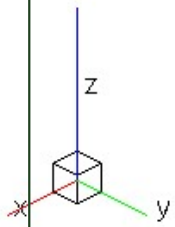
Geometry



Excitation in Z direction in every point using impact hammer.

setup 1 = punkt 1, 2, 3, 4 with ref-acc in point 1 (*acc close to node point → low amplitude, hard to estimate the damping factor)*

setup 2 = punkt 1, 2, 3, 4, 5 where ref-acc in point 5 (acc *in the middle → high amplitude, easier to estimate the damping factor*)



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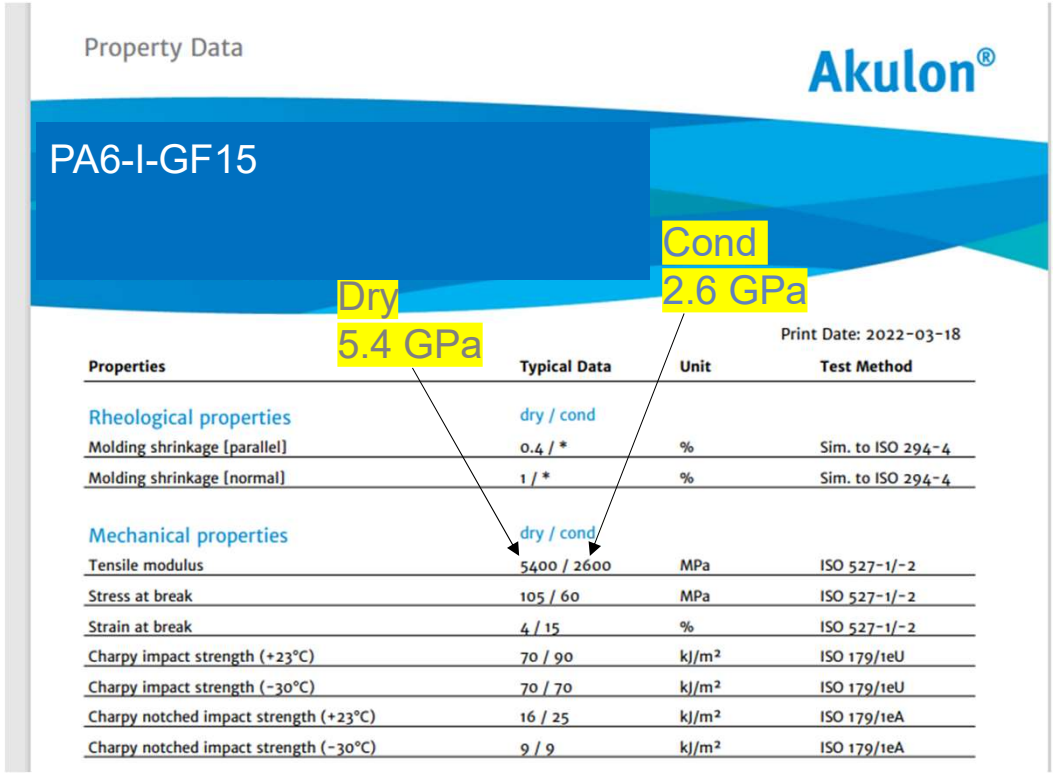
Material data PA6



Property Data

Akulon®

PA6-I-GF15

Dry
5.4 GPa

Cond
2.6 GPa

Print Date: 2022-03-18

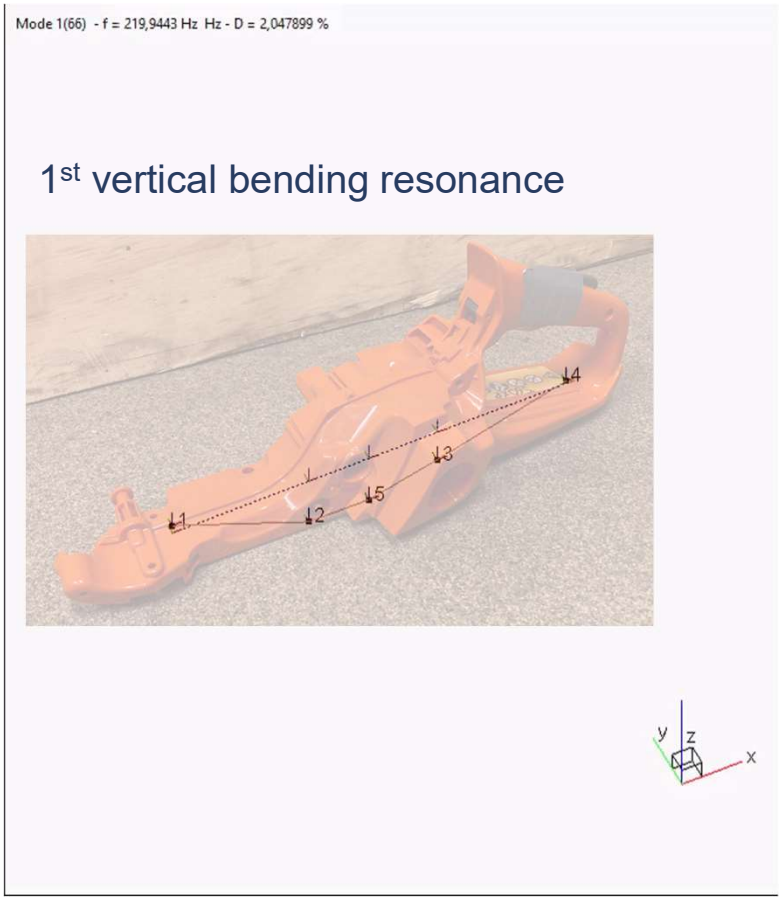
Properties	Typical Data	Unit	Test Method
Rheological properties	dry / cond		
Molding shrinkage (parallel)	0.4 / *	%	Sim. to ISO 294-4
Molding shrinkage (normal)	1 / *	%	Sim. to ISO 294-4
Mechanical properties	dry / cond		
Tensile modulus	5400 / 2600	MPa	ISO 527-1/-2
Stress at break	105 / 60	MPa	ISO 527-1/-2
Strain at break	4 / 15	%	ISO 527-1/-2
Charpy impact strength (+23°C)	70 / 90	kJ/m²	ISO 179/1eU
Charpy impact strength (-30°C)	70 / 70	kJ/m²	ISO 179/1eU
Charpy notched impact strength (+23°C)	16 / 25	kJ/m²	ISO 179/1eA
Charpy notched impact strength (-30°C)	9 / 9	kJ/m²	ISO 179/1eA

Measurements #5 - Conditioning in climate chamber

- Why?
  - Examine the materials ability to absorb water
  - Investigate the affect on resonance frequency and damping factor (for the 1st vertical bending resonance) and thereby also indirect the handle vibrations at different climates
- Tanks in the climate chamber for 72 hours with a temperature of 70°C and 99%rH (accelerated conditioning)

Measurements #5 – Test cases

1. Before conditioning
   - Note! different manufacturing dates → different amount of absorbed moisture initially
2. After conditioning
   - 18h after in room condition for cooling
   - Then 72h-interval in room condition to see if the material releases any moisture back to the air



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Step 1 Step 2 Step 3 Step 4 Step 5 Step 6 Step 7

Measurement #5 – Identified bending resonance and damping

Large changes in tank properties before and after conditioning (both SLS and PA6) → important to know!

SLS

Object #	Material	Measurement date	Manufacturing date	Setup	Conditioning	Identified 1st vertical bending resonance	
						Frequency, f_0 (Hz)	Damping ratio, D (%)
7	SLS	2022-06-09	?	1	Before	225	1,2
7	SLS	2022-07-25	?	1	Before	223	1,5
9	SLS	2022-09-01	2022-08-30	2	Before	245	1,4
7	SLS	2022-08-19	?	2	After 18h	172	4,0
7	SLS	2022-08-22	?	2	After 18+72h	184	4,3

Condition at earlier measurements on whole chainsaw with SLS-tank! Low damping → high vibrations

Higher damping ratio for PA6 before conditioning

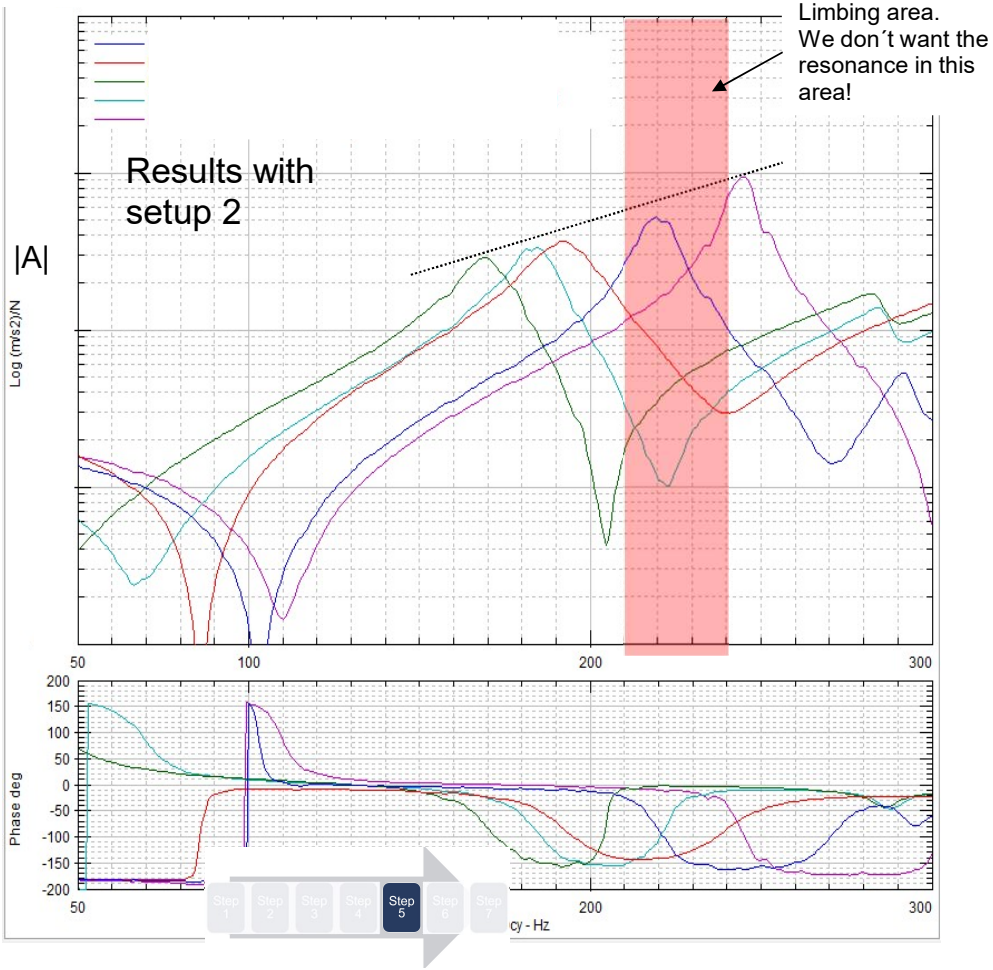
SLS and PA6 is very similar with respect to both resonance frequency and damping (extreme conditioning case!)

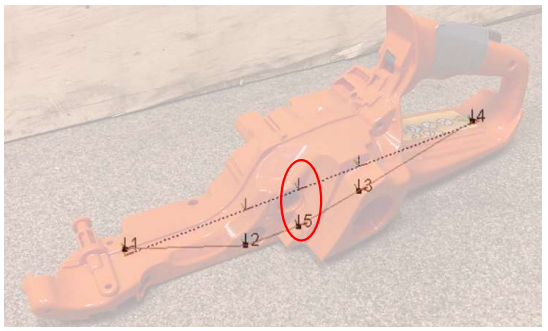
PA6

Object #	Material	Measurement date	Manufacturing date	Setup	Conditioning	Identified 1st vertical bending resonance	
						Frequency, f_0 (Hz)	Damping ratio, D (%)
2	PA6	2022-07-25	2022-06	1	Before	242	3,1
2	PA6	2022-07-29	2022-06	1	After 18h	174	4,1
2	PA6	2022-08-01	2022-06	1	After 18+72h	184	4,4
2	PA6	2022-08-04	2022-06	1	After 18+144h	185	4,1
2	PA6	2022-08-10	2022-06	1	After 18+288h	194	4,7
2	PA6	2022-08-10	2022-06	2	After 18+432h	193	5,0

Looks good (high damping), but when is it going to be saturated and what happens with the damping?

Measurement #5 – FRF results





- FRF = Frequency Response Function, i.e., the frequency response normalized with the input force 1 Newton
- Note that the resonance frequency is drastically lower directly after the conditioning and then starts to walk up again with time
- Note that the amplitude |A| is lower after conditioning because the mass is increased (more water in the material) and that the internal friction losses in the material is increased (damping)

Measurement #5 - Summary

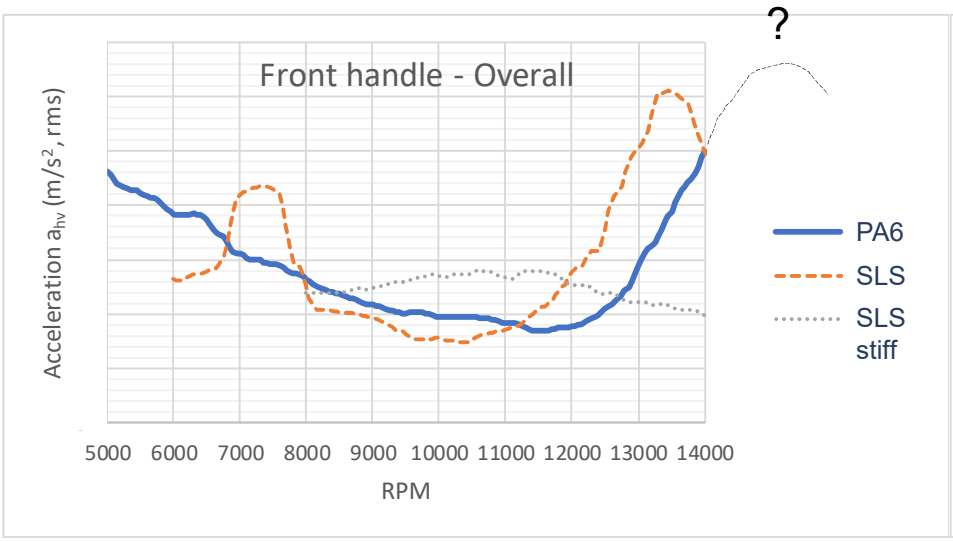
- The 1st vertical bending resonance frequency of the new PA6-tanks is identified between 170 to 245 Hz depending on the amount of water, which is not a desirable frequency region due to limbing
- However, the damping ratio for the new PA6-tanks are generally higher than SLS-tanks, at least before conditioning (dry condition), which gives lower handle vibrations
- Big difference in resonance frequency before and after conditioning for both SLS- and PA6-tanks
  - Handle vibrations will therefore also differ depending on the environment, location and time of year
  - Important to know the conditions to draw right conclusions and make relevant comparisons etc.
  - Can we find a reference state with the climate chamber?

- **Next step**: Sweep measurements on the chainsaw handles on complete product with the correct PA6-tank

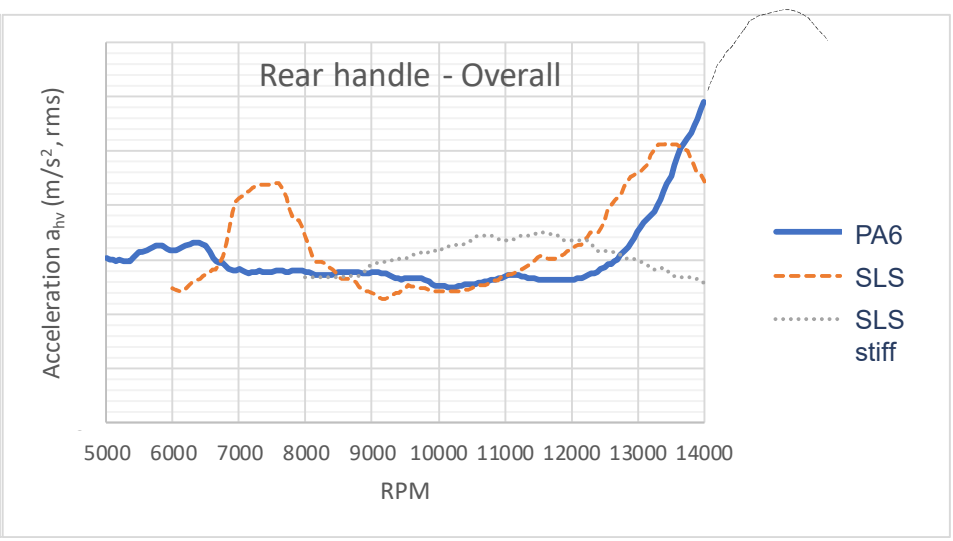
Measurement #6 – Complete product with PA6-tank

Measurement #6 – Sweep, overall

?



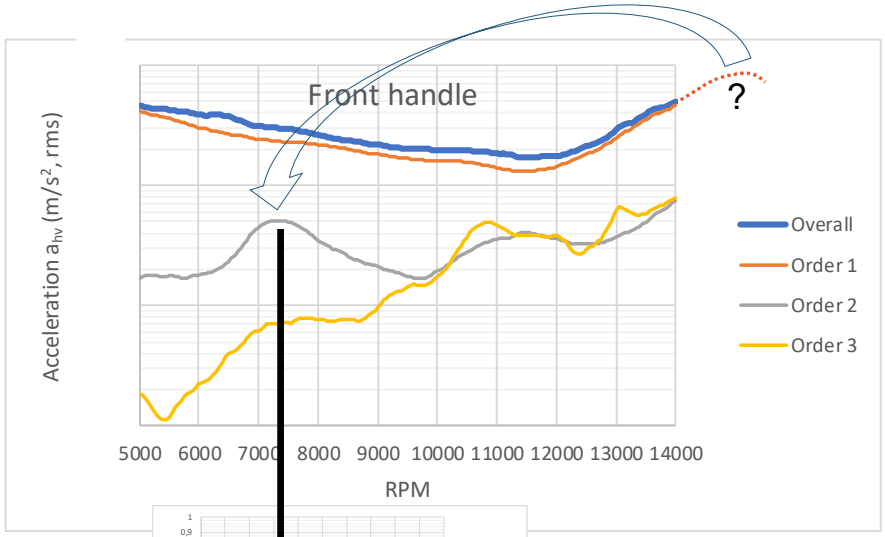
?

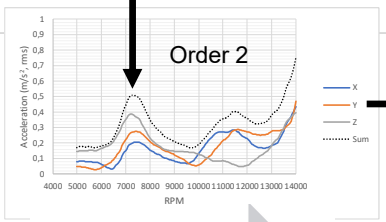


What happens if the resonance frequency is lowered to the limbing area? Problem?

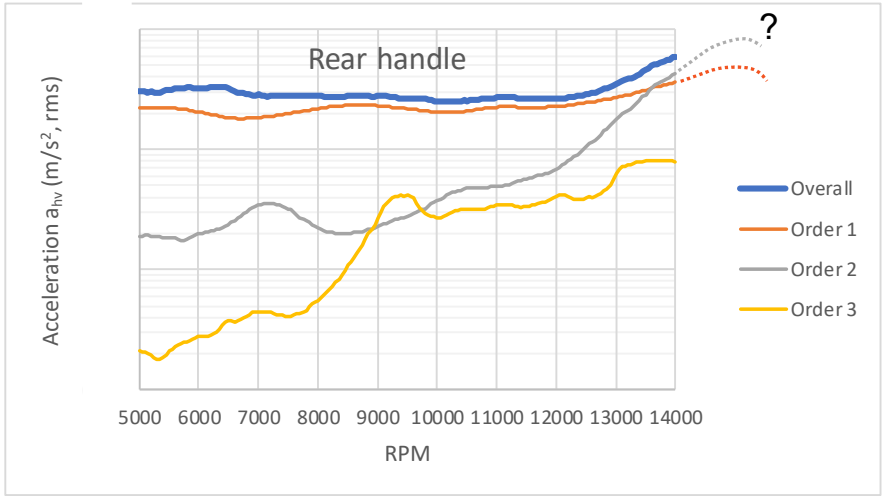
Measurement #6 – Sweep, order analysis

Logarithmic scale

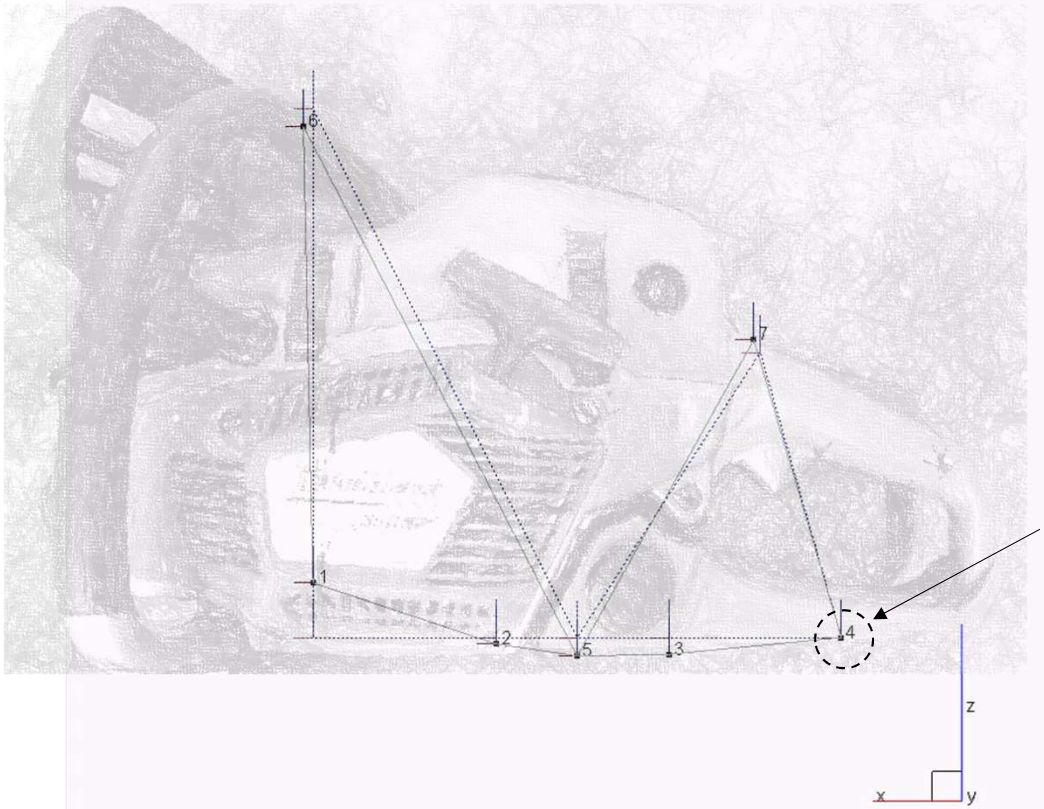




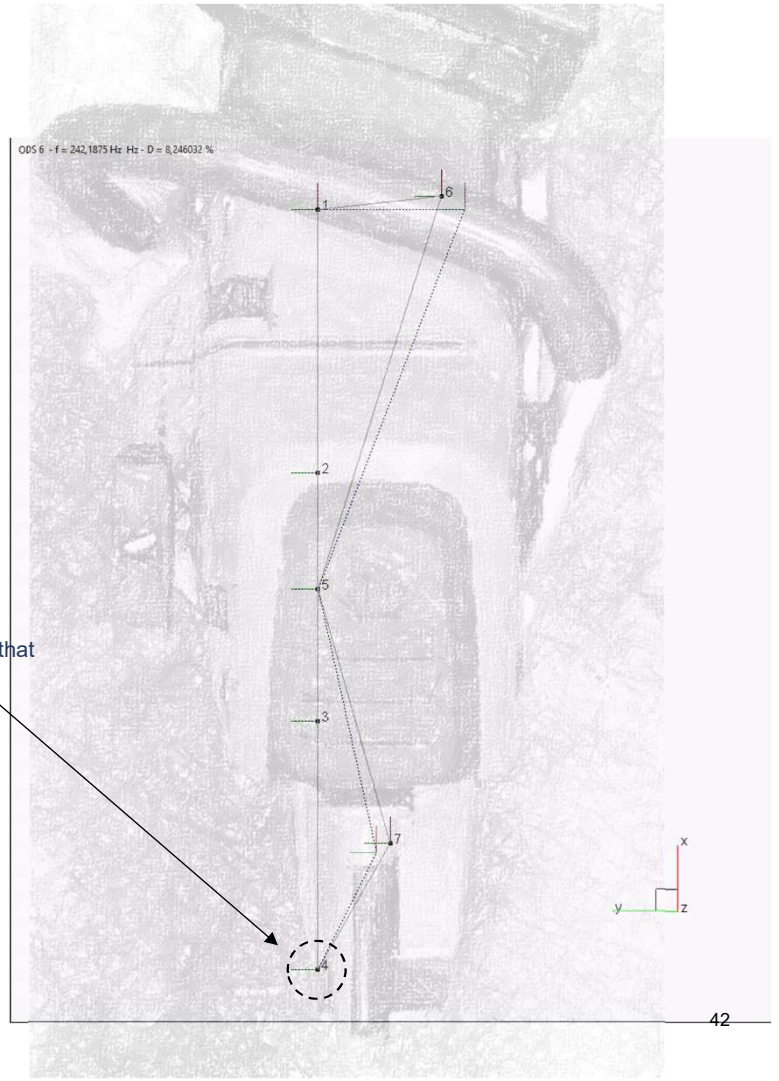
7250 rpm =
7250*2/60
= 242 Hz



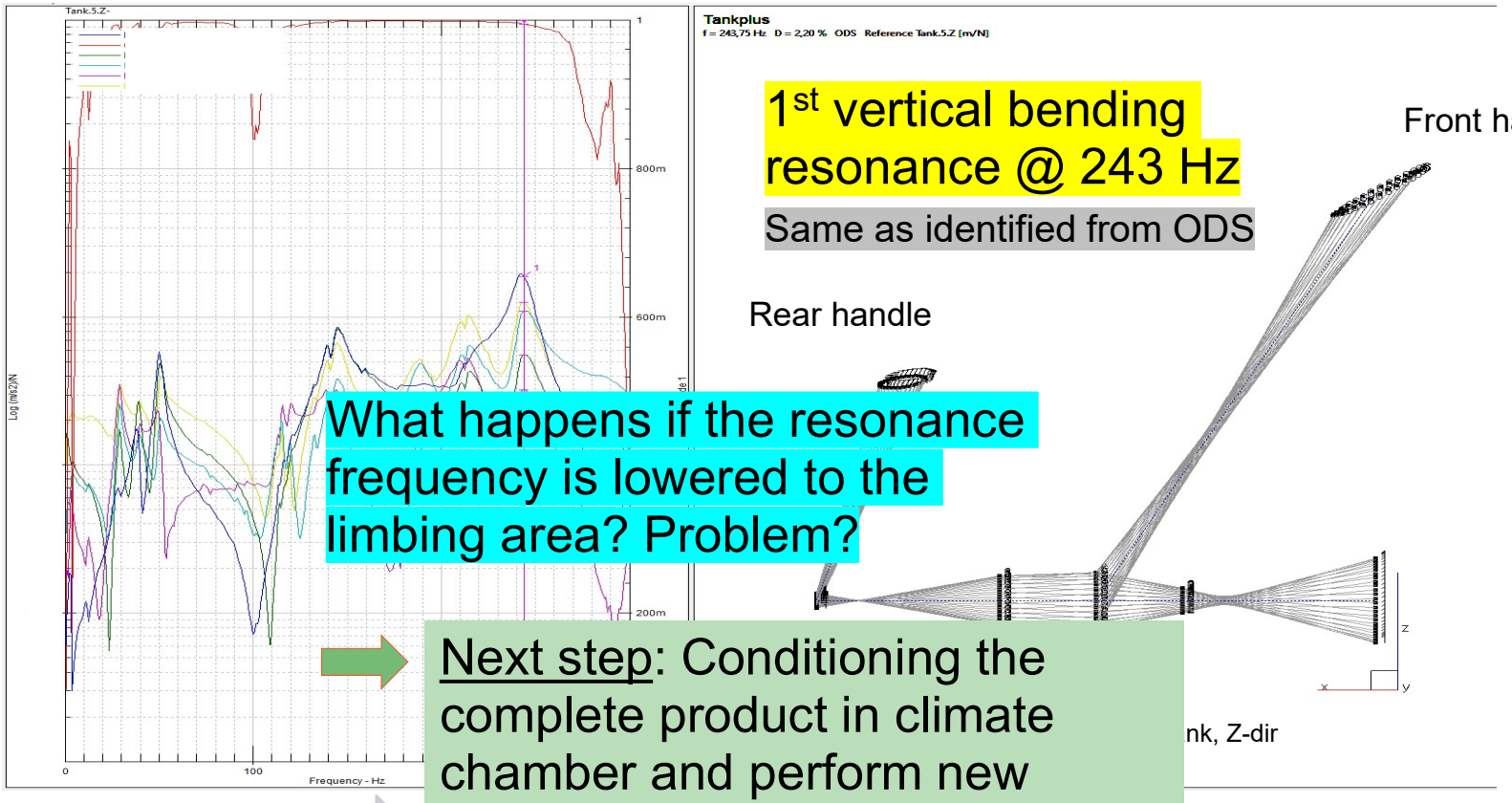
Measurement #6 – ODS @ 242 Hz



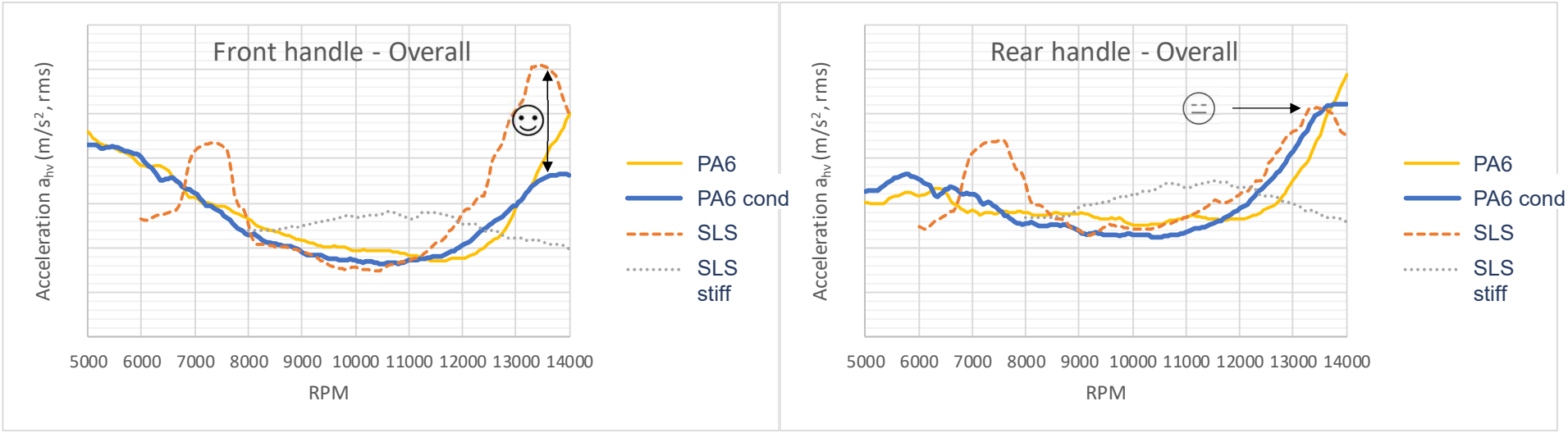
Reference point that "holds" still



Measurement #6 – Impact test on complete product



Measurement #7 – Sweep, overall, conditioned saw (**PA6 cond**)



- Conditioning 140h in climate chamber at 70°C and 62%rH to lower the resonance frequency to the limbing area
- The resonance frequency is lowered from 242 Hz to 233 Hz (=14000rpm for the 1st engine order), which is also verified with impact testing
- The vibration amplitude is much lower on the front handle with PA6 cond than with SLS due to a higher internal material damping in PA6 cond
- All together it looks quite good, and we believe that PQ will approve this chainsaw when field testing

Final comments and conclusion

- PQ did approve the chainsaw with PA6-tank ☺
- PA6 have higher internal friction losses (damping) than SLS ☺
- Still much that we need to know about the mechanical properties in different environments of SLS (and other material as well) to make good predictions and forecasts in early prototype stages

Questions?