STRUCTURAL ENGINEERING OF SATELLITES

From models to tests, through analysis

AGENDA

- Aerospacelab
- Objectives & stakes
- Environments & loads
- Failure modes
- Structural analysis
- Vibration testing

AEROSPACELAB

SATELLITES FROM A TO Z

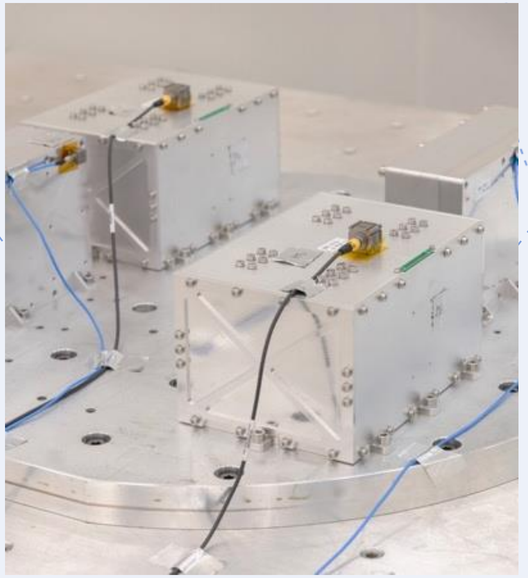
Founded in March 2018, ~350 FTE (Q2 2024)

5 years of development for a complete Satellite Product offering

IN-HOUSE SUBSYSTEMS

WE DESIGN AND MANUFACTURE

in-house subsystems

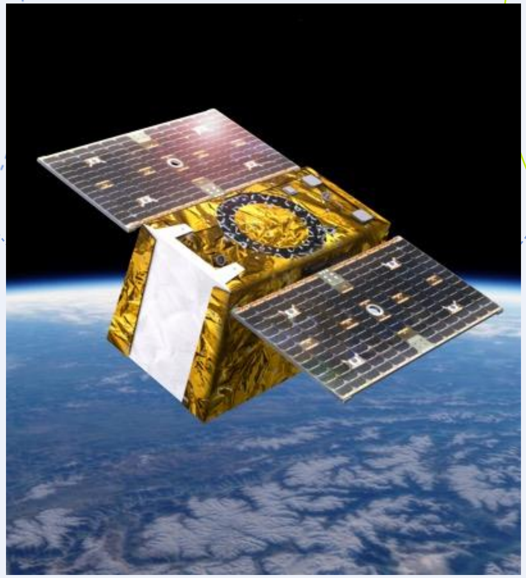


USED TO DEVELOP

satellite platforms

INTEGRATING PAYLOAD TO DELIVER

turnkey satellites



GENERATING VALUE THROUGH

operations & data analytics

Aerospacelab today

49 M € RAISED – SEED, SERIES A & SERIES B

ARTHUR

Our first satellite launched in June 2021

GREGOIRE

Our first VSP platform was launched on June 12th 2023

PVCC

Successful launch for ESA on Oct 9th 2023

FLIGHT HERITAGE

Launched 3 satellites in 2023 & 4 scheduled in 2024: 1 VHR and 3 SIGINTs

A HIGH-LEVEL TEAM

350+ FTE by Q2 2024

GLOBAL EXPANSION

Offices in Belgium, Switzerland, France and USA

ONE OPERATIONAL FINAL ASSEMBLY LINE

Since July 2022, we produce and assemble satellites internally

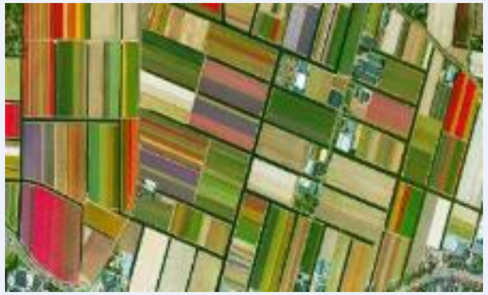

STRONGBACK RETRACT
ENGINE CHILL
STARTUP
LIFTOFF
MAX-Q
MECO
FAIRING
BOOSTBACK
T - 00:02:37
TRANSPORTER-9

Unlocking a new world of use cases

ENVIRONMENT MONITORING

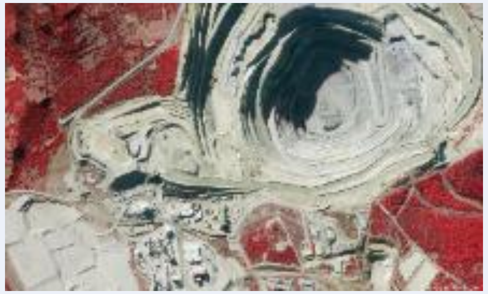
GLOBAL WARMING IMPACT ANALYSIS

NATURAL DISASTER MANAGEMENT



YIELDS MAXIMIZATION AND FORECASTS

THREAT DETECTION



SUPPORT TO OPERATIONS

AIRPORT ACTIVITIES ANALYSIS

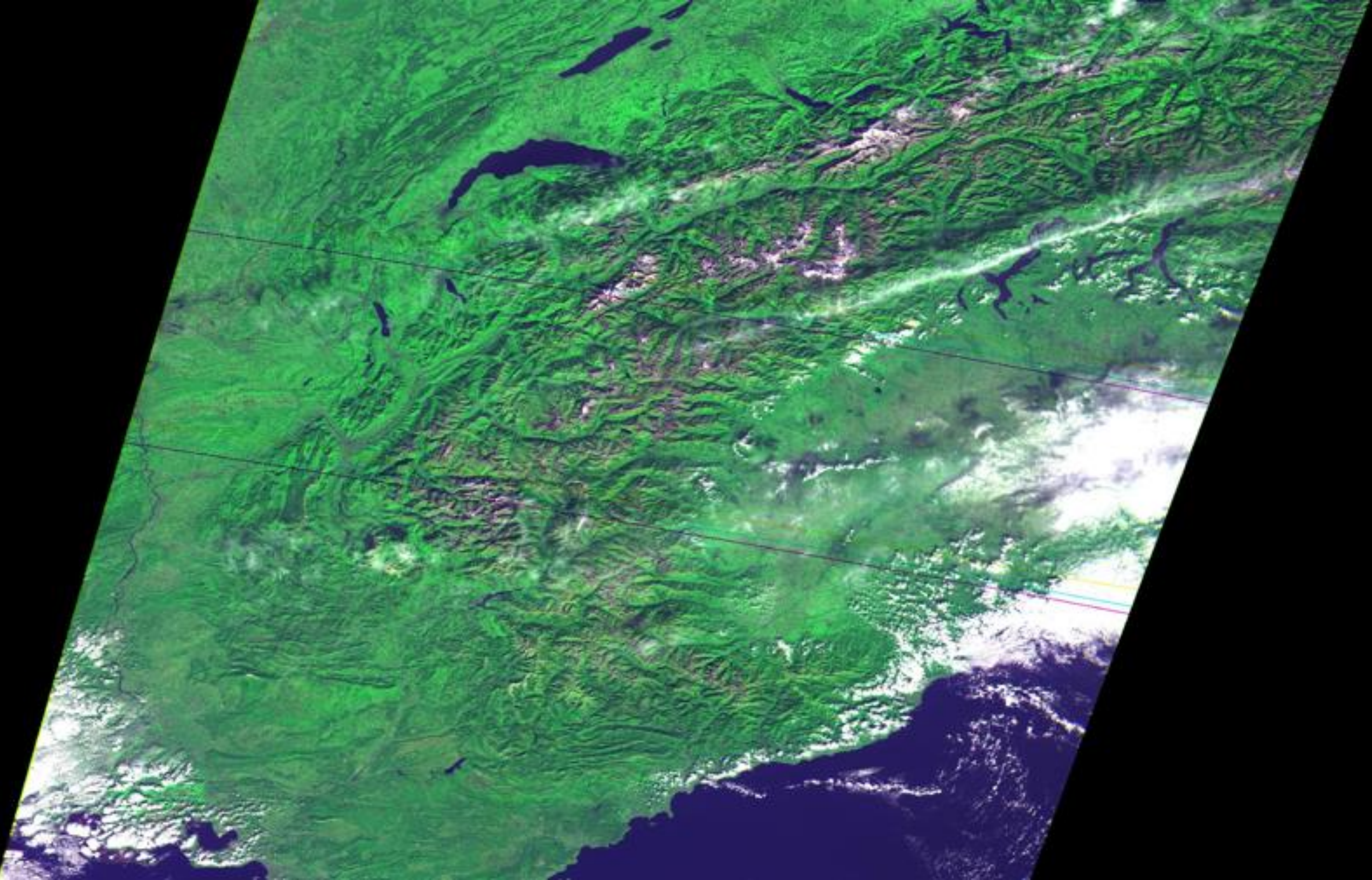
PORTS' THROUGHPUT ESTIMATIONS

INSURANCE AND REAL ESTATE SUPPORT

CRITICAL INFRASTRUCTURE MONITORING

MANUFACTURING SITE ANALYSIS

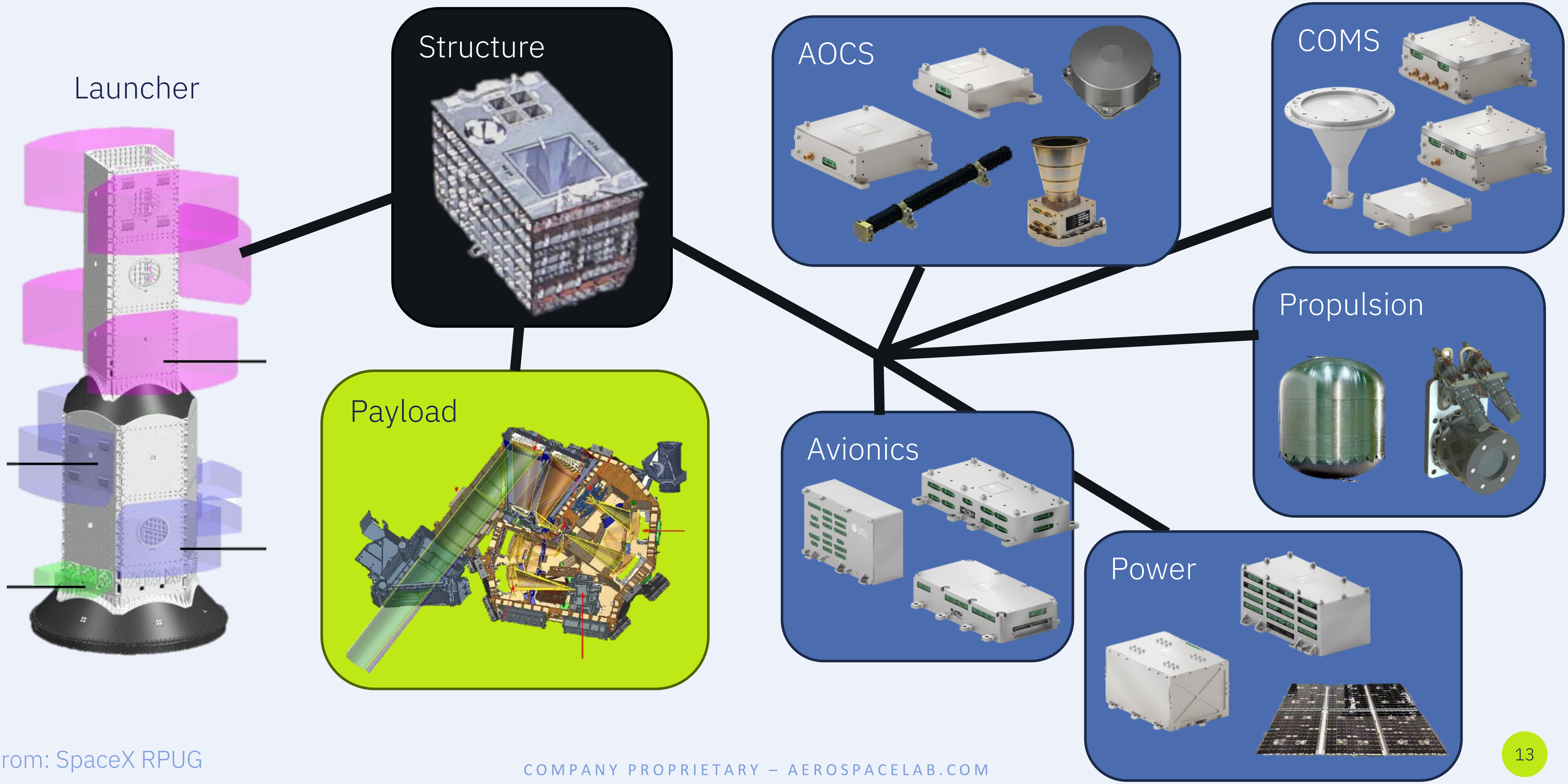
COMMODITIES INVENTORY LEVELS



OBJECTIVE & STAKES

IT SEEMS OBVIOUS, BUT IT'S NOT

THE STRUCTURE HOLDS THE SATELLITE'S COMPONENTS



From: SpaceX RPUG

IN EACH STEP OF ITS LIFE, THE SATELLITE EXPERIENCES LOADS

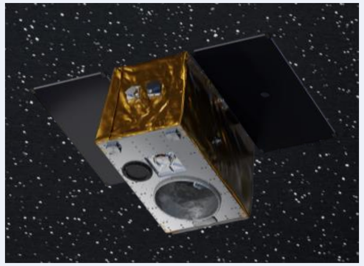
Cleanroom
Gravity, shocks, tests

Transport
Gravity, shocks, vibrations, temperature

Mating & Idling
Gravity, shocks, temperature

Launch
Acceleration, vibrations, sound

Separation & Deployment
Shocks



Flight
Microvibrations, temperature, radiation

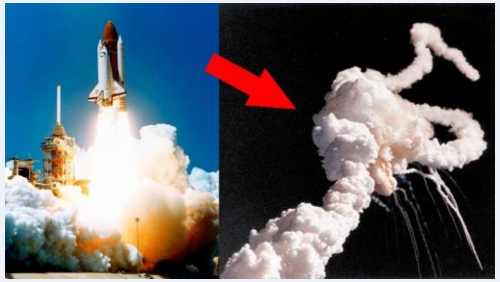
Reentry
Acceleration, vibrations, temperature

MECHANICAL FAILURE MUST BE AVOIDED (DUH)

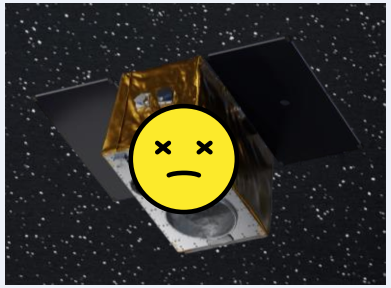
Failure: "rupture, collapse, degradation, excessive wear or any other phenomenon resulting in an inability to sustain design limit loads, pressures (e.g. MDP) and environments."

Consequences of mechanical failure:

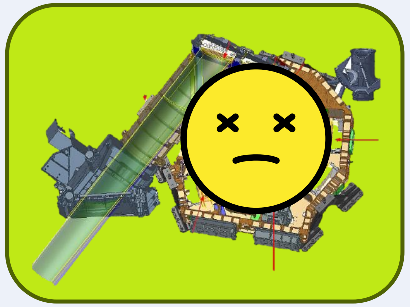
Loss of launcher



Loss of spacecraft



Loss of payload



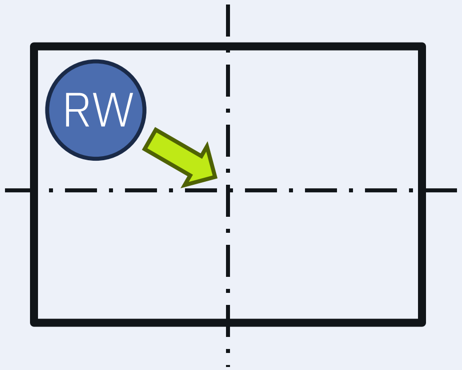
Loss of lifetime

Loss of quality

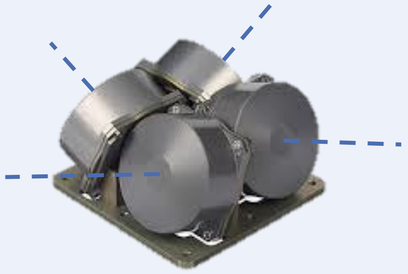
From: ECSS-E-ST-32C

ACCOMMODATION FOR AOCS CONTROLLABILITY

Reaction wheels

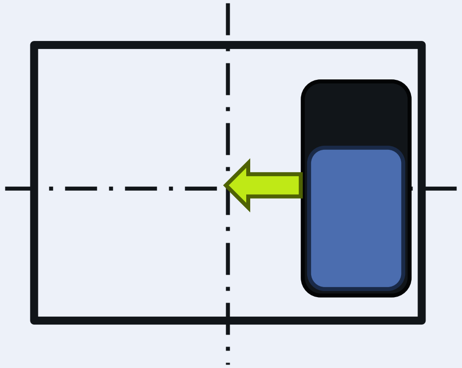


Efficiency

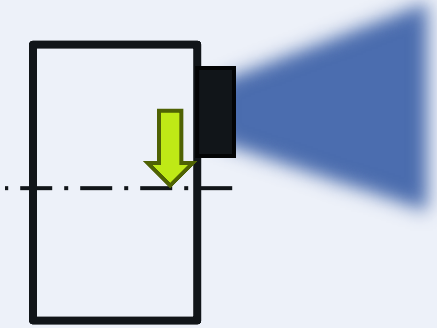


Redundancy

Propulsion

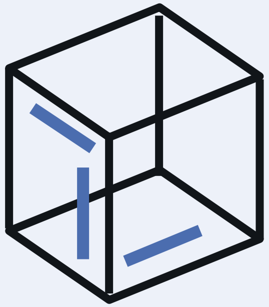


Tank

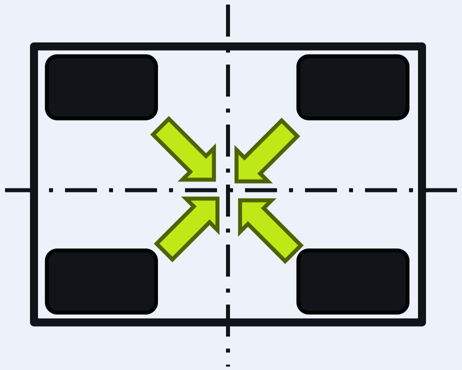


Thruster

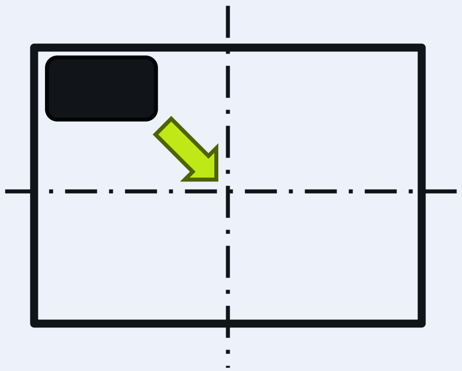
Magnetotorquers



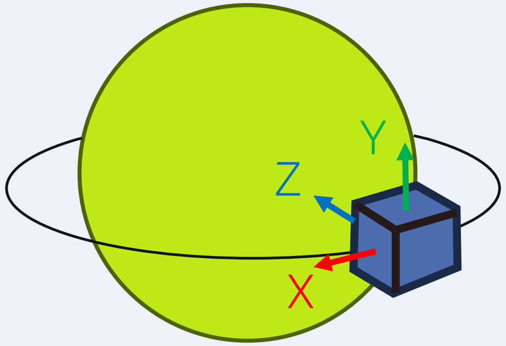
Inertia



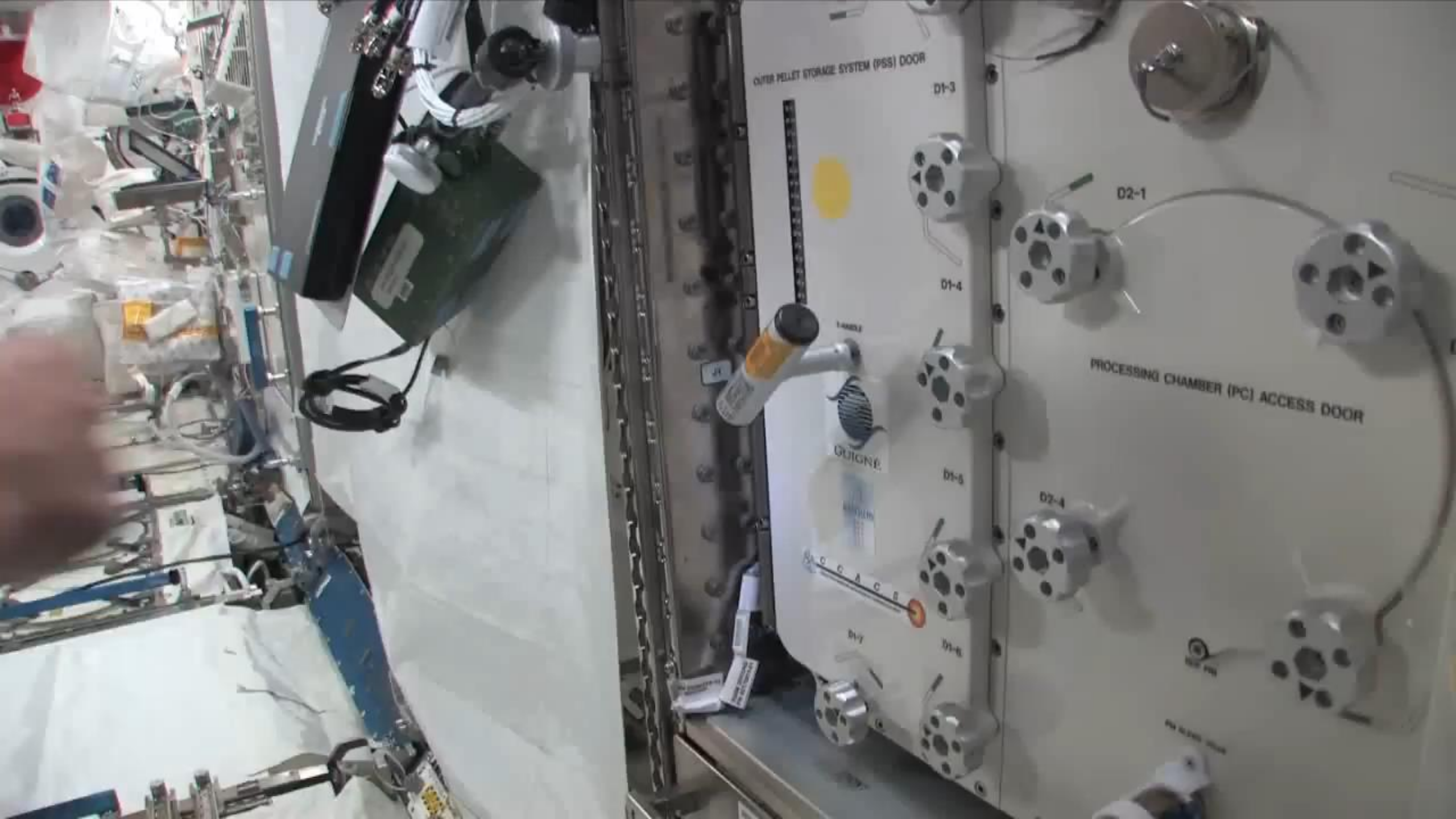
Moments



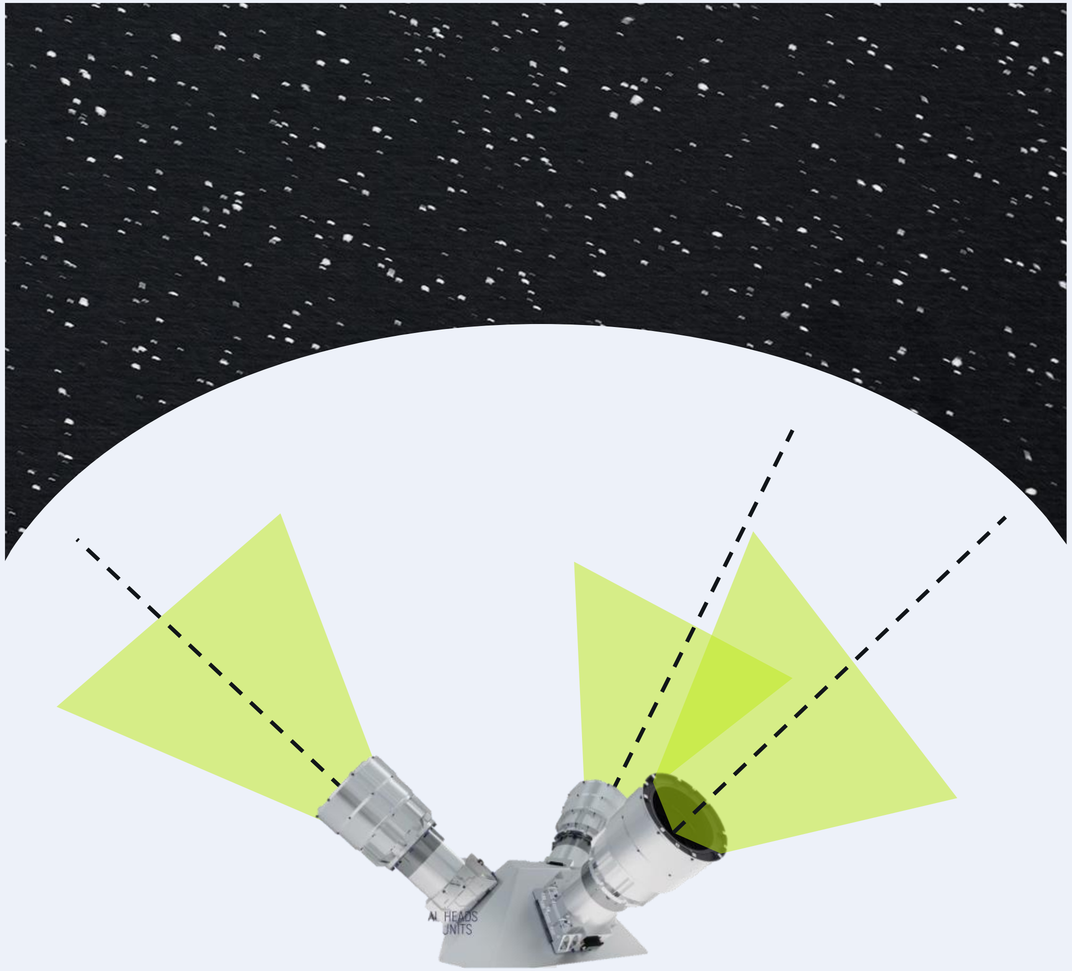
Products



Y axis


OUTER PELLET STORAGE SYSTEM (PSS) DOOR
D1-3
D1-4
D1-5
D1-6
D1-7
D2-1
D2-4
PROCESSING CHAMBER (PC) ACCESS DOOR
GUIGNÉ

STAR TRACKER ACCOMMODATION



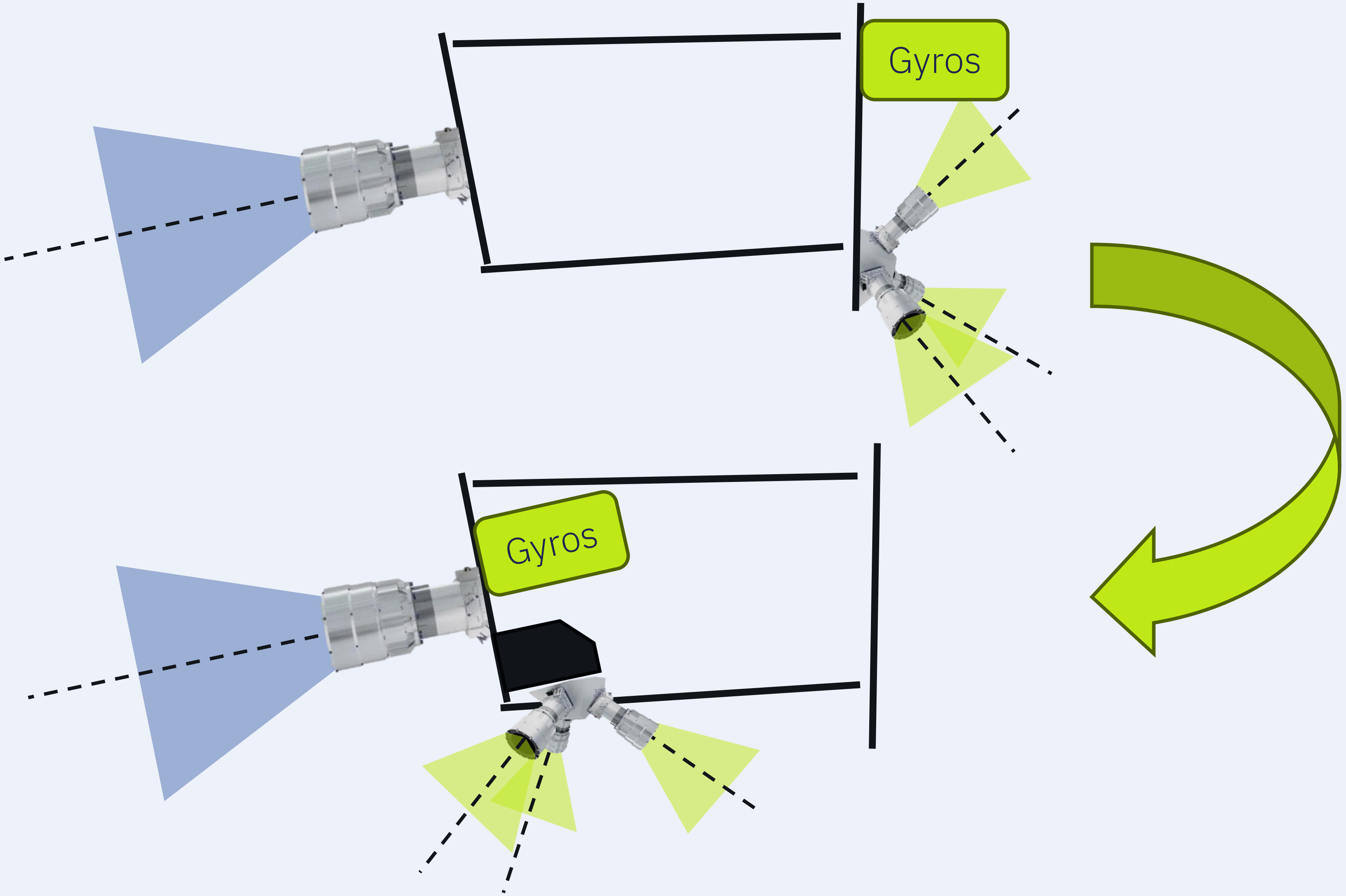
Overlapping

Blinded by sun

Crosses horizon

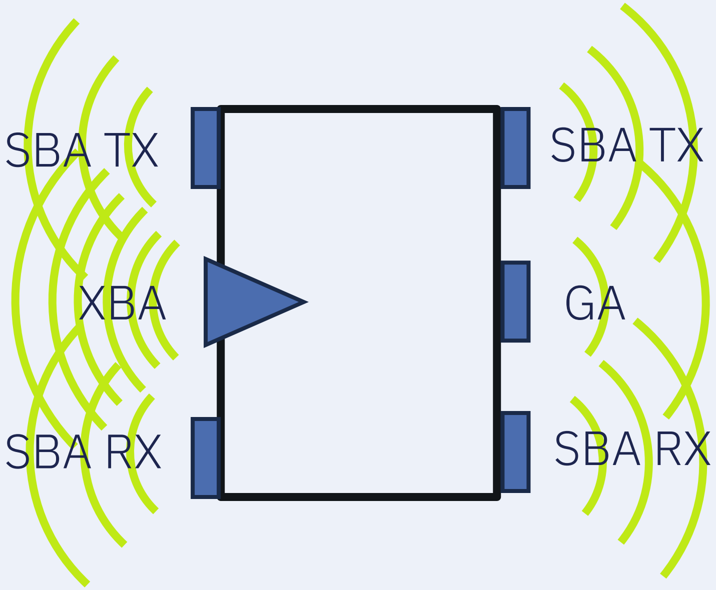
Acceptable

MINIMIZE THE MECHANICAL PATH BETWEEN SENSORS

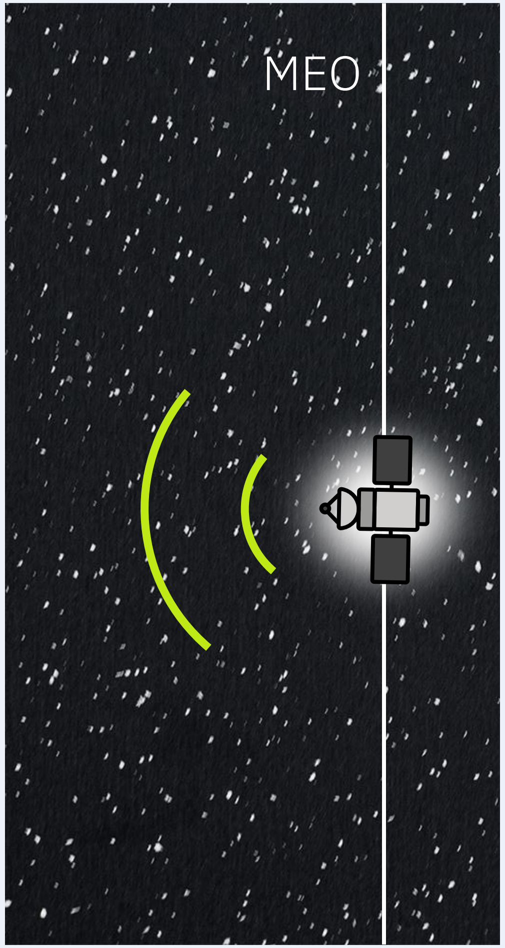


ANTENNAS ACCOMMODATION: ALL ABOUT POINTING

Nadir



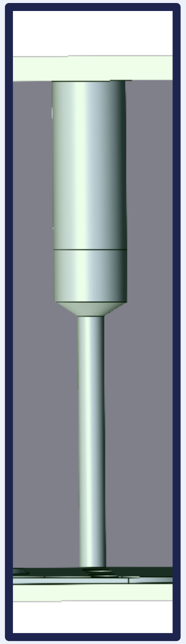
Zenith



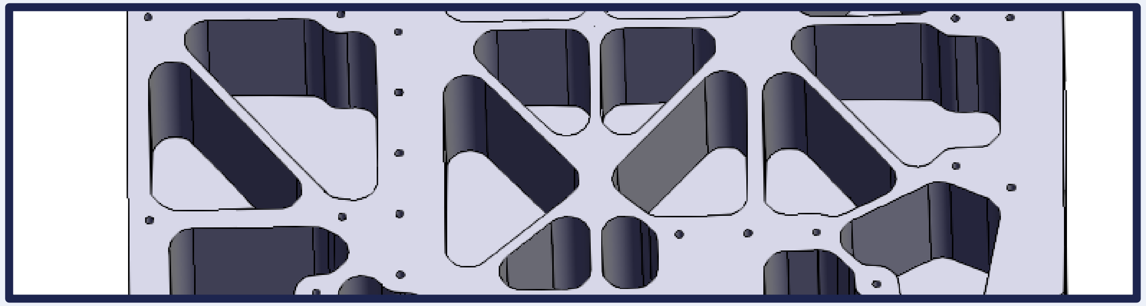
SOME UNITS ARE SENSITIVE TO EM NOISE

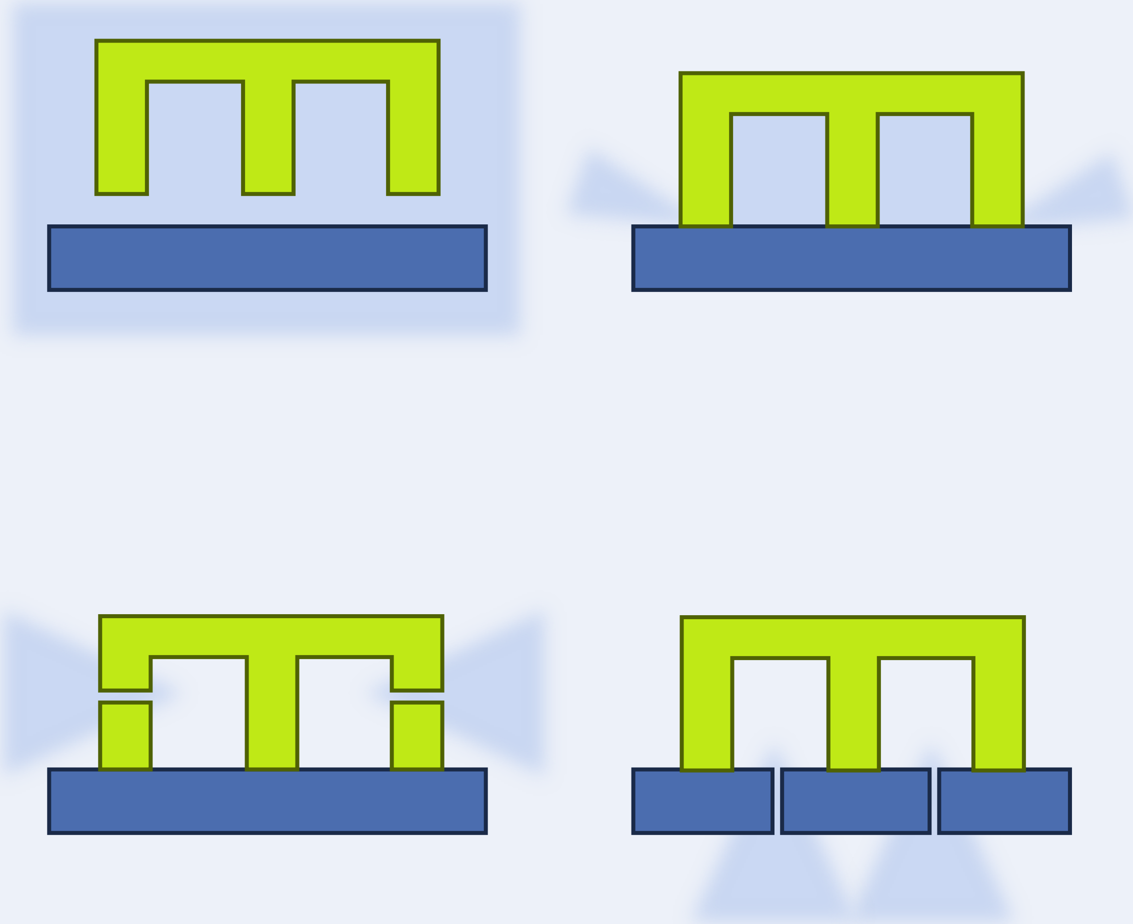
VENTING HOLES OUTGAS AWAY FROM SENSITIVE EQUIPMENT

Bolt hole:



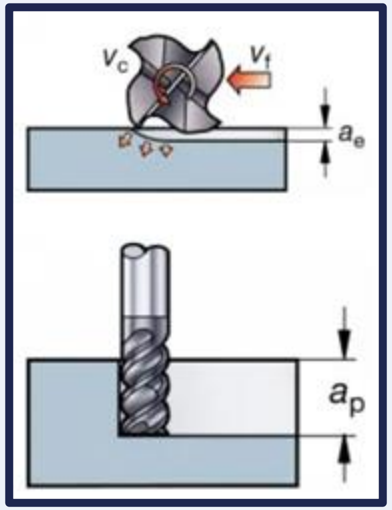
Pockets in plate:

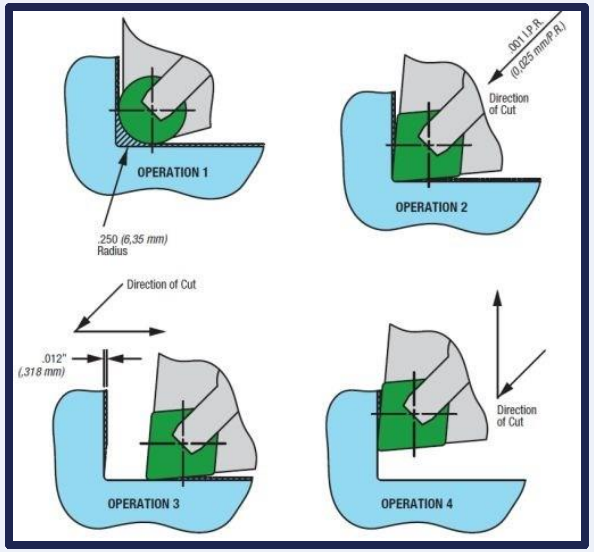


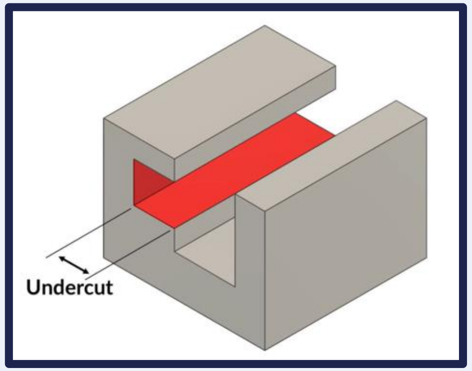


ENSURE FABRICABILITY AT LOWEST COST POSSIBLE

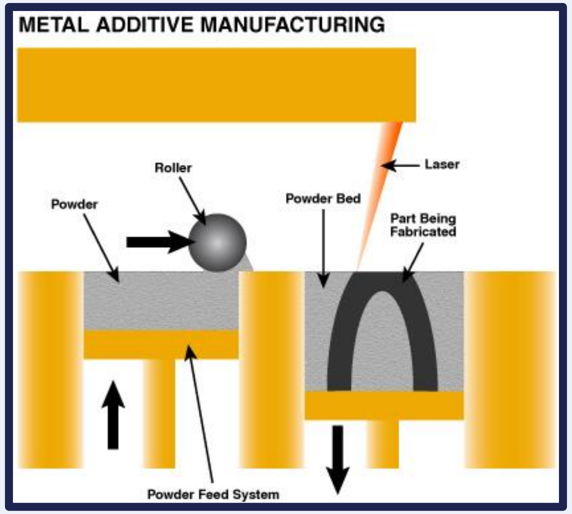
Machining

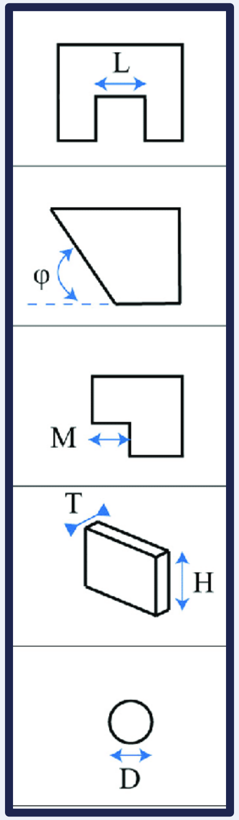






Additive manufacturing





Bridge span

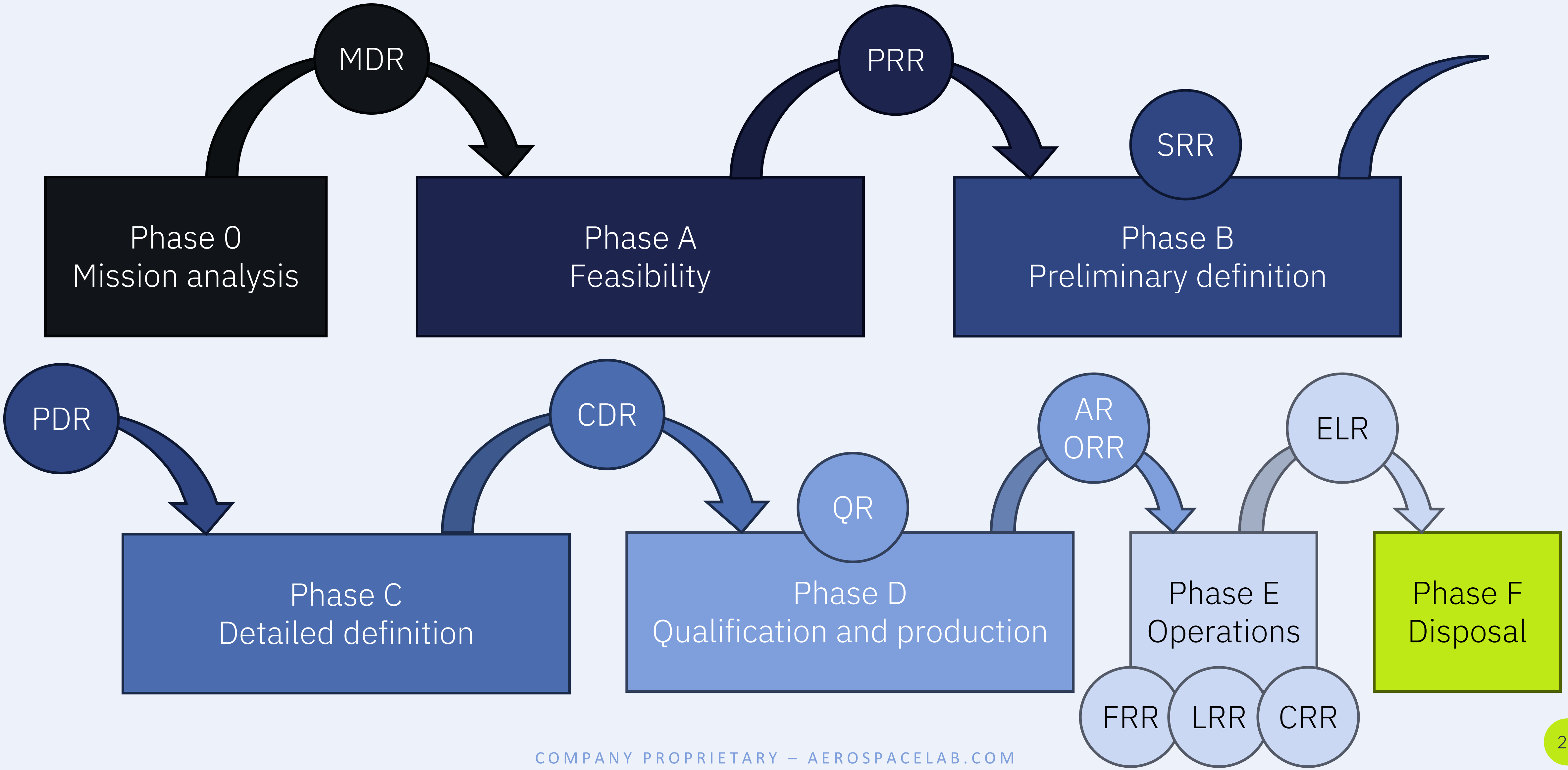
Overhang angle

Unsupported overhang

Wall thickness

Hole diameter

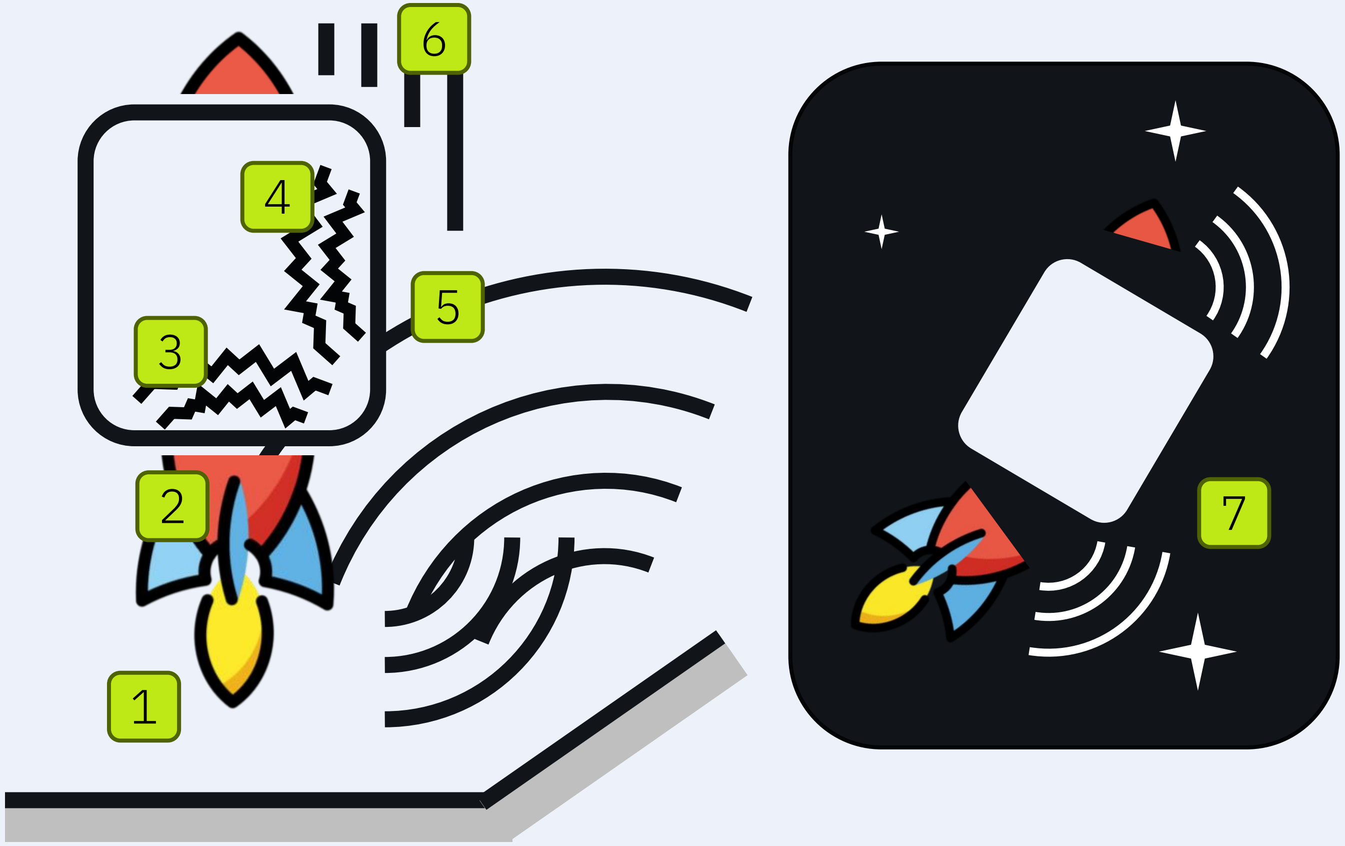
SYSTEM ENGINEERING PHASES AND REVIEWS



ENVIRONMENTS & LOADS

THE VARIOUS WAYS THE LAUNCHER MAKES OUR LIVES MISERABLE

LAUNCH LOADS COVER A WIDE FREQUENCY BAND



Static acceleration (~ 0 Hz)
1. Launcher thrust

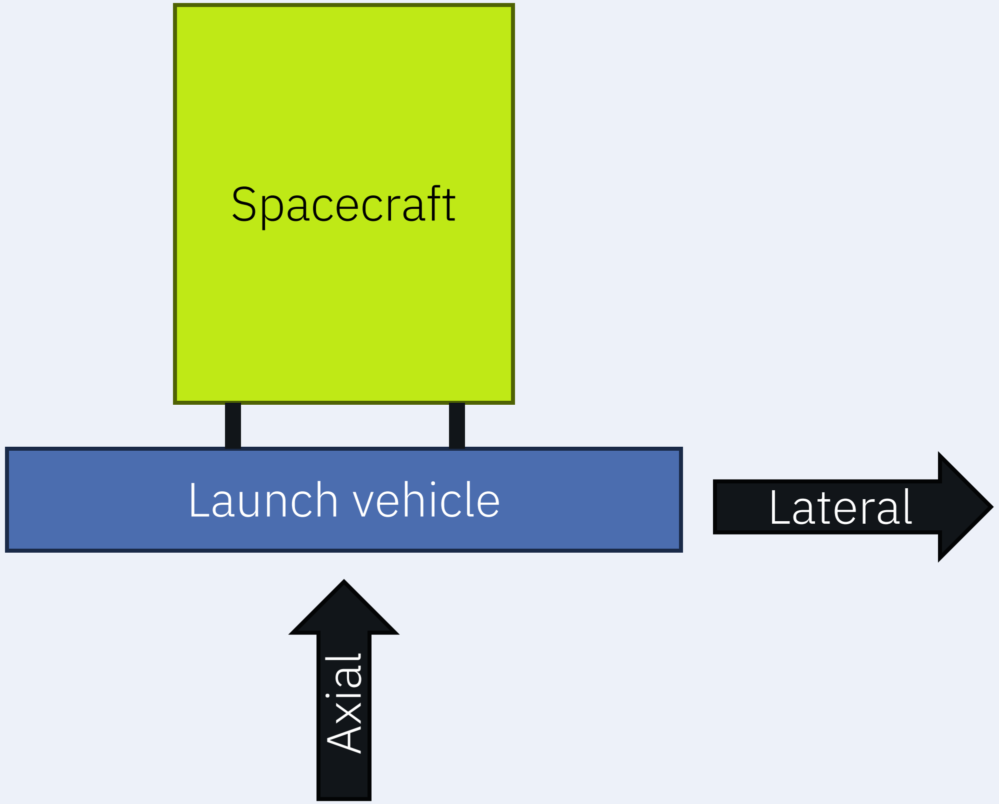
Low-frequency dynamics (0 to 100 Hz)
2. Launcher flexible modes

High-frequency dynamics (20 to 2,000 Hz)
3. Vibrations from propulsion
4. Vibro-acoustics

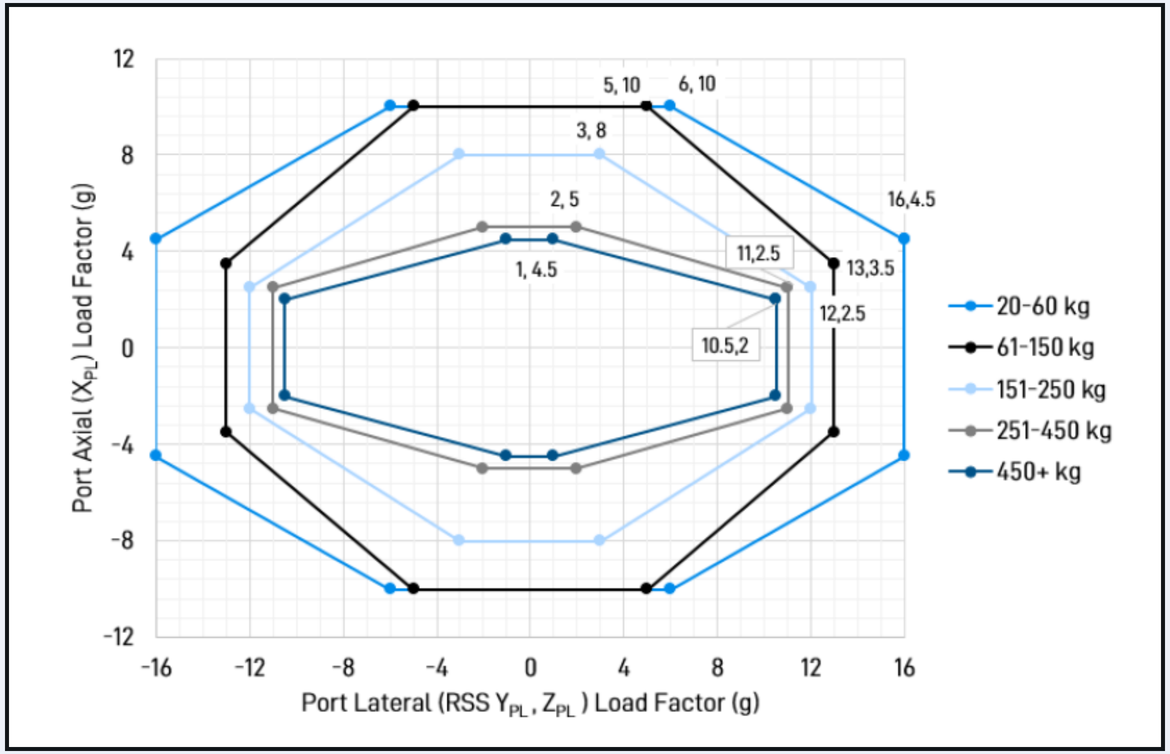
High-frequency acoustics (20 to 8,000 Hz)
5. Reflected from propulsion
6. Aerodynamics

Shocks (100 to 10,000 Hz)
7. Separation events

QUASI-STATIC LOADS COVER ALL FREQUENCIES

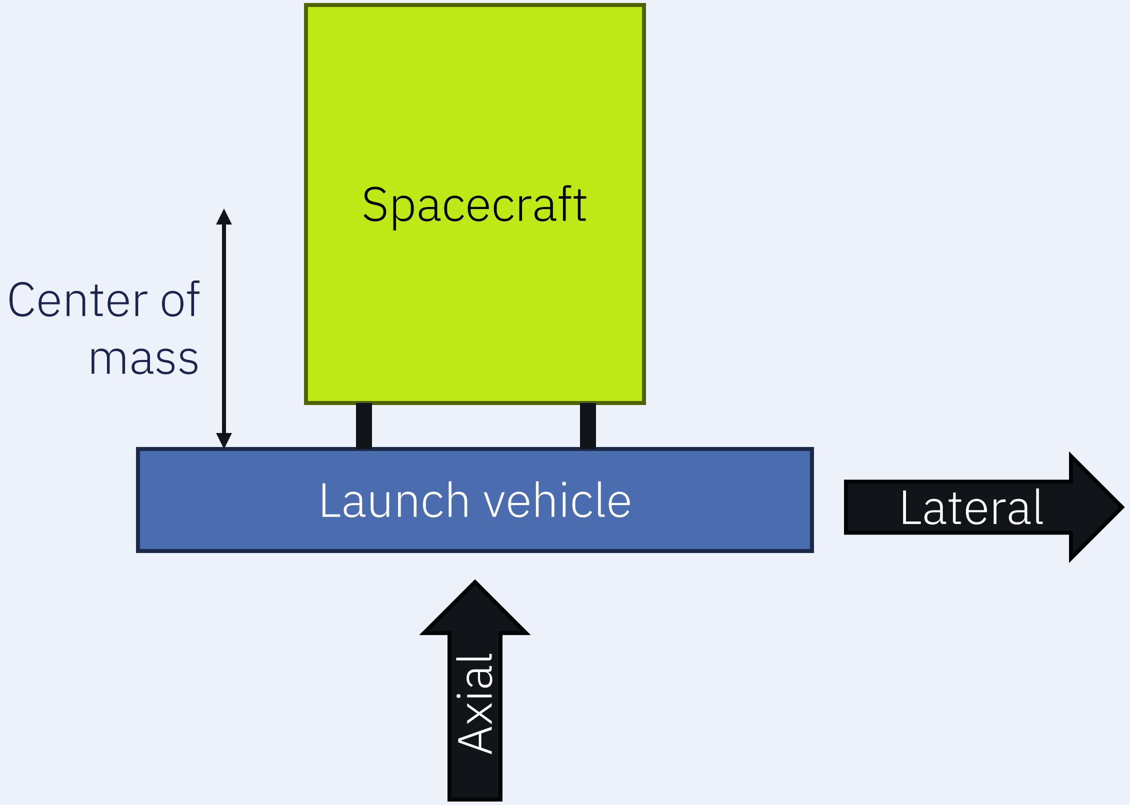


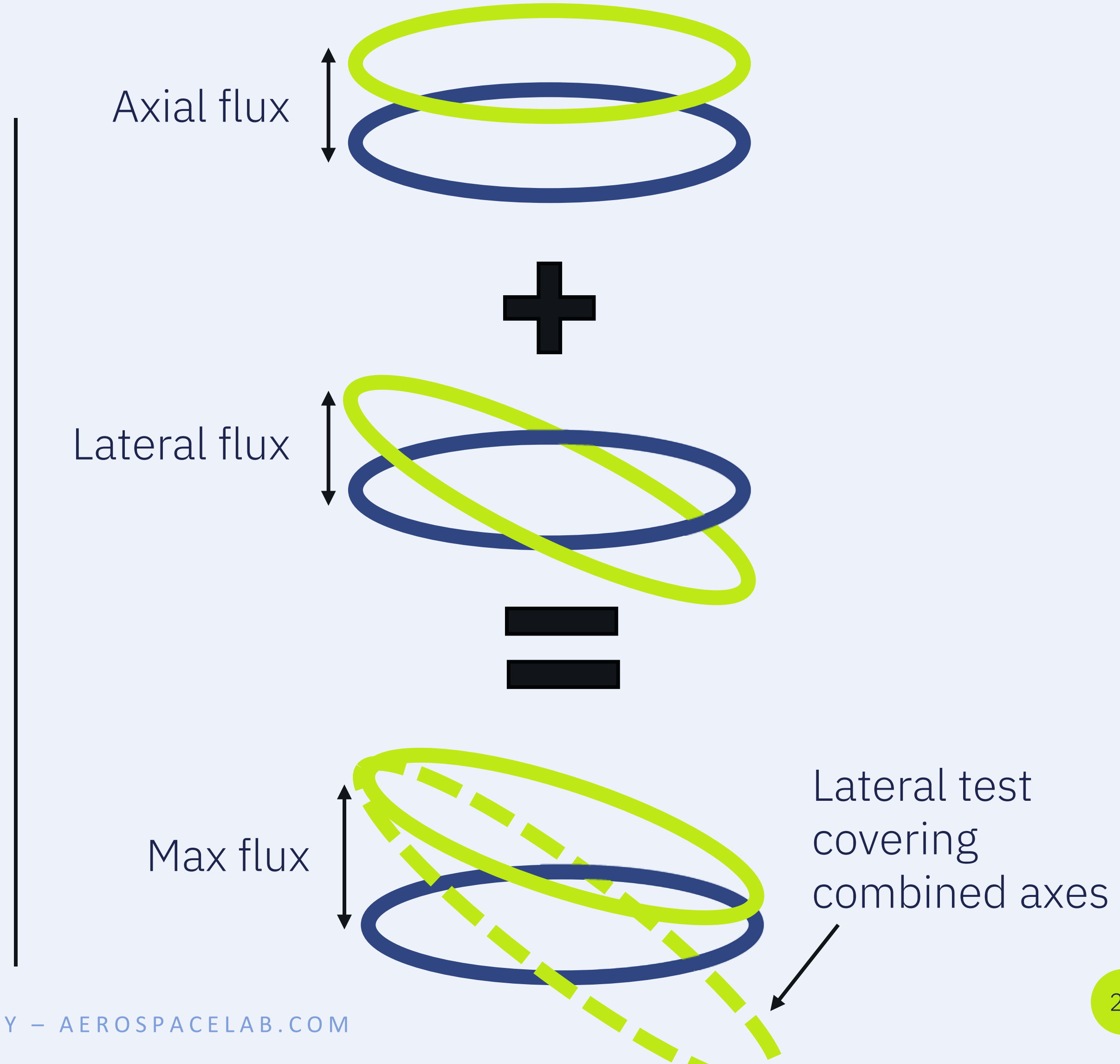
Falcon 9



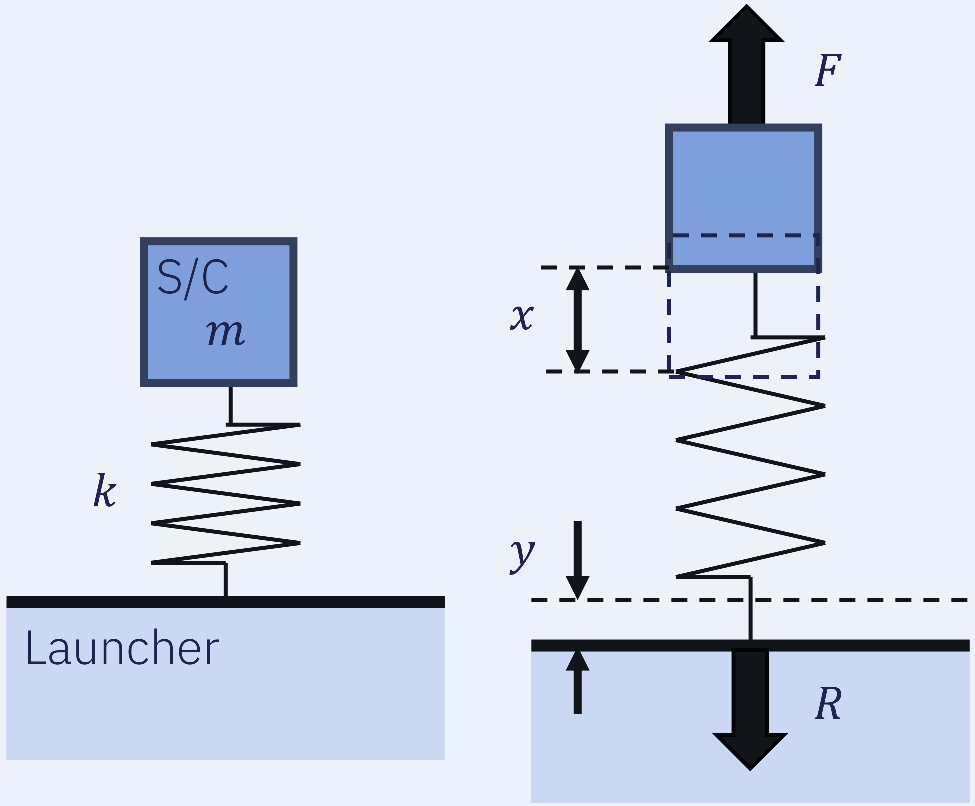
From: SpaceX RPUG

WORST INTERFACE LOADS SHOULD BE COVERED





FOUR FREQUENCY RESPONSE FUNCTIONS

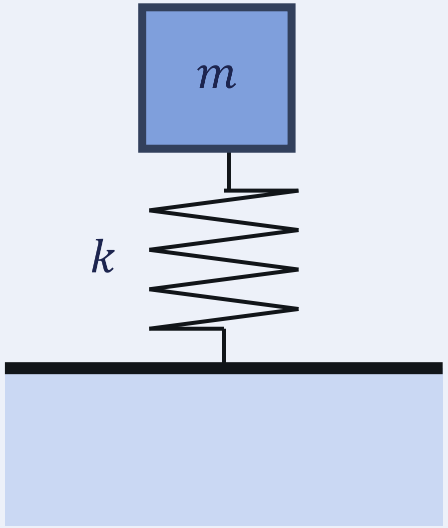


	Excitation	Response
Displacement	*y*	*x*
Force	*F*	*R*

$$\begin{bmatrix} \ddot{x}(\omega) \\ R(\omega) \end{bmatrix} = \begin{bmatrix} -\omega^2 G(\omega) & T(\omega) \\ -T(\omega) & M(\omega) \end{bmatrix} \begin{bmatrix} F(\omega) \\ \ddot{y}(\omega) \end{bmatrix}$$

G	Dyn. flexibility	[g_0/N]
T	Transmissibility	[-]
M	Dyn. mass	[N/g_0]

INFLUENCE OF PHYSICAL PARAMETERS



$$\begin{bmatrix}\ddot{x}(\omega)\\ R(\omega)\end{bmatrix} = \begin{bmatrix}-\omega^2 G(\omega) & T(\omega)\\ -T(\omega) & M(\omega)\end{bmatrix}\begin{bmatrix}F(\omega)\\ \ddot{y}(\omega)\end{bmatrix}$$

$$= \begin{bmatrix}-\frac{\omega^2}{k} H(\omega) & T(\omega)\\ -T(\omega) & mT(\omega)\end{bmatrix}\begin{bmatrix}F(\omega)\\ \ddot{y}(\omega)\end{bmatrix}$$

H	Amplification	[-]
T	Transmissibility	[-]

Design objective:
Stiffness ↗ *
Mass ↘

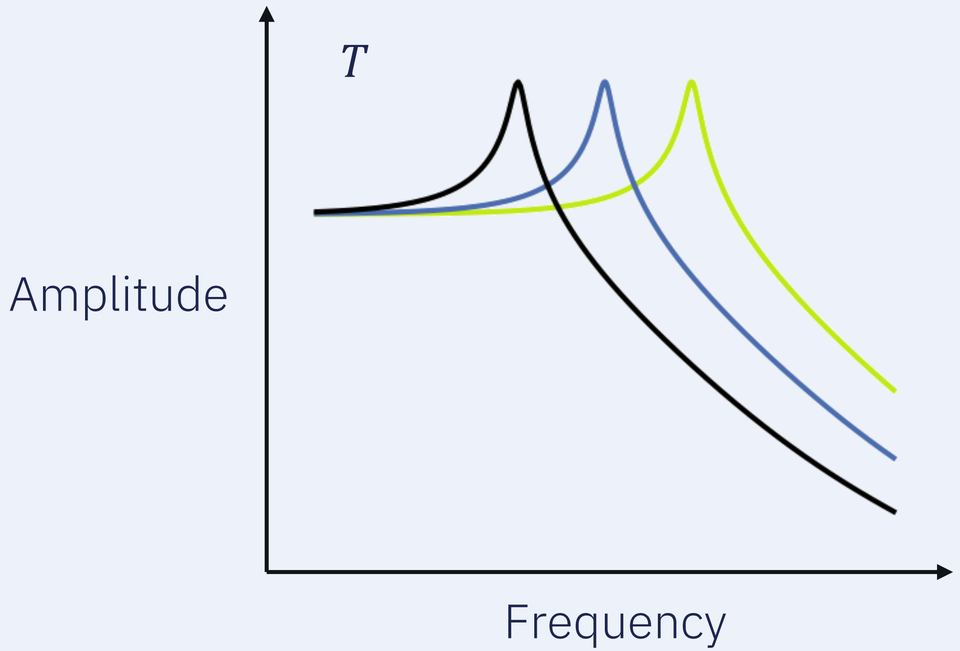
* Natural frequency...

INFLUENCE OF DYNAMIC PARAMETERS

$$\begin{bmatrix} \ddot{x}(\omega) \\ R(\omega) \end{bmatrix} = \begin{bmatrix} -\frac{\omega^2}{k}H(\omega) & T(\omega) \\ -T(\omega) & mT(\omega) \end{bmatrix} \begin{bmatrix} F(\omega) \\ \ddot{y}(\omega) \end{bmatrix}$$

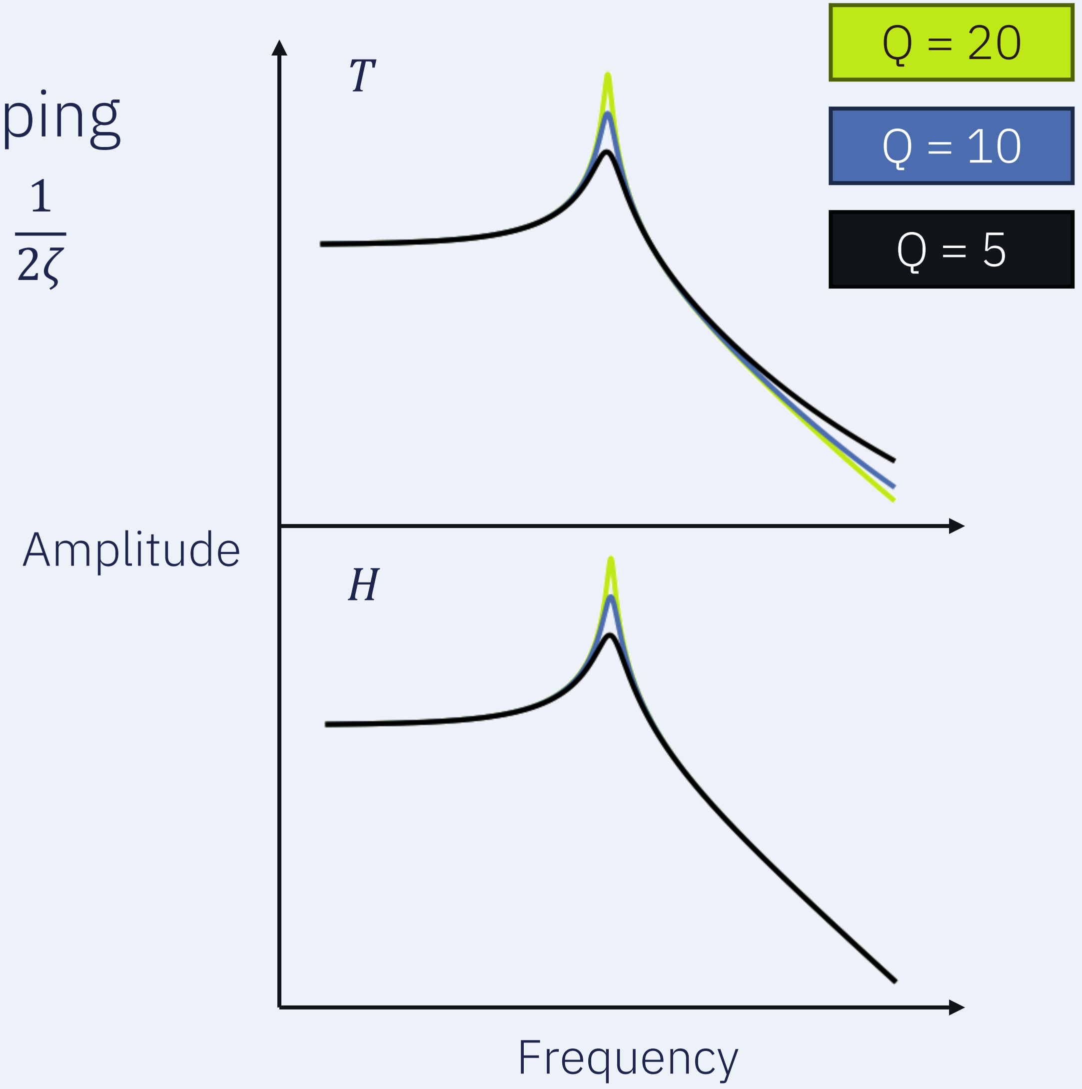
Natural frequency

$$\omega_0 = \sqrt{\frac{k}{m}}$$

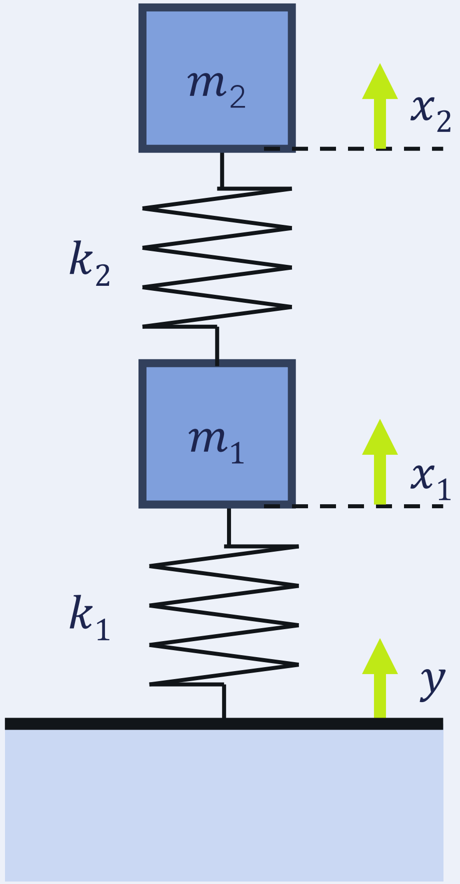


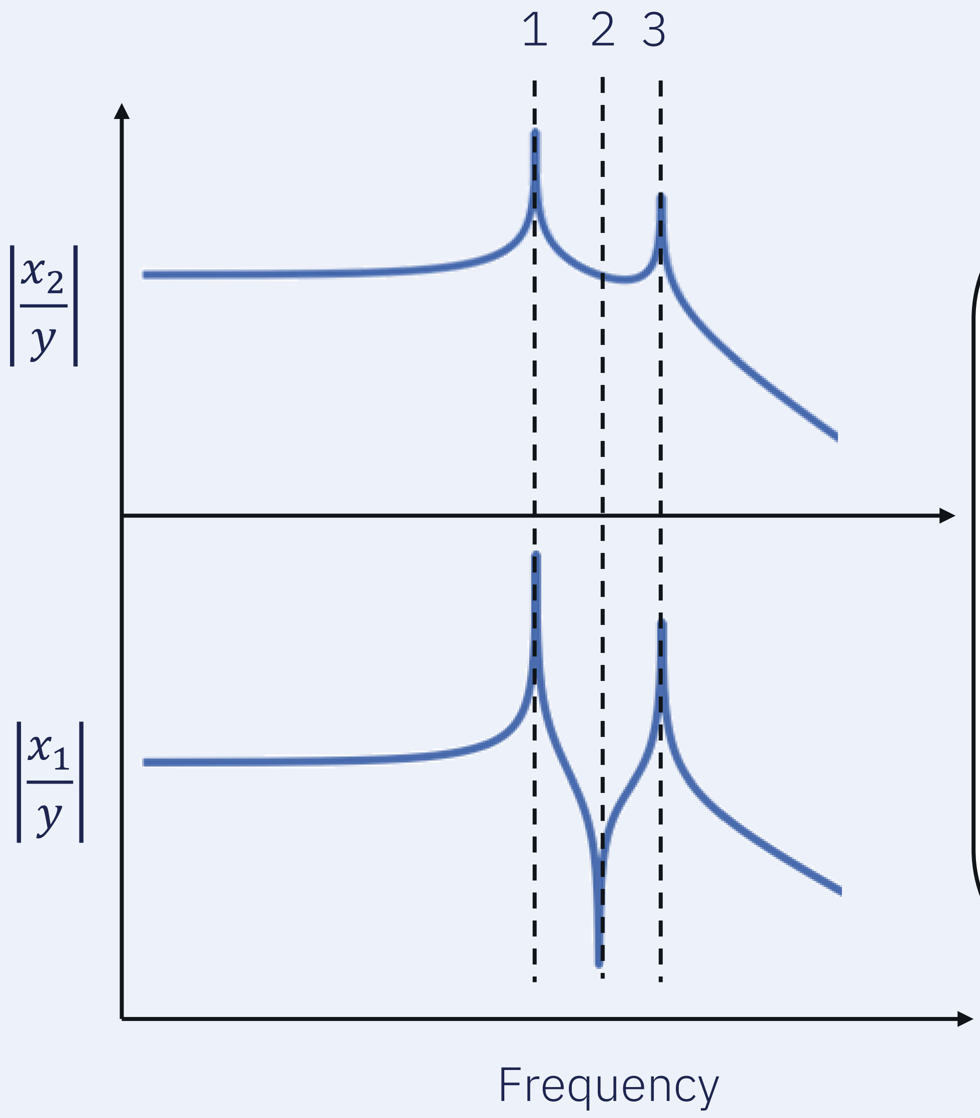
Damping

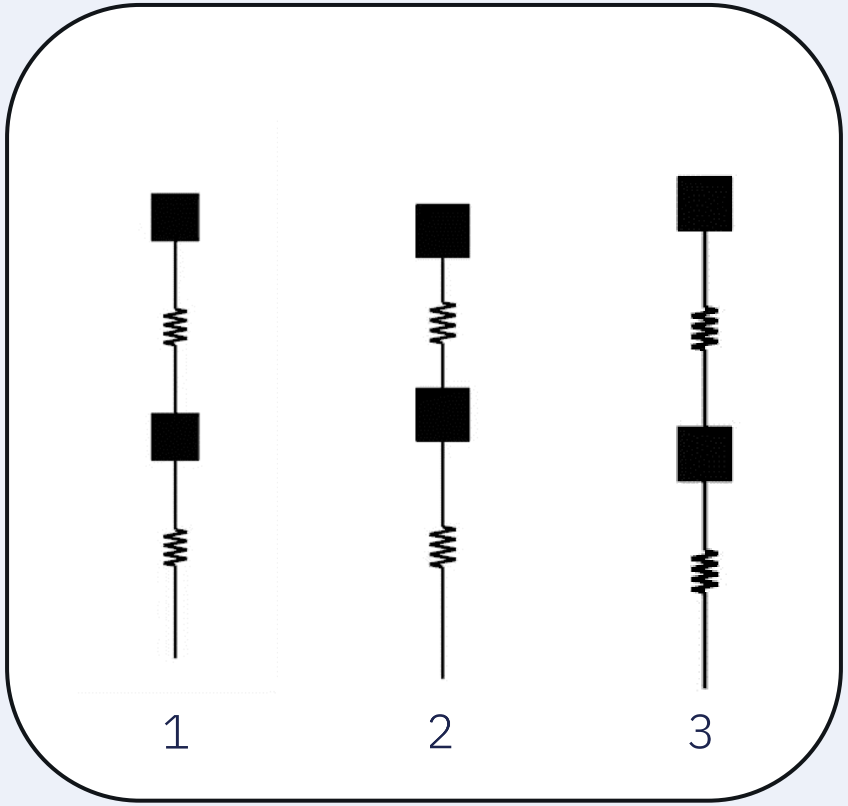
$$Q = \frac{1}{2\zeta}$$



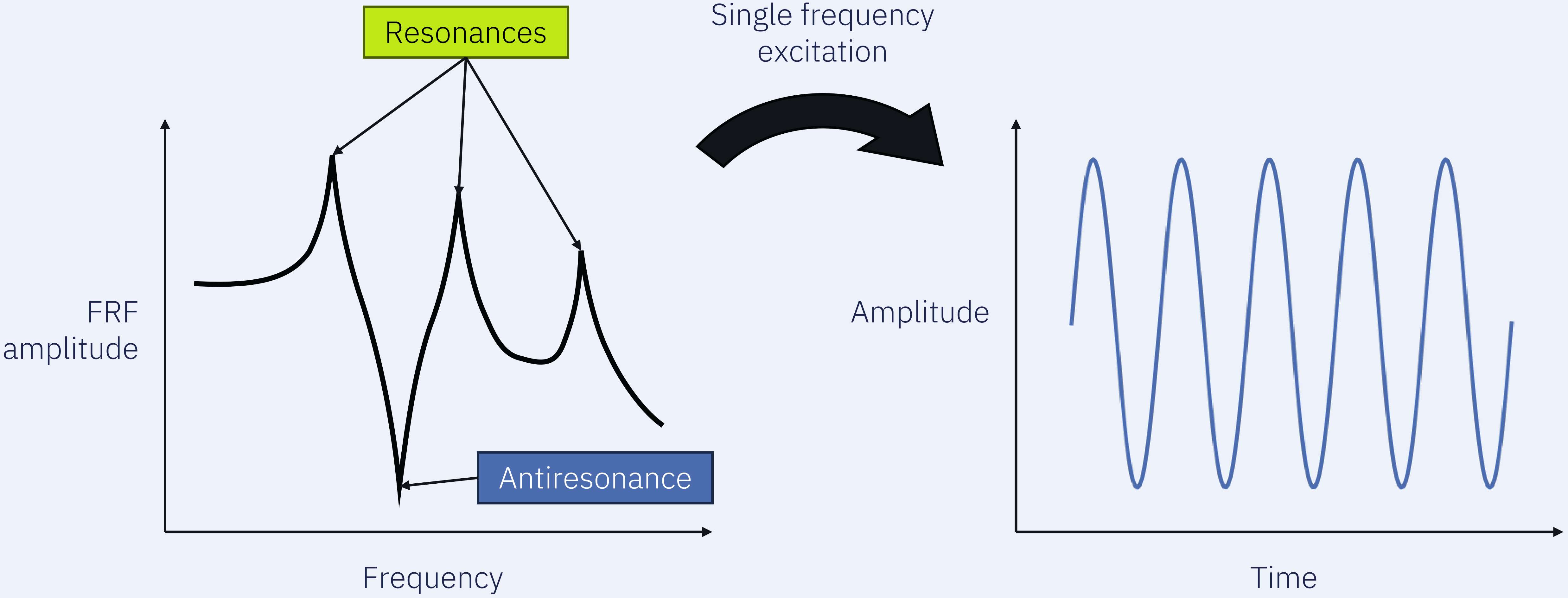
MDOF


m_2
x_2
k_2
m_1
x_1
k_1
y


1 2 3
$\left|\frac{x_2}{y}\right|$
$\left|\frac{x_1}{y}\right|$
Frequency

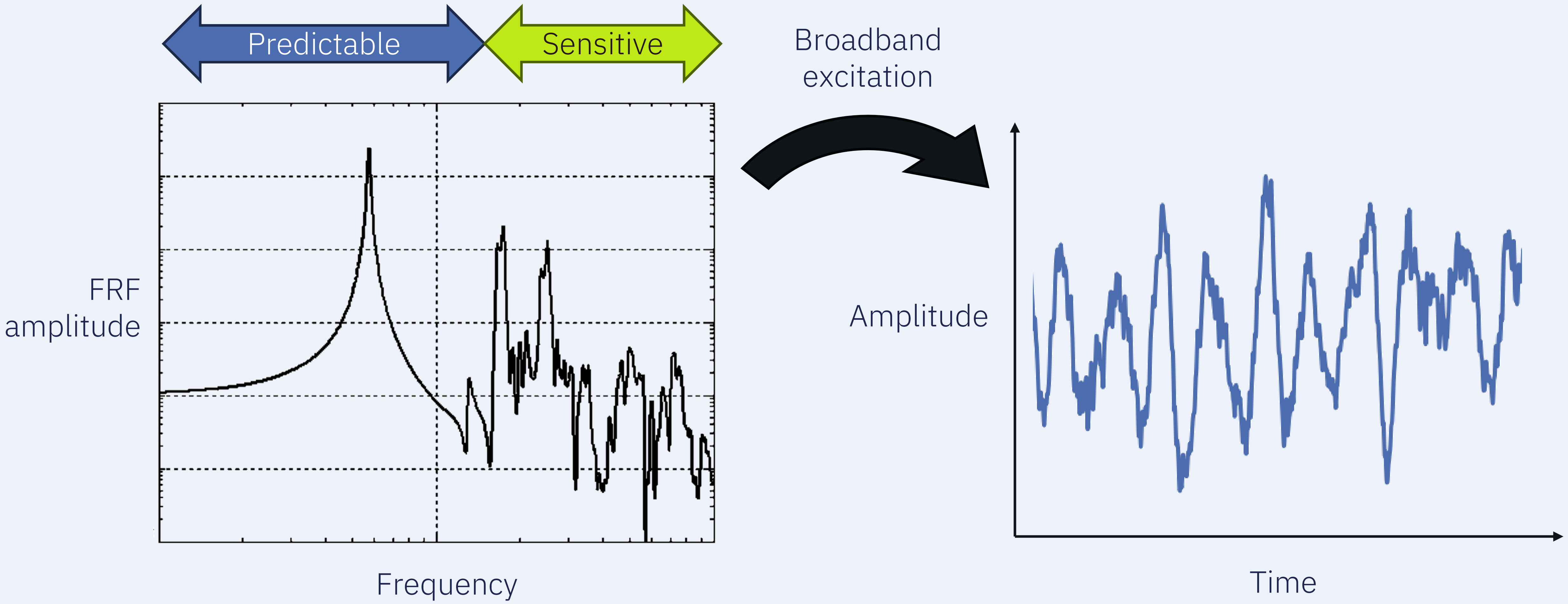

1
2
3

DETERMINISTIC BEHAVIOR MAKES UP SINE LOADS



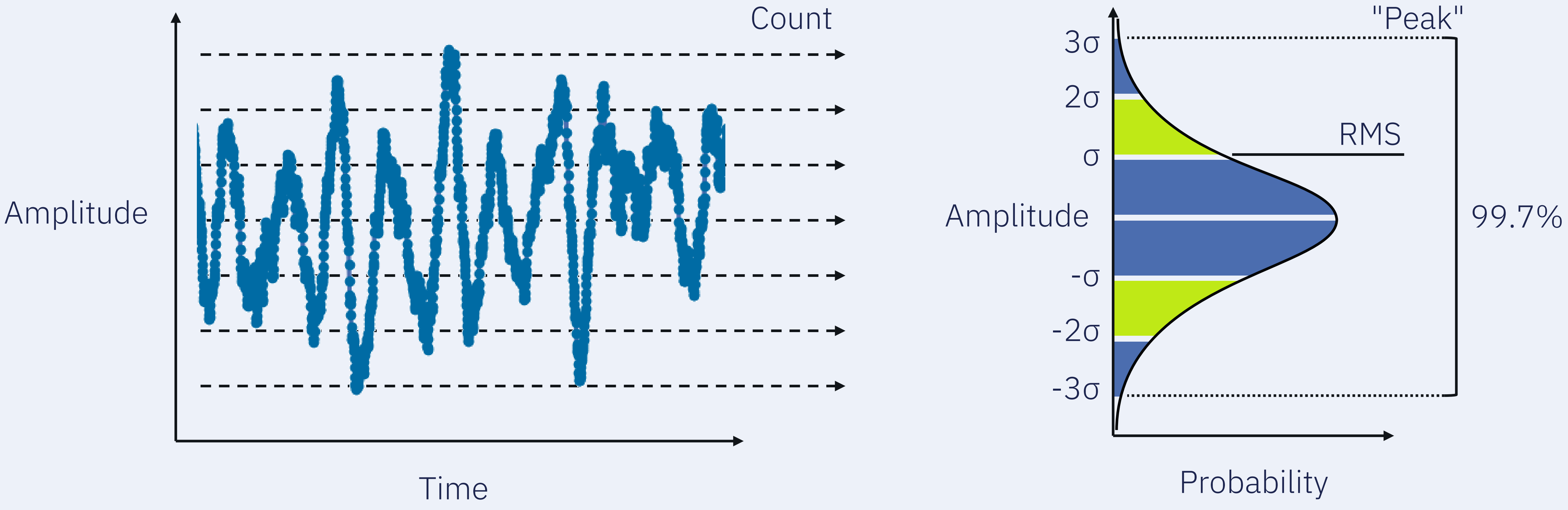
From: ECSS-E-HB-32-26A

STOCHASTIC BEHAVIOR MAKES UP RANDOM LOADS

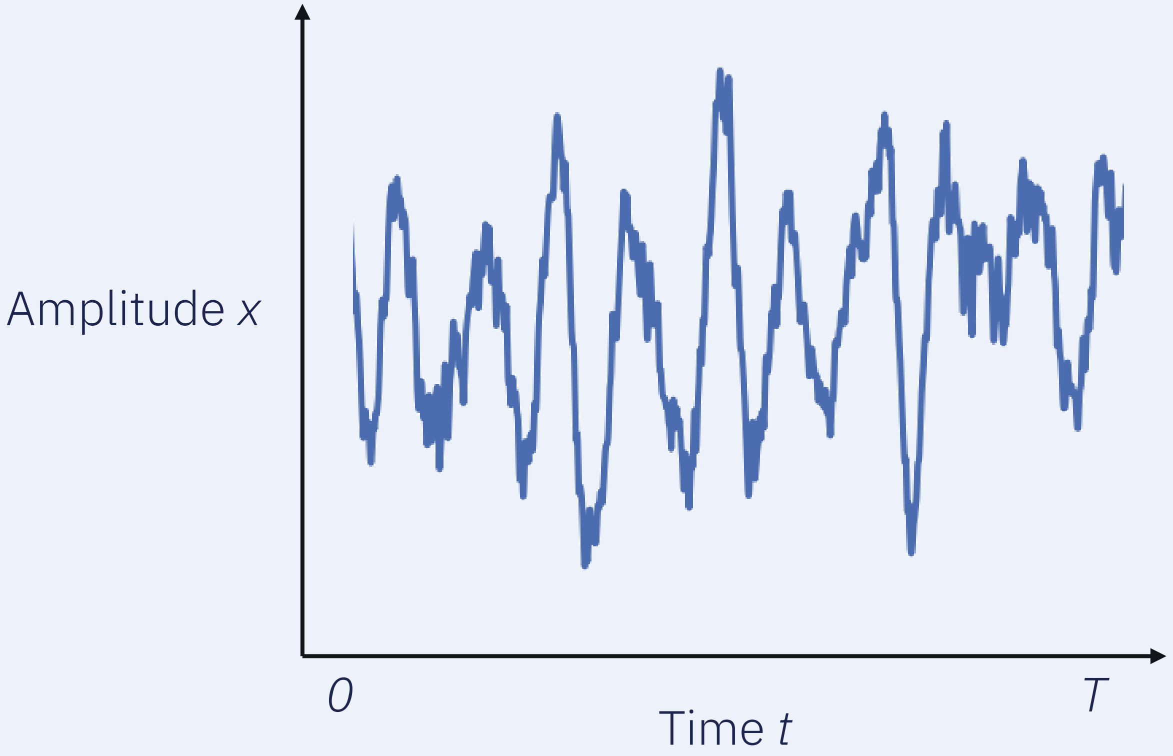


From: ECSS-E-HB-32-26A

RANDOM SIGNALS ARE ANALYZED WITH STATISTICS



PSD SHOWS POWER CONTENT IN FREQUENCY DOMAIN



$$x_{\mathrm{RMS}} = \sqrt{\frac{1}{T}\int_0^T |x|^2 \mathrm{d}t}$$

$$\int_0^T |x|^2 \mathrm{d}t = \int_{-\infty}^{\infty} |\mathcal{F}\{x\}|^2 \mathrm{d}f$$ (Parseval's theorem)

$$|\mathcal{F}\{x\}|^2 = \mathcal{F}\{\big(x^*(-t) * x(t)\big)(\tau)\}$$ (convolution theorem)

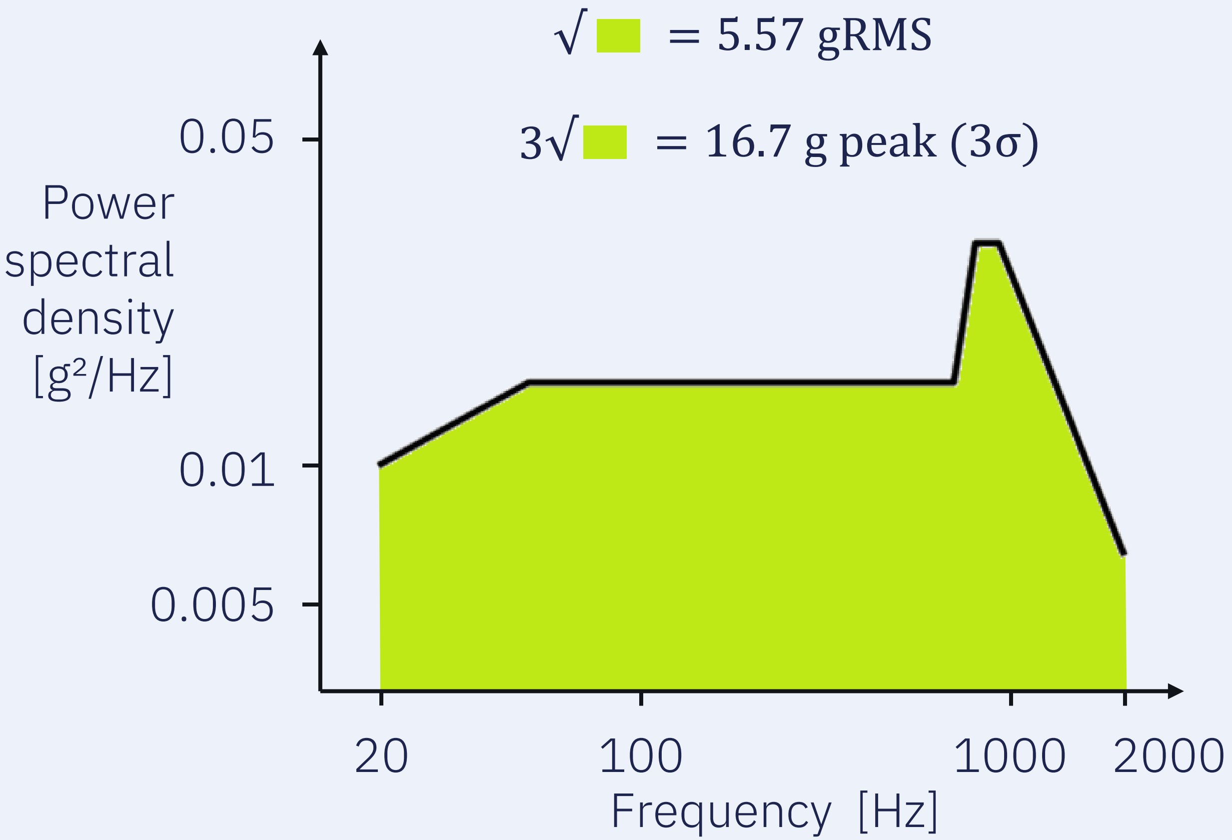
$$\frac{1}{T}\big(x^*(-t) * x(t)\big)(\tau) = R_{xx}(\tau)$$ (autocorrelation)

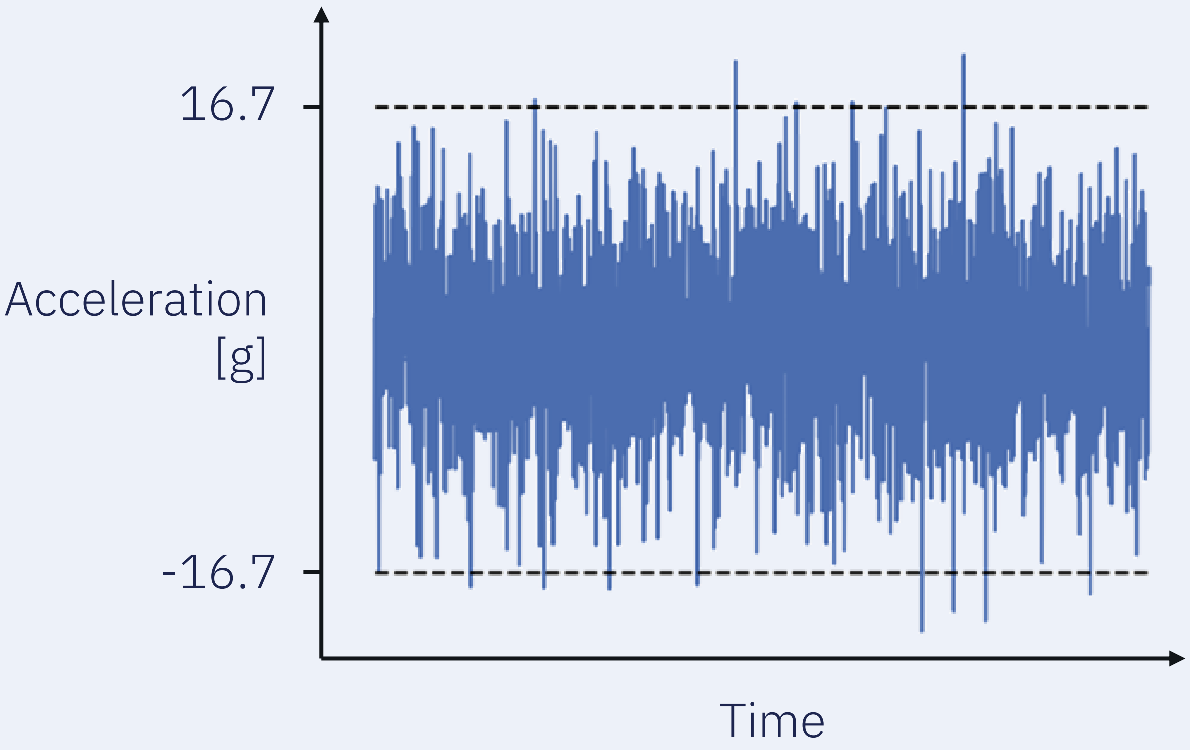
$$x_{\mathrm{RMS}} = \sqrt{\int_{-\infty}^{\infty} \mathcal{F}\{R_{xx}(\tau)\}\mathrm{d}f}$$

Power spectral density

OBTAINING THE RMS DIRECTLY FROM THE PSD

Falcon 9

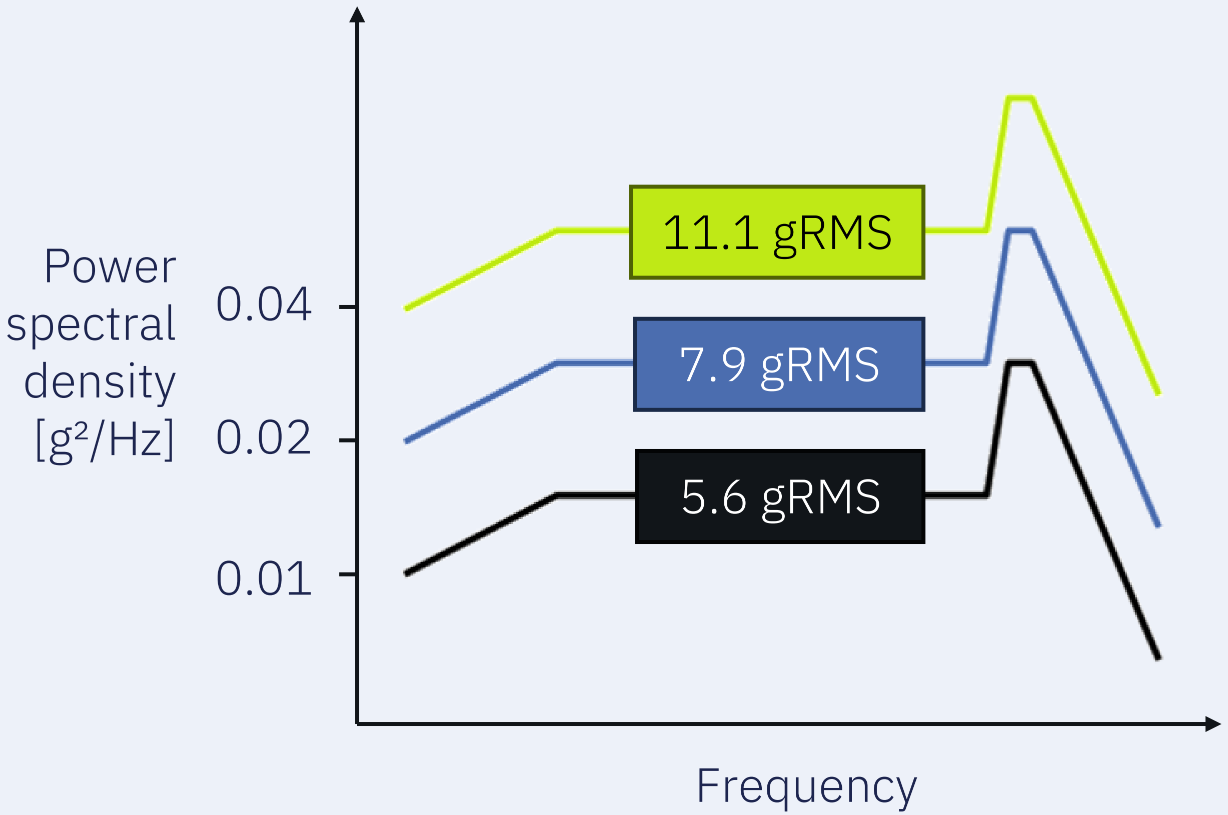




From: SpaceX RPUG

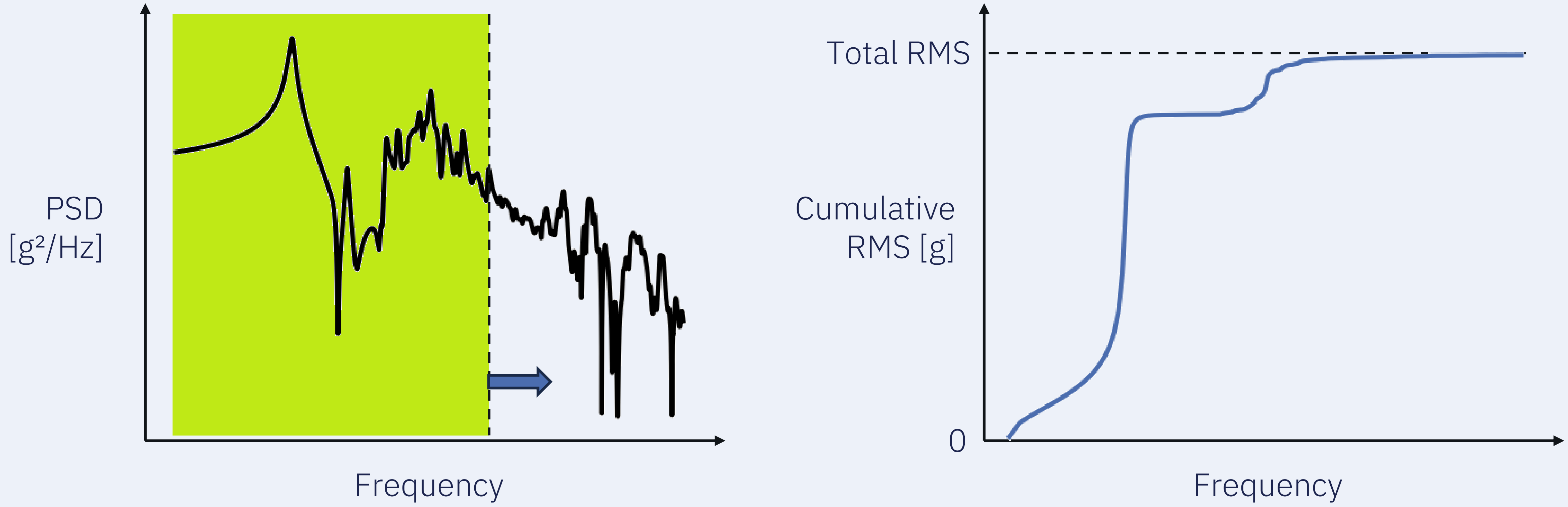
POWER SCALES AS THE SQUARE OF THE AMPLITUDE

Level	Power	Amplitude
$\text{dB} = 10\log_{10} r_\text{p}$ $\text{dB} = 20\log_{10} r_\text{a}$	$r_\text{p} = 10^{\frac{\text{dB}}{10}}$	$r_\text{a} = 10^{\frac{\text{dB}}{20}}$
+6 dB	× 4	× 2
+3 dB	× 2	$\times \sqrt{2}$
+0 dB	× 1	× 1

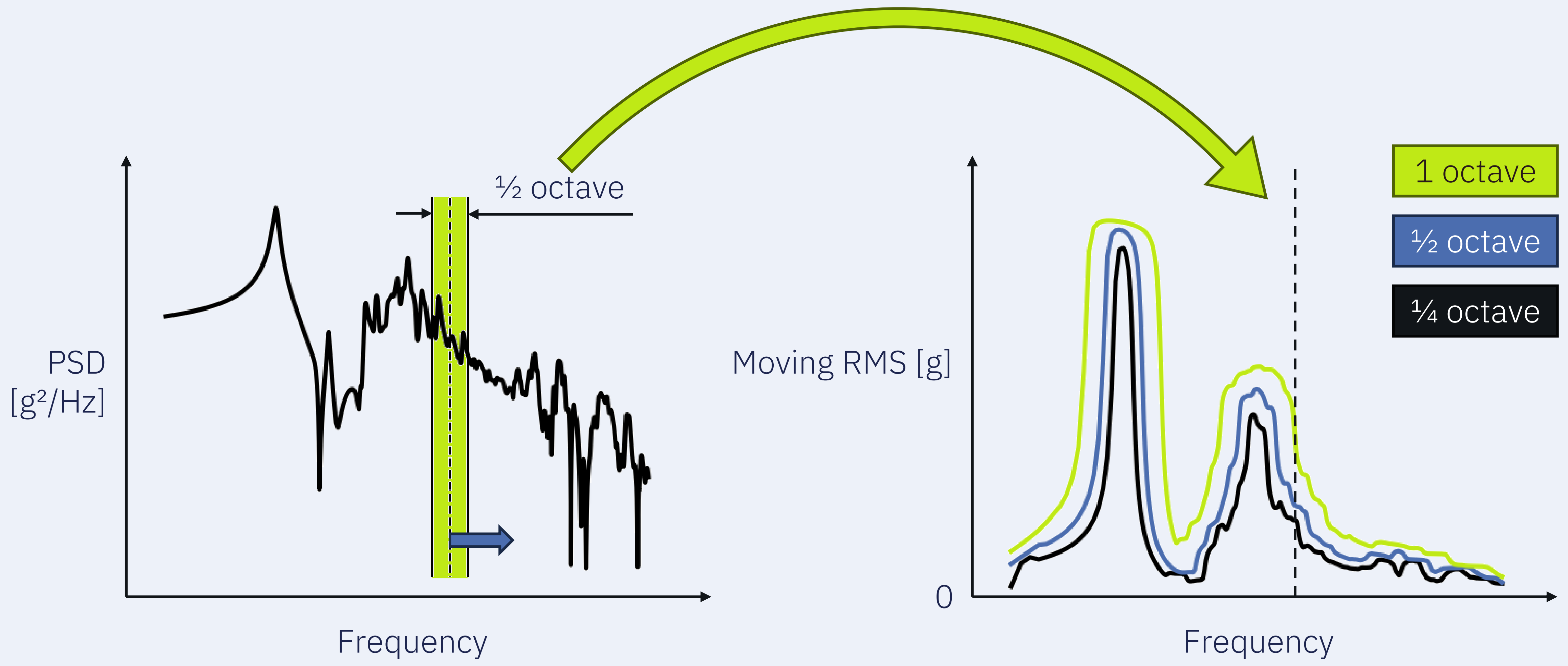


From: SpaceX RPUG

CUMULATIVE RMS SHOWS WHERE THE LEVEL COMES FROM



MOVING RMS SHOWS THE LEVEL IN FREQUENCY BANDS



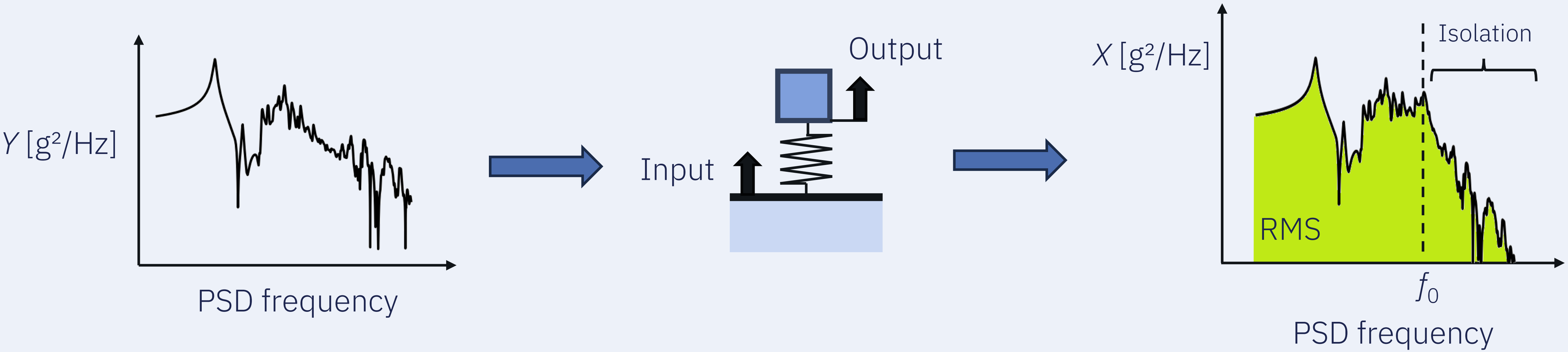
RESPONSE OF A HARMONIC OSCILLATOR TO A PSD

Input PSD: Y

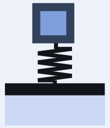
Transmissibility: T_{f_0}

Output PSD

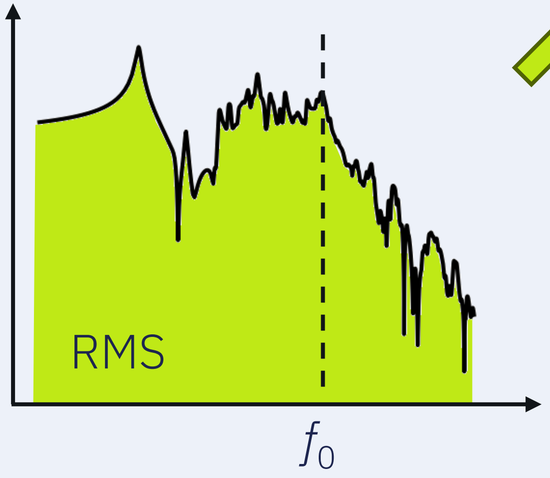
$$X(f) = \left|T_{f_0}(f)\right|^2 Y(f)$$



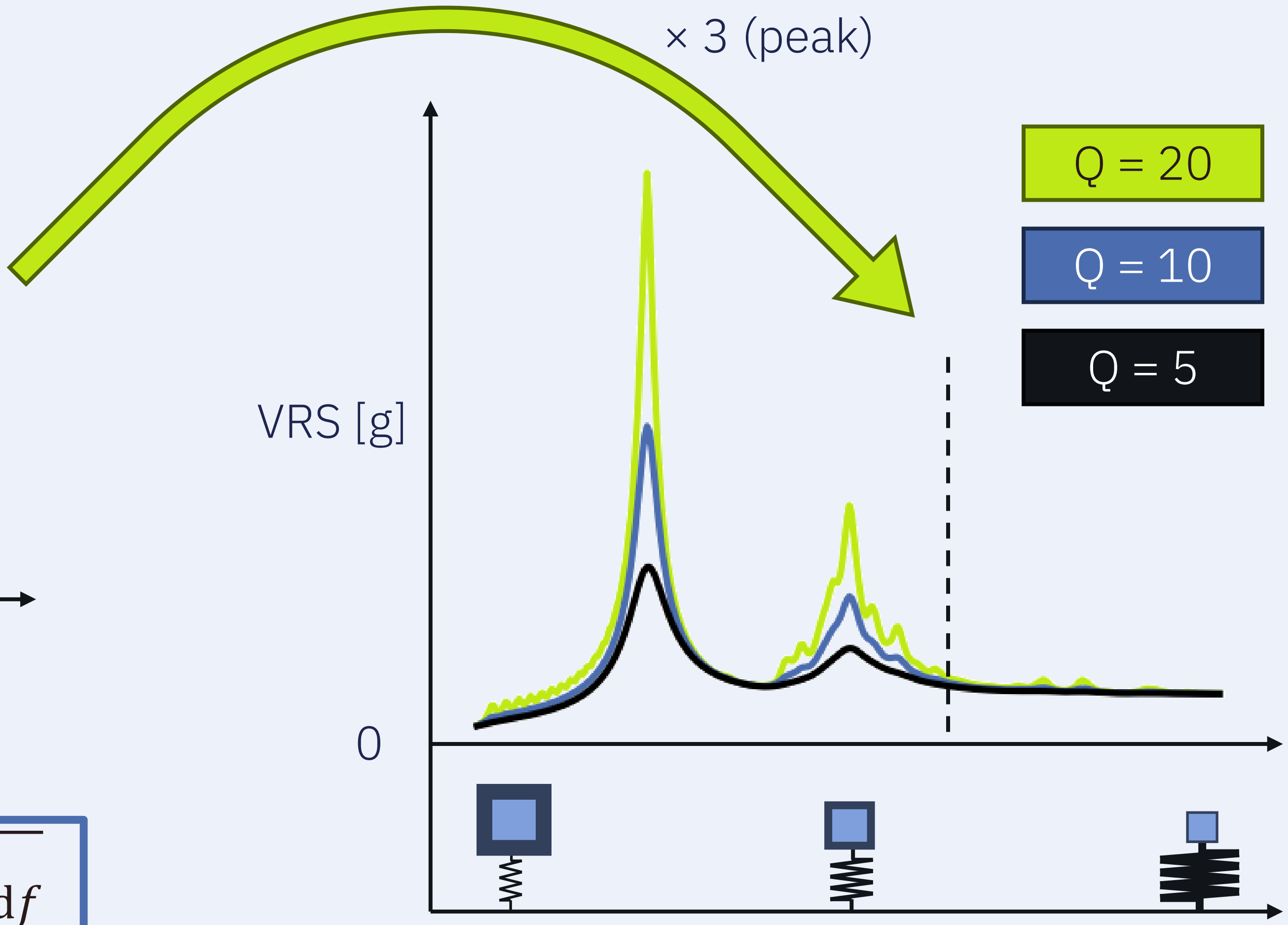
THE VIBRATION RESPONSE SPECTRUM GENERALIZES FOR EVERY OSCILLATORS

For a specific 

$$X(f) = \left|T_{f_0}(f)\right|^2 Y(f)$$

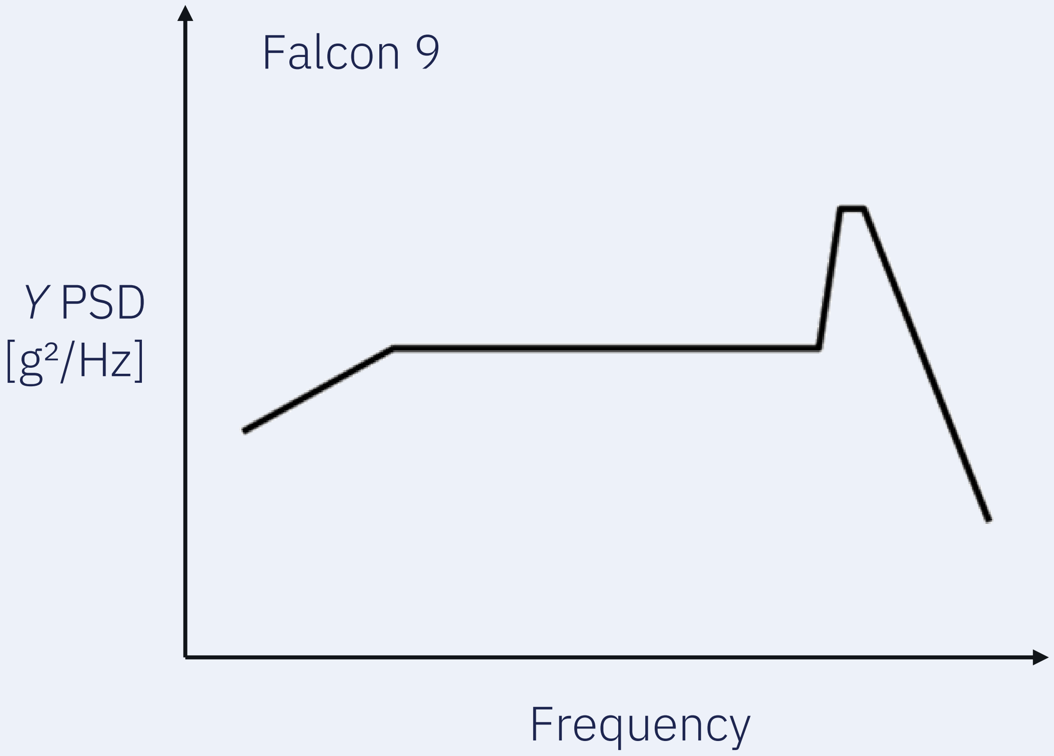


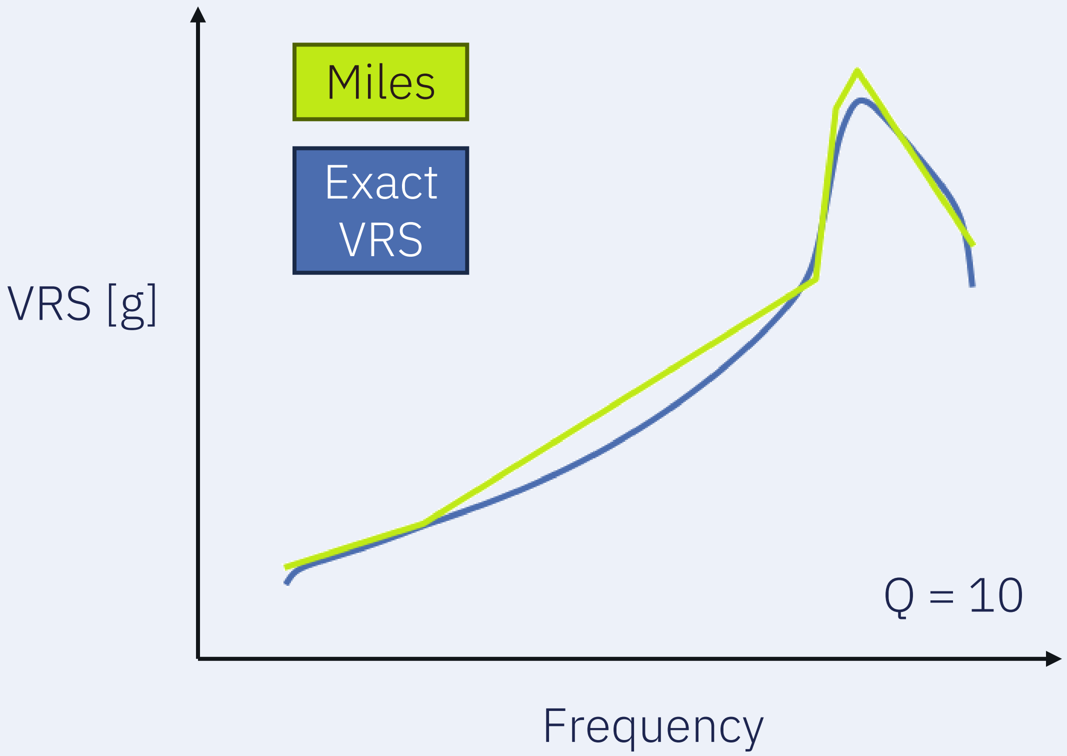
$$\mathrm{VRS}(f_0) = 3\sqrt{\int \left|T_{f_0}(f)\right|^2 Y(f)\mathrm{d}f}$$



MILES' EQUATION APPROXIMATES THE VRS FOR A FLAT PSD

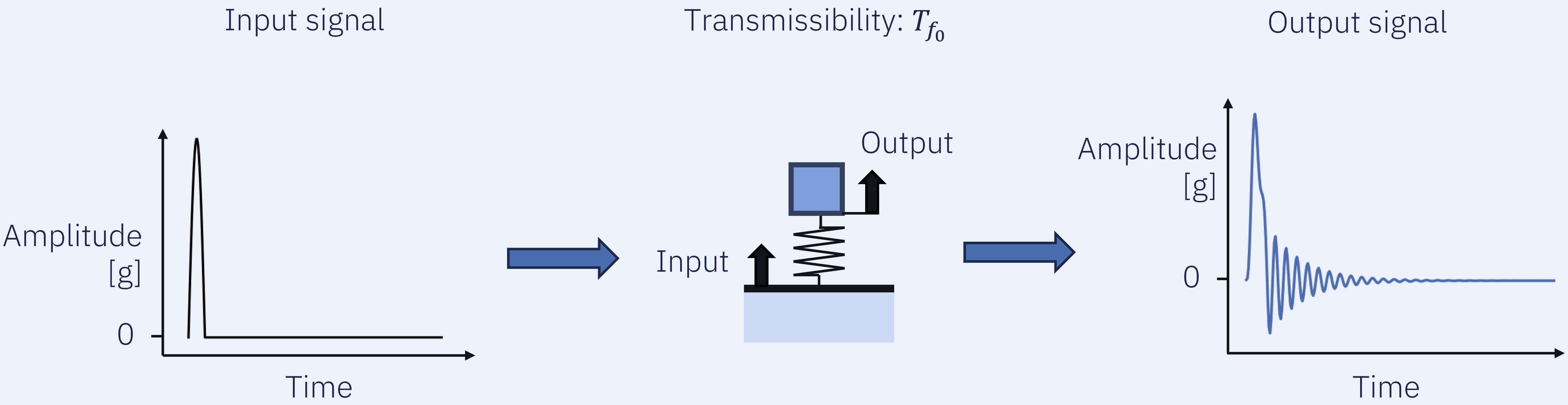
$$\mathrm{VRS}(f_0) = 3\sqrt{\int \left|H_{f_0}(f)\right|^2 Y(f)\mathrm{d}f} \approx 3\sqrt{Y(f_0)\int \left|H_{f_0}(f)\right|^2 \mathrm{d}f} = 3\sqrt{\frac{\pi}{2} f_0 Q Y(f_0)}$$



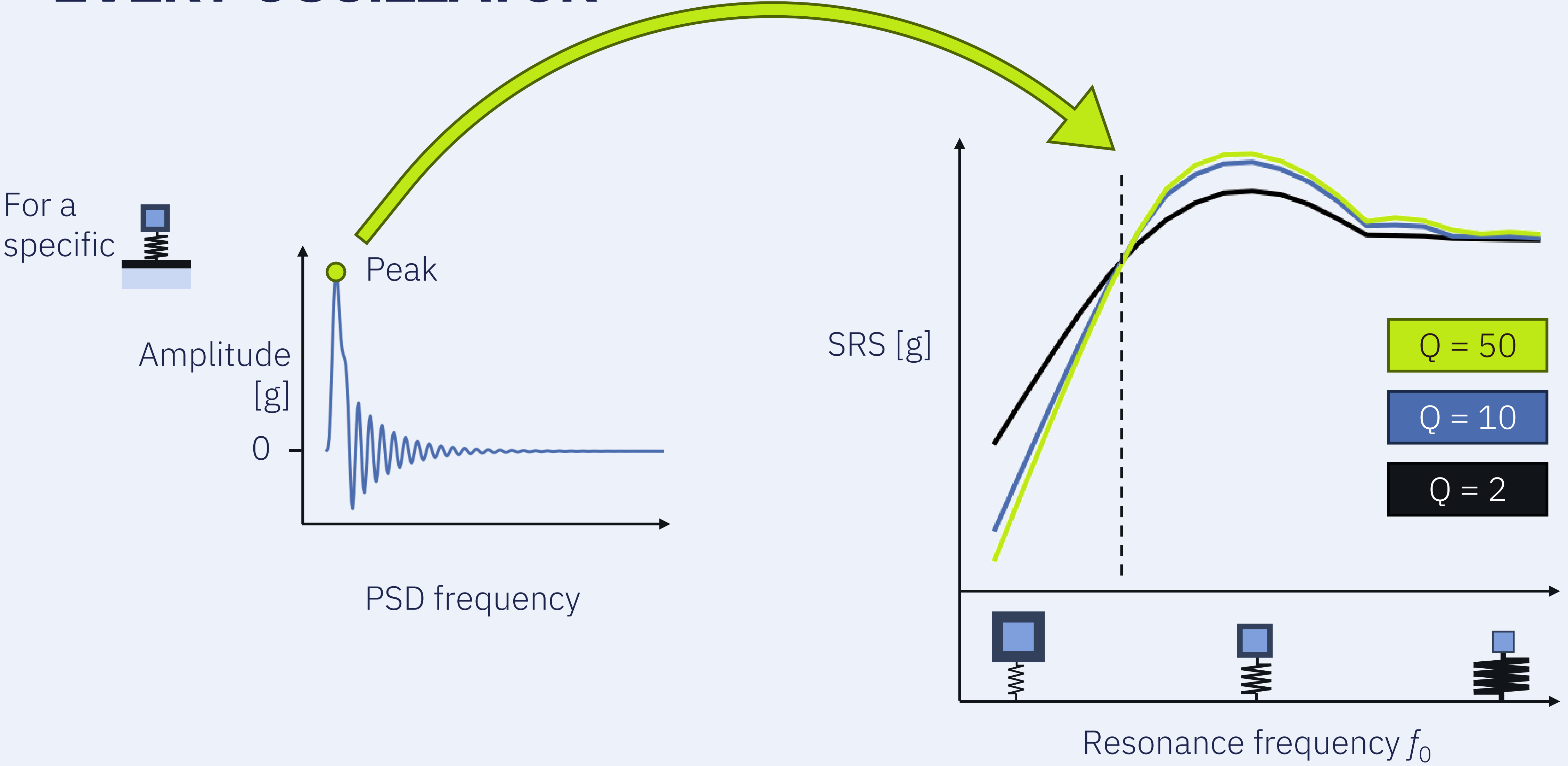


From: SpaceX RPUG

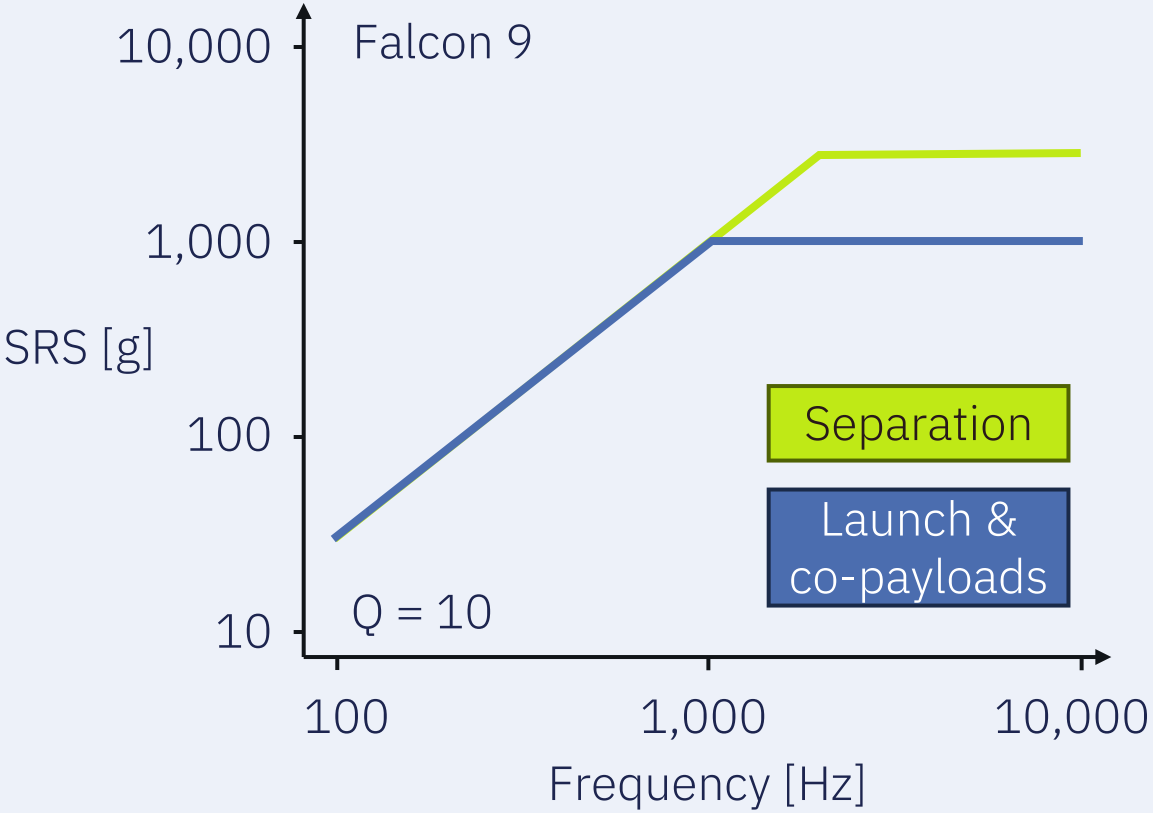
RESPONSE OF A HARMONIC OSCILLATOR TO SHOCK

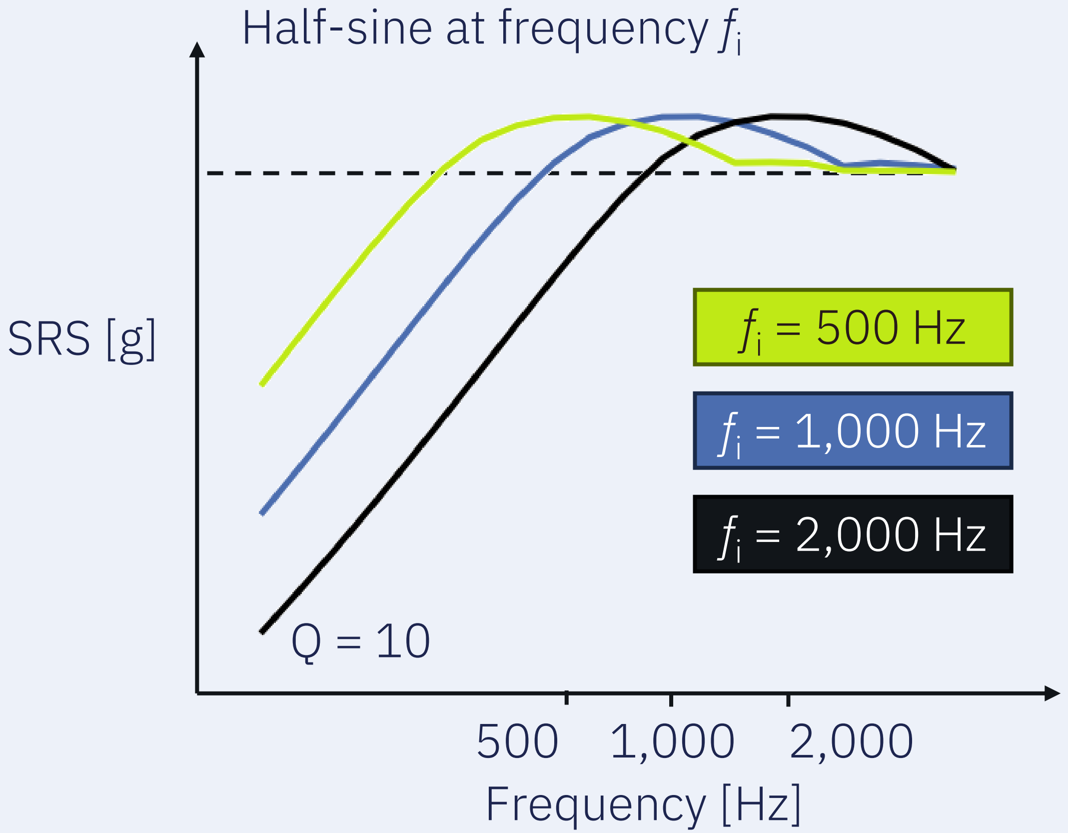


THE SHOCK RESPONSE SPECTRUM GENERALIZES FOR EVERY OSCILLATOR



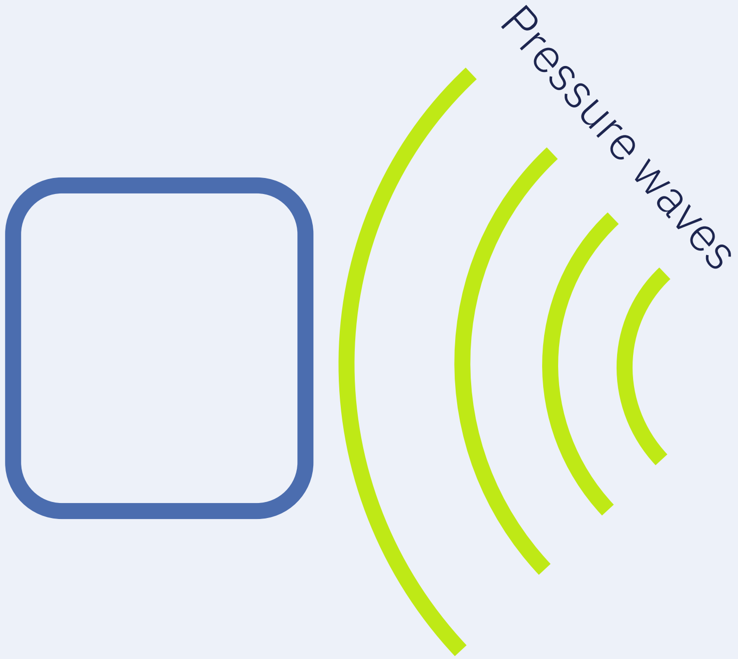
SRS OF HALF-SINE IMPULSE REACHES A PLATEAU



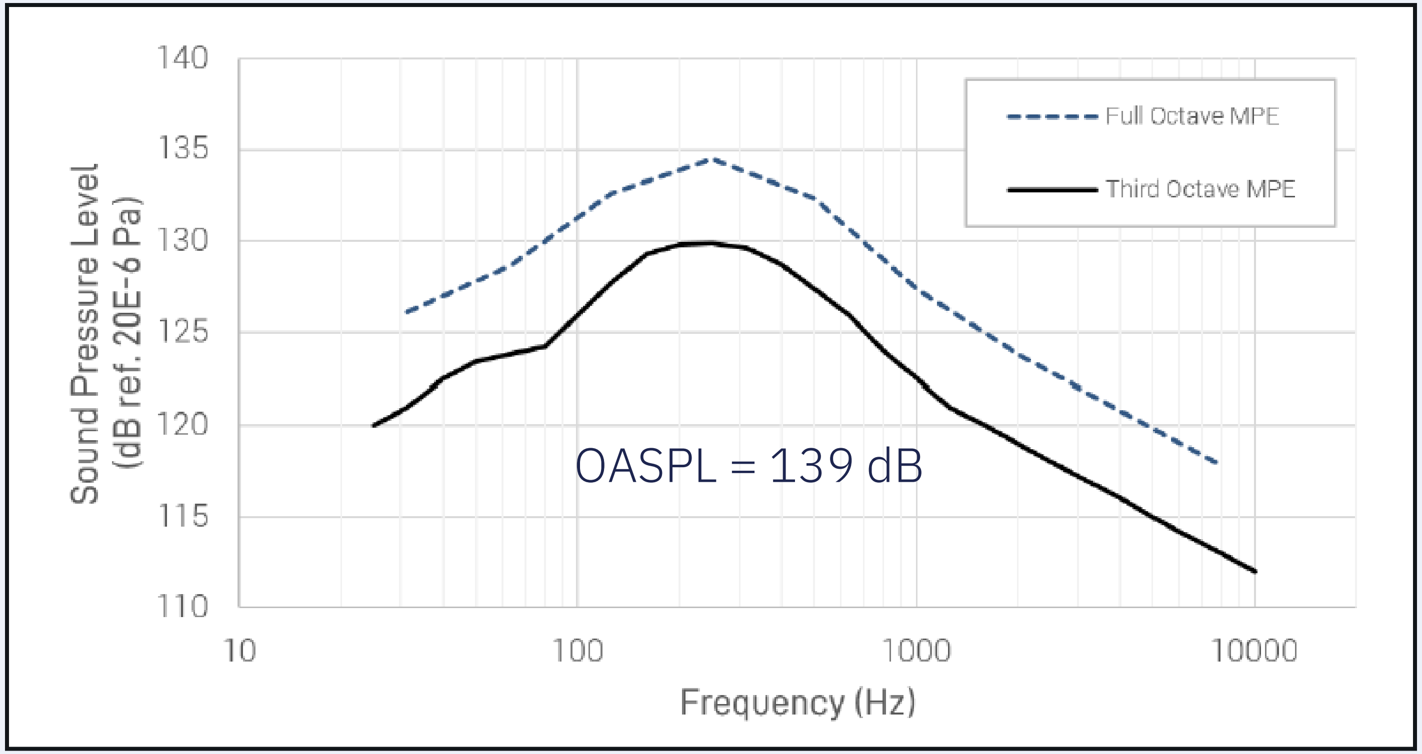


From: SpaceX RPUG

ACOUSTIC LOADS MOSTLY AFFECT LARGE AND THIN WALLS



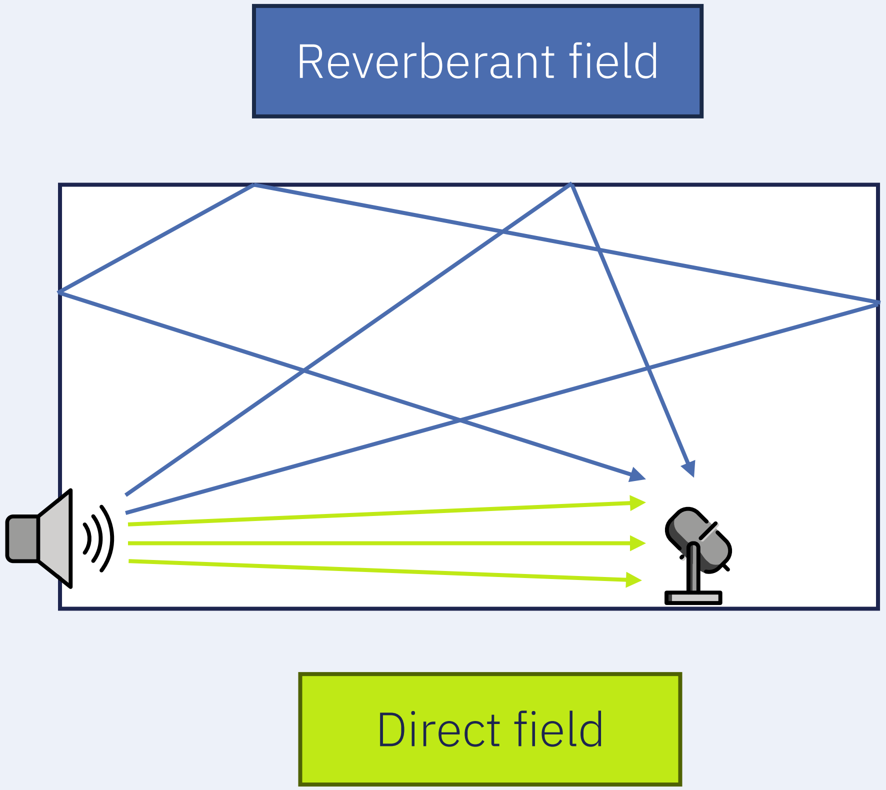
Falcon 9

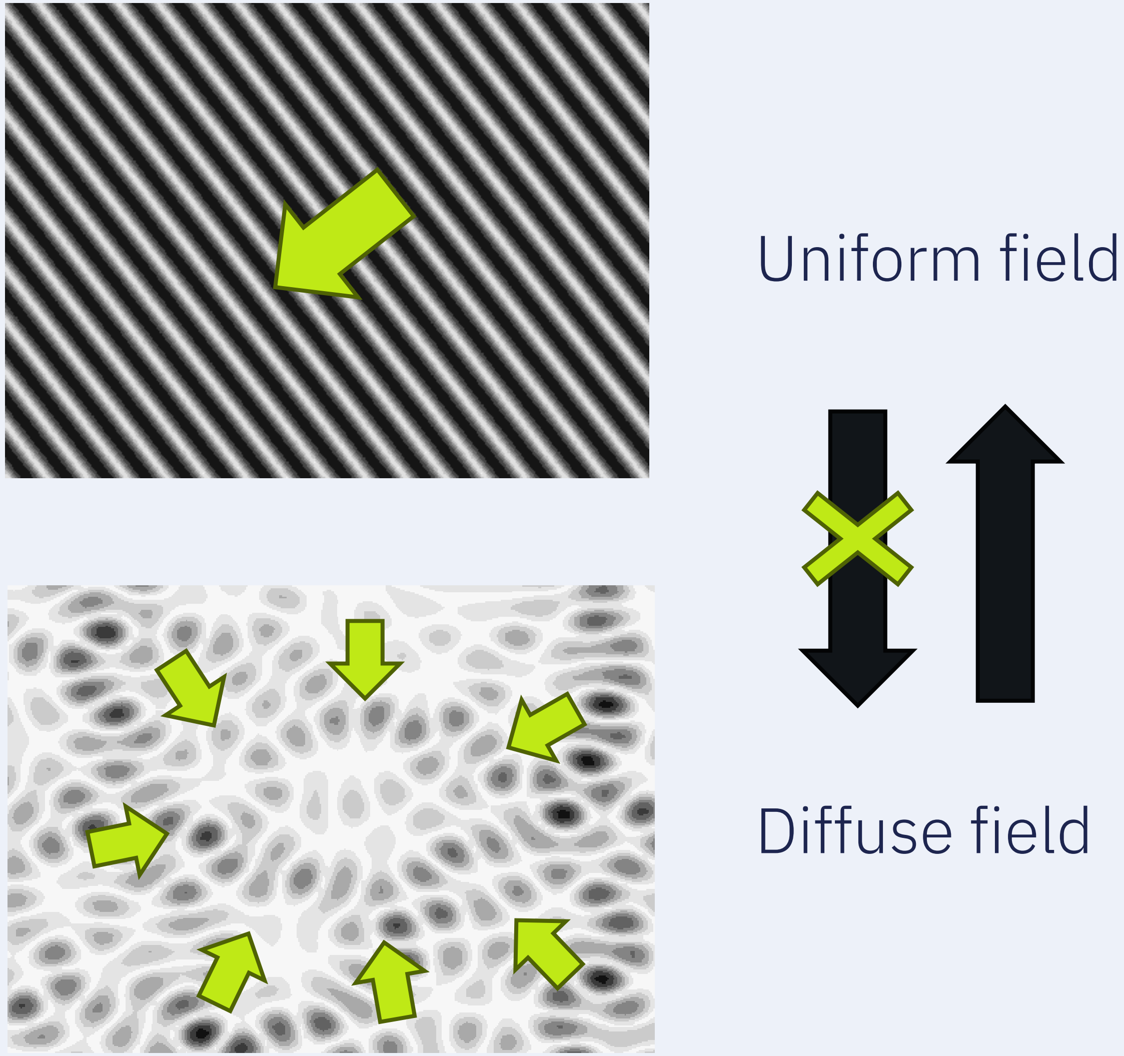


OverAll Sound Pressure Level $10 \log \left(\frac{p_{\mathrm{rms}}^2}{p_{\mathrm{ref}}^2} \right)$

From: SpaceX RPUG

FAIRING ACOUSTIC ENVIRONMENT CAN BE ASSUMED DIFFUSE

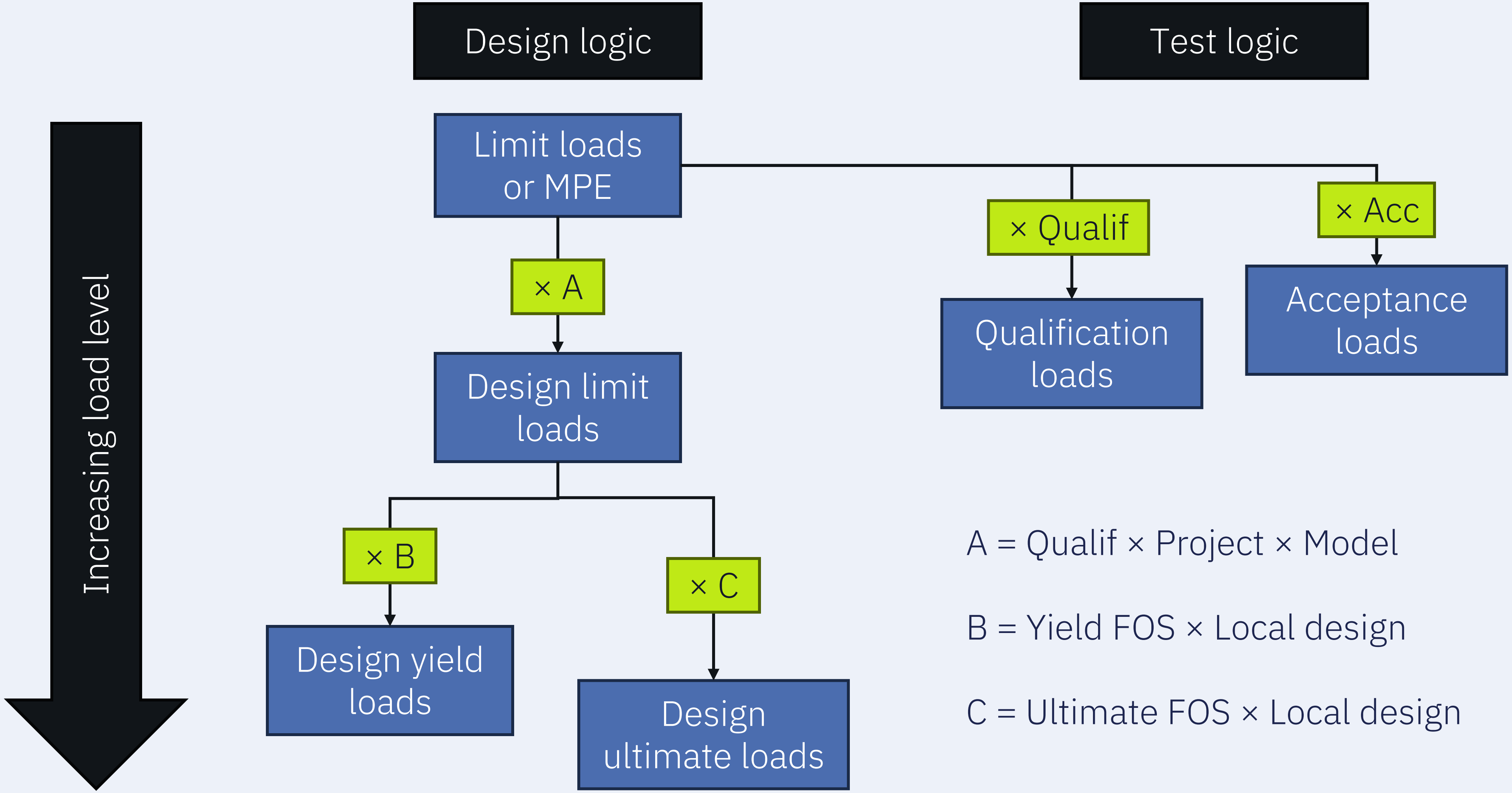




FAILURE MODES

WHAT CAN BREAK AND HOW

THE MARGINS TAKEN IN THE VERIFICATION LOGIC



A = Qualif × Project × Model

B = Yield FOS × Local design

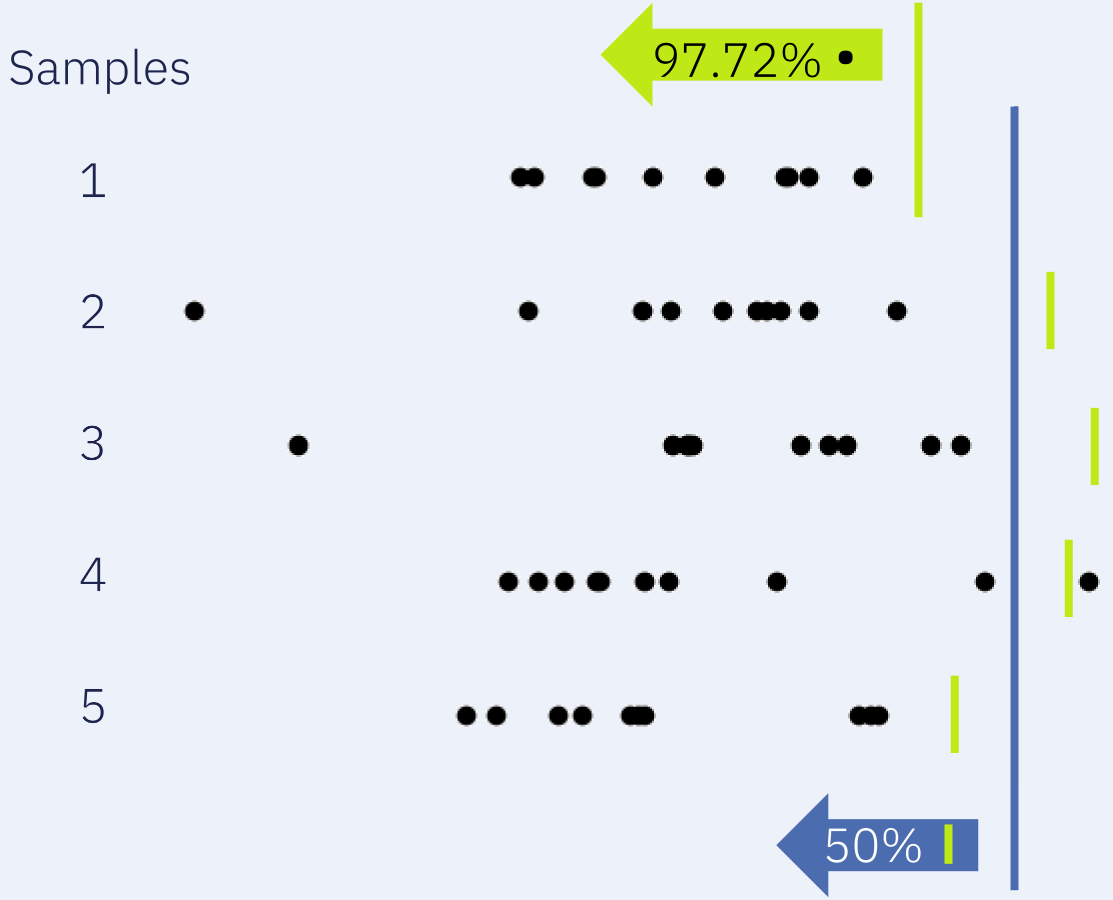
C = Ultimate FOS × Local design

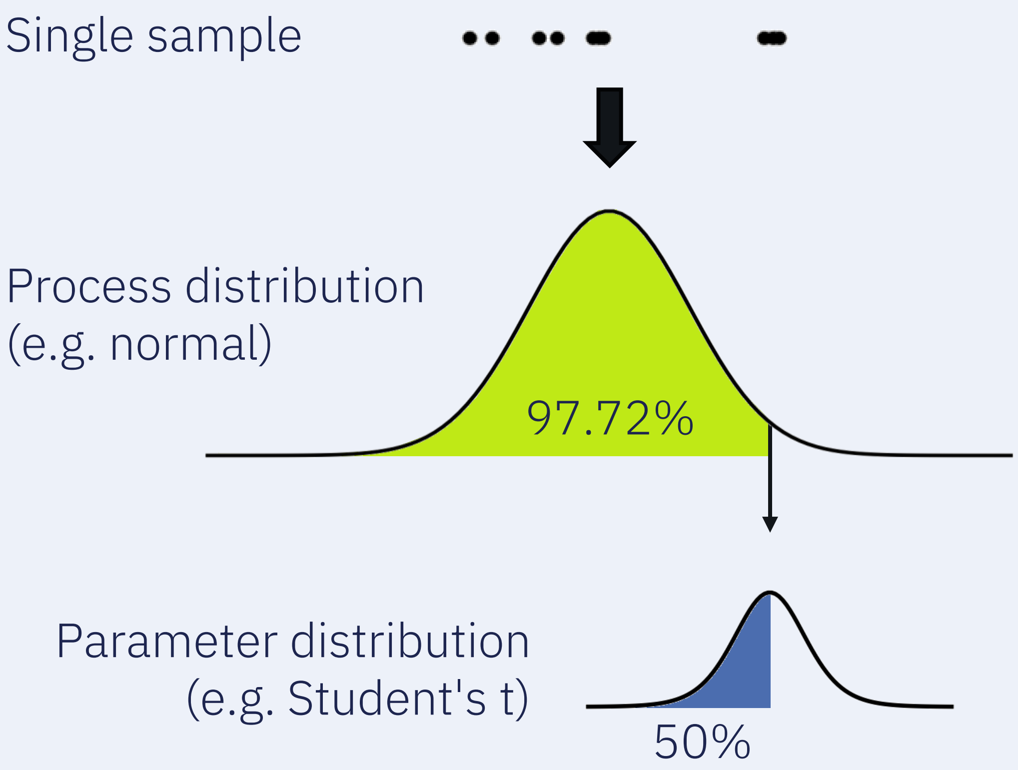
From: ECSS-E-ST-32-10C

CONFIDENCE LEVELS CHARACTERIZE UNCERTAINTY

Some standard confidence levels for limit loads:

ECSS	GEVS (loads)	GEVS (random)
99 / 90	97.72 / 50	95 / 50

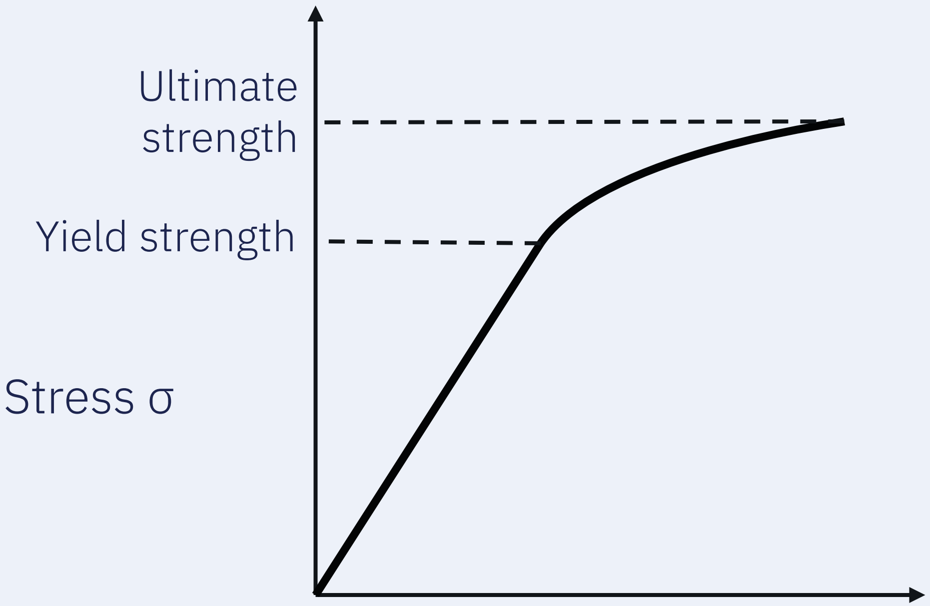




From: ECSS-E-ST-32C, GSFC-STD-7000B

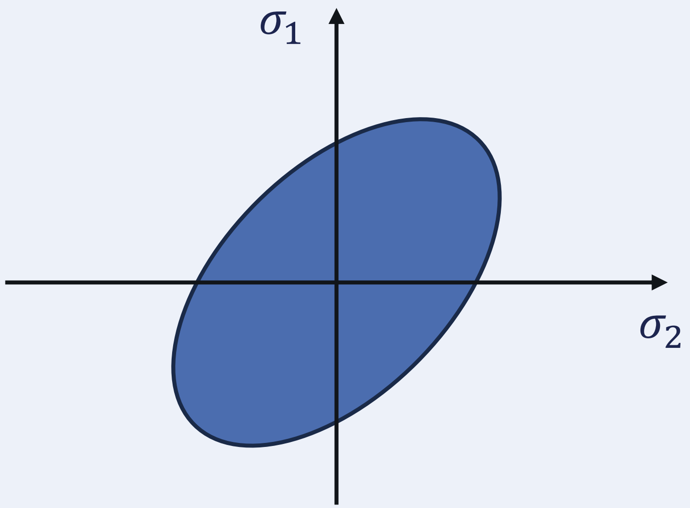
YIELD AND ULTIMATE FAILURE OF METALLIC PARTS

Tensile stress



Von Mises yield criterion

$$\sigma_{\text{vm}} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]}$$



~~Linearity assumption (FRF, PSD)~~

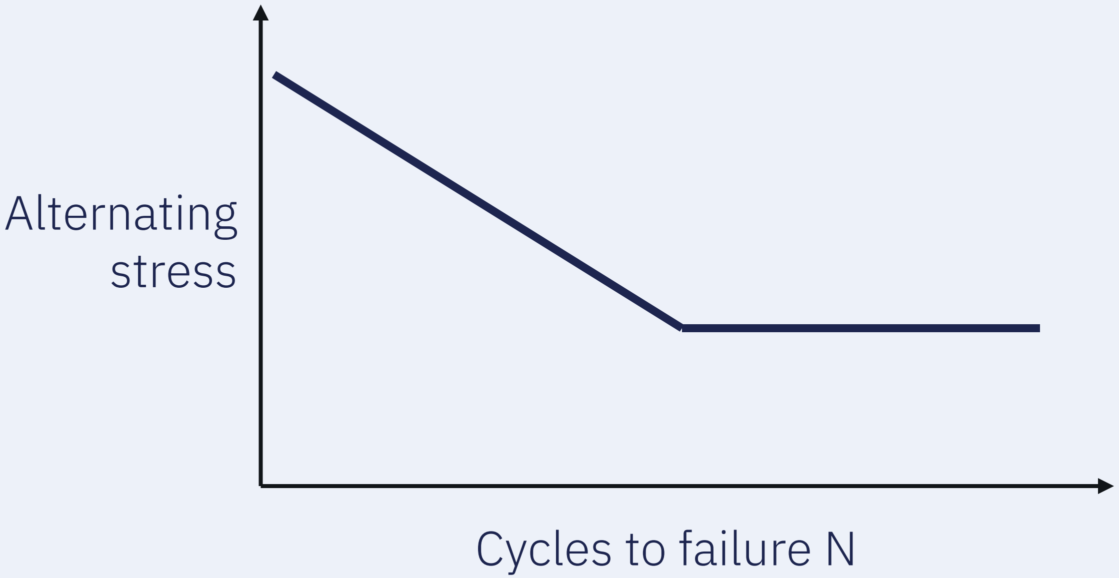
LIMIT TESTING TO A STRICT MINIMUM DUE TO FATIGUE

- Fatigue failure
  - Cyclic load
  - Stress below material strength
- Due to crack propagation
- High preload is beneficial
- Palmgren-Miner rule

$$4\sum_{i=1}^{m}\frac{n_i}{N_{\mathrm{f},i}} \leq 1$$

m stress conditions
n_i cycles
$N_{f,i}$ cycles to failure

Fatigue performance

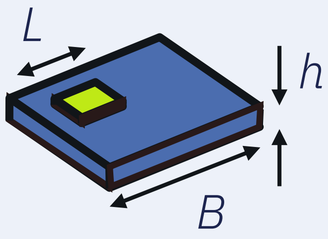


PCB COMPONENTS ARE SENSITIVE TO FATIGUE

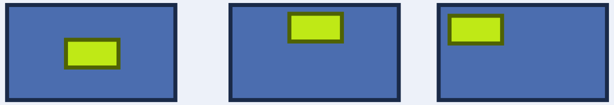
Steinberg fatigue limit

Component can survive
20M cycles at deflection

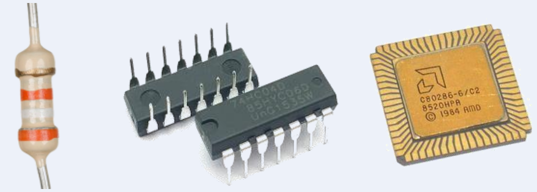
$$Z_{3\sigma\text{limit}} \frac{0.02816B}{Chr\sqrt{L}}$$



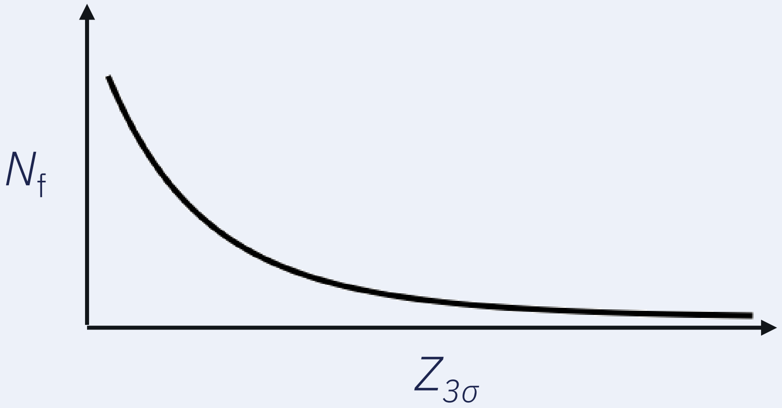
r



C



Fatigue curve



Fatigue life (# cycles)

$$N_f = 20 \times 10^6 \left(\frac{Z_{3\sigma\text{limit}}}{Z_{3\sigma}}\right)^b$$

Steinberg's fatigue model

$$b = 6.4$$

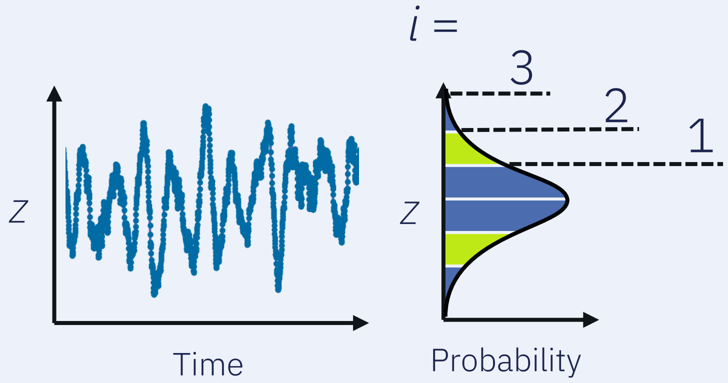
Miner's cumulative index

$$\mathrm{CDI} = 4 \sum_{i=1}^{m} \frac{n_i}{N_{f,i}} \leq 1$$

Actual life (# cycles)

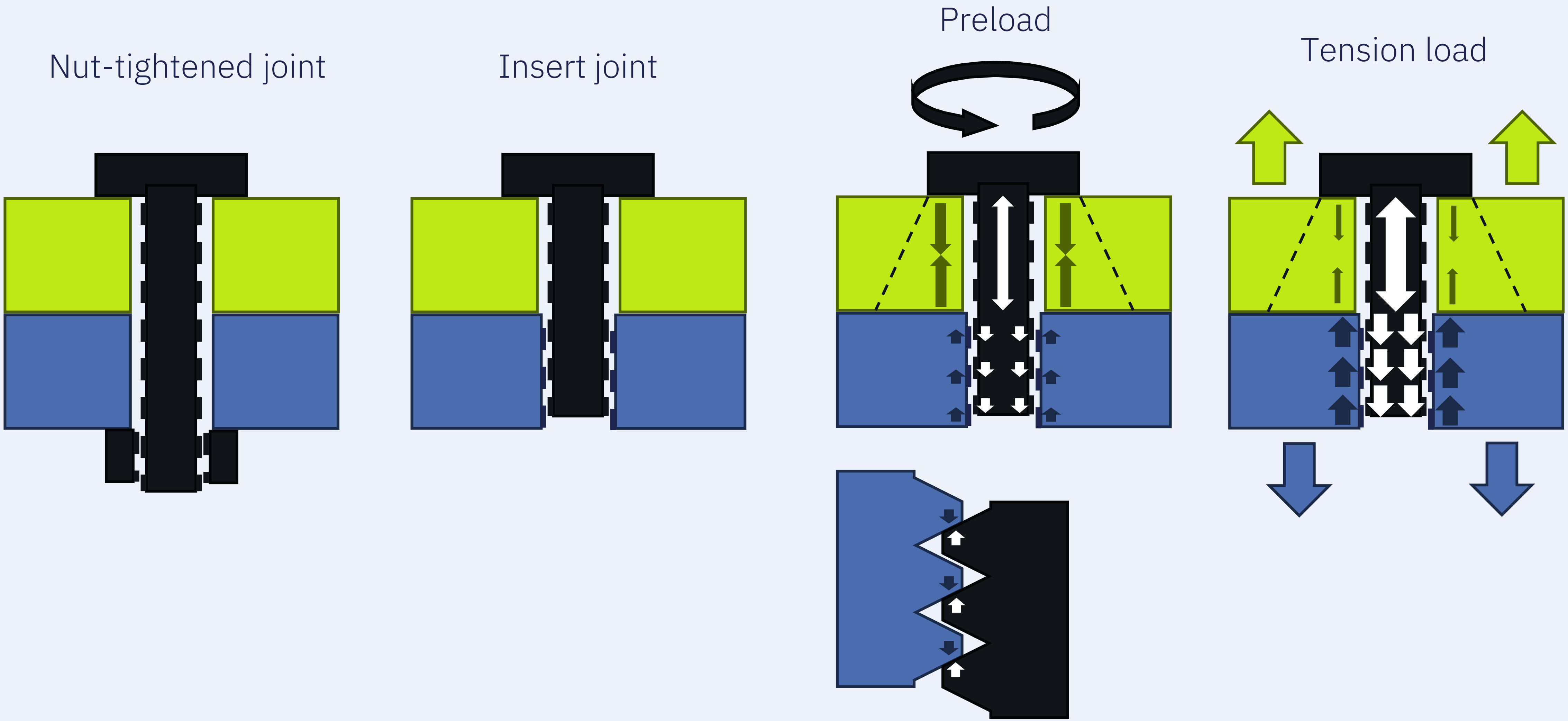
$$n = f \times T$$

PCB mode freq. f, test duration T



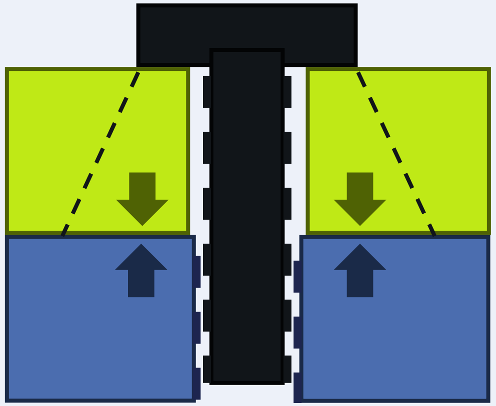
From: García et al., AIP Conf. Proc. (2018)

BOLTED JOINTS CLAMP FLANGES AGAINST ANOTHER PART

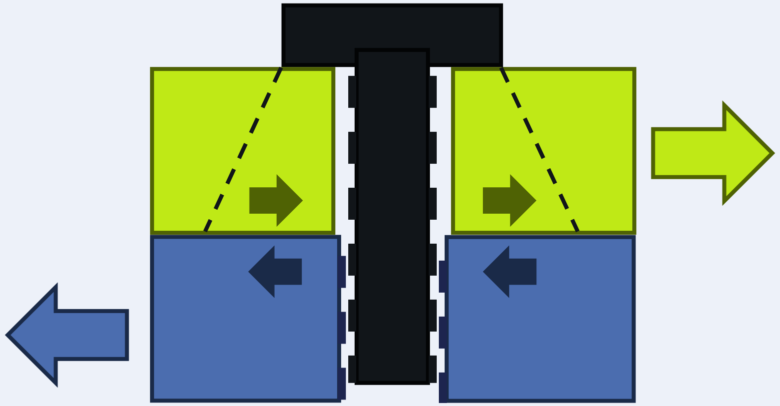


FRICTION GRIP JOINTS USE STATIC FRICTION IN SHEAR

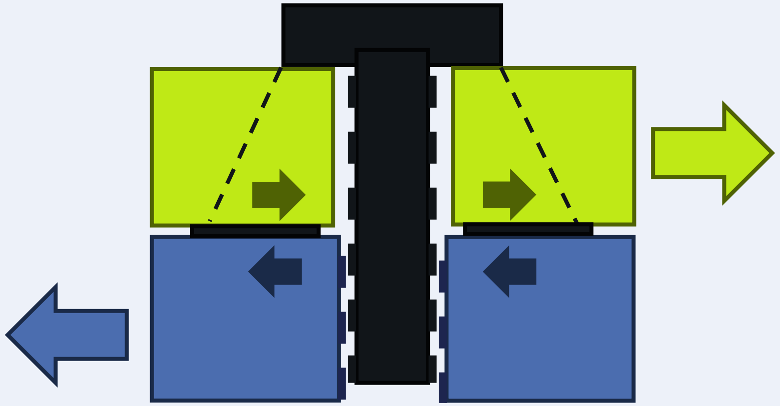
Preload



Shear load

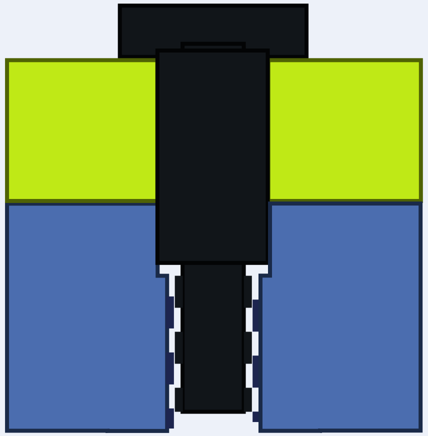


Friction shim

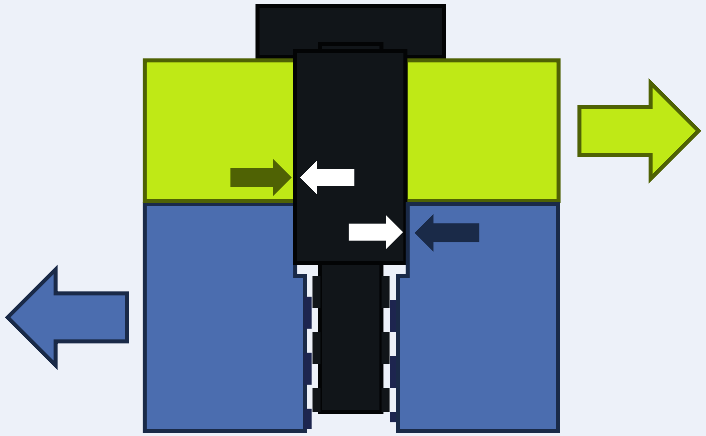


BEARING JOINTS ARE FOR LOW TOLERANCE APPLICATIONS

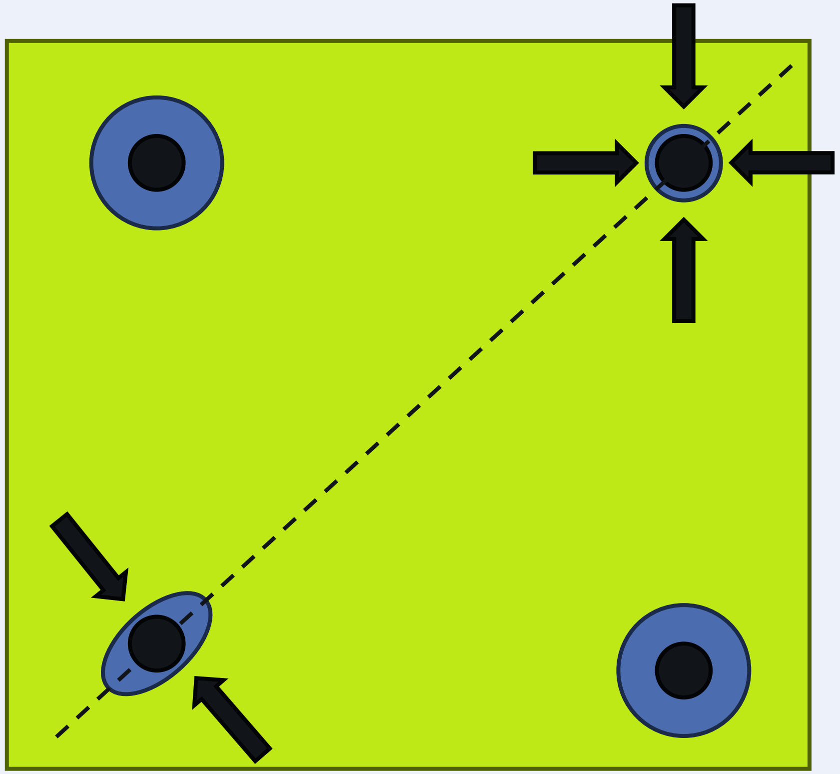
Shoulder fastener



Shear load

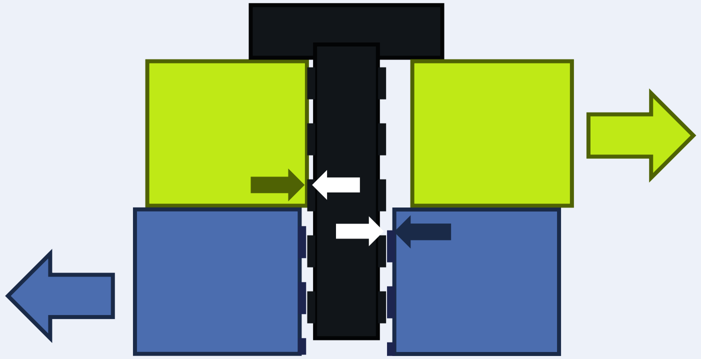


Avoid hyperstaticity

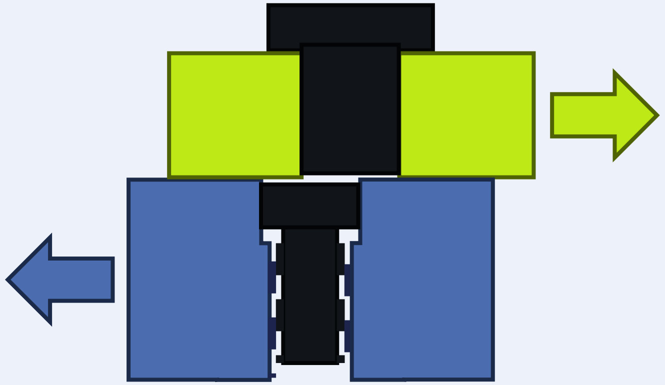


BOLT FAILURES MODES (FASTENER)

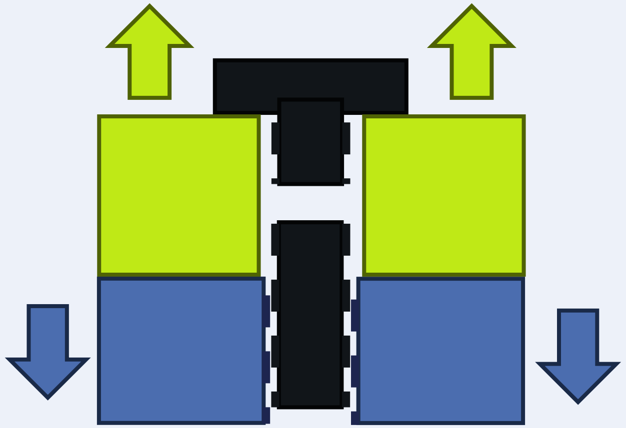
Slipping ➔ bearing failure



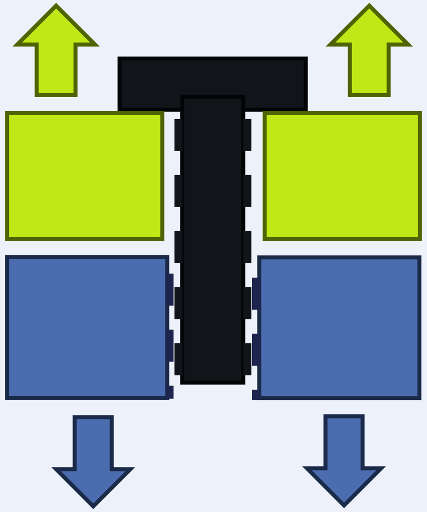
Fastener shear failure



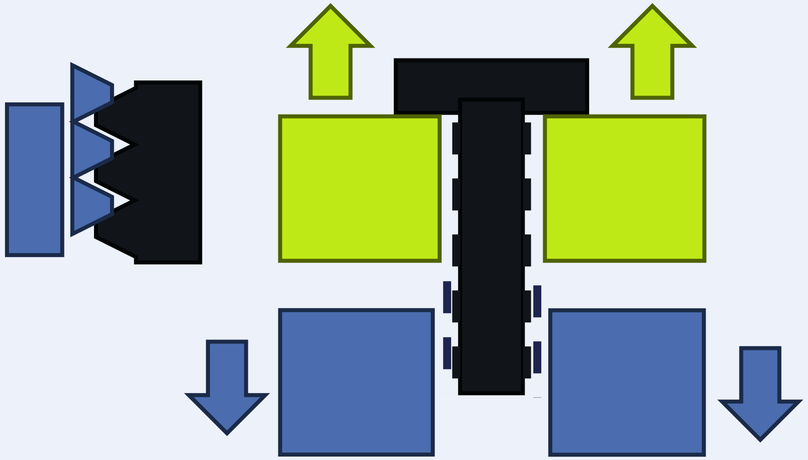
Fastener tensile failure



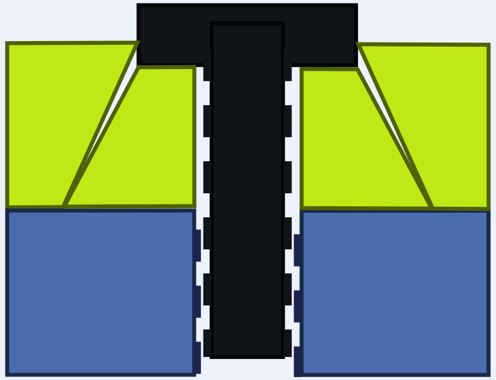
Gapping



Thread shear pull-out



Crushing of flange

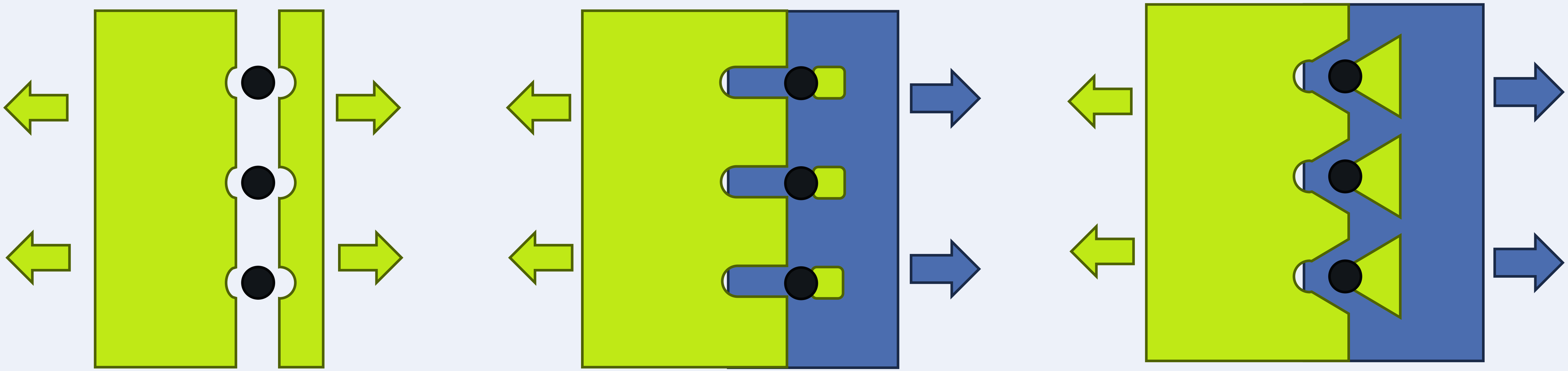


BOLT FAILURE MODES (FLANGE)

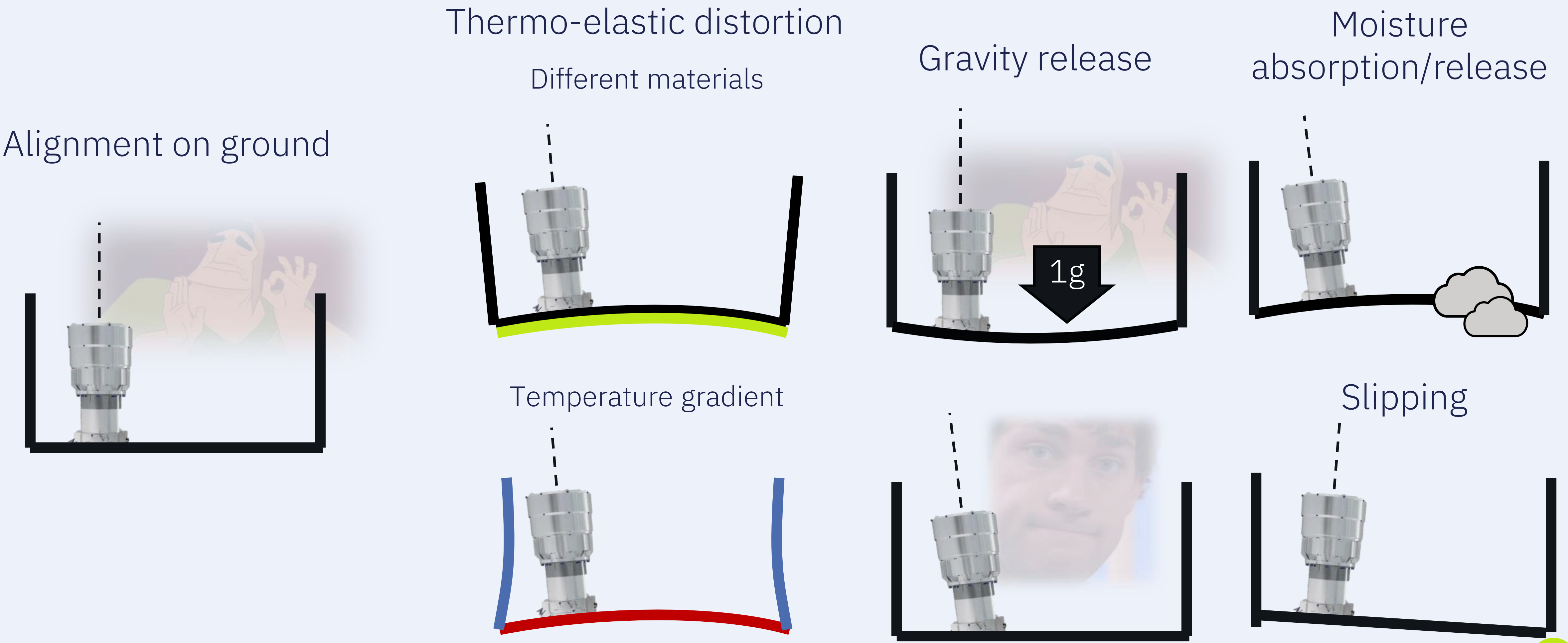
Flange tension failure

Flange shear-out

Flange tear-out



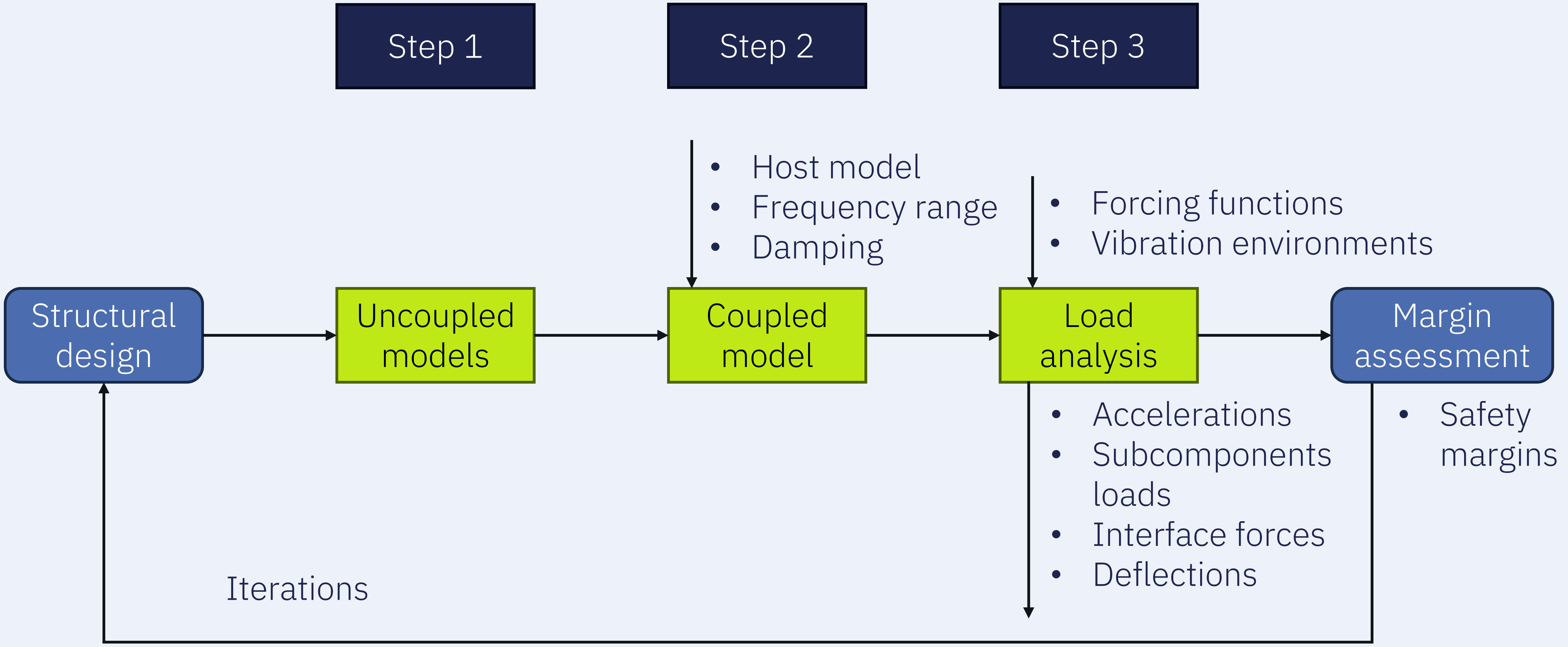
DIMENSIONAL STABILITY



STRUCTURAL ANALYSIS

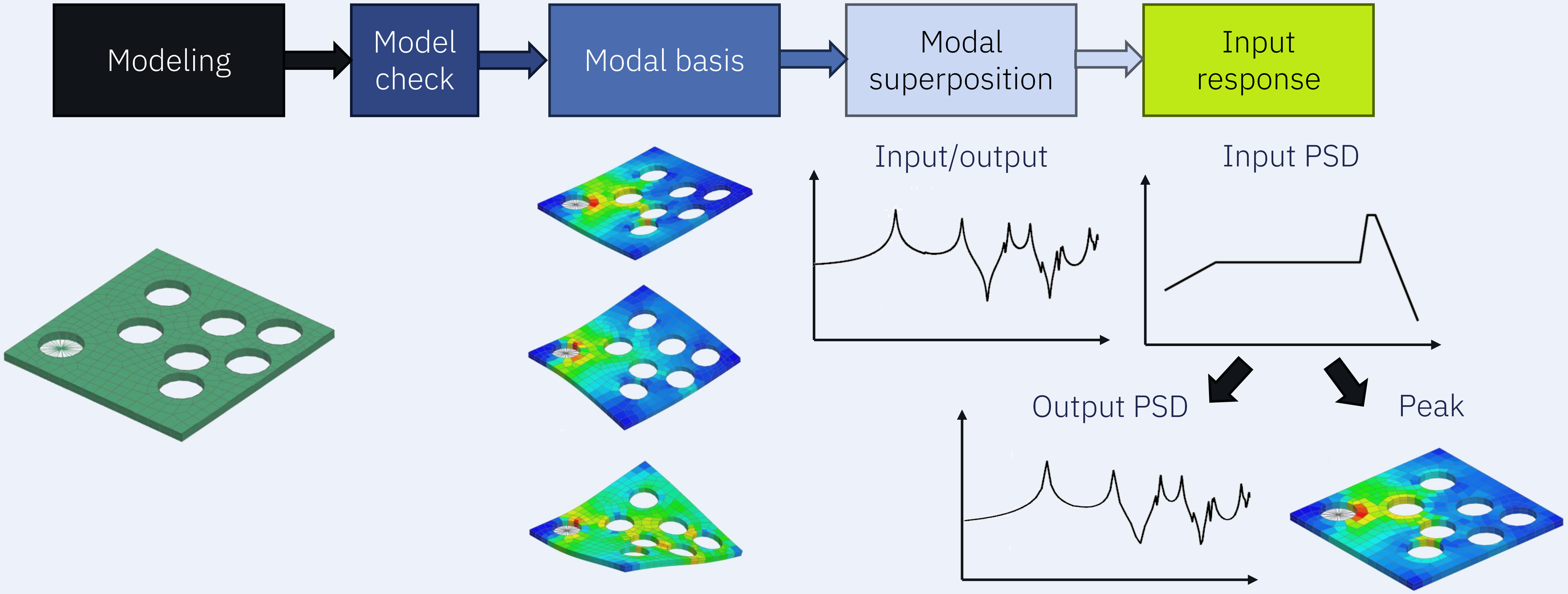
FILLING UP THE COMPANY'S SERVERS 101

LOAD CYCLE ANALYSIS FOR STRUCTURAL DESIGN



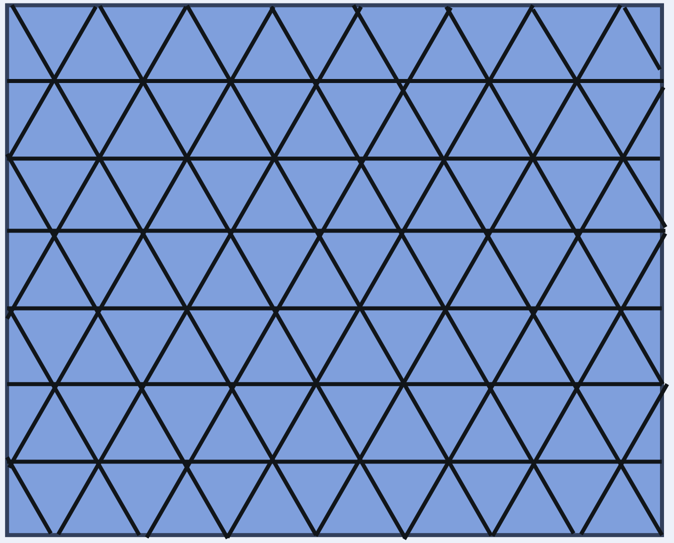
From: NASA-STD-5002

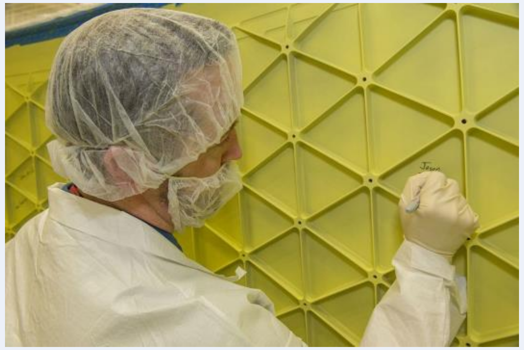
STRUCTURAL ANALYSIS WORKFLOW



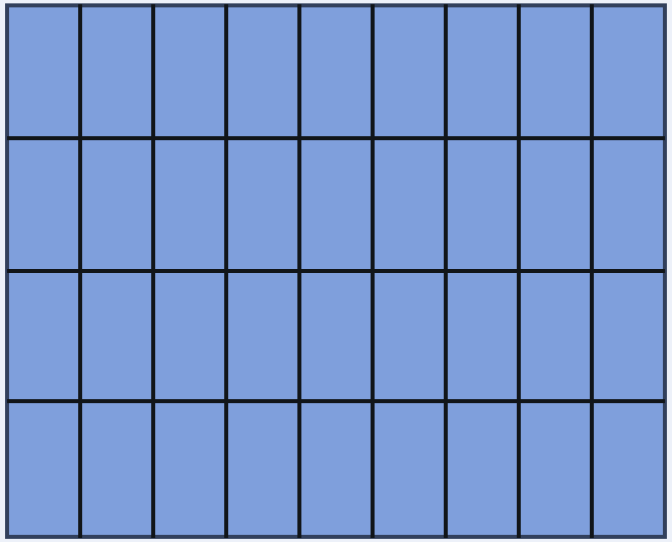
GRID PANELS APPROACH HOMOGENEOUS BEHAVIOR

Isogrid

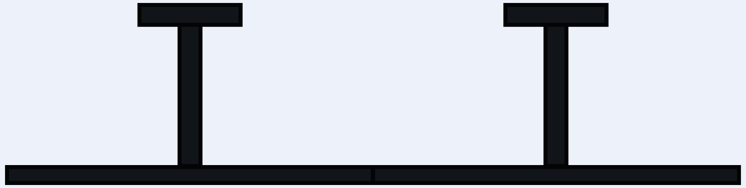




Orthogrid

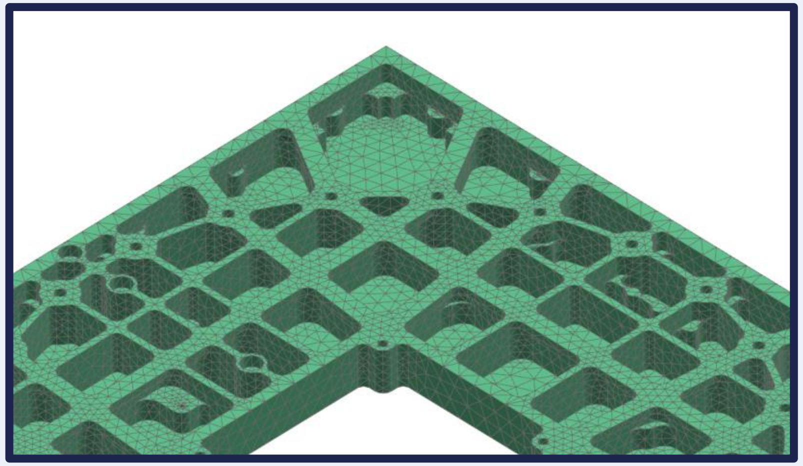


Stiffener profile

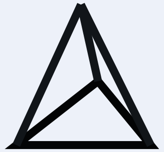


A FINITE ELEMENT MODEL CAN BE MORE OR LESS ACCURATE

~100k elements

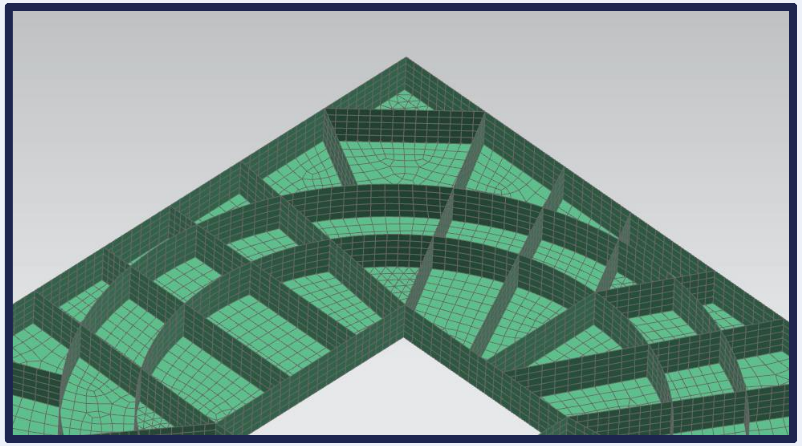


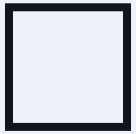
CHEXA



CTETRA

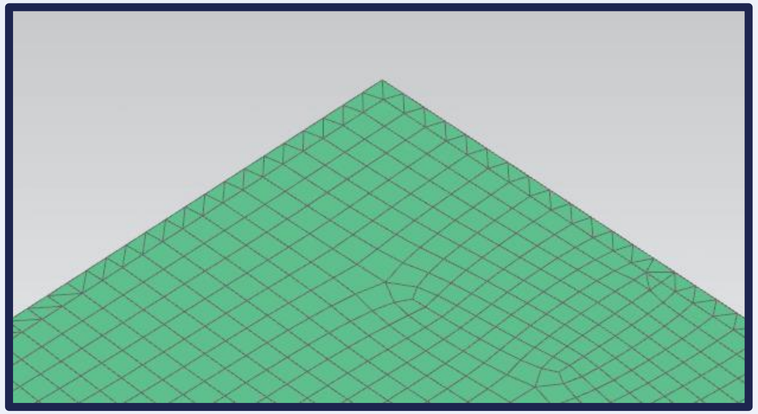
~10k elements

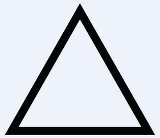




CQUAD

~1k elements

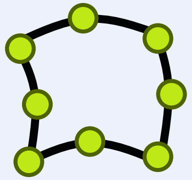




CTRIA

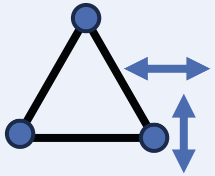
Linear vs parabolic:

CQUAD4

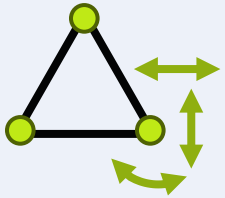


CQUAD8

Rotation DOF:

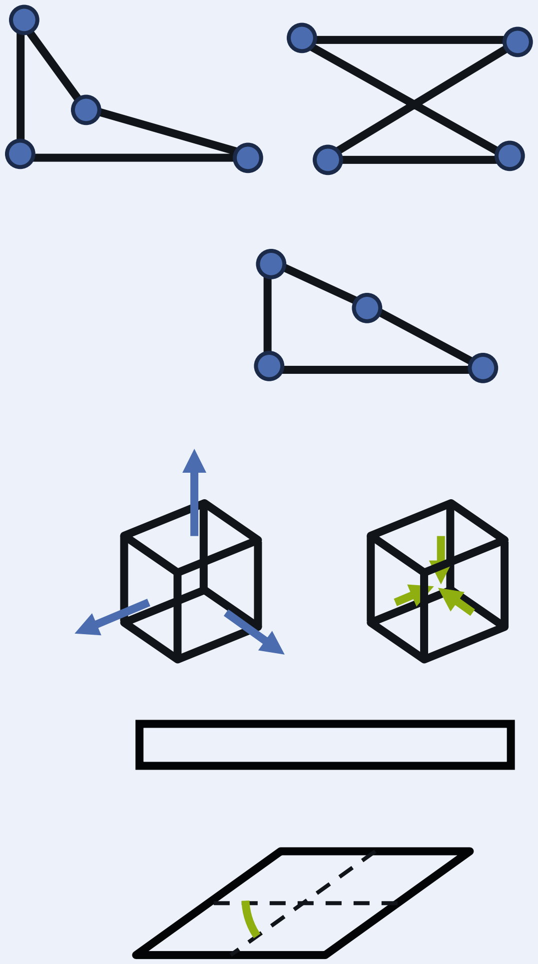


CTRIA3



CTRIAR

ELEMENT QUALITY IS ESSENTIAL FOR VALID RESULTS



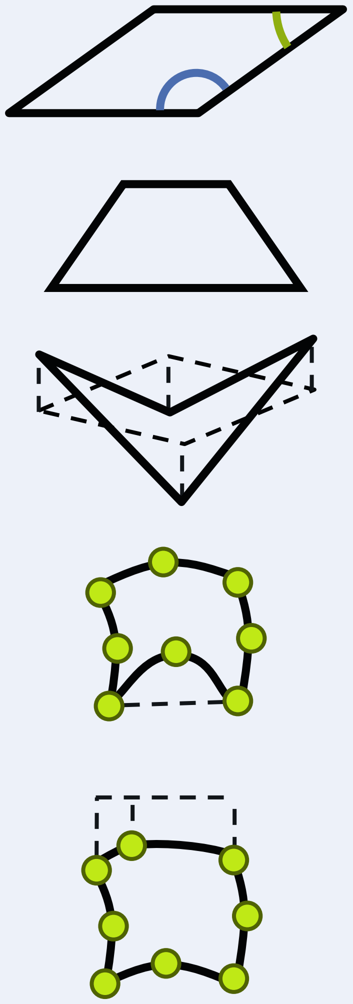
Jacobian sign

Jacobian zero

Volume sign

Aspect ratio

Skew angle



Max & min interior angles

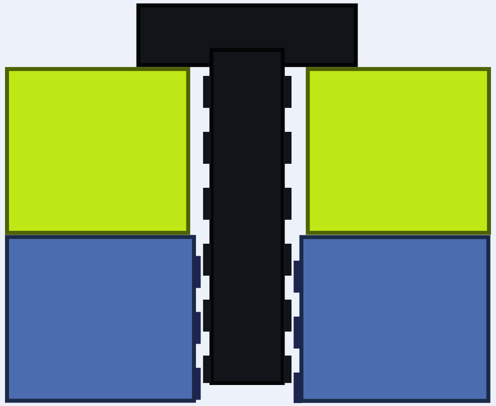
Taper

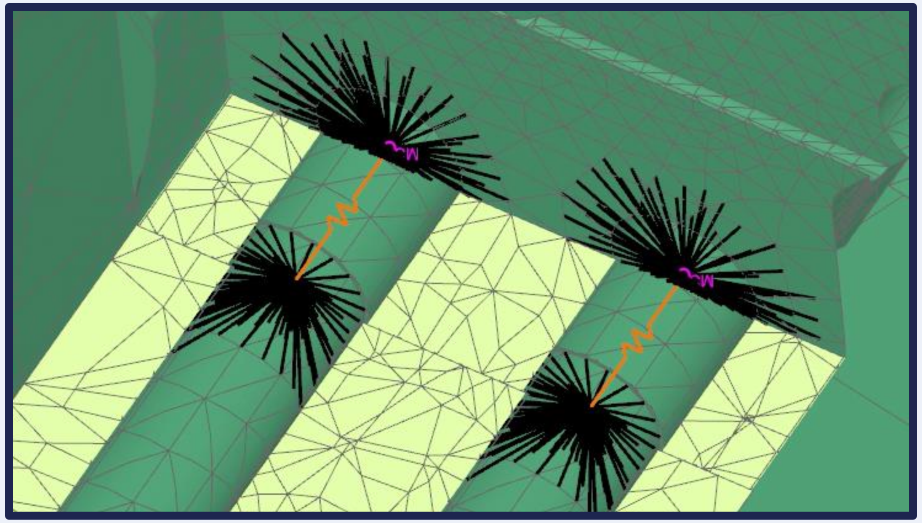
Warp

Edge point included angle

Edge point length ratio

BOLTS ARE MODELLED WITH EQUIVALENT PROPERTIES



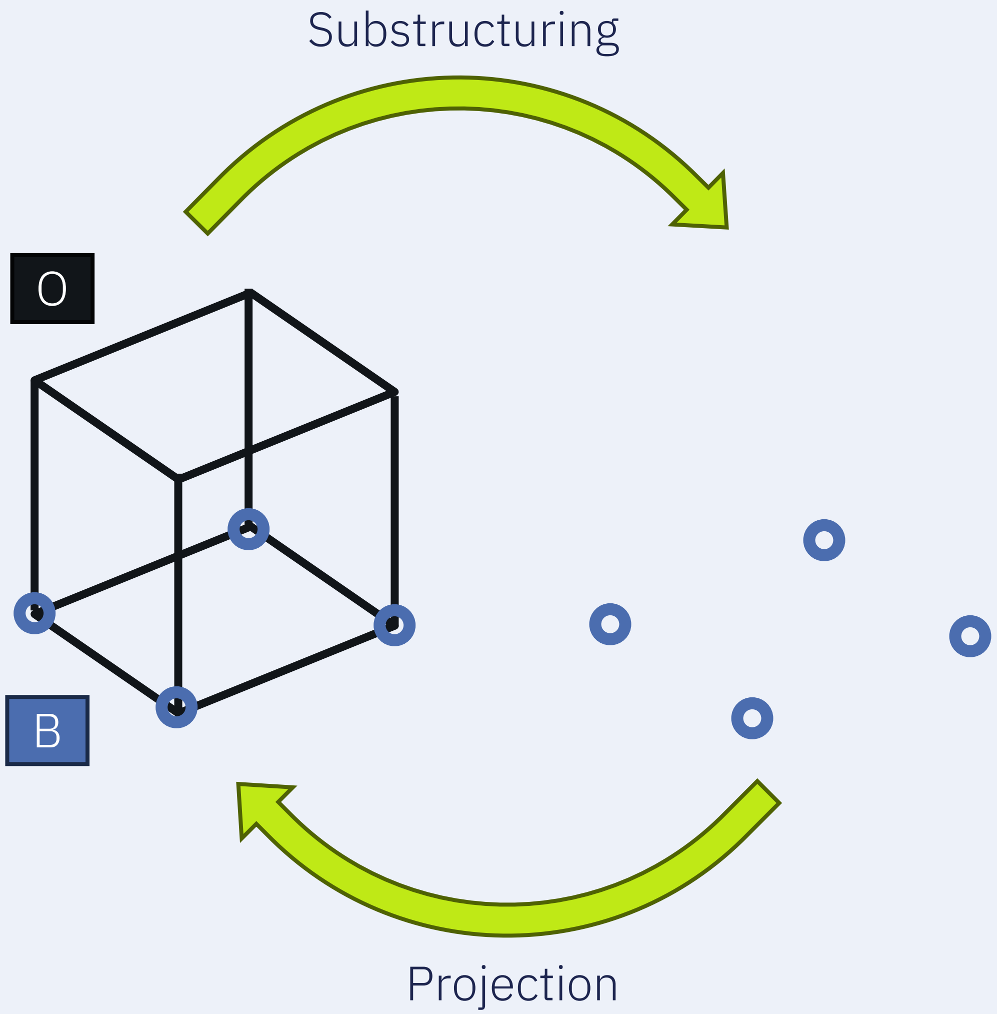


Mass point
- Fastener
- Washer

Spring element
- Flange
- Fastener

Rigid element
- Fastener head
- Washer
- Fastener thread

SUPERELEMENTS ALLOW LIGHT BUT ACCURATE MODELS



Static reduction (Guyan)

$$\begin{bmatrix} K_{BB} & K_{BO} \\ K_{OB} & K_{OO} \end{bmatrix} \begin{bmatrix} q_B \\ q_O \end{bmatrix} = \begin{bmatrix} f_B \\ f_O \end{bmatrix}$$

$$\begin{bmatrix} q_B \\ q_O \end{bmatrix} = T_{\mathrm{G}} q_B = \begin{bmatrix} I \\ -K_{OO}^{-1} K_{OB} \end{bmatrix} q_B$$

$$(K_{BB} - K_{BO} K_{OO}^{-1} K_{OB}) q_B = f_B - K_{BO} K_{OO}^{-1} f_O$$

Dynamic reduction (Craig-Bampton)

$$(-\omega^2 M + i\omega C + [K + iK_4]) \begin{bmatrix} q_B \\ q_O \end{bmatrix} = \begin{bmatrix} f_B \\ f_O \end{bmatrix}$$

$$\begin{bmatrix} q_B \\ q_O \end{bmatrix} = T_{\mathrm{CB}} \begin{bmatrix} q_B \\ Q \end{bmatrix} = \begin{bmatrix} I & 0 \\ -K_{OO}^{-1} K_{OB} & \Phi_{OO} \end{bmatrix} \begin{bmatrix} q_B \\ Q \end{bmatrix}$$

$$T_{\mathrm{CB}}^{\mathrm{T}} (-\omega^2 M + i\omega C + [K + iK_4]) T_{\mathrm{CB}} \begin{bmatrix} q_B \\ Q \end{bmatrix} = T_{\mathrm{CB}}^{\mathrm{T}} \begin{bmatrix} f_B \\ f_O \end{bmatrix}$$

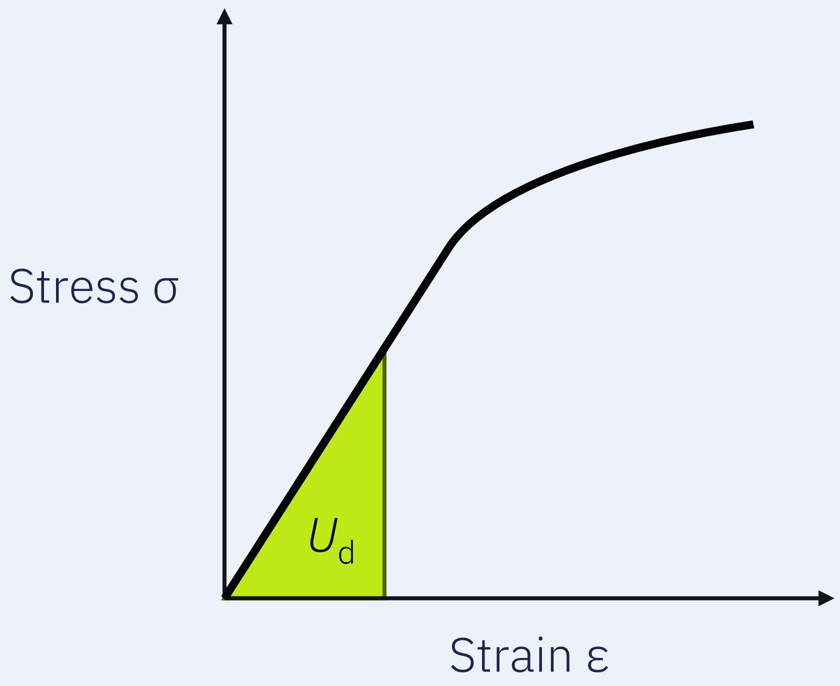
STRAIN ENERGY DENSITY SHOWS WEAK POINTS

Strain energy density

$$U_d = \int \sigma\epsilon \, d\epsilon$$

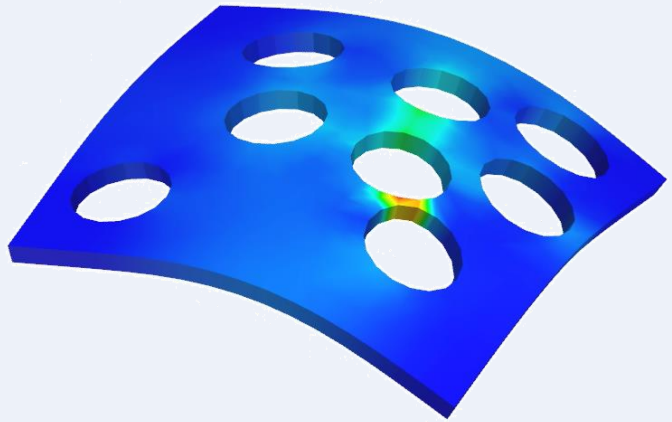
Strain energy

$$U = \iiint U_d \, dV$$

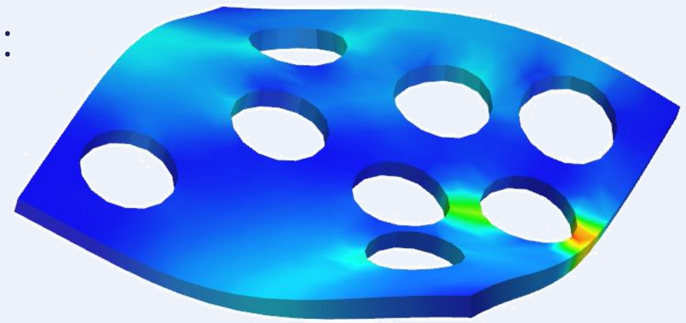


Strain energy density in free-free modes

Mode 1:

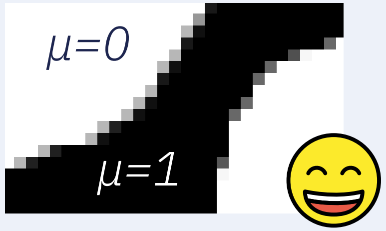


Mode 2:



TOPOLOGY OPTIMIZATION REMOVE USELESS ELEMENTS

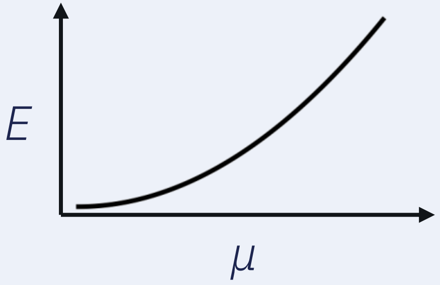
Filling factor $\mu \in [0,1]$



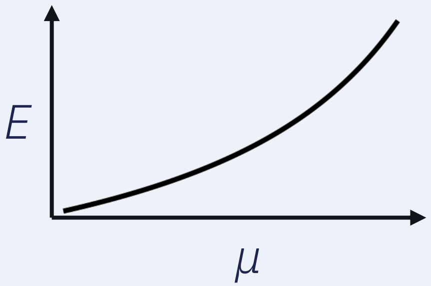
Material density $\rho = \mu\rho_0$

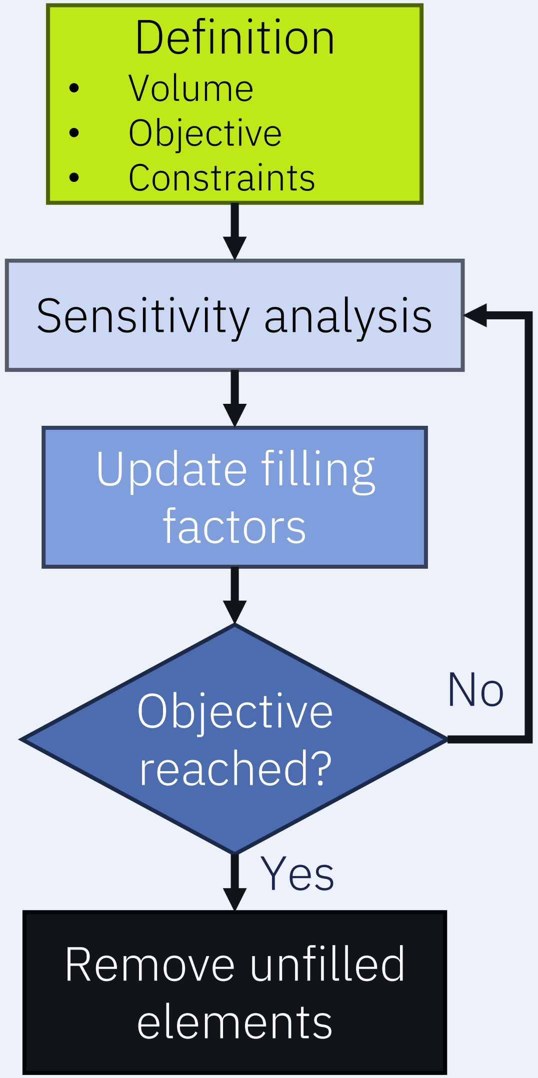
Young's modulus $\mathrm{E}(\mu)$

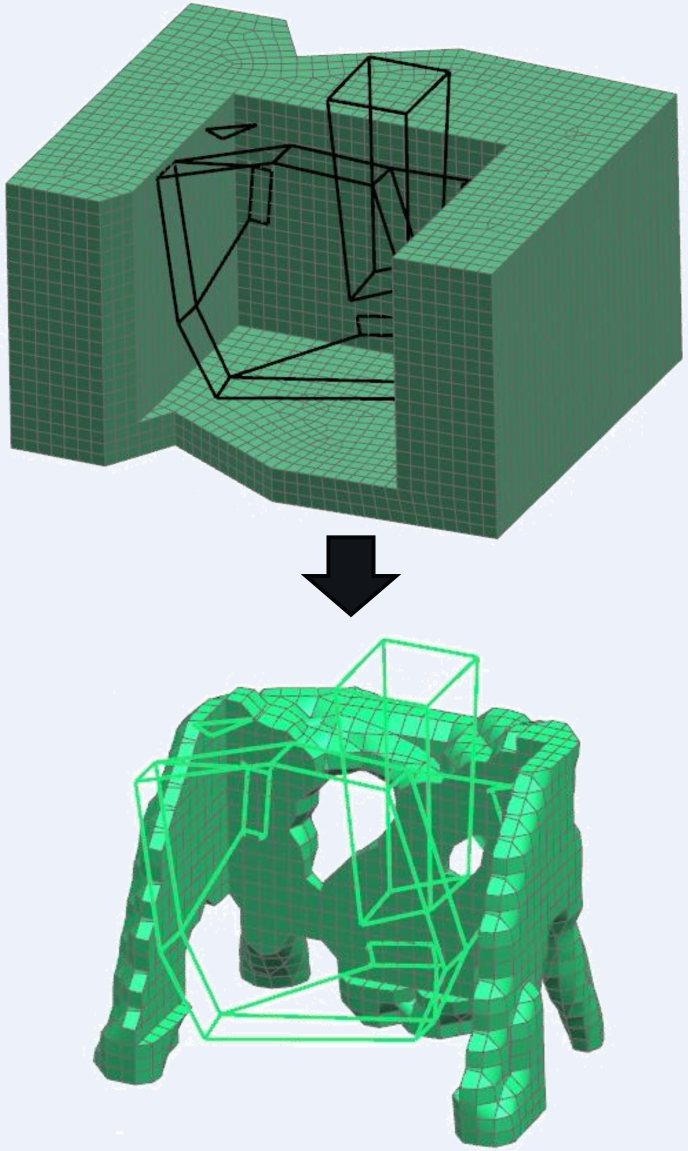
Power law



Rational law

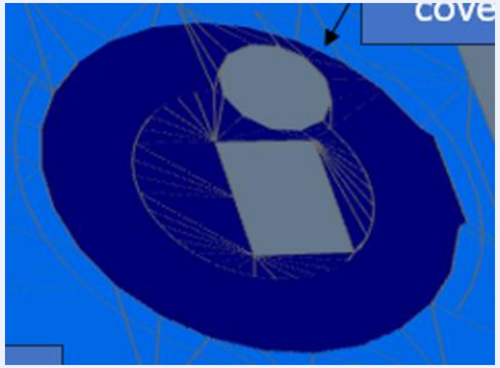




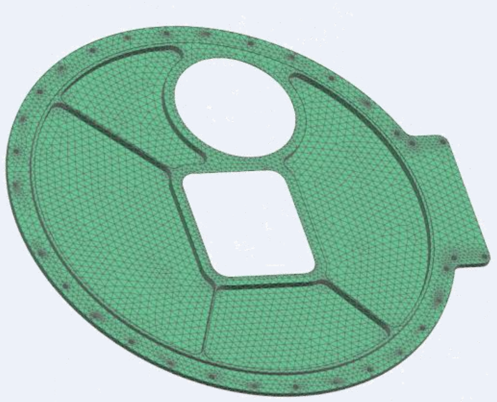


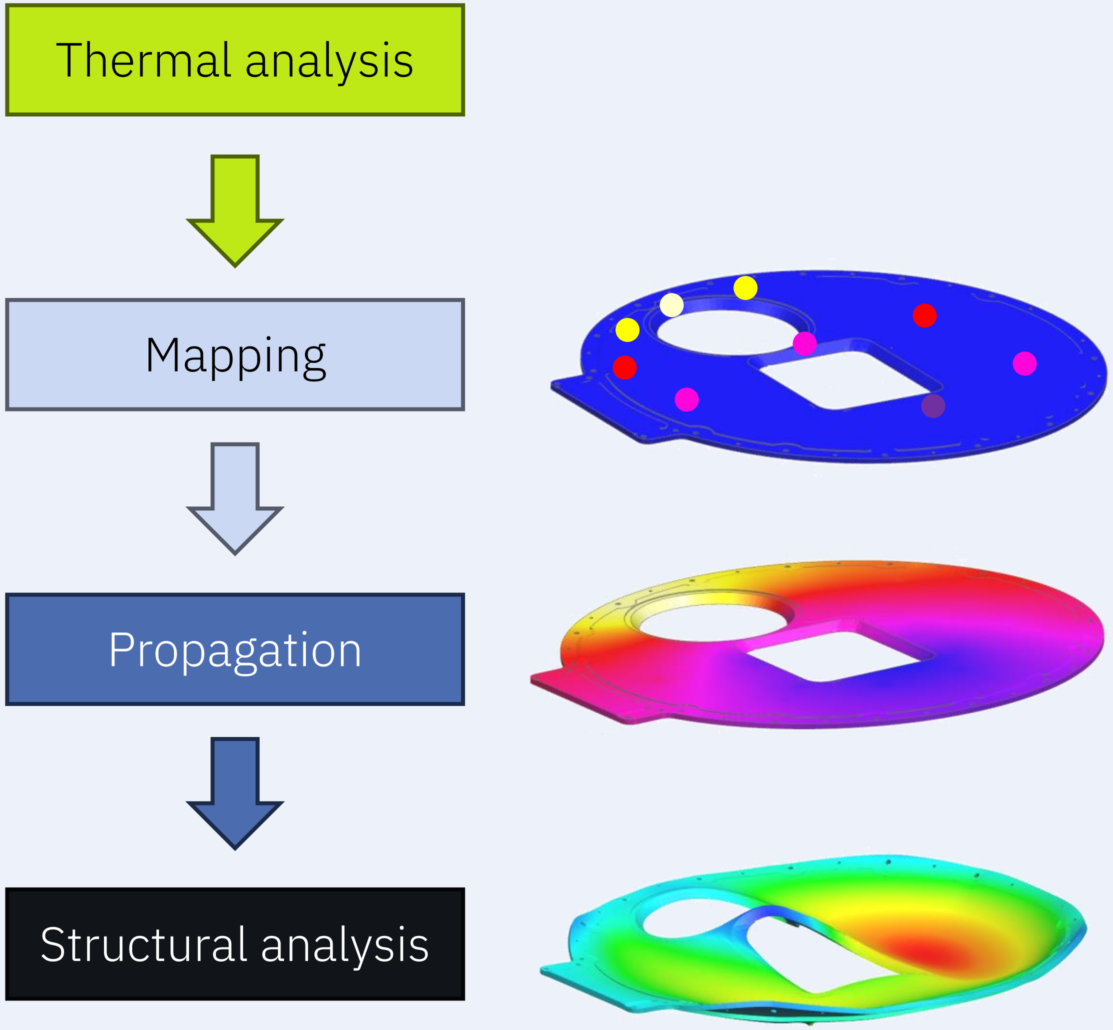
STRUCTURAL AND THERMAL DO NOT USE THE SAME FEM

Thermal model



Structural model





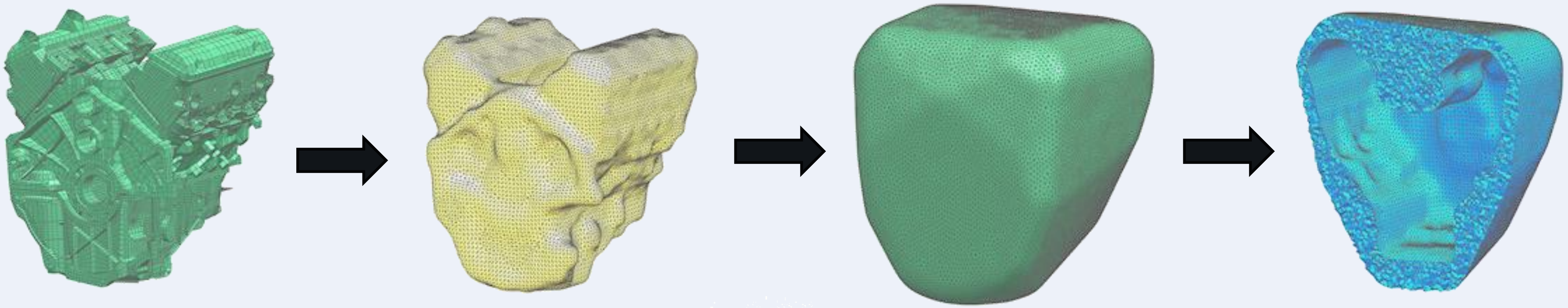
ACOUSTIC MODELING

Structural mesh

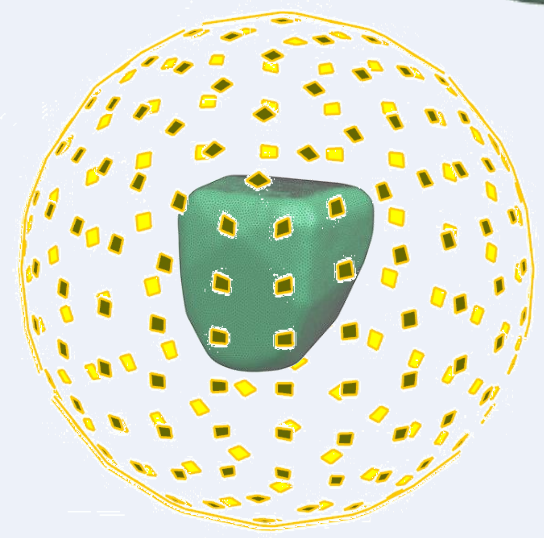
Inner boundary of acoustic mesh

Outer boundary of acoustic mesh

Acoustic mesh



Microphone mesh:



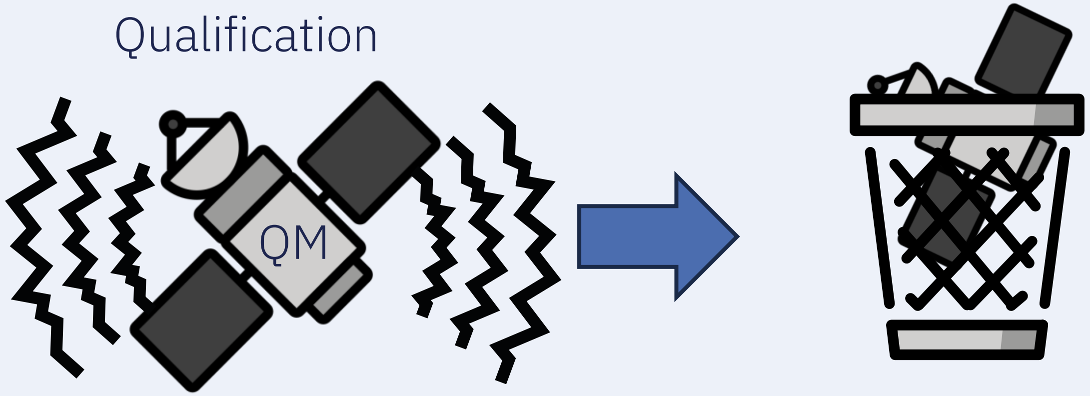
VIBRATION TESTING

THE MOMENT YOU KNOW WHETHER YOU SCREWED UP

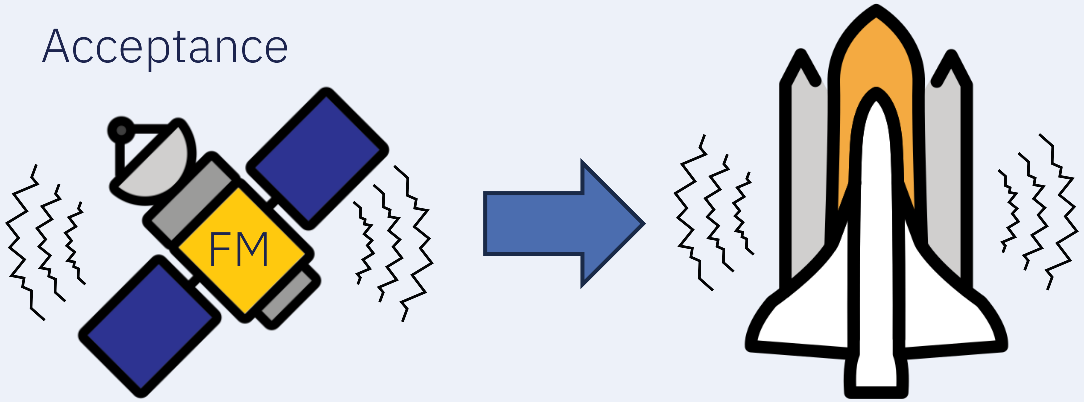
THE TWO APPROACHES TO QUALIFICATION LOGIC

Qualification approach

Qualification

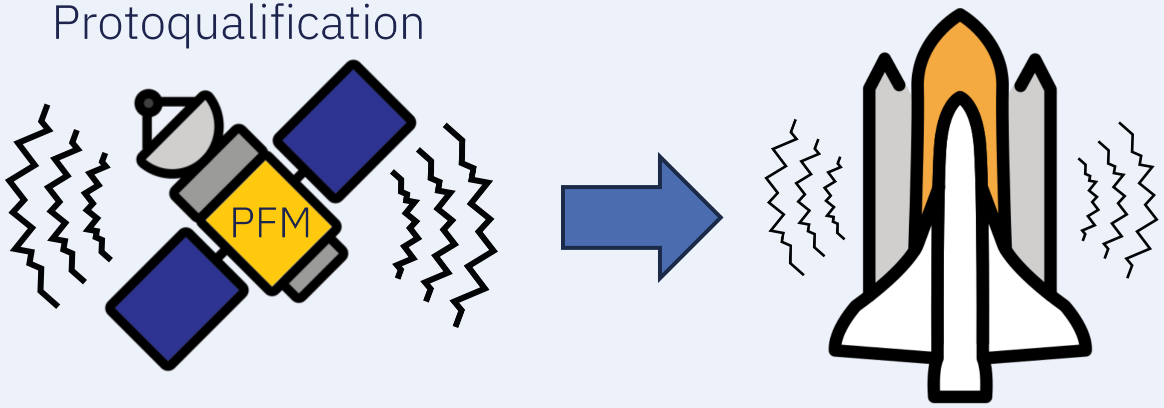


Acceptance



Protoflight approach

Protoqualification



THE ULTIMATE OBJECTIVE IS TO MINIMIZE RISK

Qualification

- Objective = prove that the article will survive limit loads
- Check of design
- Better to overtest than understest

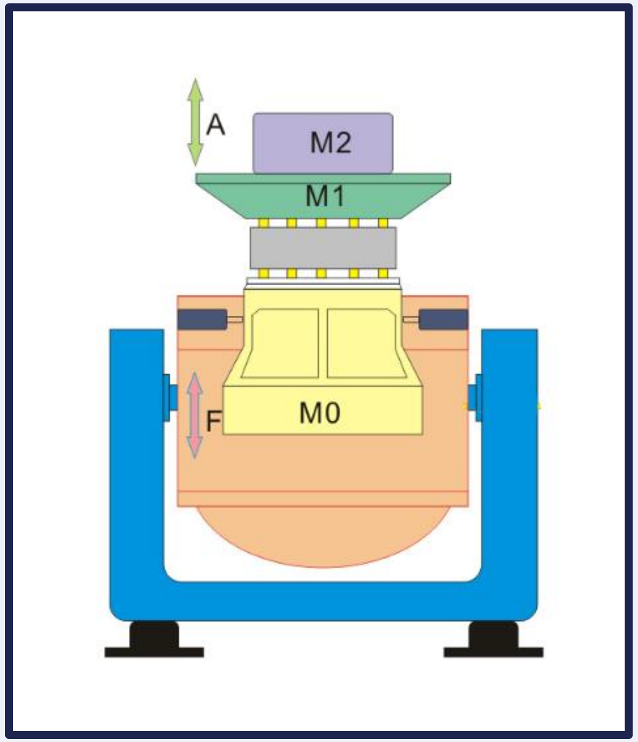
Acceptance

- Objective = prove that the article is equivalent to the QM
- Check of workmanship
- Better to undertest than overtest

Each test on the FM is an additional risk

(Fatigue, stochastic luck)

ELECTRODYNAMICAL SHAKER USED FOR VIBRATION TESTS

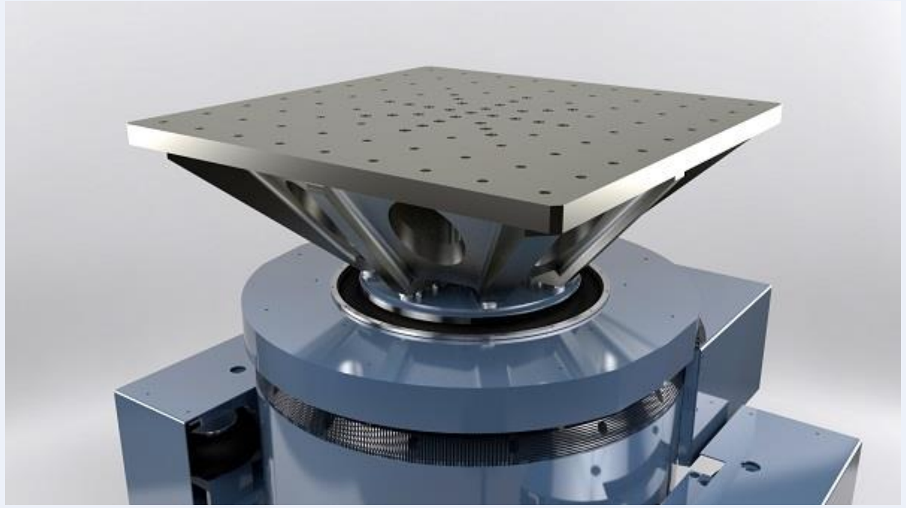


Multi-axis shaker

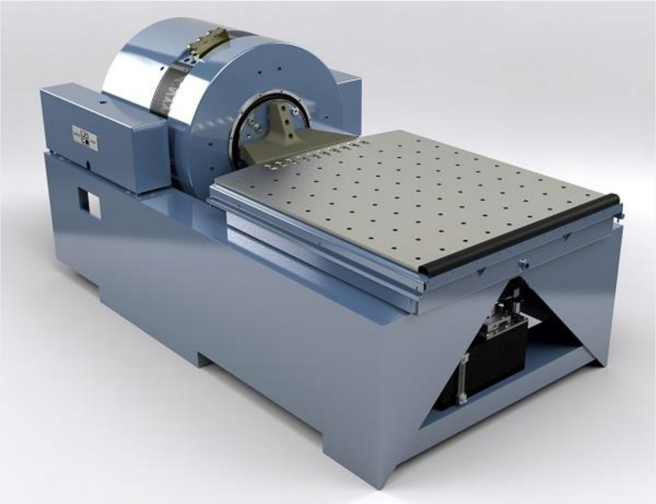
From: Amade-Tech, Halt & Hass

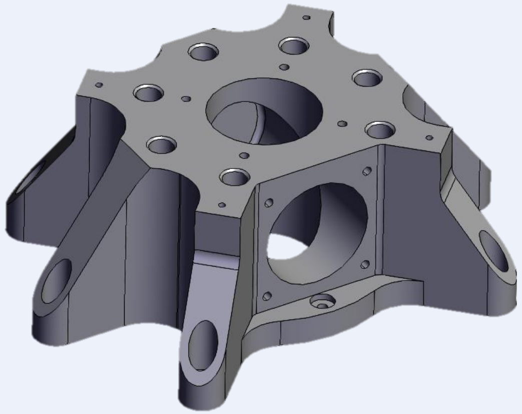
MGSE: MECHANICAL GROUND SUPPORT EQUIPMENT

Head expander

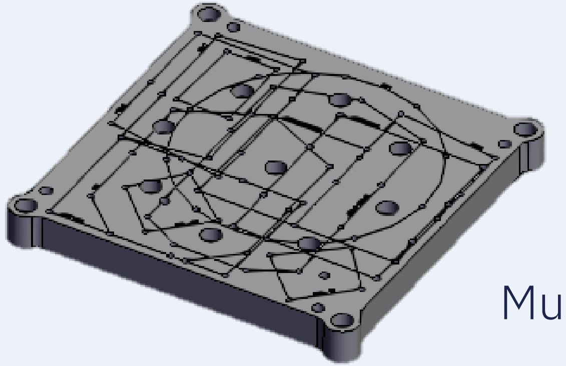


Slip table





Fixture IP/OOP

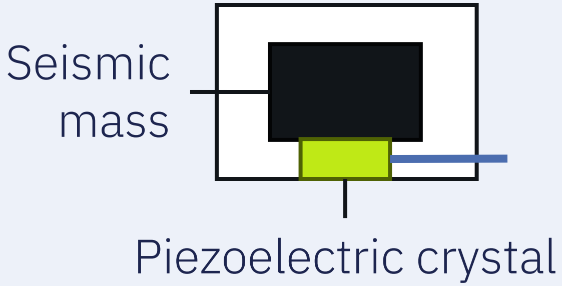


Multi-unit fixture

From: Unholtz Dickie

OUTPUT OF VIBRATION TESTING IS MEASURED BY SENSORS

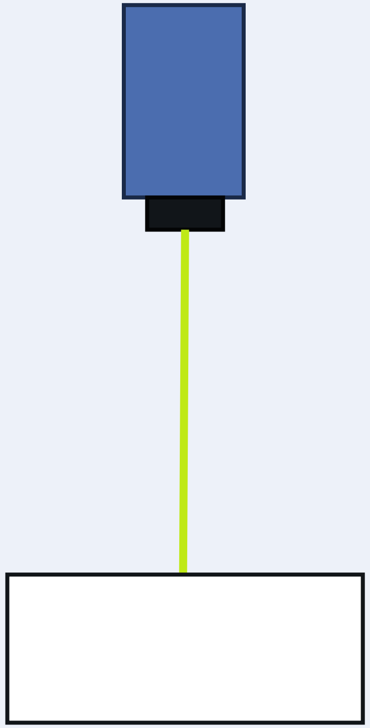
Accelerometers



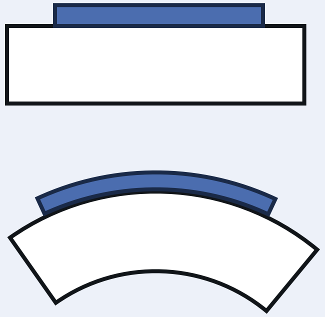
Uniaxial

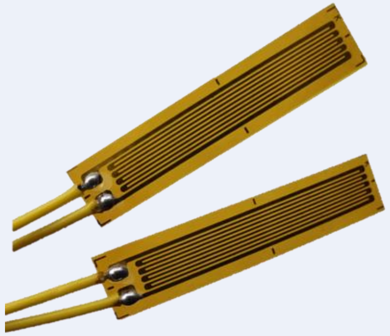
Triaxial

Laser interferometers



Strain gauges

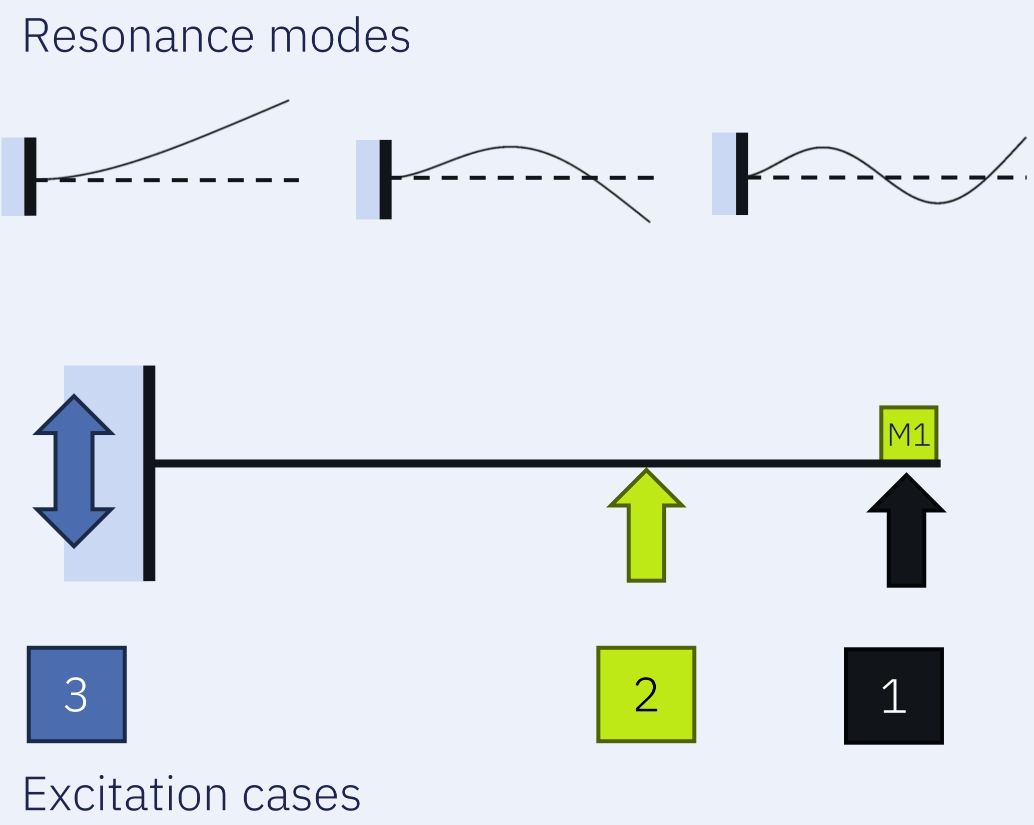


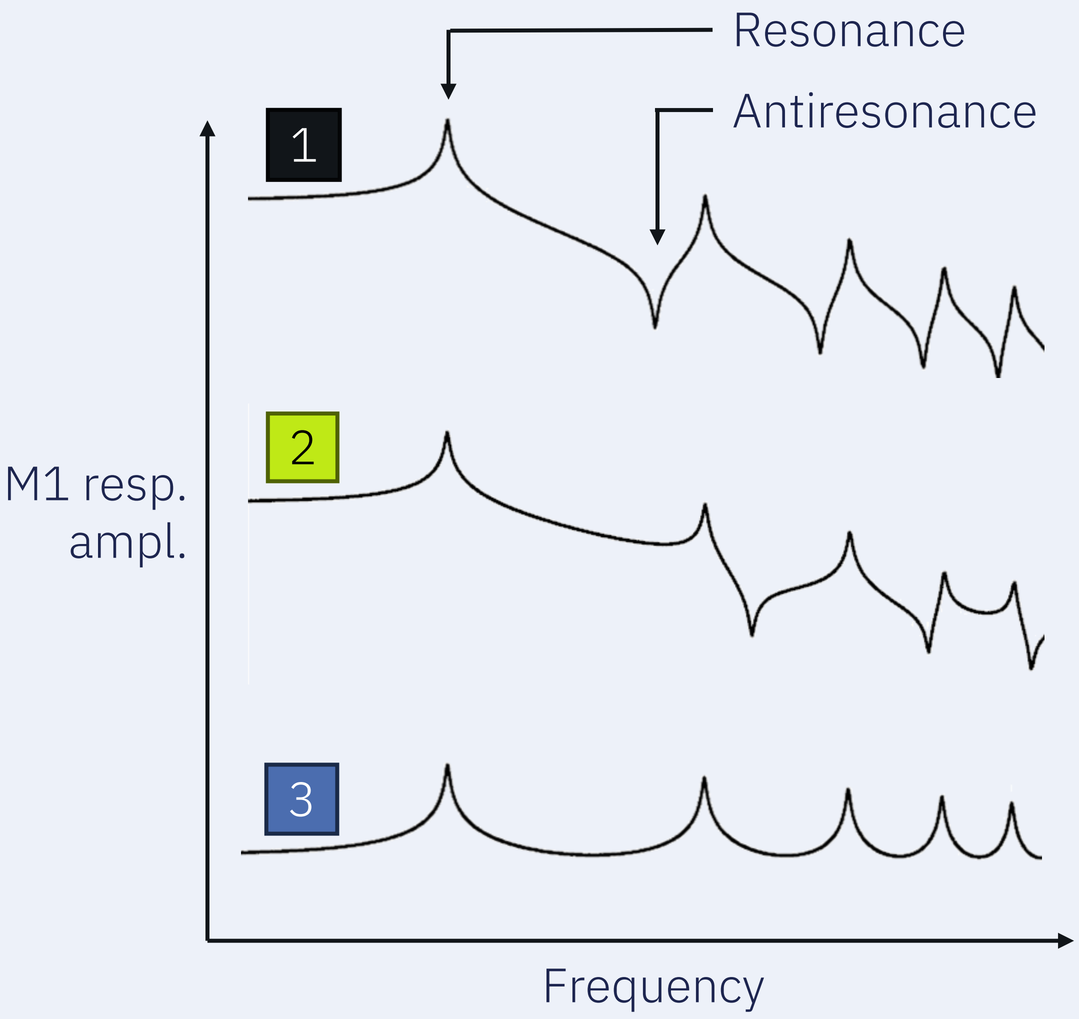


Load cells

- Strain gauge
- Capacitive
- Pneumatic
- Hydraulic
- Piezo…

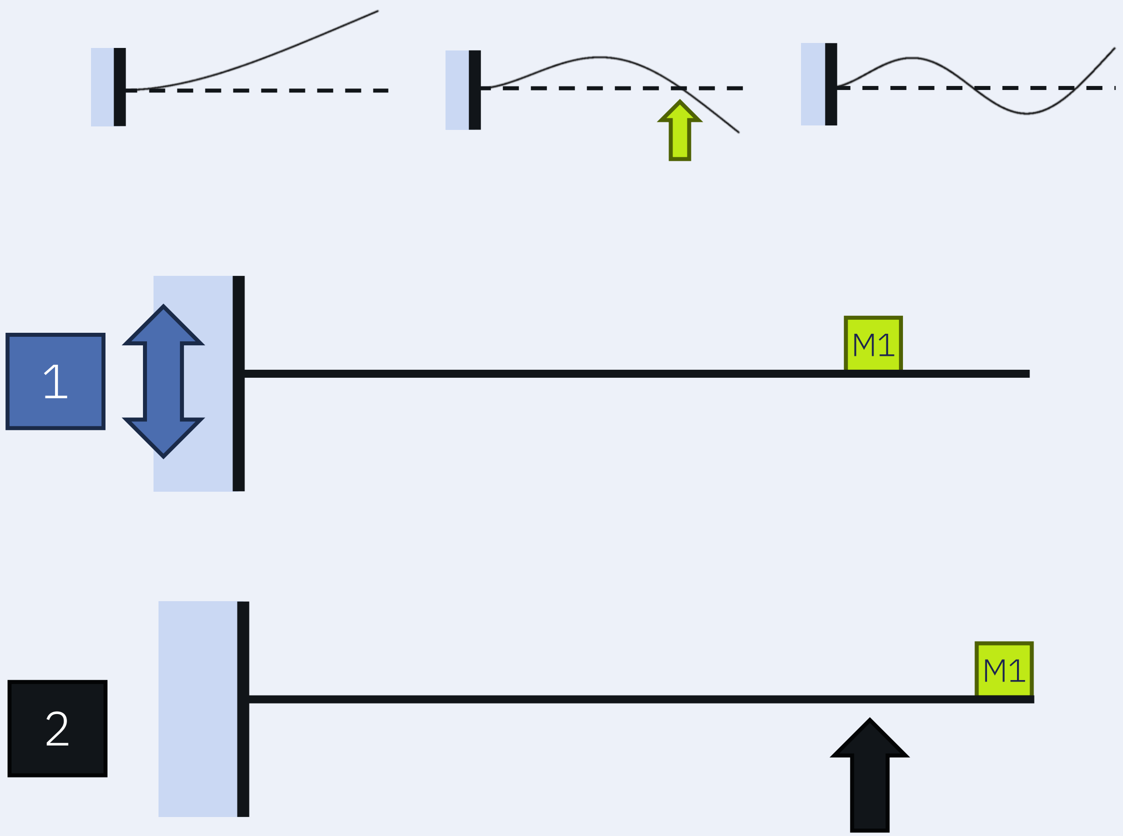
RESONANCES ARE STRUCTURE-DEPENDENT, ANTIRESONANCES ARE TEST-DEPENDENT

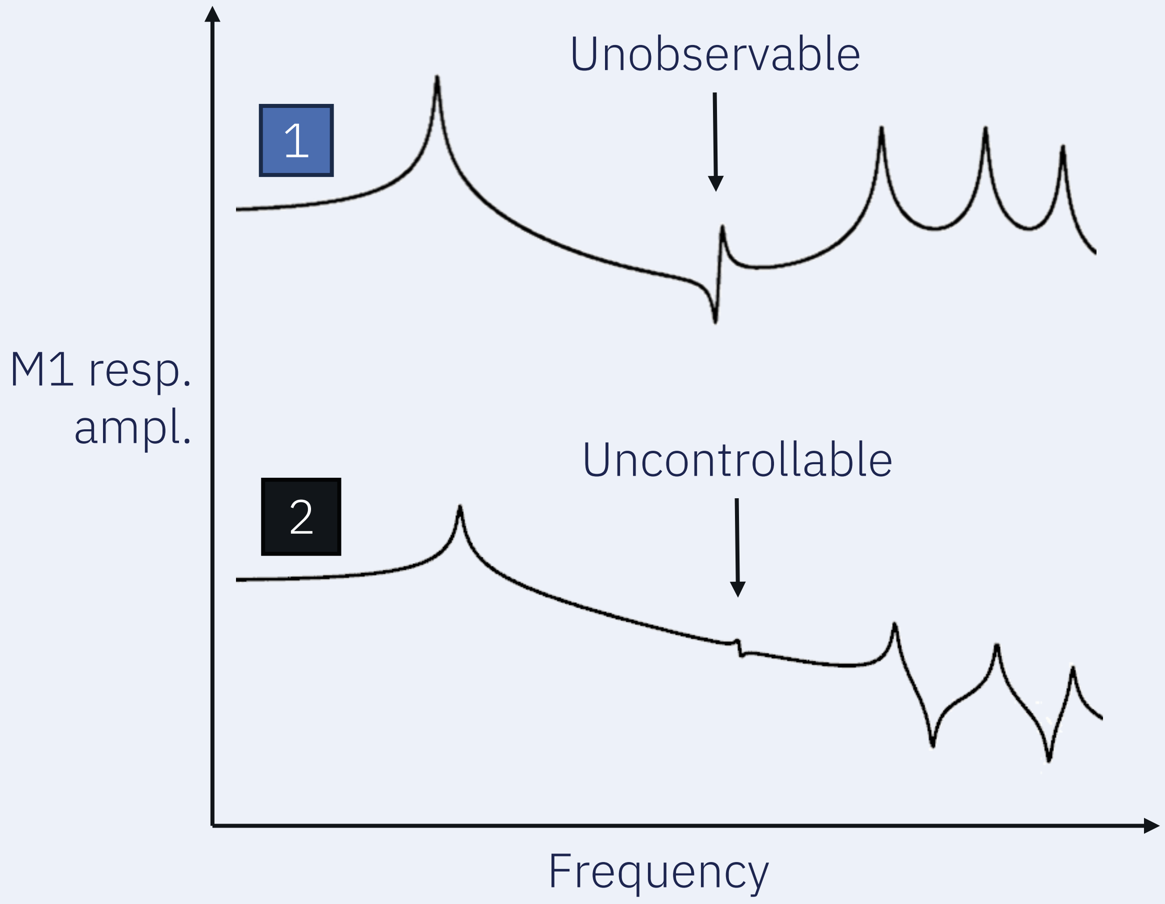




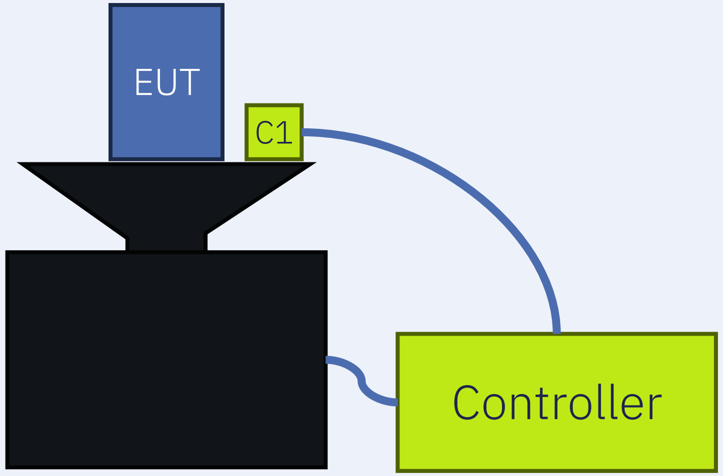
UNOBSERVABLE OR UNCONTROLLABLE MODES ARE INVISIBLE

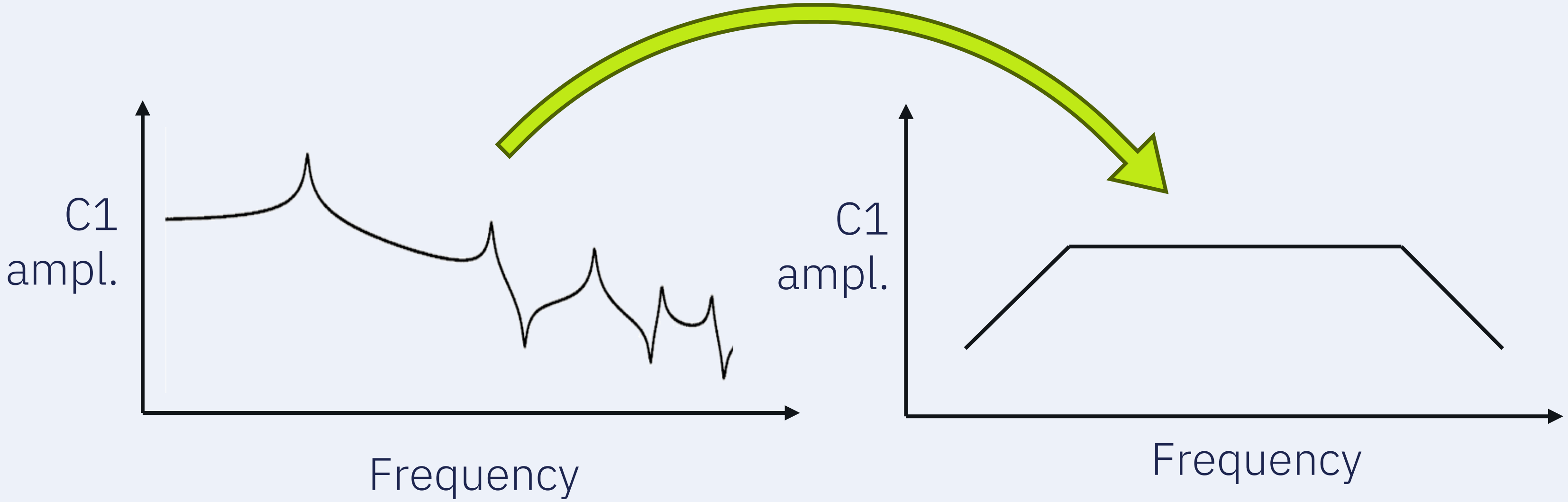
Resonance modes

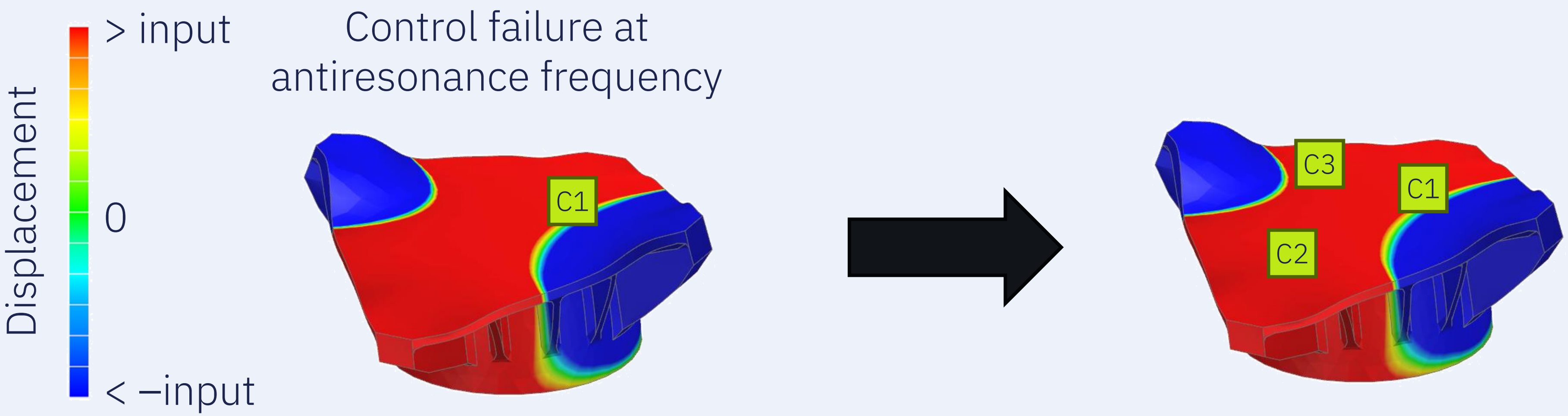




CONTROL SENSORS SHOULD BE PLACED WITH CARE



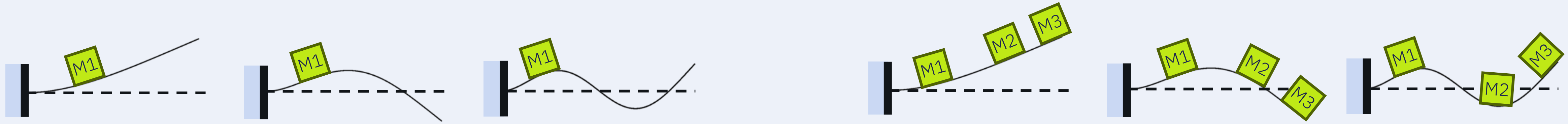


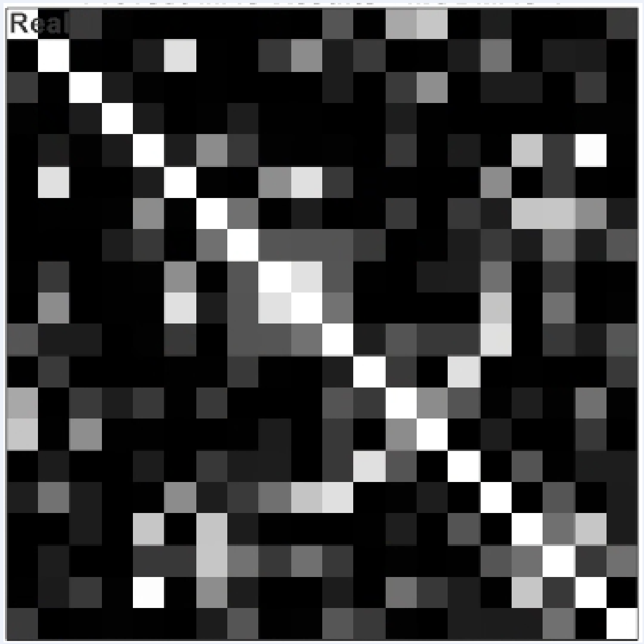


Control strategy

- Minimum ➔ overtest
- Maximum ➔ undertest
- Average ➔ both

AUTOMAC MATRIX FOR MEASUREMENT SENSOR PLACEMENT

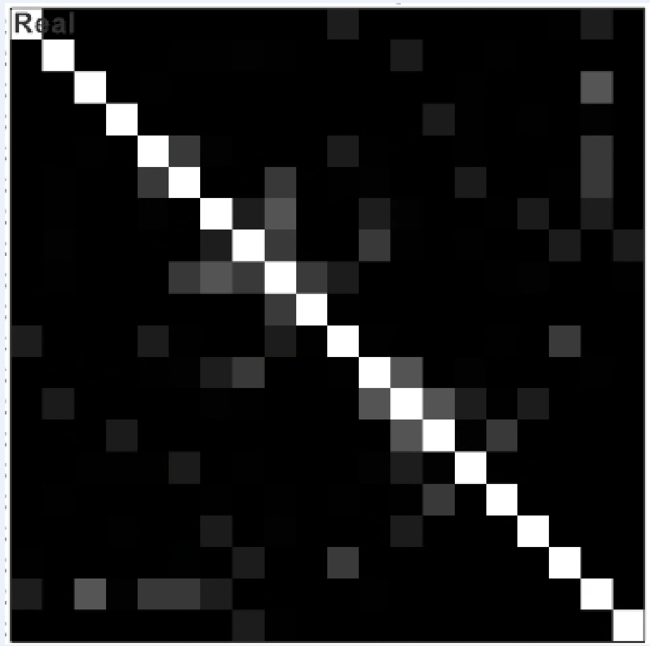




Example: 20 modes

← 2 triax acceleros

8 triax acceleros →



Consider the impact of your sensor (mass, stiffness…)

LOW-LEVEL TESTS ARE FOR RESONANCE SEARCH

Low-level sine

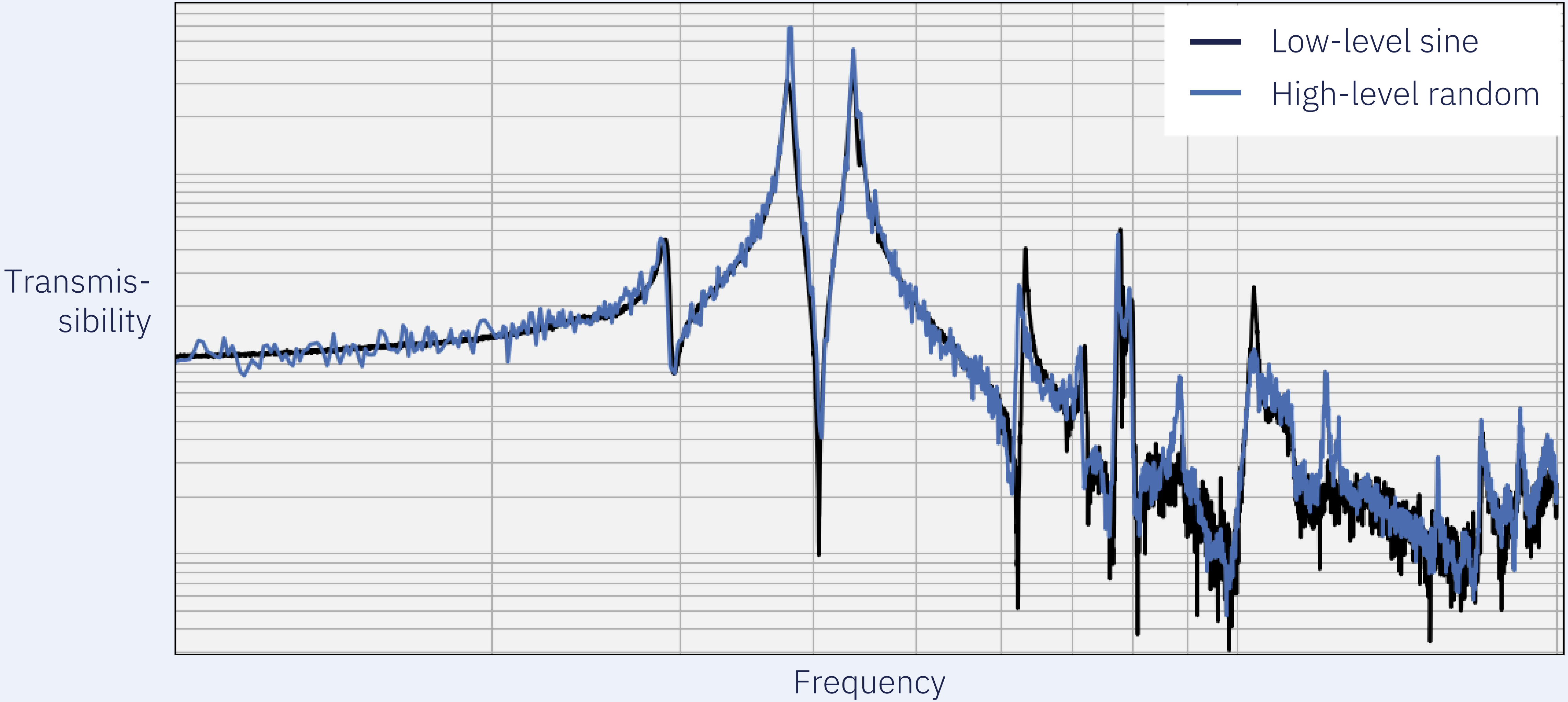
- Standard in the industry
- Modes only excited for a short time
- Low damping ➔ high g's
- Some values: 0.2 g, 0.5 g, 1 g…

Low-level random

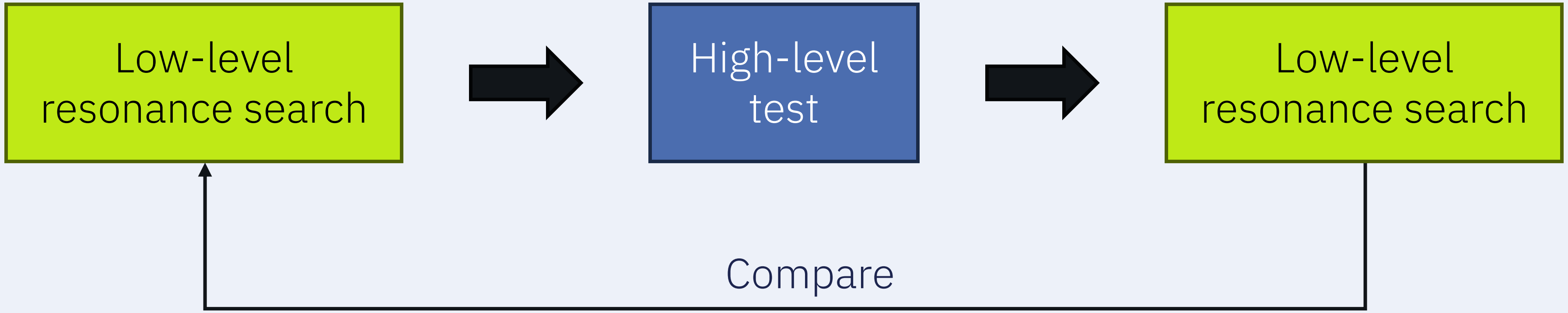
- Standard at ASL
- Modes continuously excited
- Low g's
- Some values: 1gRMS…

Not everyone agrees on what is low-level

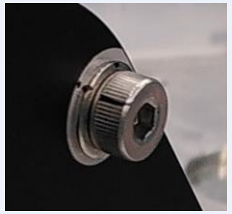
LOW-LEVEL AND HIGH-LEVEL BEHAVIOR MAY VARY



LOW-LEVEL TESTS CHECK STRUCTURAL INTEGRITY



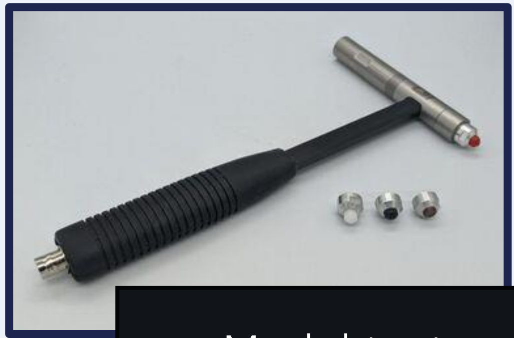
Success criteria:



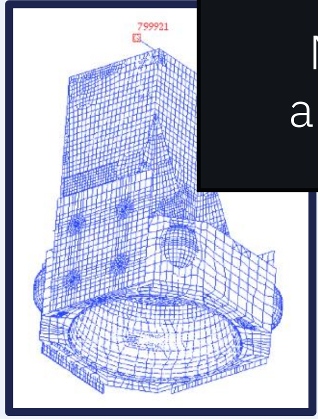
- No visible degradation
- No untightening of screws
- Functional test

- Upper limit to frequency shift (e.g. 5%)
- Upper limit to amplitude shift (e.g. 20%)
- Compliance with frequency requirements

LOW-LEVEL TESTS ALLOW MODEL CORRELATION & UPDATING



Modal test
- Resonance search
- Ping test



Modal analysis

Correlation
- Mapping
- Matching
  - Frequencies
  - MAC
- Cost function

Updating
- Sensitivities
- Correction

From: Géradin, Mechanical Vibrations (2015)

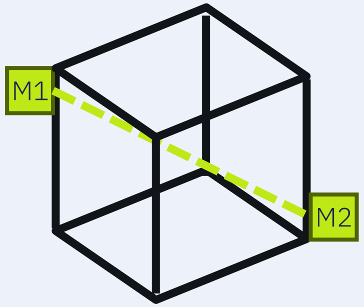
QUASI-STATIC TESTS CHECK THE STRUCTURAL LOAD PATHS

Dedicated test
- Static load
- Burst sine

Combined test
- Sine sweep
- Random

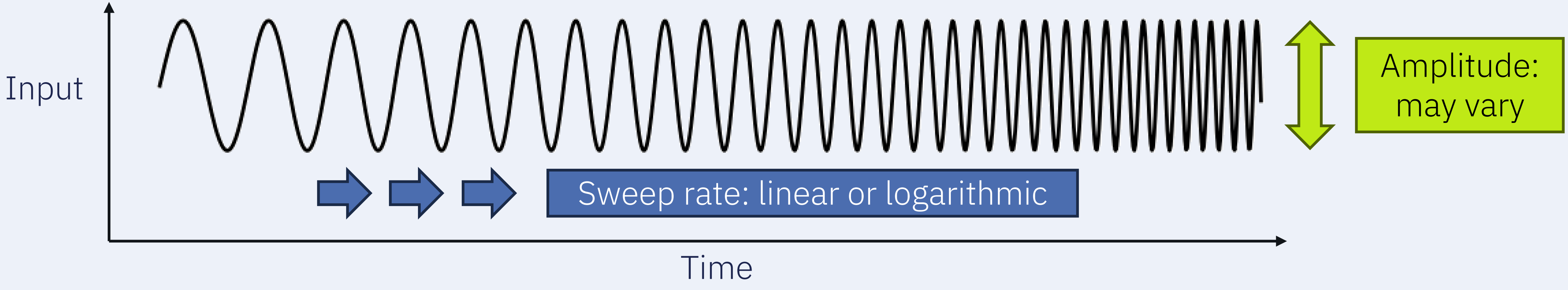
Lower than first natural frequency $\left(\frac{2}{3}, \frac{1}{\sqrt{2}}, \dots\right)$

Measurement at the CoG:

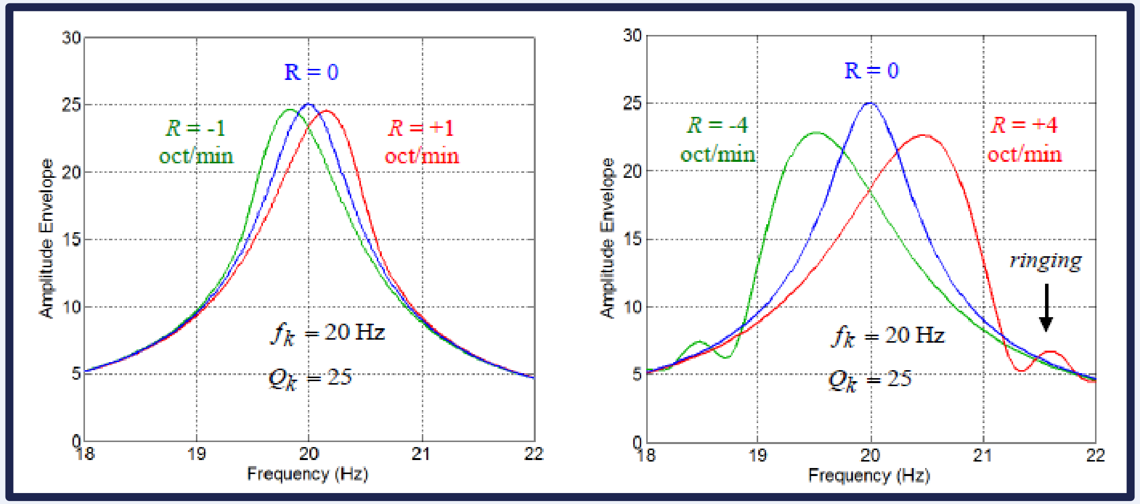


From: NASA Goddard Space Flight Center

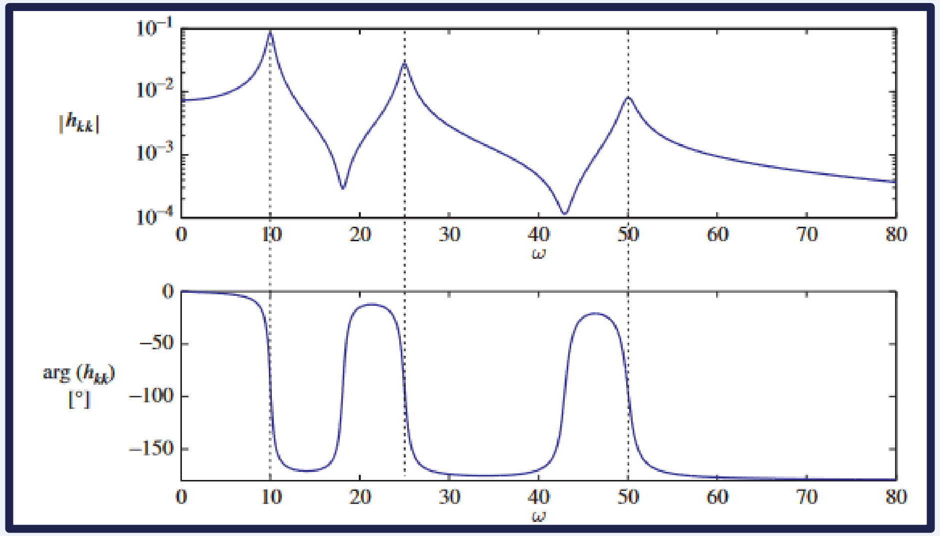
DETERMINISTIC LOADS ARE TESTED USING SINE SWEEPS



Impact of too high sweep rate

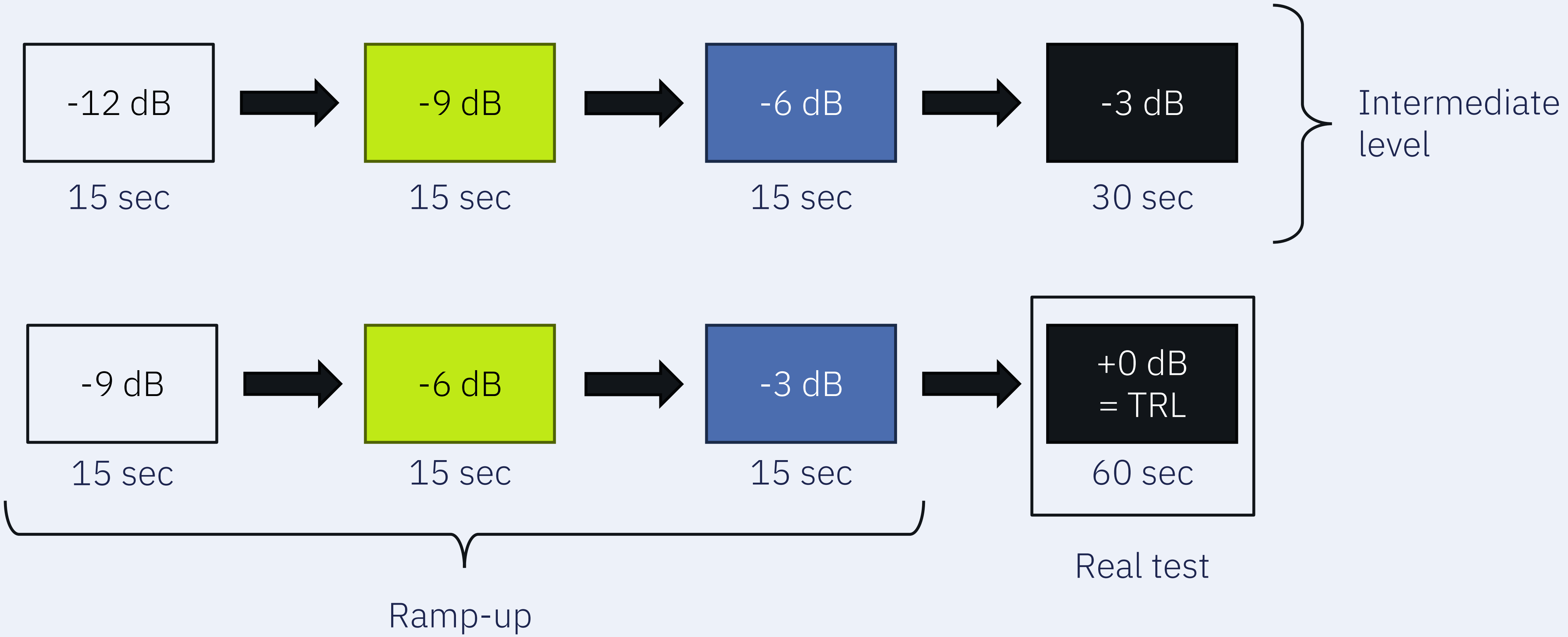


Spectra contain phase information

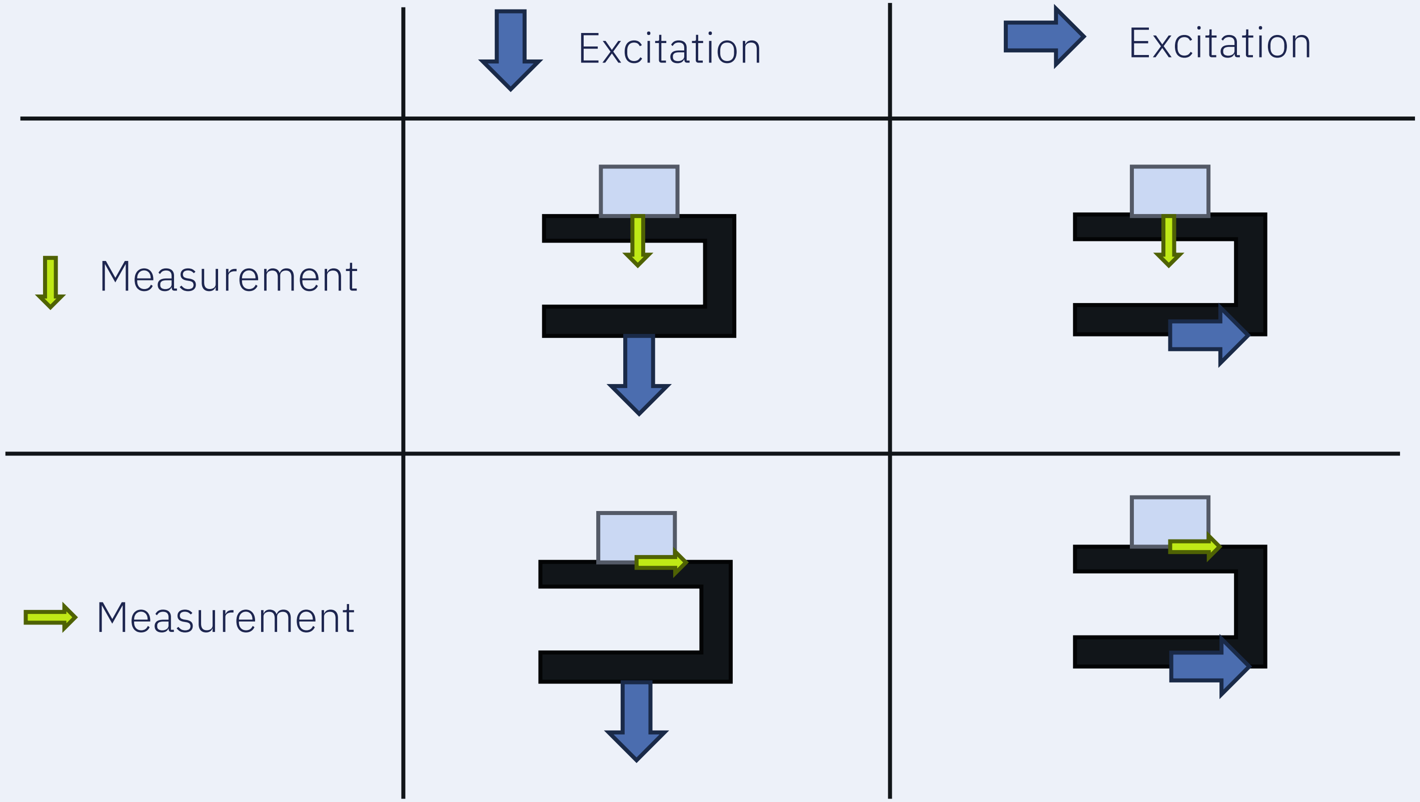


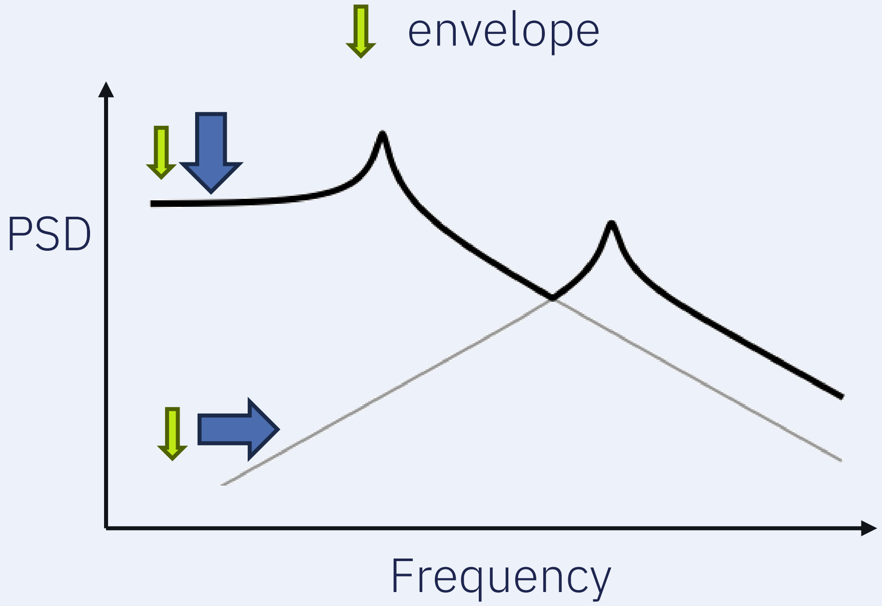
From: ECSS-E-HB-32-26A

RANDOM TESTS CHECK INTEGRITY UNDER STOCHASTIC LOADS

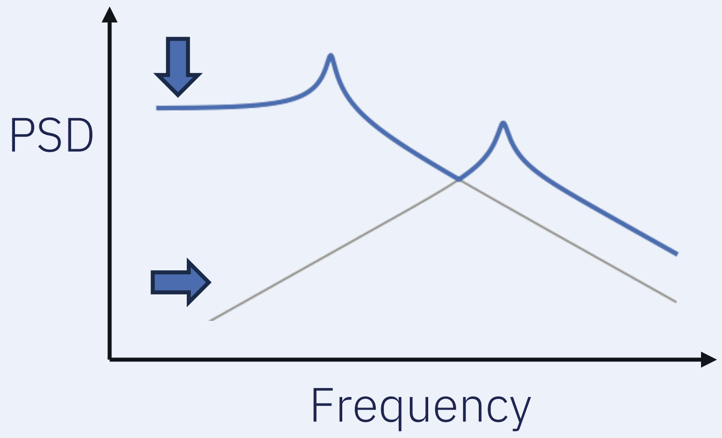


A RANDOM ENVELOPE MUST COVER EVERY CROSS-AXIS

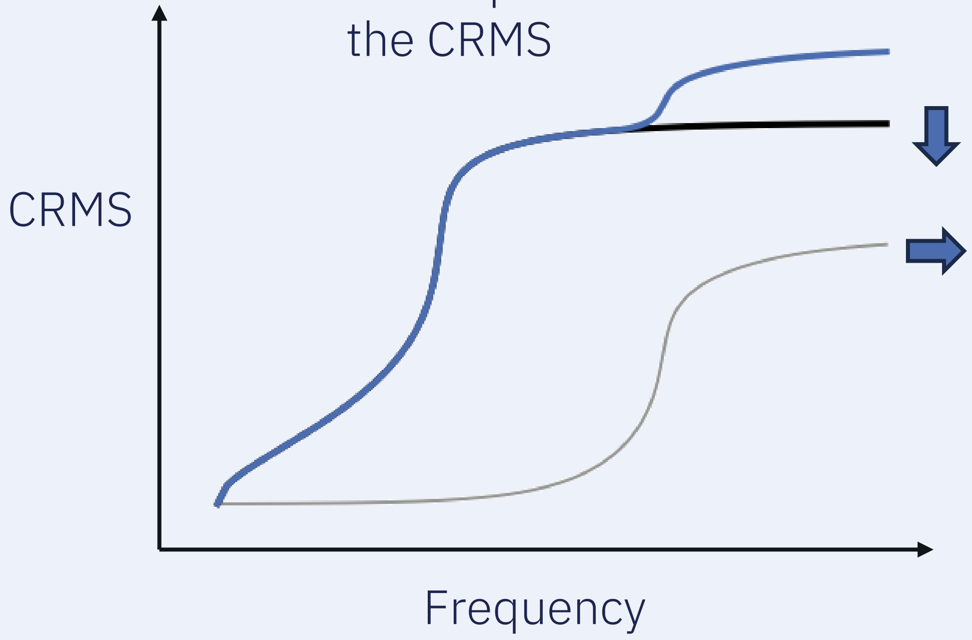




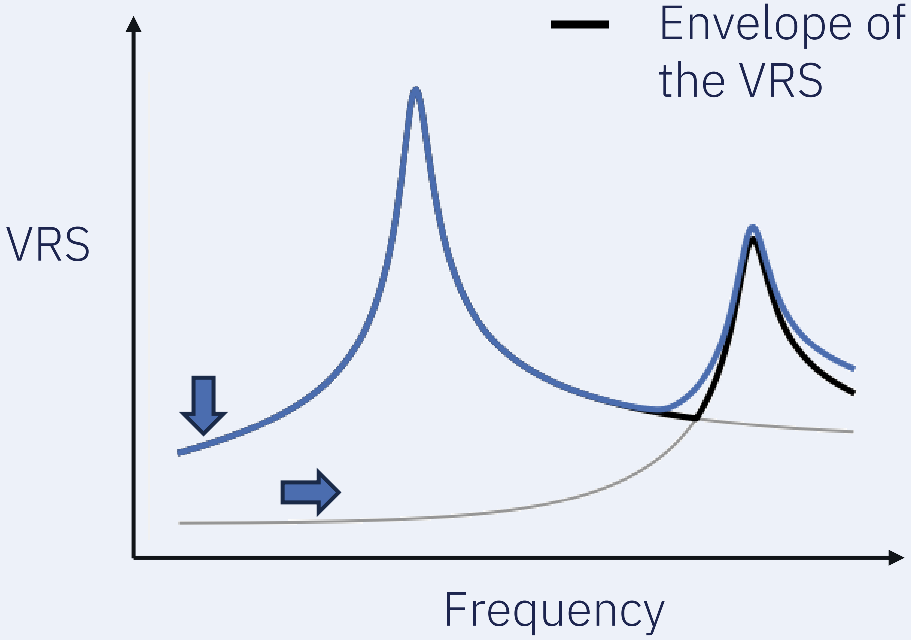
ENVELOPING IS NOT COMMUTATIVE



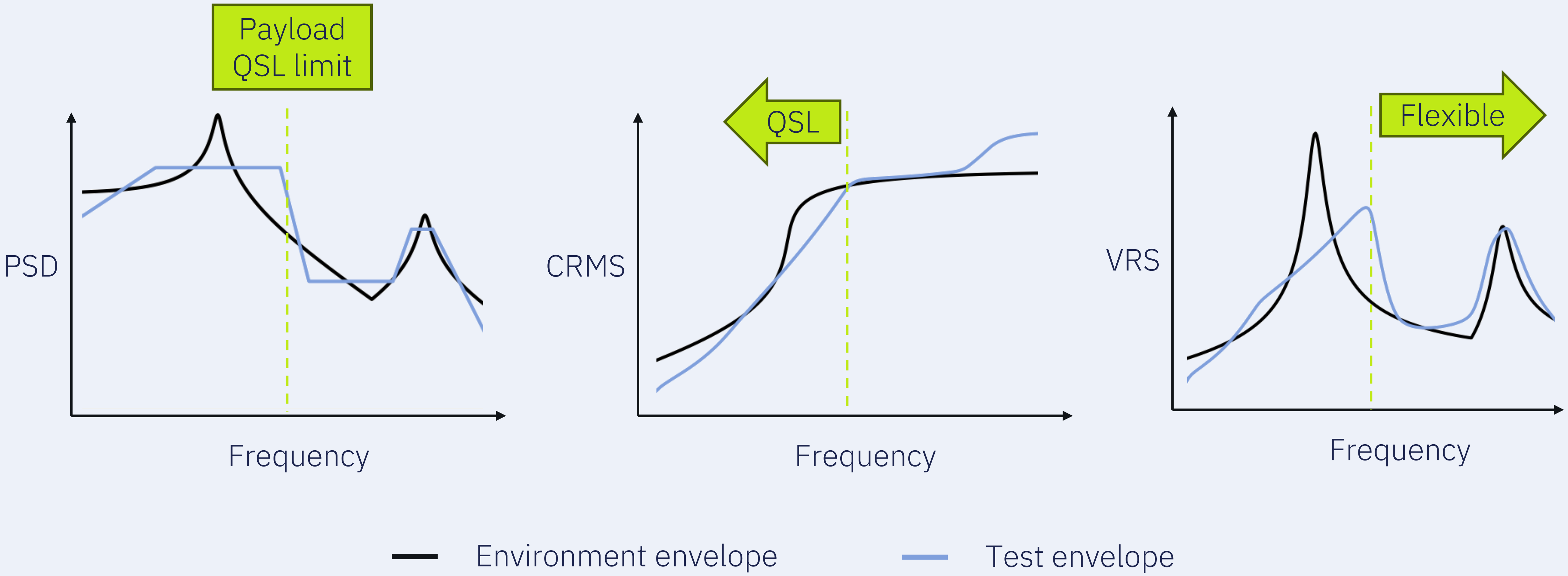
- CRMS of the envelope
- Envelope of the CRMS



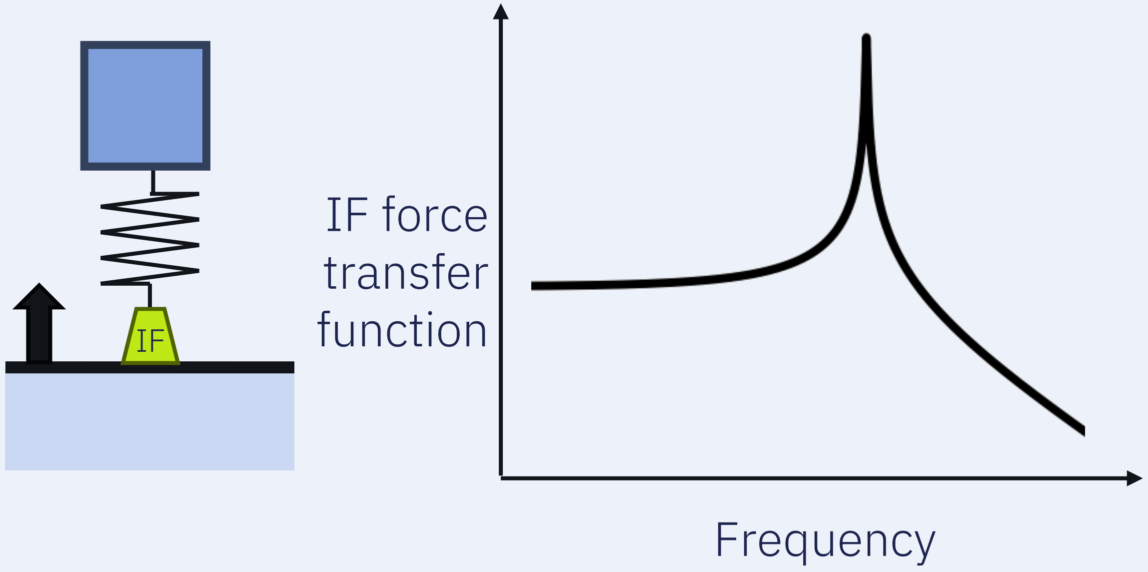
- VRS of the envelope
- Envelope of the VRS

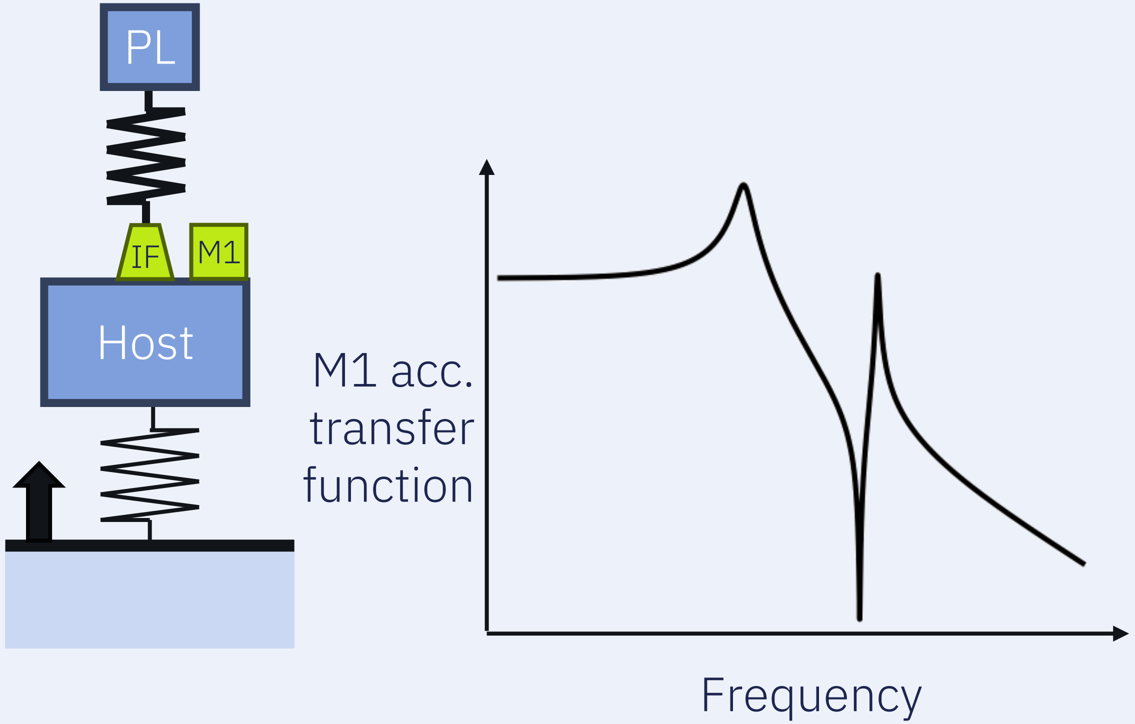


TEST ENVELOPE COVERS QSL AND FLEXIBLE RANGES

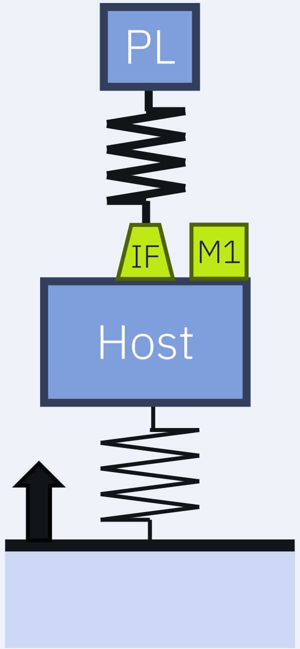


COUPLED ANTIRESONANCES CORRESPOND TO UNCOUPLED RESONANCES

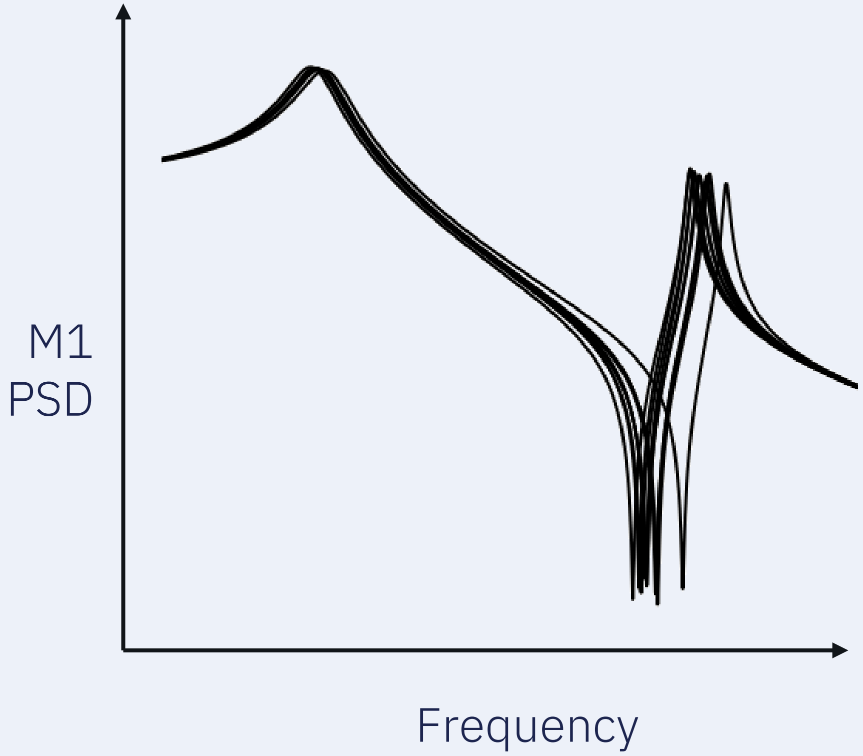


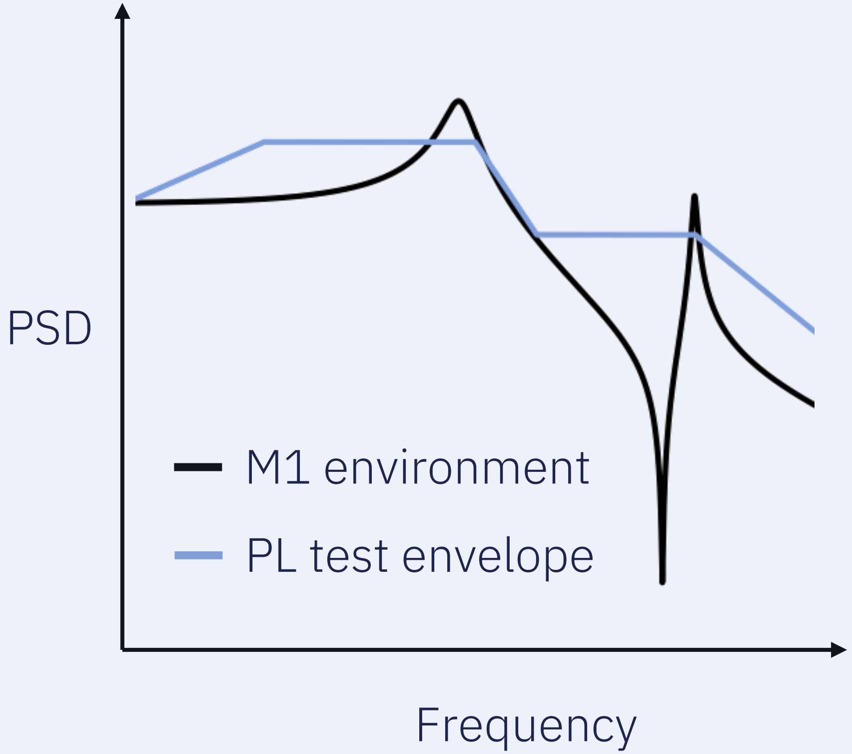


ANTIRESONANCES ARE IGNORED IN TEST ENVELOPES

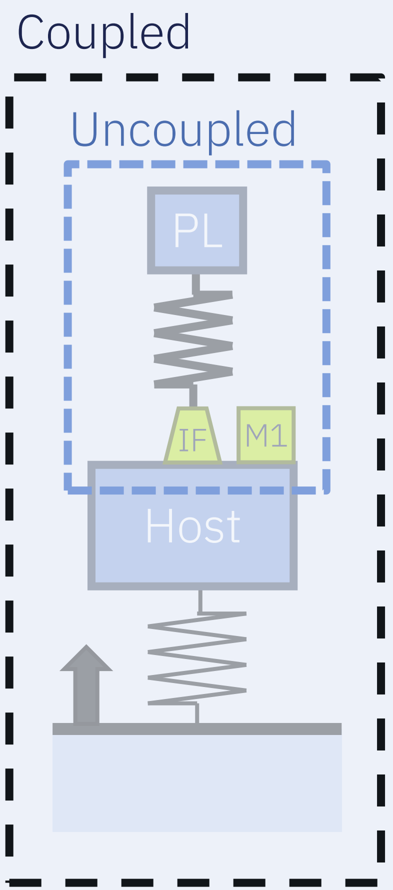


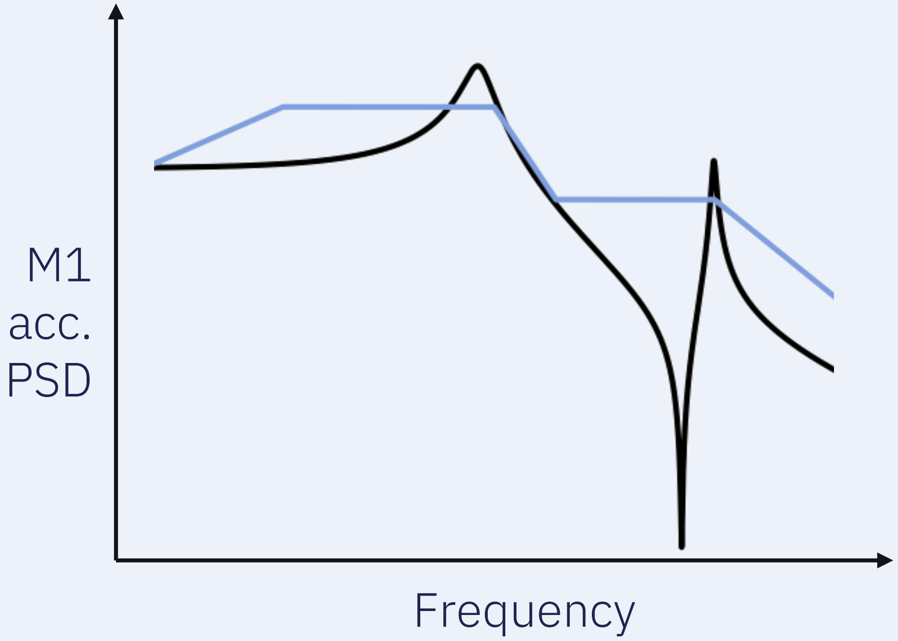
10% uncertainty on payload

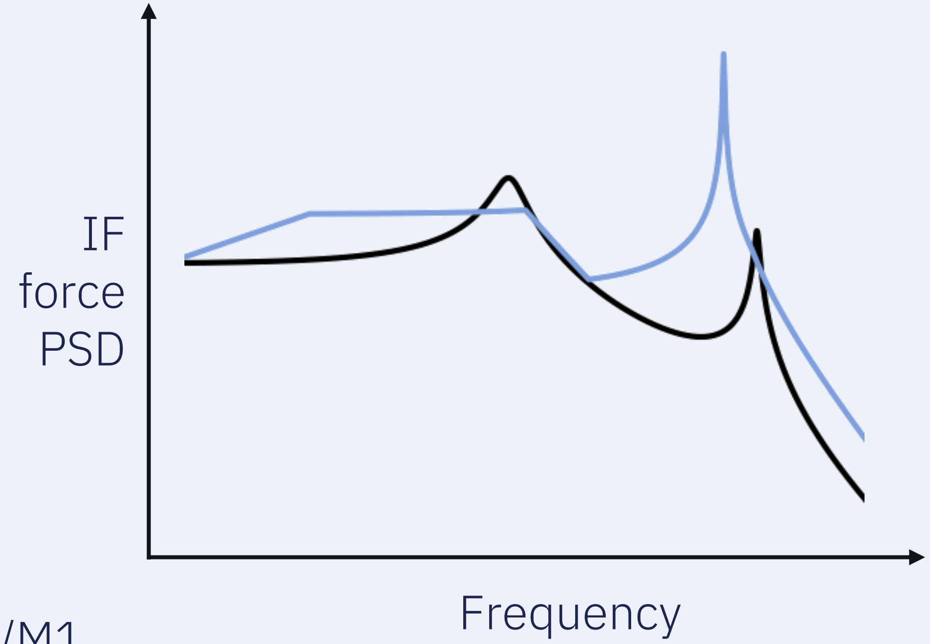


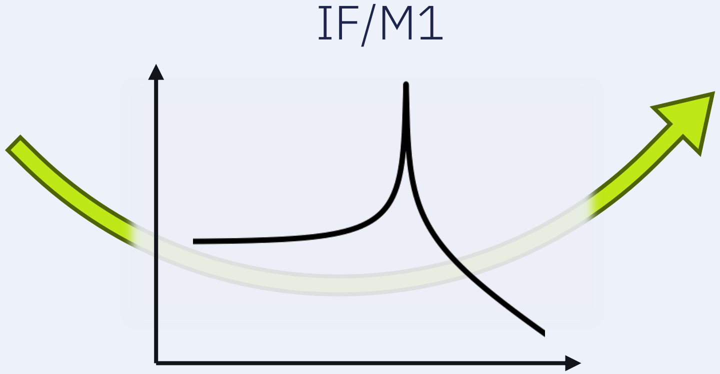


REMOVING ANTIRESONANCES LEADS TO OVERTESTING

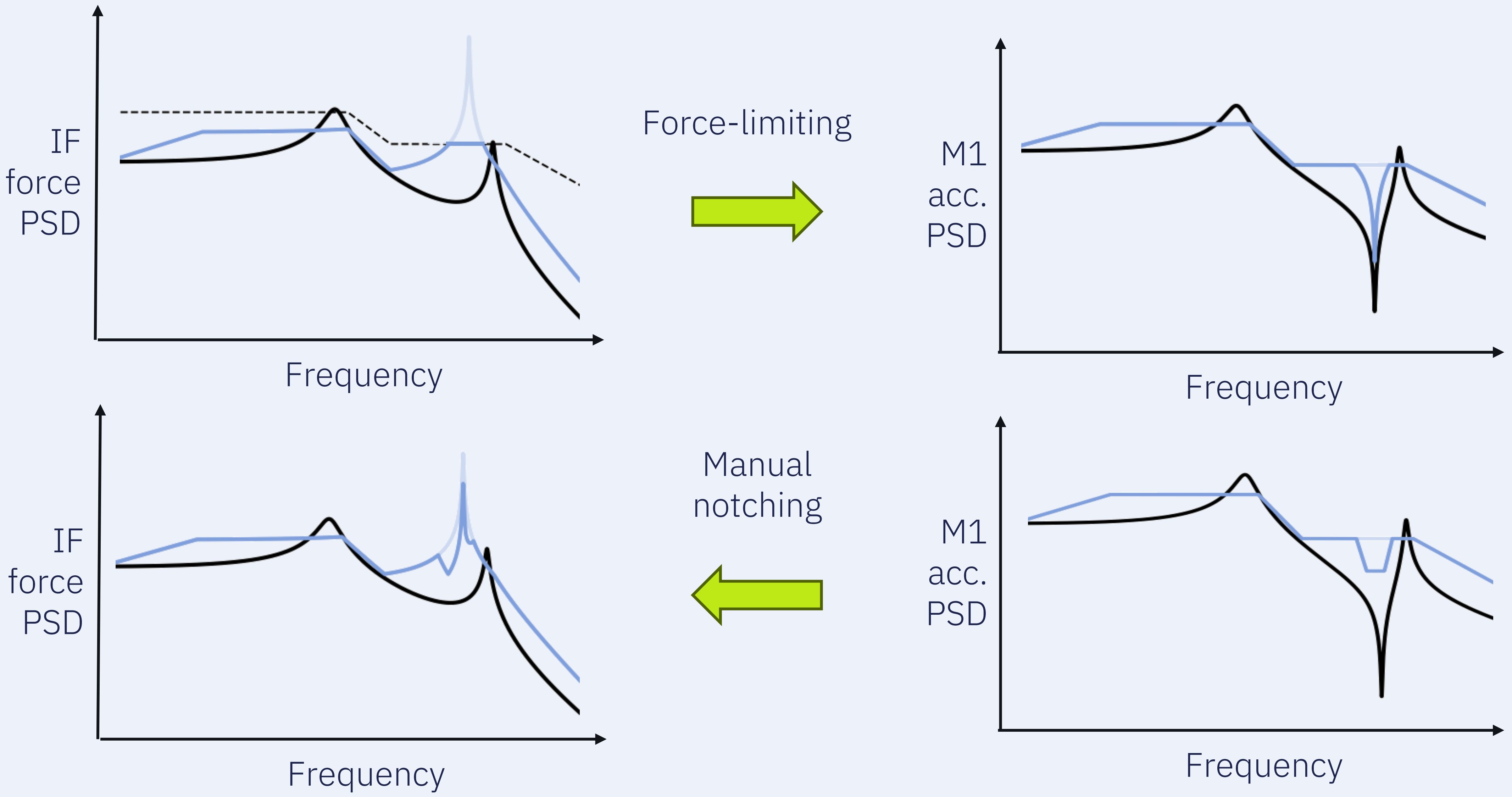




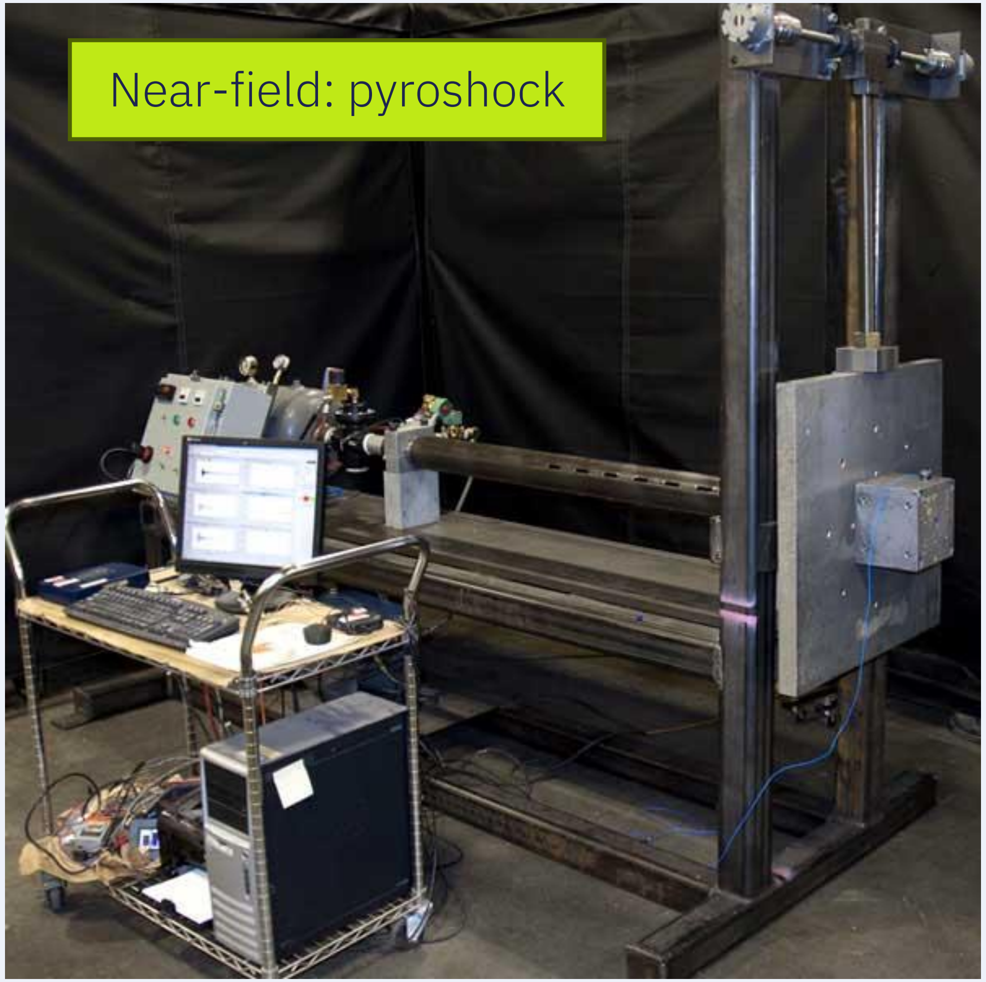




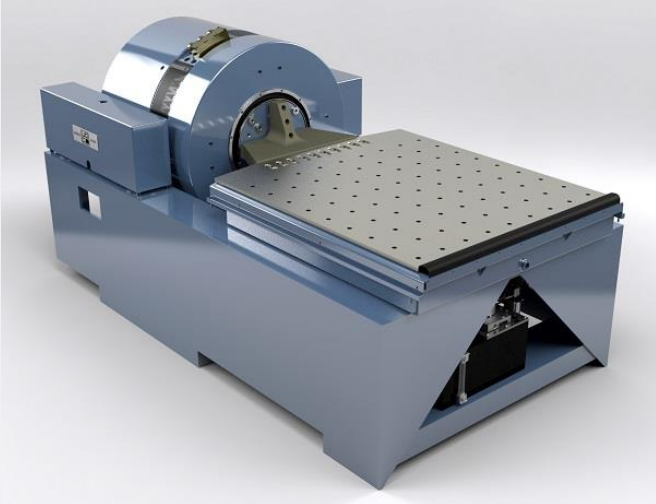
NOTCHING REINTRODUCES ANTIRESONANCES



SHOCK TESTS ARE OFTEN MADE WITH RINGING PLATE



Far-field: shaker



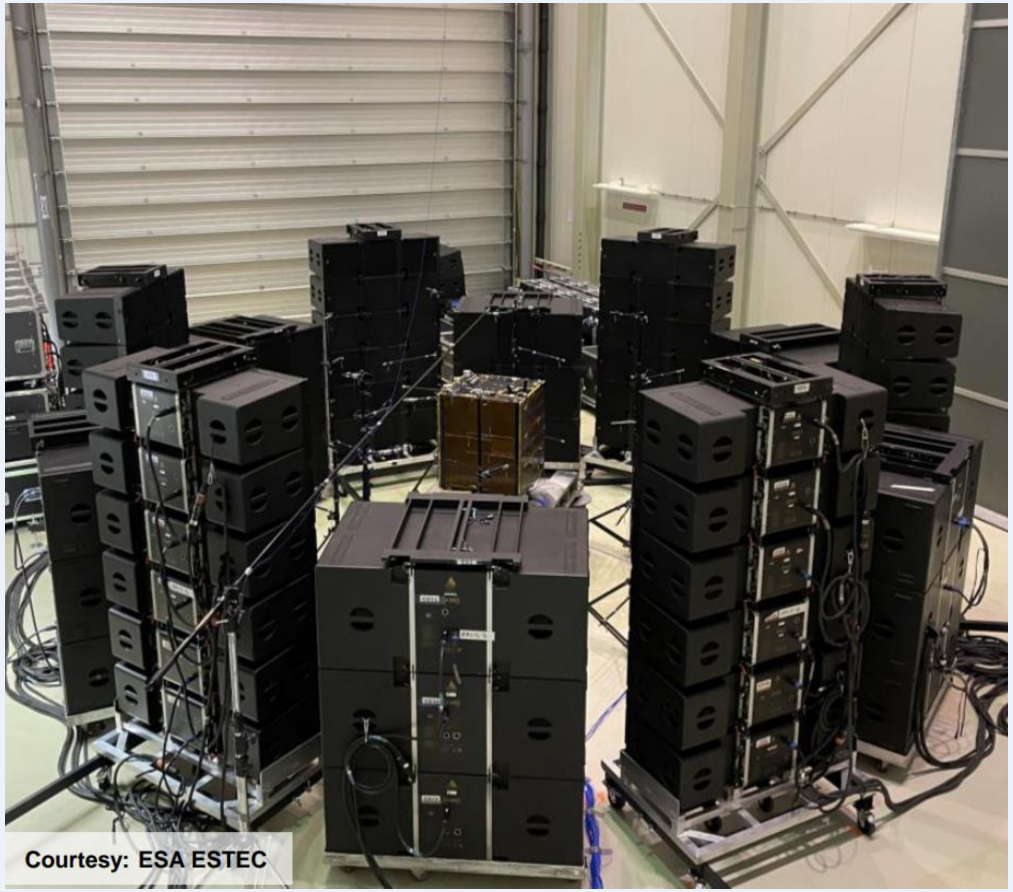
From: Dayton T. Brown; ESTEC; Unholtz Dickie

ACOUSTIC TESTING

Reverberant field acoustic noise testing

Courtesy: ESA ESTEC

Direct field acoustic noise testing



Courtesy: ESA ESTEC

THANK YOU

FEEL FREE TO ASK YOUR QUESTIONS

BONUS SLIDES

ISOLATION AIMS TO REDUCE VIBRATION LOADS