WGS

Project 20-10P-374

Waveguide switch based on friction free mechanism

Final Presentation Review

(ALM-PRO-6749)

Almatech & CSEM

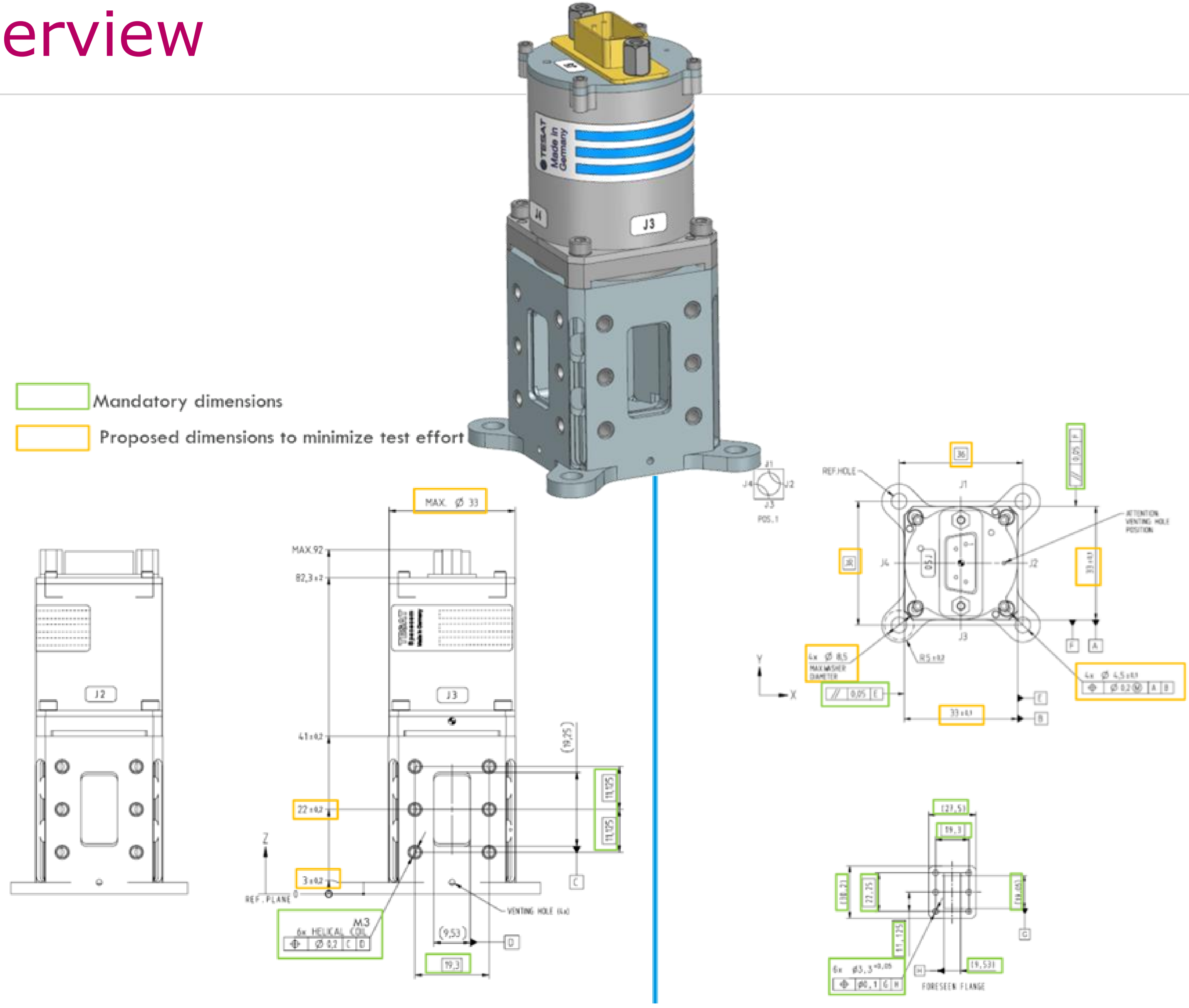
Lausanne, December 2nd, 2024

Agenda

- Introduction
- Objectives
- Design Overview
- Testing and Results
- Challenges and Lessons Learned
- Roadmap and Future Work
- Conclusion

Introduction: Project Overview

- Objective: Development of a friction-free RF waveguide switch based on the WR75 C-switch from TESAT.
  - C-switch request two stable positions
  - 90° of rotation
- Focus:
  - Eliminate lubricants by removing friction parts such as bearings in actuator and mechanism
  - Improve reliability (no particles that can impact function of the mechanism).
- Goal: Advance TRL from 2 to 5.
  - Functional Tests
  - Laboratory RF performances tests on EM
  - Representative environmental tests on EM
  - Lifetime tests

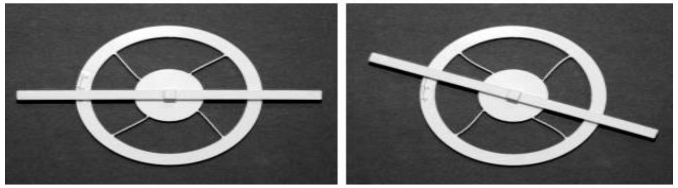


Key Objectives

- Design and manufacture a friction-free mechanism that fulfill or even exceed actual performances requirements of the actual commercial waveguide C-switch WR75 from TESAT.
  - Key aspects taken into consideration:
    - RF Performances
    - Thermal dissipation of RF through mechanism structure
    - Cleanliness (no particle generation)
- Validate friction free mechanism design through functional, performance, and environmental tests.

State of the Art Mechanism (1/2)

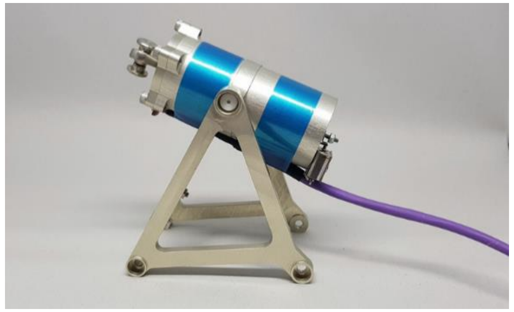
Groups	Physical principles	Main advantages	Main drawbacks
Flexible hinges	Elastic deformation	Limited number of parts Stored elastic energy provided additional force for the change of position Accurate motion Average lateral stiffness	Limited range of motion Creep issues related to the stored elastic energy Thermal isolator No internal latching No discrete positions
Bi-stable and multi-stable	Buckling	Limited number of parts Simple control law (open loop) Internal latching Discrete positions Accurate motion	Limited range of motion Small angular range Thermal isolator Low lateral stiffness
Bimetals	CTE mismatch	Potential actuator included Compactness (blade shape)	Limited range of motion Small angular range Sensitive to temperature changes Feedback control required

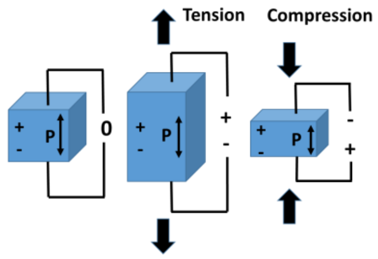


(a) the initial stable position (b) the second stable position

State of the Art Mechanism (2/2)

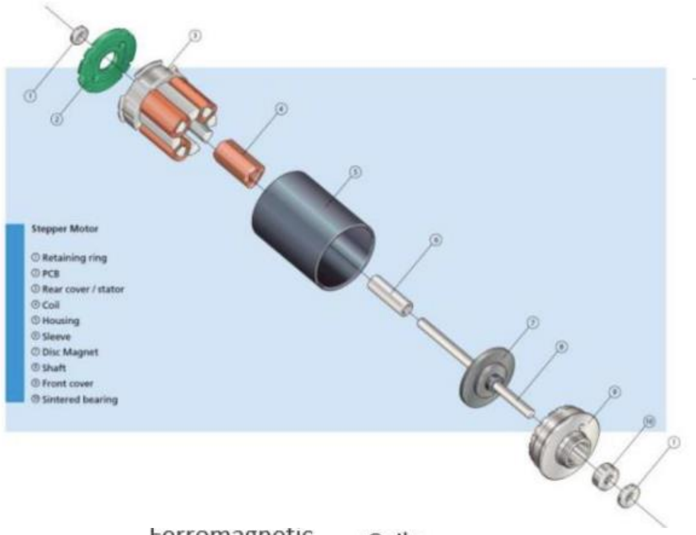
Groups	Physical principles	Main advantages	Main drawbacks
SMA materials	SMA	Potential actuator included Compactness	Limited range of motion Small angular range Sensitive to temperatures changes Feedback control required
Piezo electric materials	Piezo electric	Potential actuator included Compactness	Limited range of motion Small angular range Sensitive to temperature changes Feedback control required
Magnetic bearings	Electro magnetism	Potential actuator included Possible rotation over 360°	Small angular range Feedback control required Complex control law

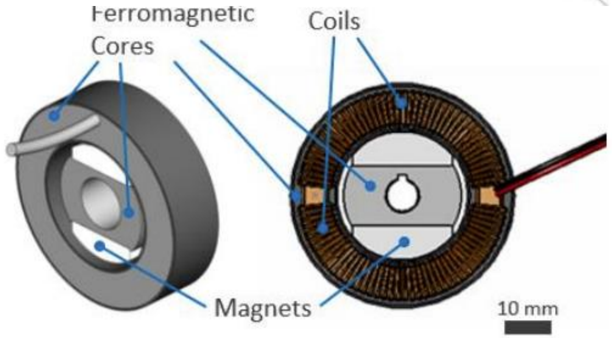


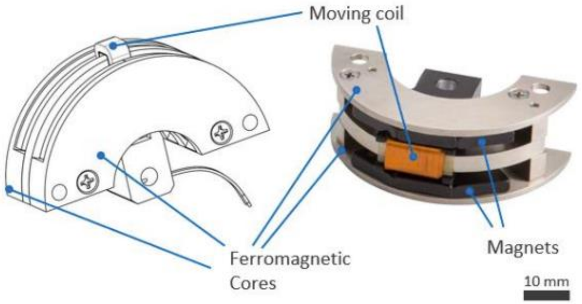


State of the Art: Actuators

Groups	Physical principles	Main advantages	Main drawbacks
Stepper motor	Electro-magnetic	Low inertia High angular accuracy High acceleration High torque/mass ratio Open-loop position control	Classical ball bearing used to ensure rotor/stator centering Low residual (cogging) torque Moderate to high parasitic forces Moderate to high complexity Moderate torque/power ratio
Torque motor	Electro-magnetic	High torque/mass ratio Robust and simple construction Absence of ball bearings in commercially available products	Absence of no-current stable position Moderate to high parasitic forces High inertia Closed-loop position control Moderate torque/power ratio
Voice-coil	Electro-magnetic	Low inertia Absence of ball bearings in commercially available products Small parasitic forces High torque/power ratio	Absence of no-current stable position Closed-loop position control Low Torque/Mass ratio Moderate to low complexity





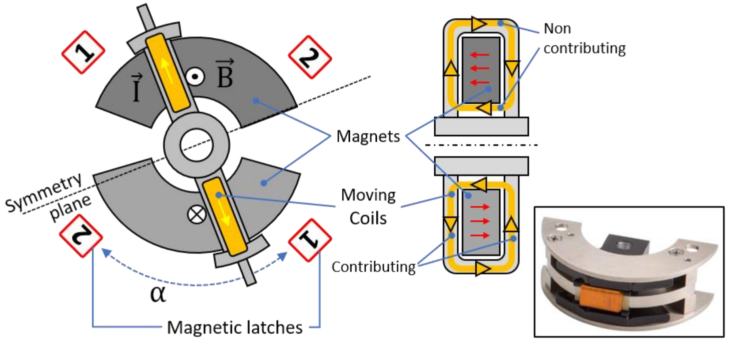


Solution Trade-off (1/2)

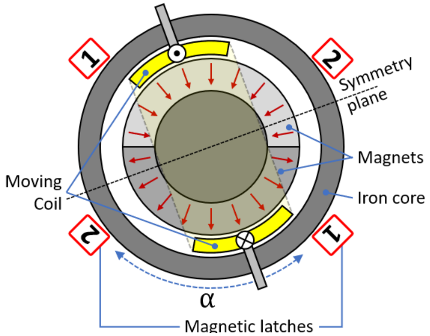
- Four solution configurations were evaluated in detail through a trade-off:
  - Flexible hinge + Voice Coil configuration 1
  - Flexible hinge + Voice Coil configuration 2
  - Bi-stable + Voice Coil configuration 1
  - Bi-stable + Voice Coil configuration 2
- Considering the following different criteria and their weighting:
  - Mechanical Performances (weight 0.6)
  - Thermal performances (weight 0.6)
  - Physical performances (weight 0.6)
  - Design risks (weight 1.6)
  - Cost (weight 1.6)

Flexible Hinge

Bistable pivot



Voice coil configuration 1 (Rotary Voice Coil Actuator)



Voice coil configuration 2 (Cylindrical Voice Coil Actuator)

Solution Trade-off (2/2)

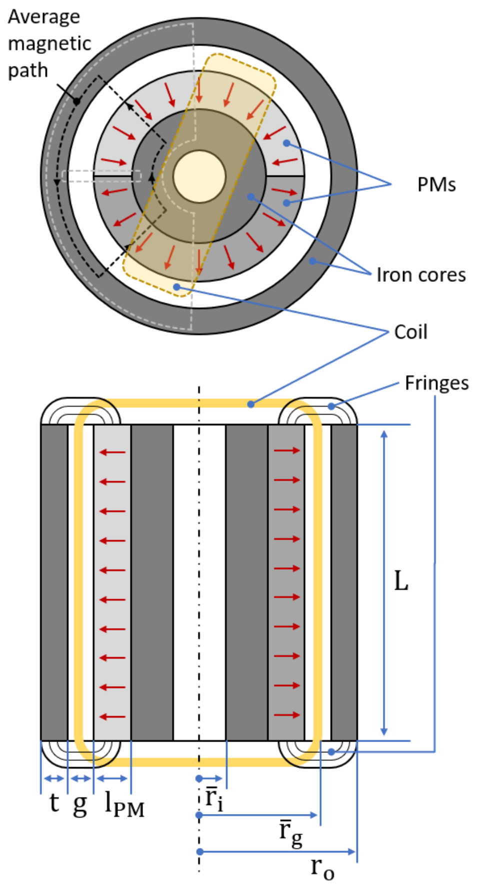
- Selected Combination was a bistable mechanism with a voice coil actuator such as in configuration 2

- Reasons for Bistable
  - Long term mechanical stability with stable locking positions essential for RF operations
  - Redundancy with the voice coil latching

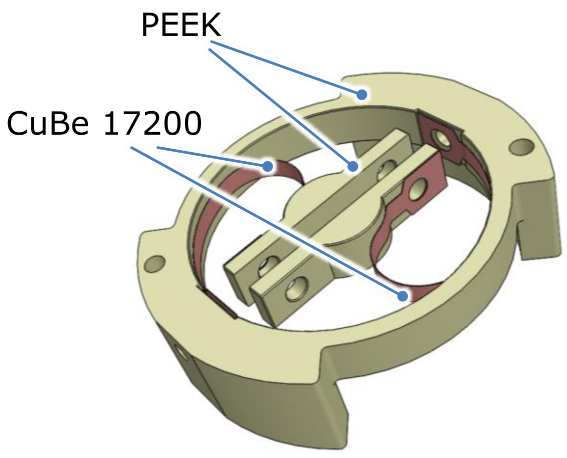
- Reasons for Voice coil in configuration 2
  - In addition to common properties of voice coil such as friction free or high reactivity for precise movements the cylindrical voice coil offer in addition:
    - Torque adjustment flexibility (Torque can be adjusted by modifying active coil length without changing the average radius of the actuator)
    - Simple construction (fewer moving parts, less complex to manufacture and assemble, reliability improved)
  - For the reasons presented above, the cylindrical voice coil is the best option to be used for space application for such kind of friction free mechanism

Voice coil Design and Development

Radial flux slender configuration

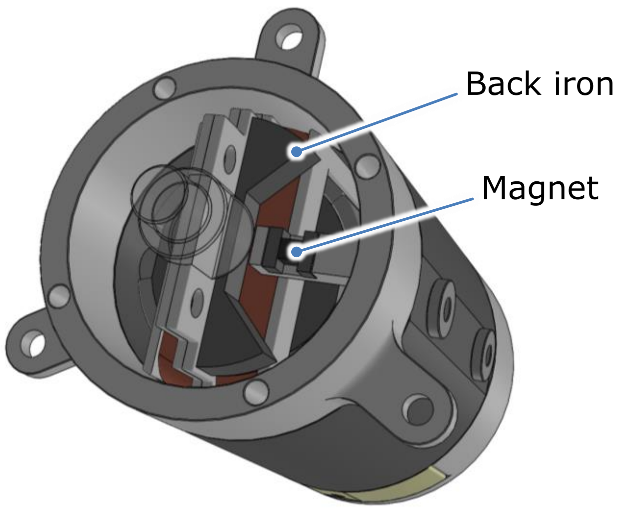


CuBe mobile connections



Outer guide radius	12	(mm)
Inner guide radius	4	(mm)
Bending radius	4	(mm)
Width	2	(mm)
Thickness	0.03	(mm)
Rolling ribbon length	28	(mm)
CuBe Young modulus	131000	(MPa)
Conductivity	1.16E+07	(S/m)
$\sigma_{max\ bend}$	**491.25**	(MPa)
Torque on VCA due to rolling ribbon	**0.15**	(mNm)
Rolling resistance	**79.50**	(mΩ)

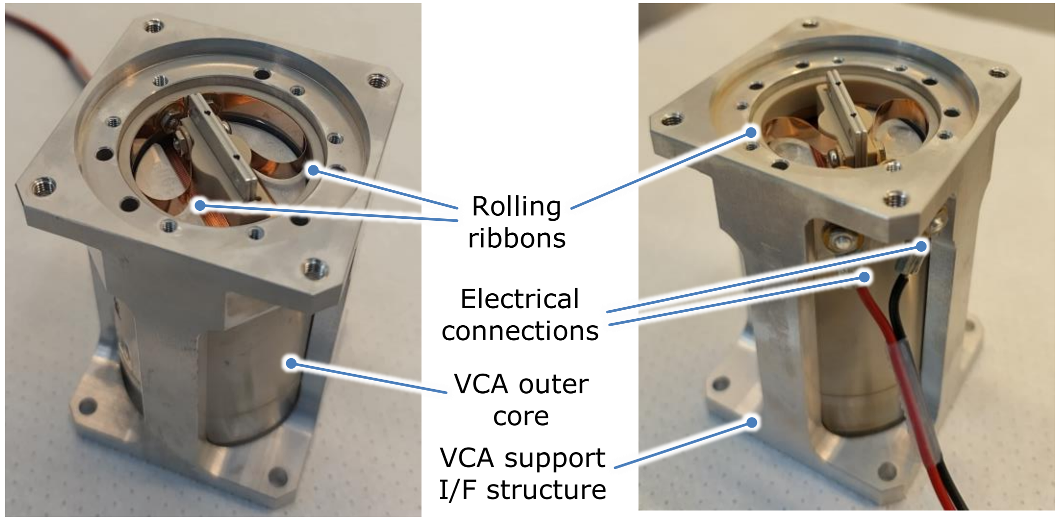
Latching mechanism



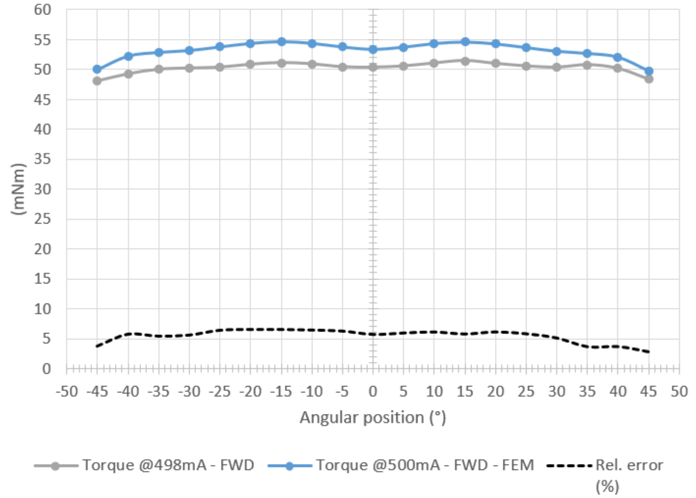
- Maintain the footprint constraints
- Torque proportional to the stator height h_{tot}

Voice coil Design and Development

Mounting and performance verification

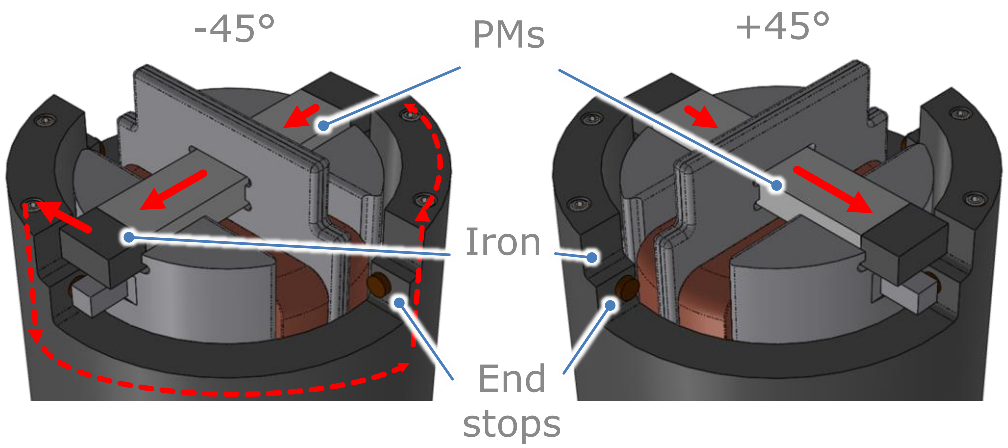


Comparison of VCA torque - FEM Vs Measurements



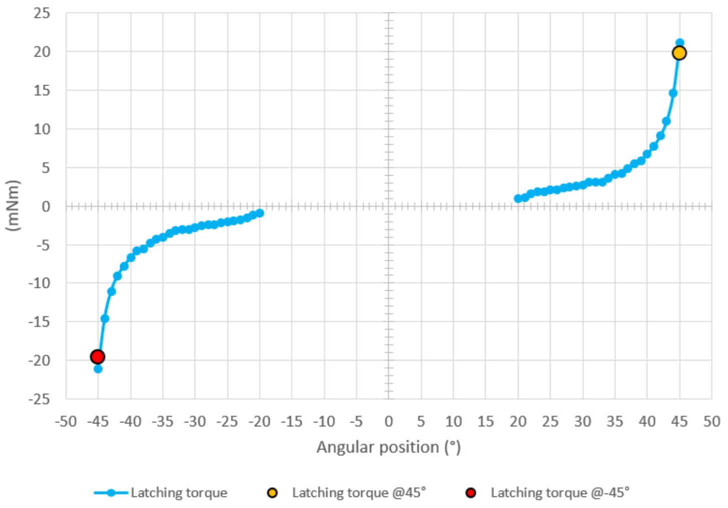
Max. err. 6.5%

Latching mechanism improvement



- Reduction in complexity (12 → 5 parts)

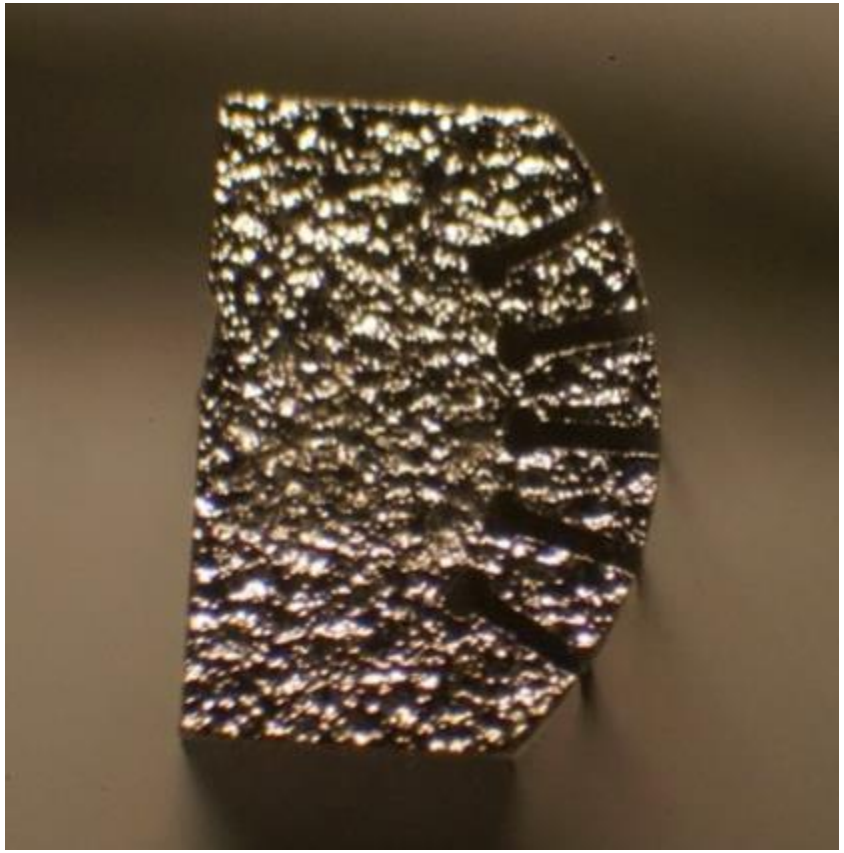
Latching Torque - FEM Vs Measurements



Max. err. 4.9%

Bistable Pivots Design and Development

- Flash nickel tests
  - Representative samples treated with a thin nickel layer.
  - Coating uniformity and thickness measured using an X-ray fluorescence spectrometer (Fischerscope® XRAY XAN 250).
  - Results:
    - Consistent nickel thickness observed on aluminium stator and rotor rings (5mu).
    - Demonstrated process repeatability.

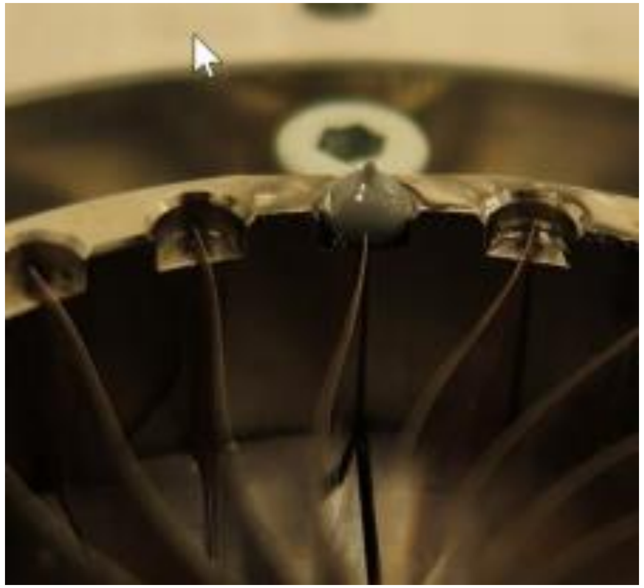


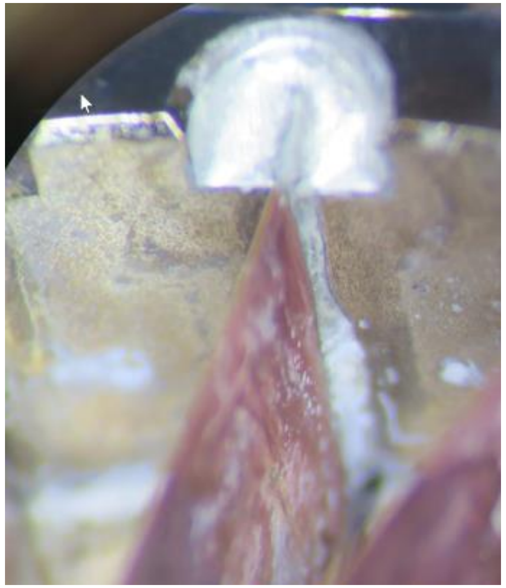
Bistable Pivots design and development

- Soldering Test results

  – CuBe blades were inserted into grooves in aluminum supports to test the soldering process using Sn63Pb37 alloy. Although results were qualitative, the solder adhesion was considered satisfactory for most samples.

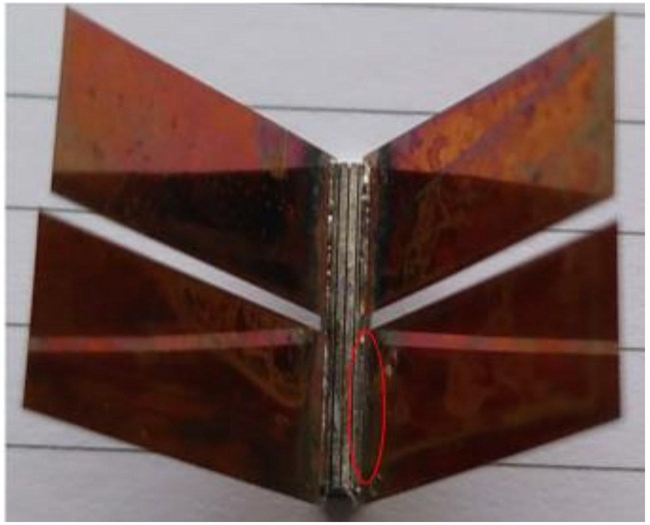
  – For the final manufacturing of the bistable mechanism, an automated soldering dispenser was employed. Lead-free solder (Sn96Ag4) was chosen to comply with ESA's desire to discontinue the use of lead-based alloys for soldering. To ensure strong adhesion of the solder to the blade surfaces, a high-performance flux, INH1, was required.



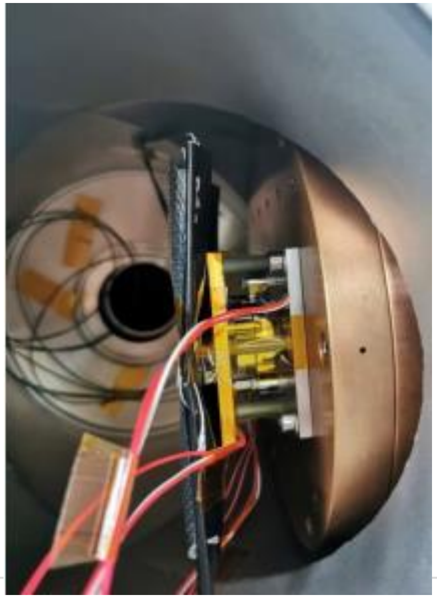


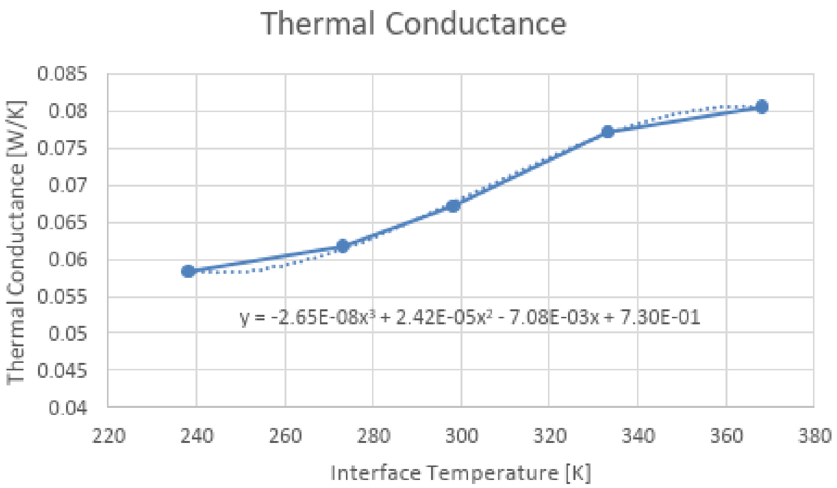
Bistable Pivots design and development

- Tensile Tests
  - Objective: Test the strength of soldered joints.
  - Method: Applied progressive tension to a CuBe blade clamped between two plates.
  - Results:
    - Most joints withstood up to 20 N, meeting expected load requirements.
    - Some joints failed due to insufficient solder material in the groove



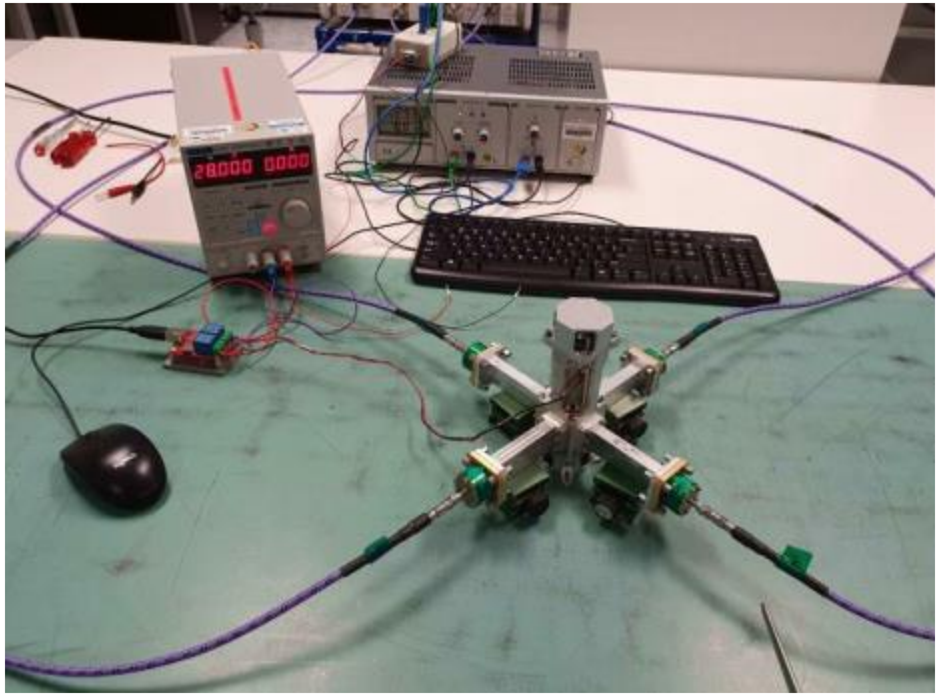
- Thermal conductance tests
  - Conductance value of the same order of magnitude as grease lubricated ball bearings in the better conditions (e.g. preload, all balls in contact…)
  - Resonable conductance variance over temperature variation





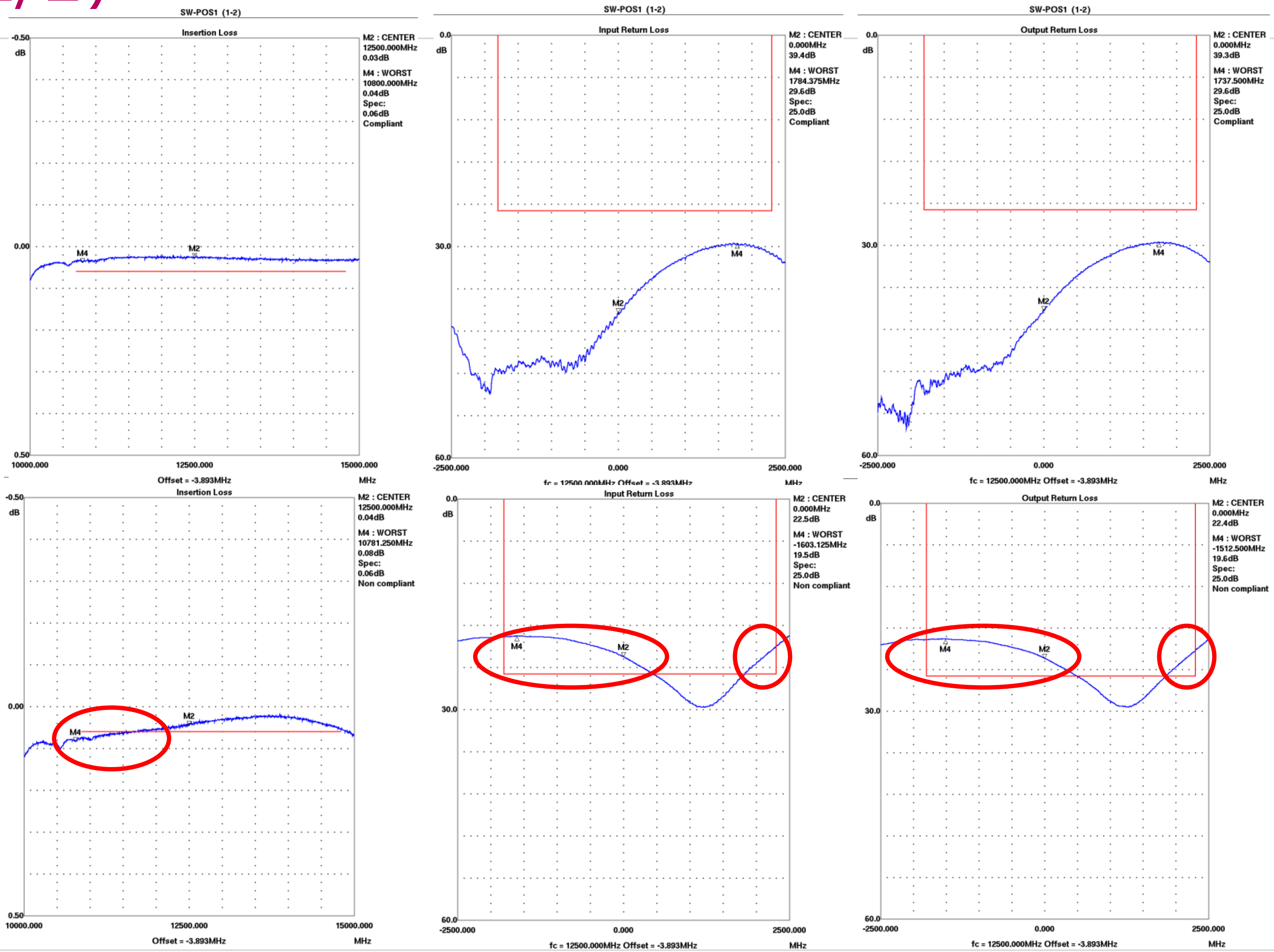
Performance Testing (1/2)

- Initial functional tests.
  - 1200 actuations for both SN01 /SN02
  - Incoming 10 actuations on both sides and then measurement and verification measurement of following criteria followed by 10 activations
    - Measurement of coil resistance ~28 Ohms
    - Switching time measurement for both positions ~17ms
    - Minimal current activation measurement for both position (ref motorisation margin) ~170mA (Motorisation margin~3)
    - RF performances (next slide)



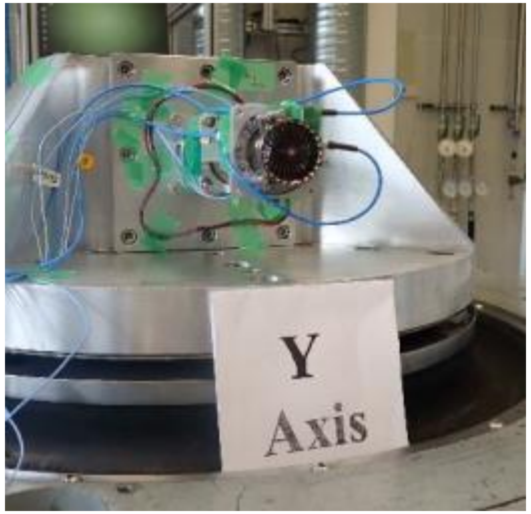
Performance Testing (2/2)

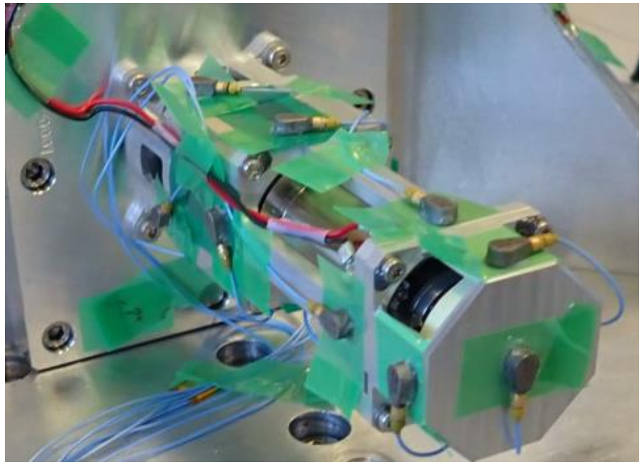
- RF performance analysis (SN01 and SN02 results)
  - Similar results on SN01 /SN02:
  - Compliant in POS1
    - Insertion Loss (1-2 and 3-4)
    - Input Return Loss (1-2 and 3-4)
    - Output Return Loss (1-2 and 3-4)
    - Isolation 1-3, 1-4, 2-3 and 2-4
  - Not compliant in in POS2
    - Insertion Loss (1-4 and 2-3)
    - Input Return Loss (1-4 and 2-3)
    - Output Return Loss (1-4 and 2-3)
    - Isolation 1-2, 1-3, 2-4 and 3-4



Vibration tests (setup configuration)

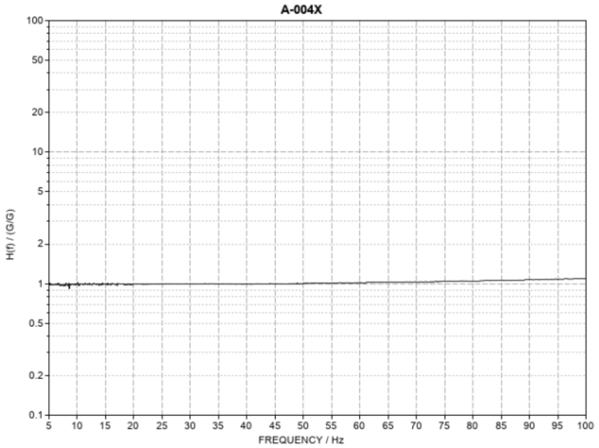
- Two setup configuration testes
  - SN01:
    - Without top cover
    - Triaxial accelerometer on top rotor bistable pivot
    - Triaxial accelerometer on top motor housing
  - SN02:
    - Nominal configuration
    - Uniaxial accelerometer on stator parts
    - No accelerometer on rotor

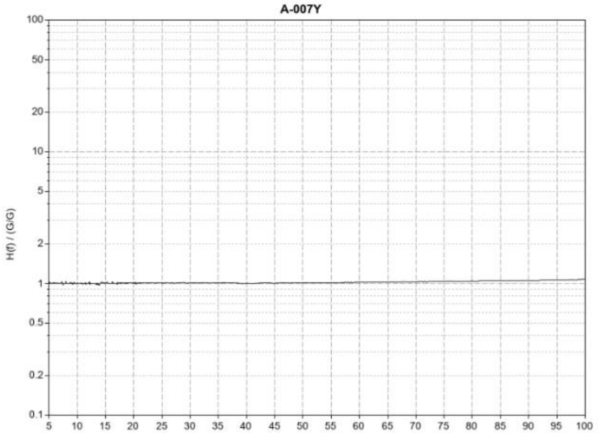


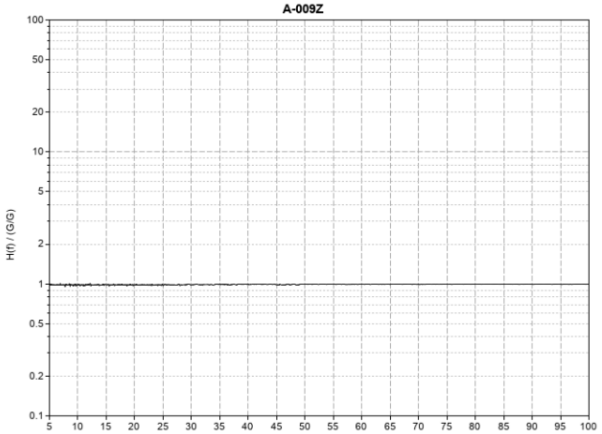


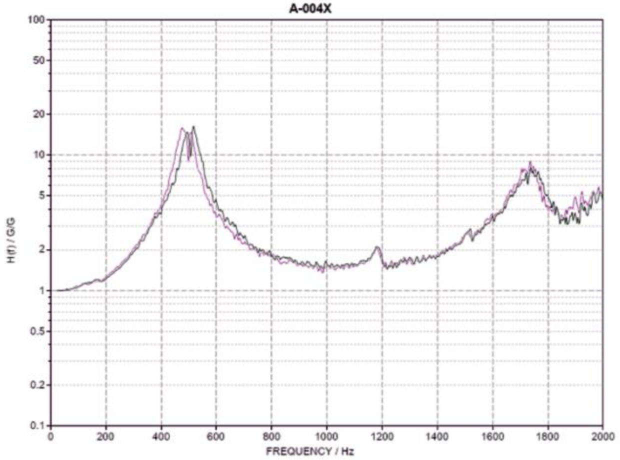
Vibration Tests (SINE)

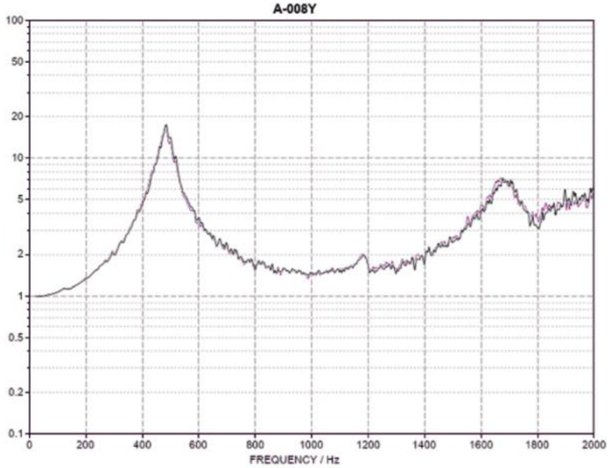
- Test setup and results summary.
  - Sine test passed without any issue for SN01 (SINE X and Y) and SN02 model (SINE X, Y and Z)

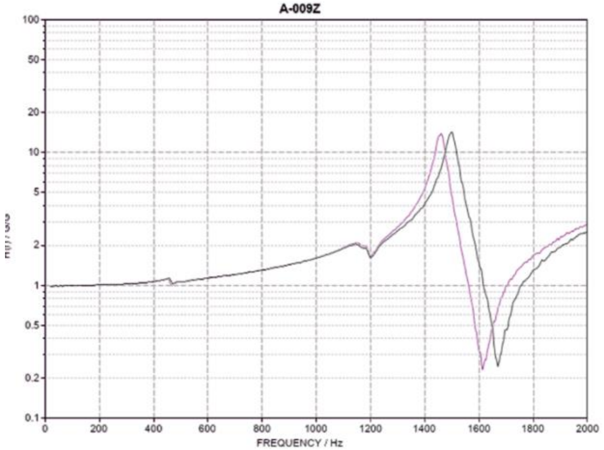






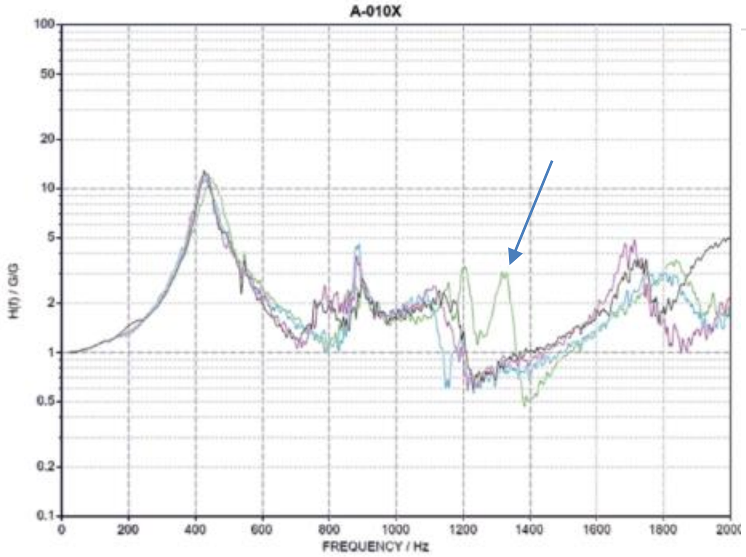


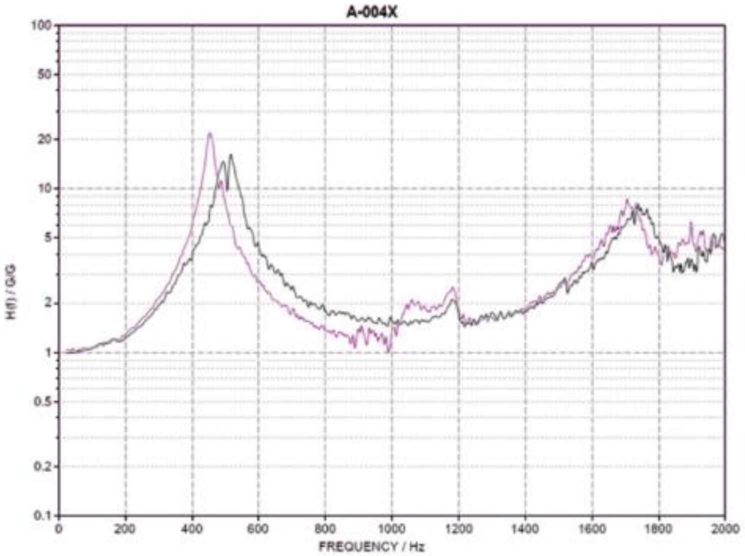




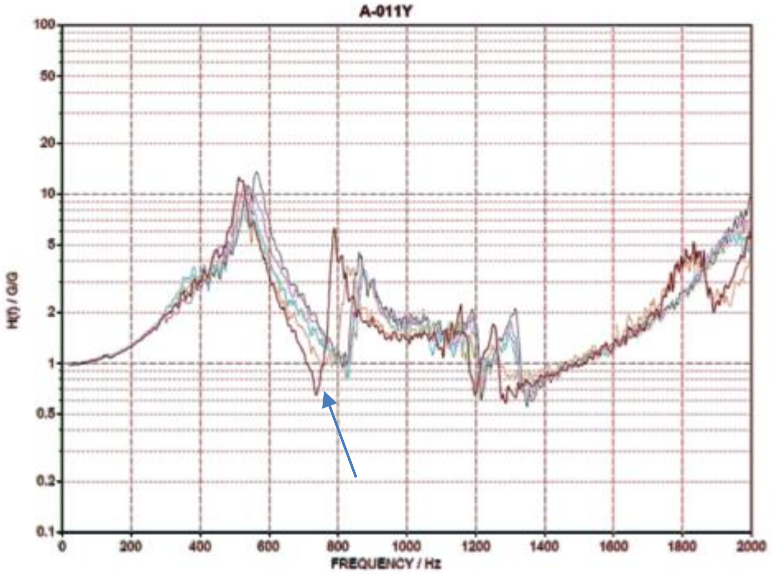
Vibration Tests (RANDOM) 1/2

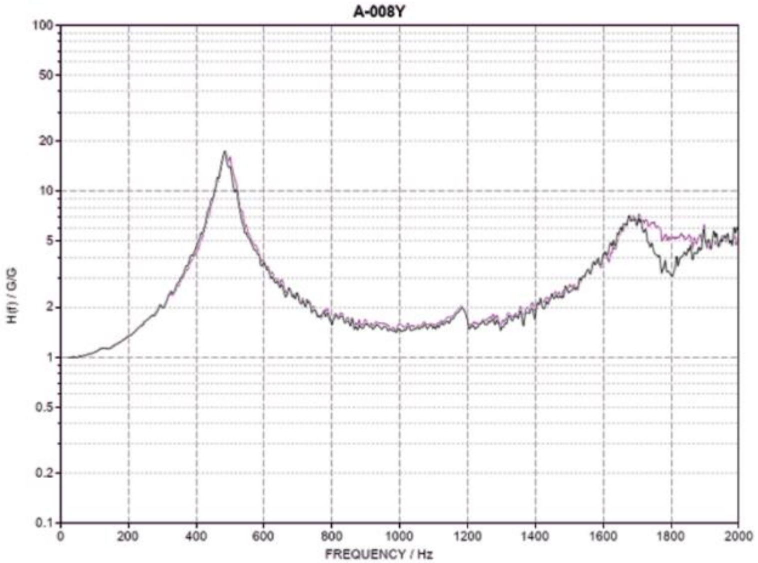
- RND X





- RND Y

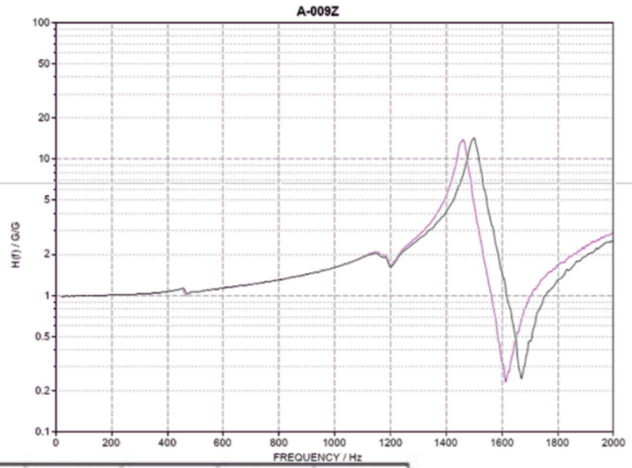




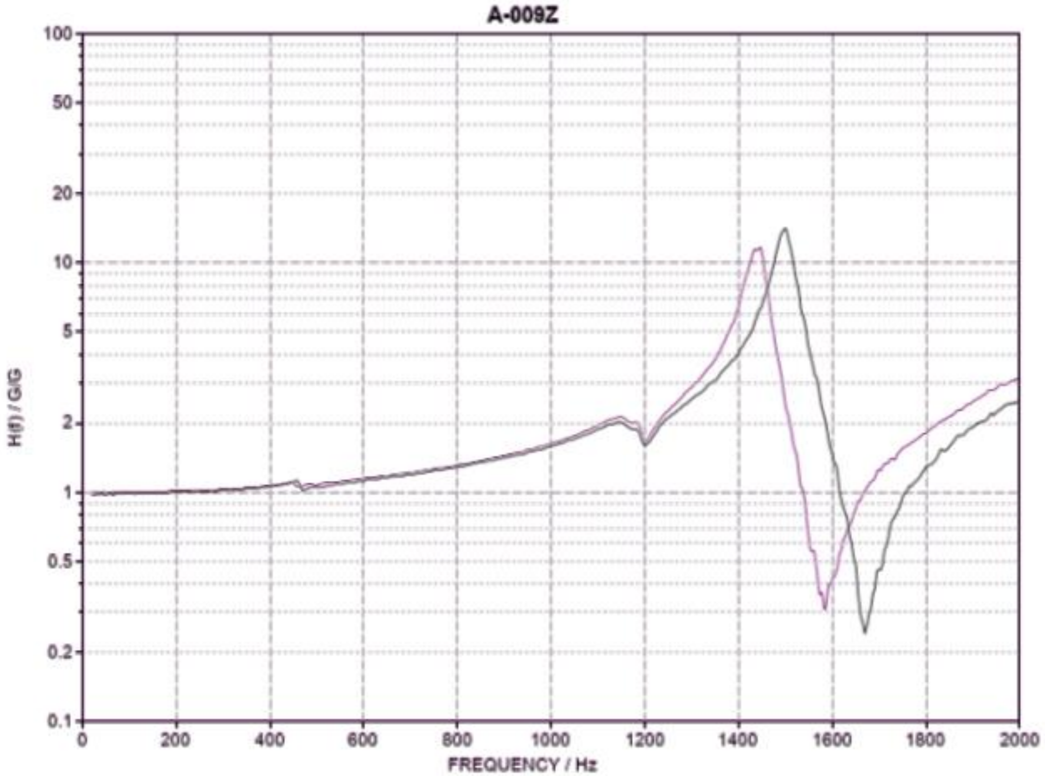
Vibration Tests (RANDOM) 2/2

- RND Z (SN2 ONLY)

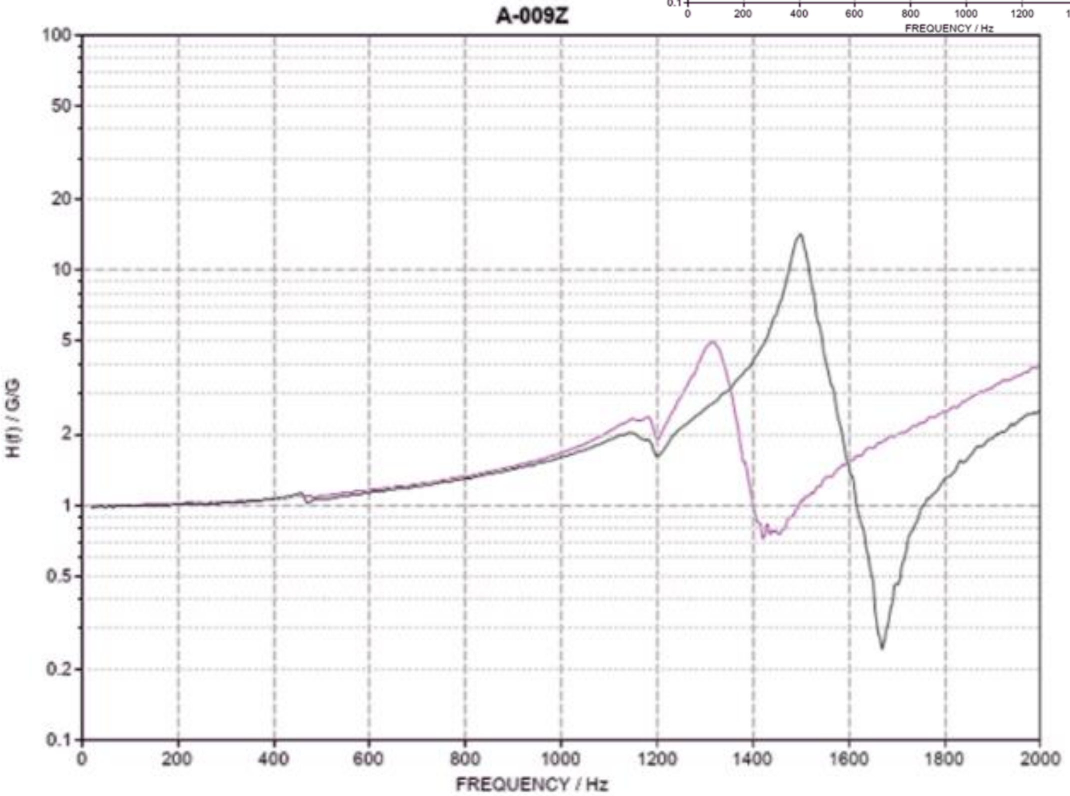
After Sine Z



-3dB

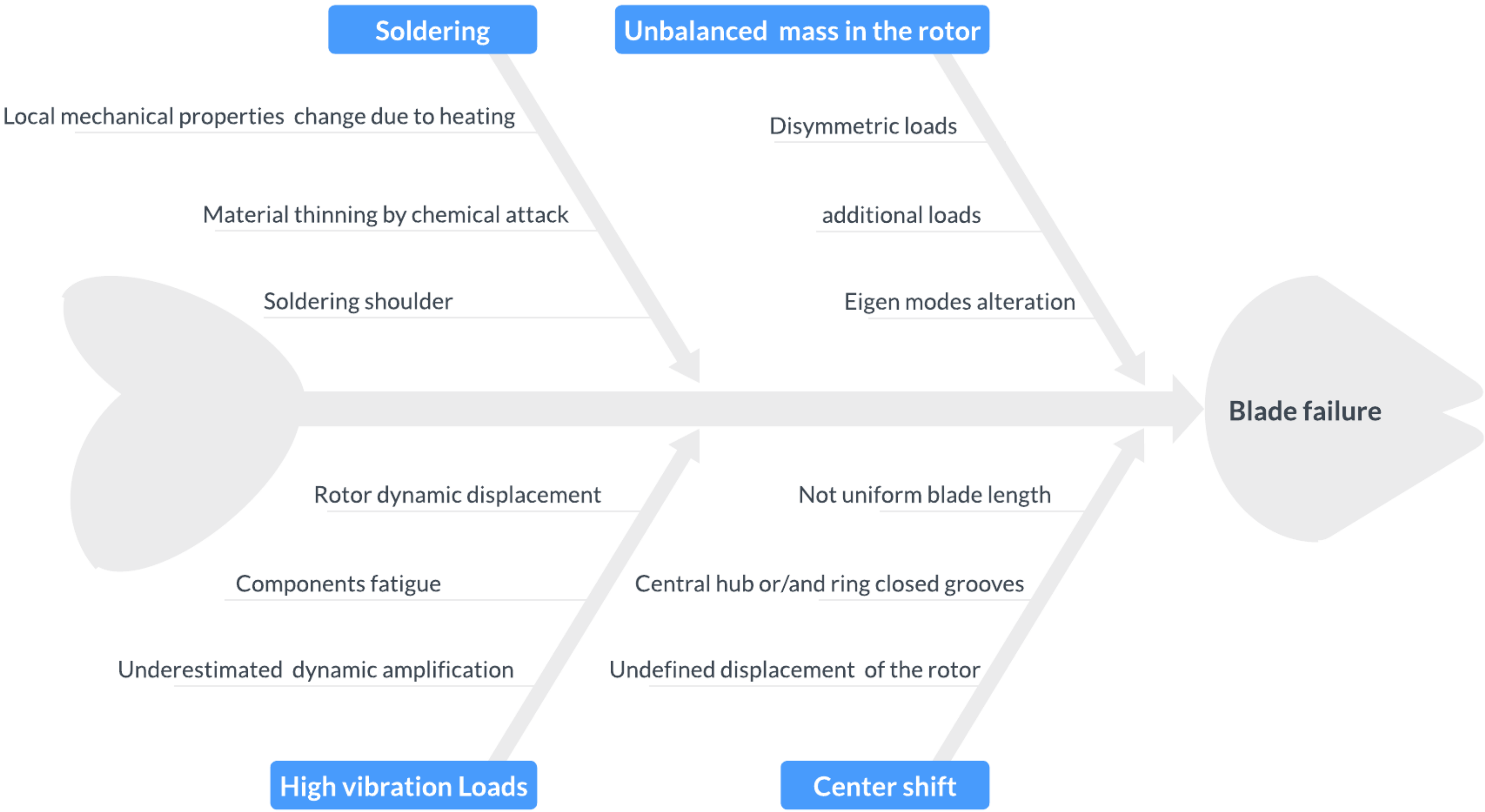


0dB



- Identified issues: blade rupture and misalignment.

General Fishbone diagramme of blade failure in pivots



Influence of rotor accelerometer in the Eigen modes (1/2)

- Frequency

With Cover

MODE NO.	FREQUENCY [Hz]	T1 [%]	T2 [%]	T3 [%]	R1 [%]	R2 [%]	R3 [%]
TOTAL Fraction		*95.9%*	*95.9%*	*98.1%*	*93.4%*	*93.4%*	*93.8%*
1	329.080000	4.6%	62.8%	0.0%	66.2%	4.8%	0.0%
2	333.111200	63.6%	4.5%	0.0%	4.8%	65.9%	0.0%
3	514.577300	0.0%	0.0%	0.0%	0.0%	0.0%	40.8%
4	760.077100	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
5	844.565300	0.0%	0.0%	0.0%	0.0%	0.0%	5.0%
6	954.453800	0.0%	1.6%	0.0%	0.1%	0.0%	0.0%
7	1147.763000	0.3%	17.1%	0.0%	9.2%	0.1%	0.0%
8	1194.250000	0.0%	0.0%	83.1%	0.0%	0.0%	0.0%
9	1202.943000	19.6%	0.3%	0.2%	0.1%	10.7%	0.0%
10	1478.711000	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%
11	1512.270000	0.0%	0.0%	0.0%	0.0%	0.0%	10.6%
12	1526.836000	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%
13	1540.499000	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%
14	1545.203000	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%
15	1554.534000	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%
16	1586.760000	0.0%	1.2%	0.0%	0.2%	0.0%	0.0%
17	1747.547000	0.0%	0.0%	0.0%	0.0%	0.6%	0.0%
18	1765.067000	0.0%	0.1%	0.0%	0.7%	0.1%	0.0%
19	1774.792000	0.0%	0.0%	2.2%	0.0%	0.0%	0.0%
20	1892.726000	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
21	1967.563000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

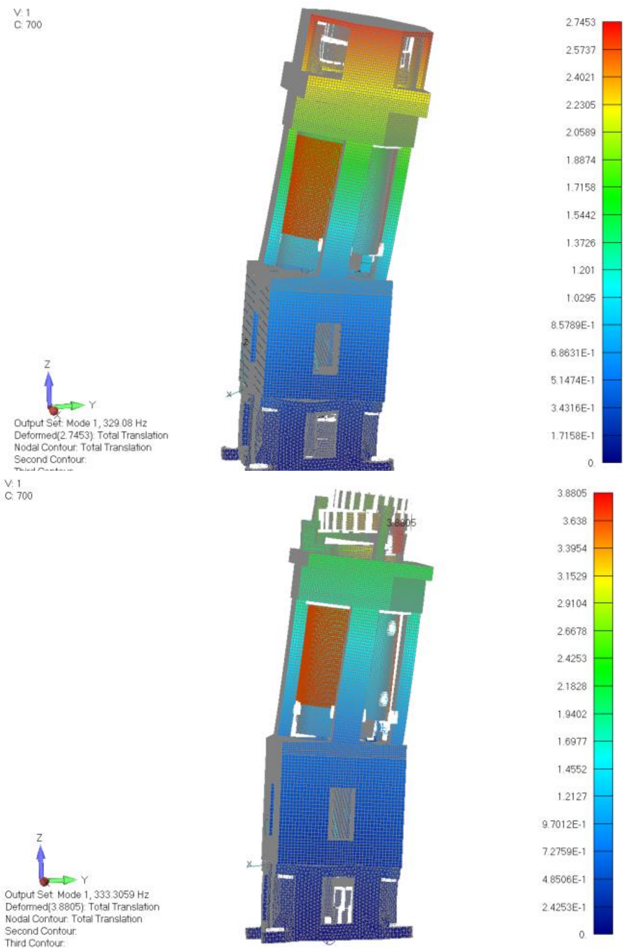
WO Cover and with additional accelerometer

MODE NO.	FREQUENCY [Hz]	T1 [%]	T2 [%]	T3 [%]	R1 [%]	R2 [%]	R3 [%]
TOTAL Fraction		*95.9%*	*95.9%*	*98.1%*	*93.0%*	*93.0%*	*93.7%*
1	333.305900	0.3%	63.8%	0.0%	67.3%	0.3%	1.0%
2	341.467800	67.9%	0.5%	0.0%	0.4%	68.4%	0.1%
3	458.859700	0.4%	3.5%	0.0%	1.3%	0.2%	24.7%
4	603.708100	0.1%	0.7%	0.0%	0.0%	0.0%	13.9%
5	806.009800	0.0%	0.0%	0.0%	0.0%	0.0%	5.4%
6	934.665200	0.0%	1.7%	0.8%	0.1%	0.0%	0.0%
7	1158.437000	1.9%	7.1%	37.0%	3.9%	1.1%	0.0%
8	1187.272000	2.5%	8.3%	21.0%	5.5%	1.5%	0.0%
9	1210.255000	14.1%	0.2%	19.1%	0.1%	8.0%	0.0%
10	1478.736000	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
11	1517.419000	0.1%	0.1%	0.9%	0.1%	0.1%	0.0%
12	1538.854000	0.0%	0.0%	0.0%	0.0%	0.3%	0.0%
13	1543.371000	0.0%	0.1%	0.1%	0.1%	0.0%	0.0%
14	1557.745000	0.2%	0.0%	0.0%	0.0%	0.1%	0.0%
15	1581.034000	0.1%	0.7%	1.5%	0.2%	0.0%	0.0%
16	1668.426000	0.0%	0.4%	3.0%	0.1%	0.3%	0.1%
17	1690.184000	0.0%	0.0%	0.0%	0.0%	0.0%	11.7%
18	1726.638000	0.2%	0.1%	1.6%	0.0%	1.0%	0.0%
19	1758.233000	0.1%	0.2%	0.1%	1.0%	0.1%	0.0%
20	1886.540000	0.0%	0.2%	0.1%	0.2%	0.1%	0.0%
21	1957.373000	0.4%	0.1%	0.0%	0.0%	0.2%	0.0%
22	1970.052000	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%

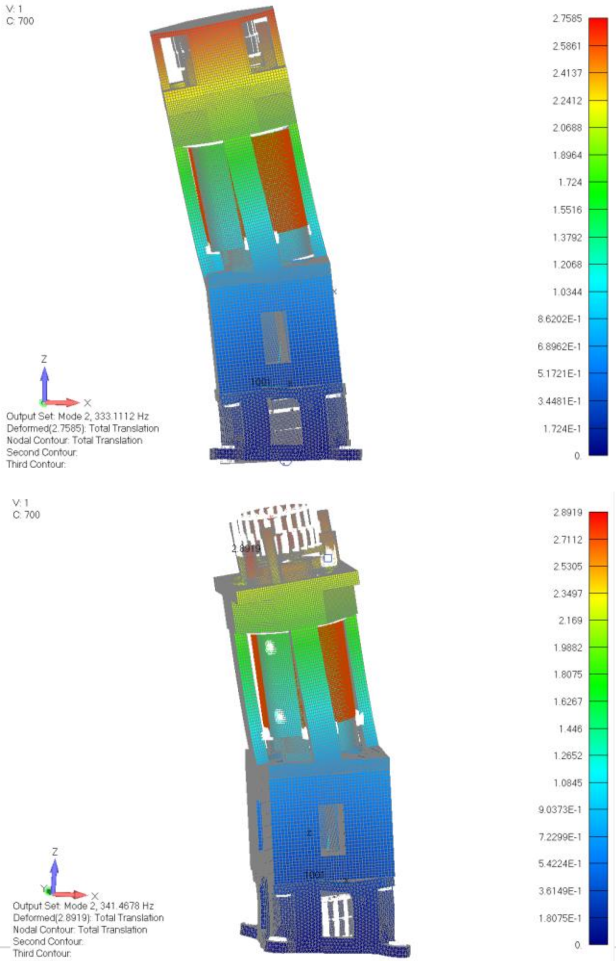
Influence of rotor accelerometer in the Eigen modes (2/2)

- Mode Shapes

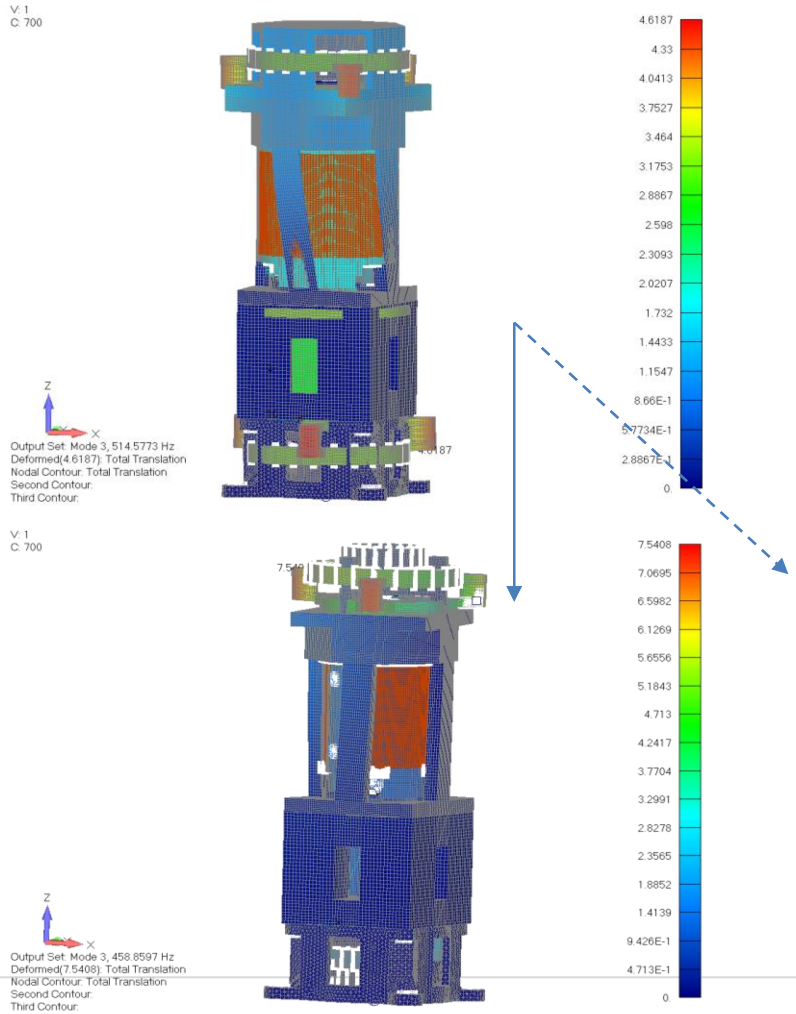
Mode 1



Mode 2



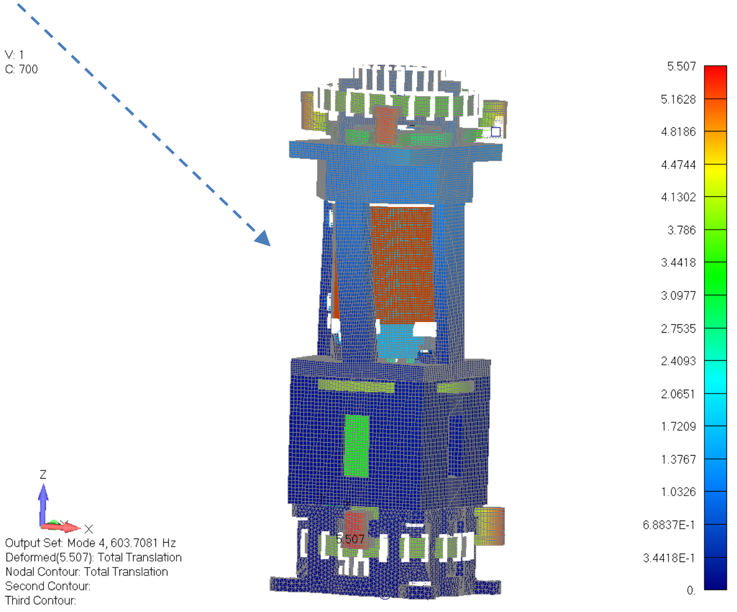
Mode 3



Influence of rotor accelerometer in the Eigen modes (2/2)

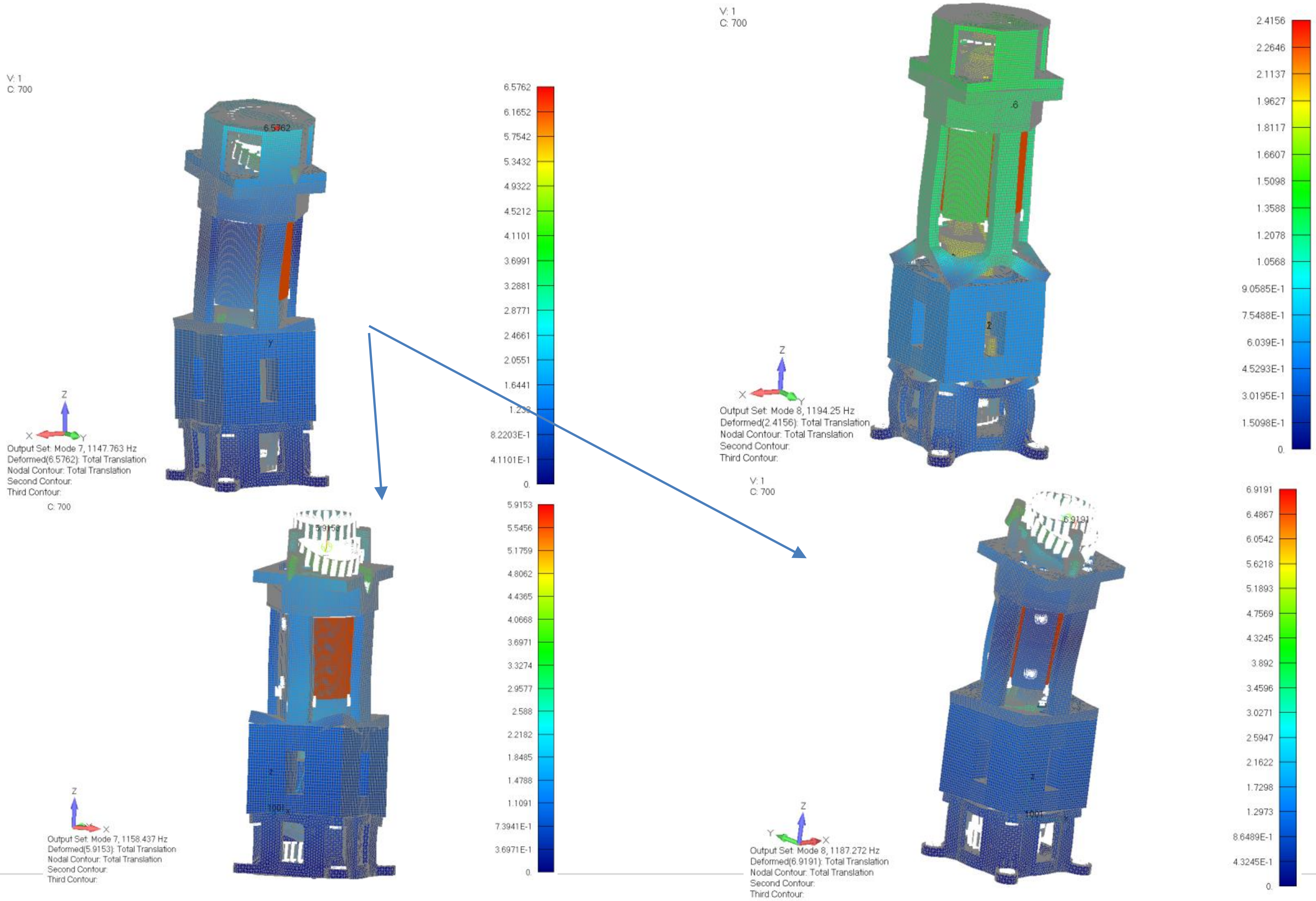
- Mode Shapes

Mode 4



Mode 7

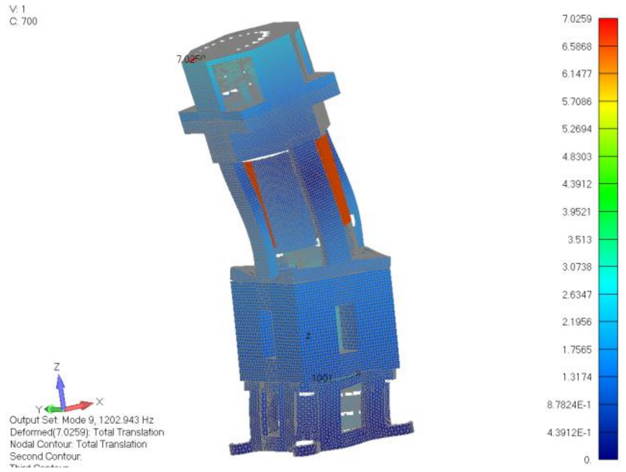
Mode 8

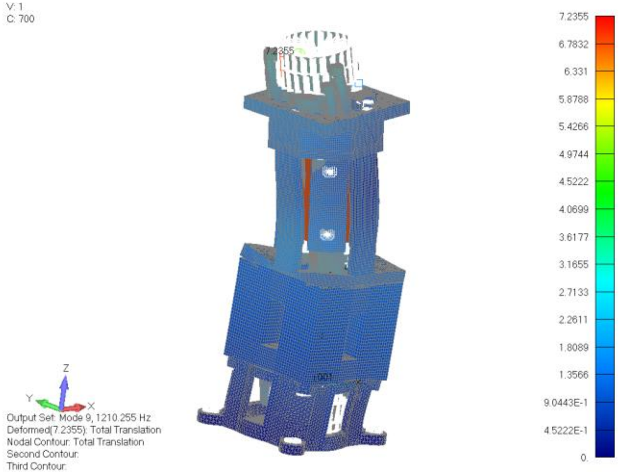


Influence of rotor accelerometer in the Eigen modes (2/2)

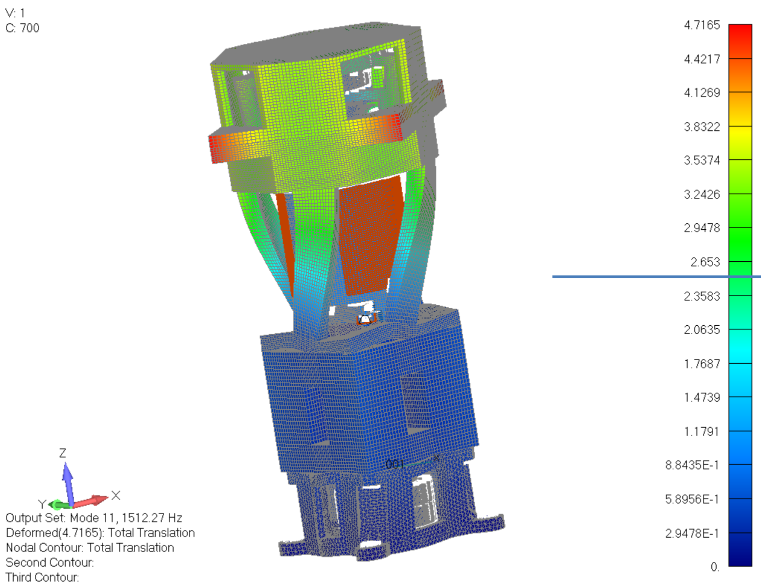
- Mode Shapes

Mode 9

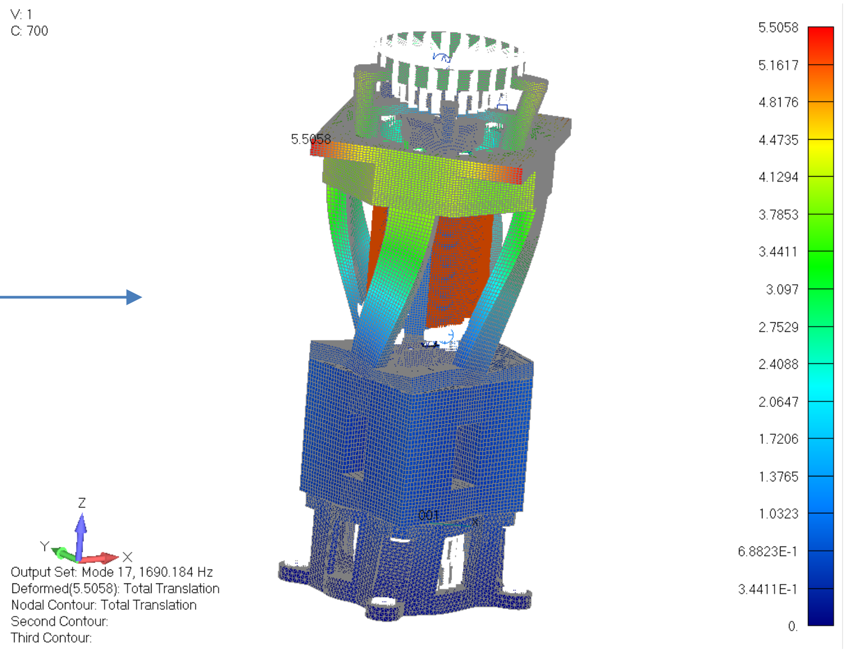




Mode 11



Mode 17



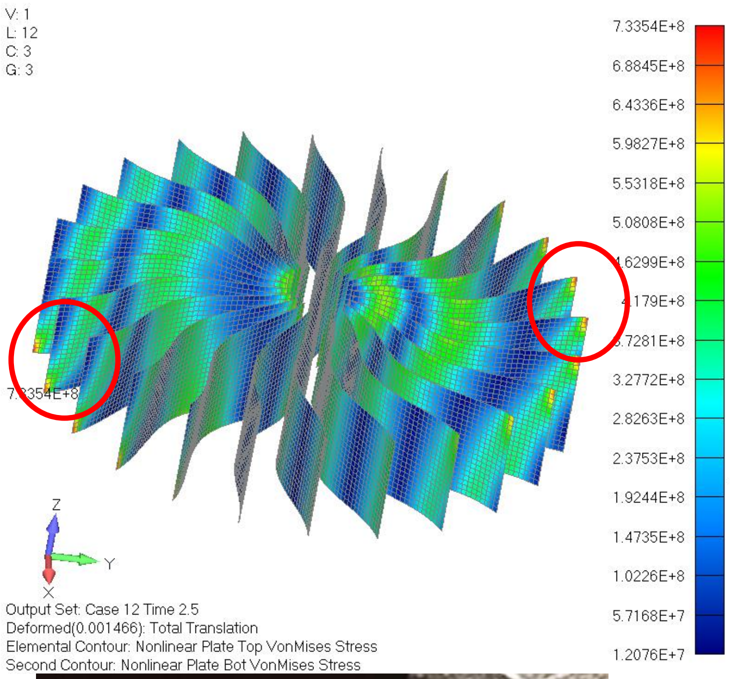
Issue Random Y (SN01) (WO Cover and additional acc.)

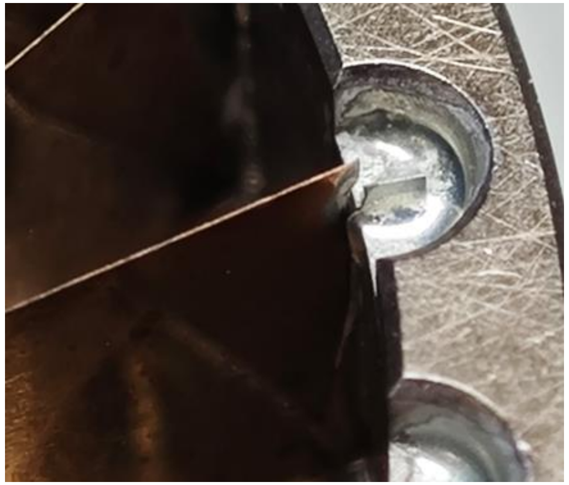
- Reasonable impact in frequency search due to small amount of broken blades

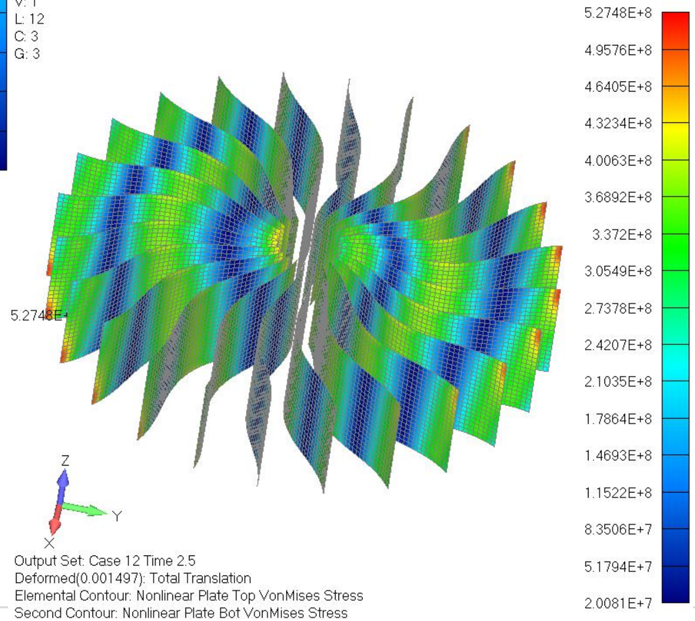
- In simulations, stresses don't exceed neither yield and ultimate limits of material but considering that these mechanical stresses are in the area where take place the chemical attack it could be sufficient considering this is a repeated load occurring ~90 000 times during RND Y test at 0dB to break the blades.

  – MoSy= 0.16
  – MoSu= 0.19

- Most probable root cause in addition with chemical attack is the unbalanced mass added by the accelerometer (compare both figure on the right side). The fatigue is more the induced effect of this unbalance load.

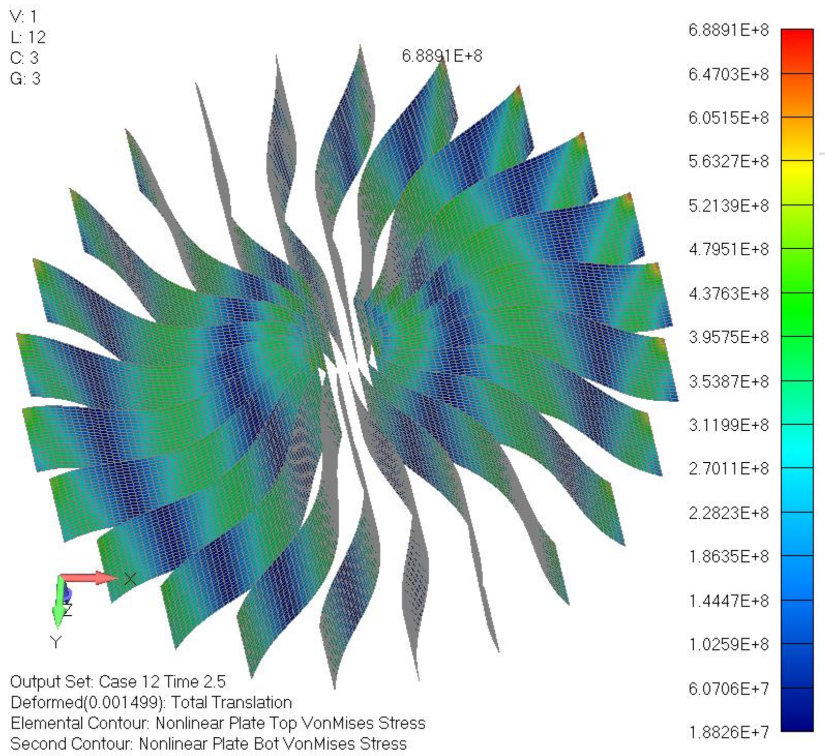


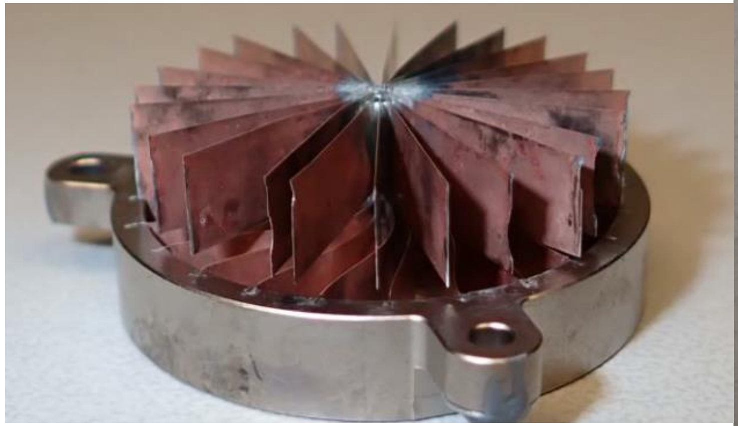




Issue on Random Z (WGS SN02)

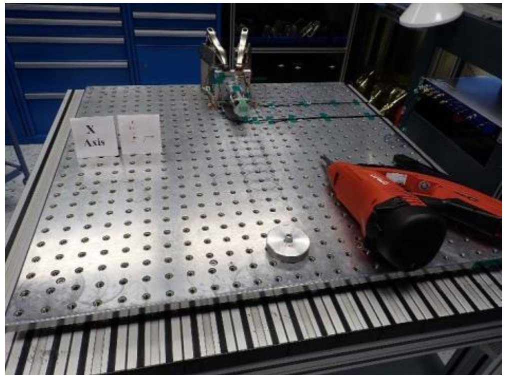
- Osciliating axial forces on the blades => fatigues.
- Sligtly above “infinite” life fatigue mechanical stress limit defined at 550MPa
- Margin of safety:
  - WRT Yield (Sfy=1.21): 0.24
  - WRT Ultimate (Sfu=1.375):0.26
- BUT Altered mechanical properties of the blades at the location of maximal stresses due to soldering chemical attack (at least thinner in this area).
- Crack initiations at interface between rings

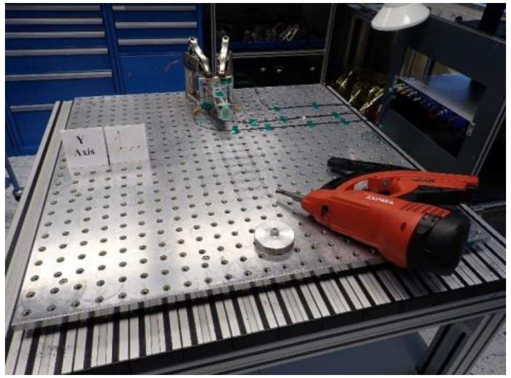


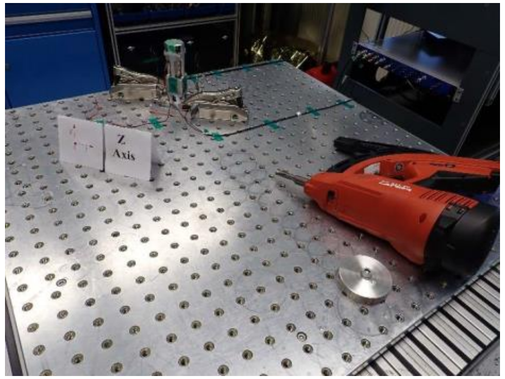


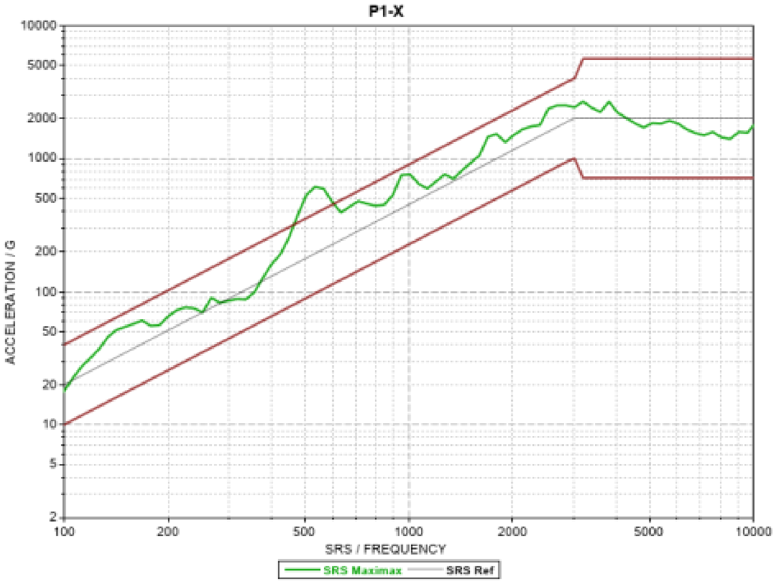
Shock test

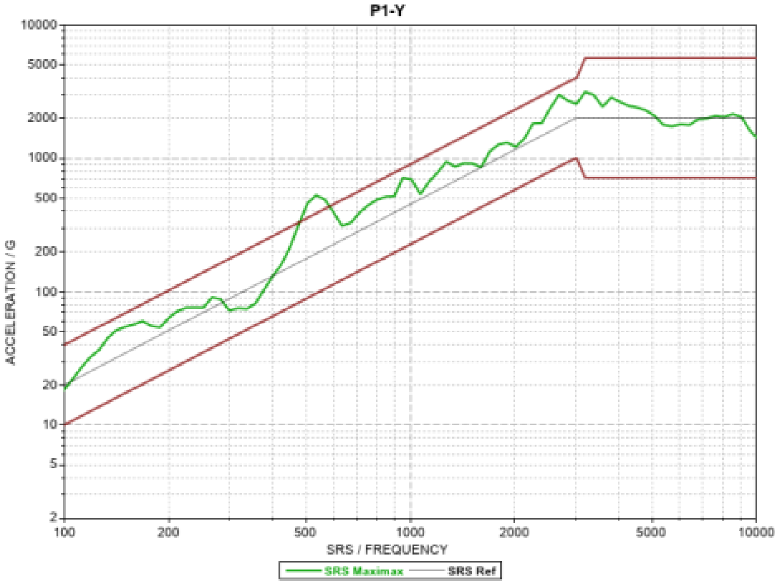
- Performed successfully
  - No further damage on mechanism observed





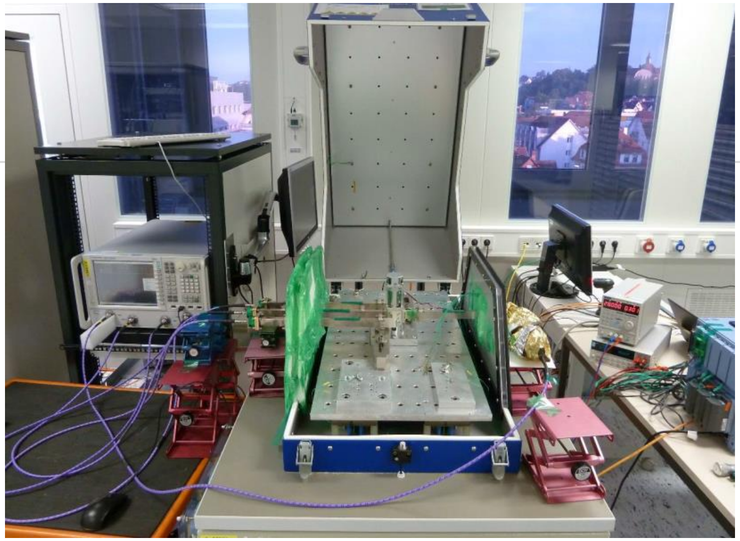


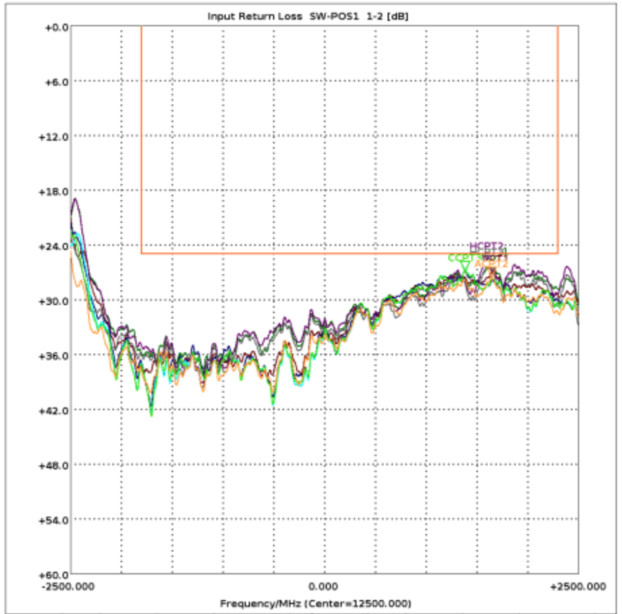




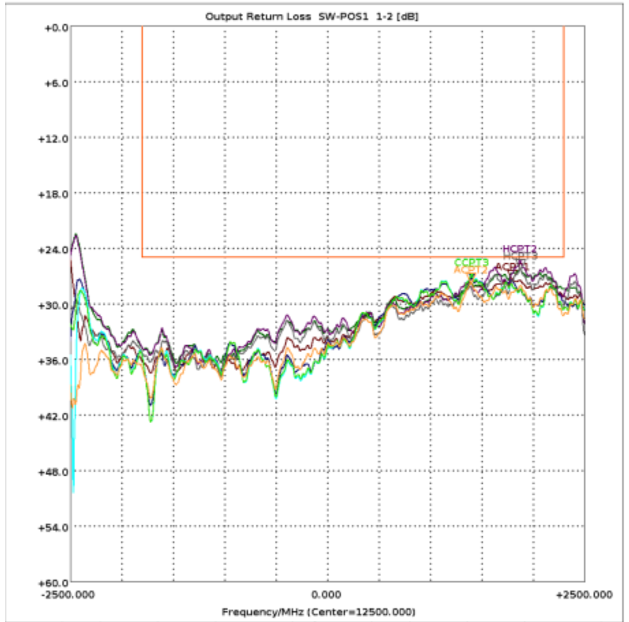
Thermal Shock and Cycling tests

- Results of thermal performance evaluation.
- Observations on RF stability.

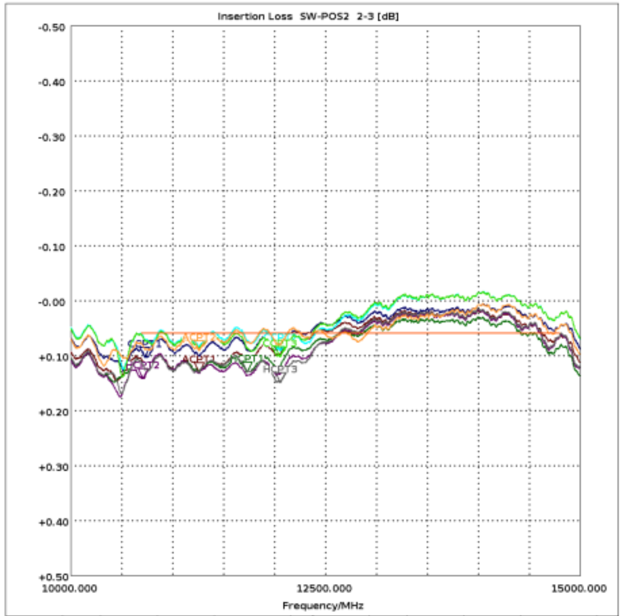




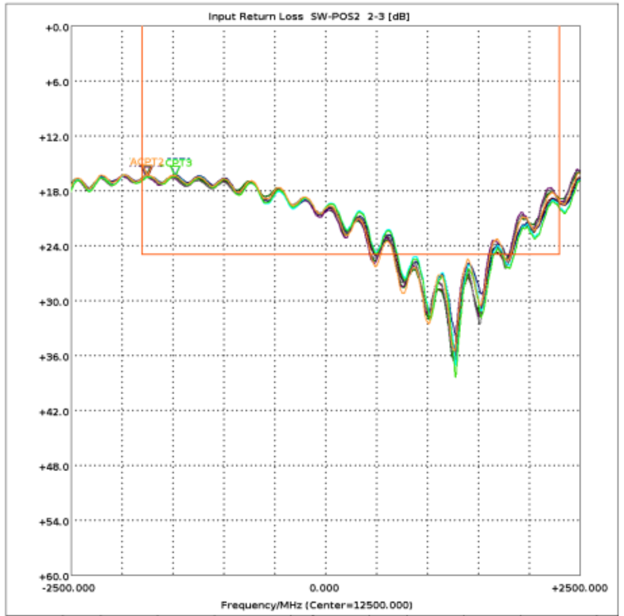
TEST	DegC	MARKER	SPEC.	FREQUENCY		TEST	DegC	MARKER	SPEC.	FREQUENCY	
ACPT1	20.0	27.1	25.0	+1653.125							
HCPT1	97.0	26.2	25.0	+1646.875							
CCPT1	-35.0	27.0	25.0	+1387.500							
HCPT2	97.0	25.6	25.0	+1600.000							
HCPT3	87.0	26.3	25.0	+1603.125							
CCPT2	-33.5	26.9	25.0	+1387.500							
CCPT3	-25.0	26.9	25.0	+1387.500							
ACPT2	20.0	27.6	25.0	+1646.875							



TEST	DegC	MARKER	SPEC.	FREQUENCY		TEST	DegC	MARKER	SPEC.	FREQUENCY	
ACPT1	20.0	27.5	25.0	+1796.875							
HCPT1	97.0	26.4	25.0	+1878.125							
CCPT1	-35.0	27.3	25.0	+1406.250							
HCPT2	97.0	25.6	25.0	+1875.000							
HCPT3	87.0	26.3	25.0	+1878.125							
CCPT2	-33.5	27.0	25.0	+1403.125							
CCPT3	-25.0	27.1	25.0	+1403.125							
ACPT2	20.0	27.8	25.0	+1400.000							



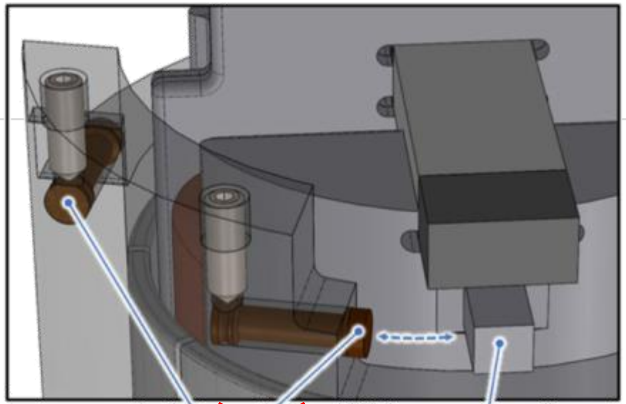
TEST	DegC	MARKER	SPEC.	FREQUENCY		TEST	DegC	MARKER	SPEC.	FREQUENCY	
ACPT1	20.0	0.13	+6.00E-2	11265.625	nc						
HCPT1	97.0	0.13	+6.00E-2	11737.500	nc						
CCPT1	-35.0	0.10	+6.00E-2	10731.250	nc						
HCPT2	97.0	0.14	+6.00E-2	10712.500	nc						
HCPT3	87.0	0.15	+6.00E-2	12059.375	nc						
CCPT2	-33.5	+9.00E-2	+6.00E-2	12062.500	nc						
CCPT3	-25.0	0.10	+6.00E-2	12053.125	nc						
ACPT2	20.0	+9.00E-2	+6.00E-2	11262.500	nc						

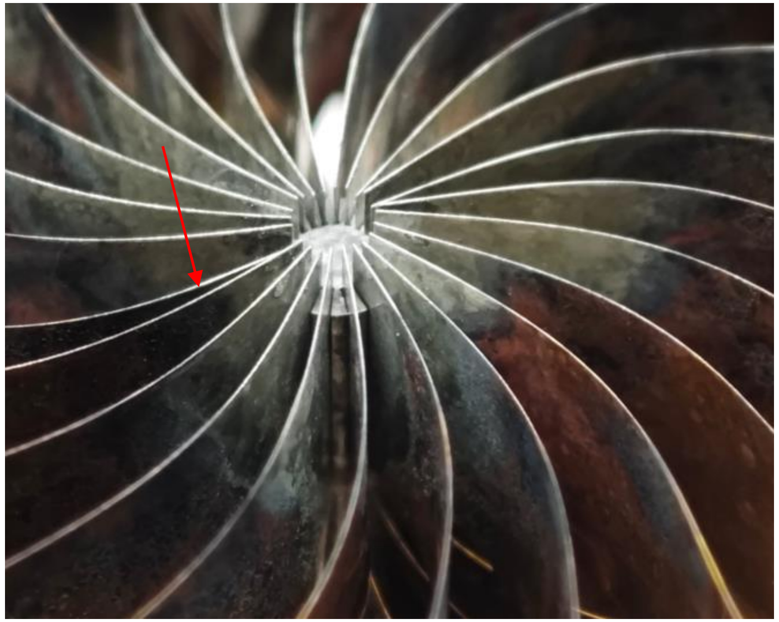


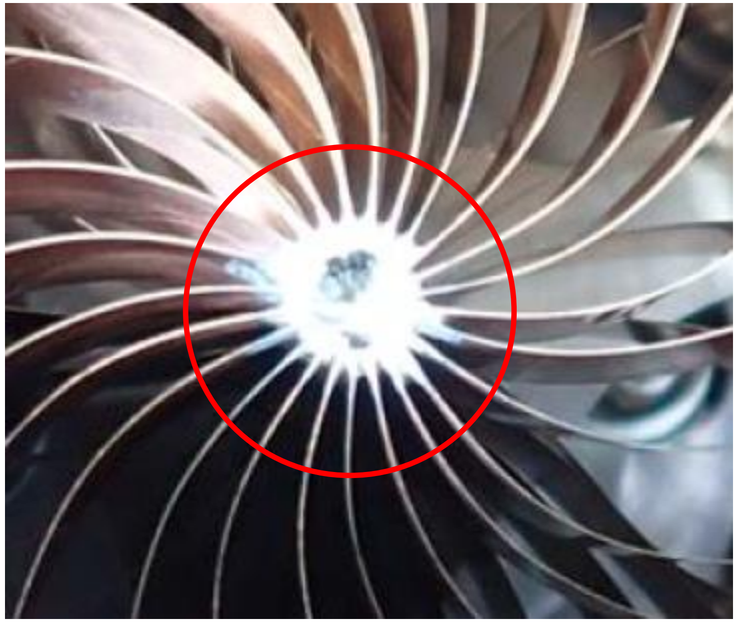
TEST	DegC	MARKER	SPEC.	FREQUENCY		TEST	DegC	MARKER	SPEC.	FREQUENCY	
ACPT1	20.0	16.4	25.0	-1743.750	nc						
HCPT1	97.0	16.4	25.0	-1756.250	nc						
CCPT1	-35.0	16.3	25.0	-1471.875	nc						
HCPT2	97.0	16.5	25.0	-1759.375	nc						
HCPT3	87.0	16.5	25.0	-1753.125	nc						
CCPT2	-33.5	16.4	25.0	-1471.875	nc						
CCPT3	-25.0	16.5	25.0	-1471.875	nc						
ACPT2	20.0	16.3	25.0	-1746.875	nc						

Performance Deviation Analysis

- Key factors:
  - RF Rotor-stator misalignment (Assembly tolerances chain/center shift/angular stroke)
  - Manufacturing /assembly variations. -> RF performances / Pivot performances
  - Stress distribution determination in bistable
    - Challenging as small perturbations may have a greater or lesser impact that is difficult to predict.







Challenges Encountered

- Mechanical failures of pivots.
  - Modal Analysis of pivots in buckled state is not possible with current FEM tools and extrapolation from general model to pivots is approximative and time consuming to be used for each cases.
  - Manufacturing process, defects or dissymmetry could have significant impact on the mechanical strength of the bistable leading to them failure.
- Impact of small manufacturing deviations.
  - As we have seen in the performance analysis deviations of small manufacturing details may have significant impact at system level such as:
    - RF performances (Rotor/stator alignment)
    - END stop position accuracy
    - Bistable pivots lifetime / failure / rotation stroke
    - WGS lifetime
- High vibration loads
  - Was challenging to commit

Lessons Learned

- Importance of quality control for all manufacturing operations on the bistable pivots.
- Need of integrate features in the design that help to align elements without need to adjust position by measurement.
  - Alignment by machining tolerances
- Avoid the use of flux for soldering considering potential surface treatment of the blades such as flash nickel.

Proposed Improvements (bistable)

- Pivot manufacturing refinements
  - Features to improve manufacturing uniformity
- Surface treatment advancements
  - Flash nickel on the blades
- Enhanced pivot designs and FEM
  - Features to improve manufacturing uniformity
  - Better

Proposed Improvements (VCA motor)

- Redesign on parts interfaces to ease the assembly process/interface with rotor and pivots
- Integration of RF rotor with the voice coil moving part
- Integration of standard connections (D-Sub connector)
- Integration of elements for telemetry (reed-relays?)
- Optional exploration of alternative actuators for size and mass reduction purpose.

Future Work

- Improvements of Bistable Manufacturing process
  - Manufacturing process of the bistable pivots and specially the soldering process are very challenging.
  - Potential approaches to consider include flash nickel treatment of the blades to prevent chemical attack before soldering, as well as material and design modifications, which are being considered to improve resistance to mechanical stress.
- Extended testing for long-term durability.
  - Once manufacturing improvements of the bistable pivots are achieved one of the first test to perform at bistable pivot level or at WGS system level are the lifetime tests under vacuum and thermal cycling conditions.
  - In case of performed at system level, lifetime tests will allow to qualify at the same time the voice coil actuator and the bistable pivots.
- Focus on mass and size optimization.
  - Aside from the points mentioned above, the biggest challenge for future work will be enhancing compactness and reducing mass to remain competitive with current commercial space WGS. Possible way forward are the inclusion of the RF parts inside the actuator or the modification of actuator type.

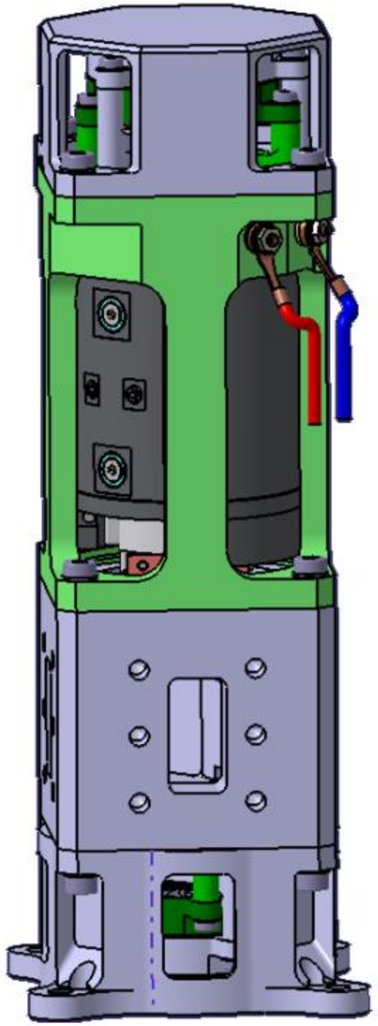
Conclusion

- Summary of project achievements.
  - Achievement of fully functional WGS friction free mechanism
  - ~TRL 5
  - Functional Bistable design
  - Functional and reliable voice coil actuator

- Remaining challenges and next steps.
  - Improve design to reduce size and mass
    - Integration of RF features inside actuator
  - Improve design manufacturing process of bistable
    - Add design features to avoid unwanted soldering shoulders
    - Avoid the use of flux by performing blades surface treatment
    - Better Jigs to avoid misalignment during automated soldering process
  - Improve simulation prediction of bistable

Comparison with Existing Models

- Advantages and limitations compared to the TESAT WR75 model.



Advantages	Disadvantages
Friction Free	Mass (3.8x more)
Reliability (Theoretical to be proved by test)	Size
Thermal behaviour (conduction through the bistable pivots)	Resistance to mechanical loads
Switching time (then times less)	

Thank you for your attention