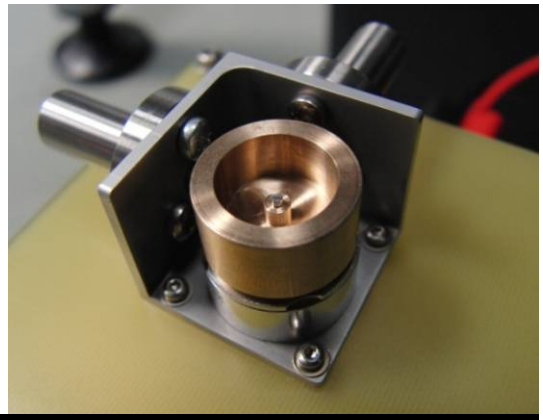

Development of a Nano-Satellite Reaction Wheel System with Commercial Off-The-Shelf Motors

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7th ESA Roundtable on Micro & Nano Technologies for Space Applications,
14 September 2010, ESTEC, Noordwijk, The Netherlands

Presented by G.F. Brouwer

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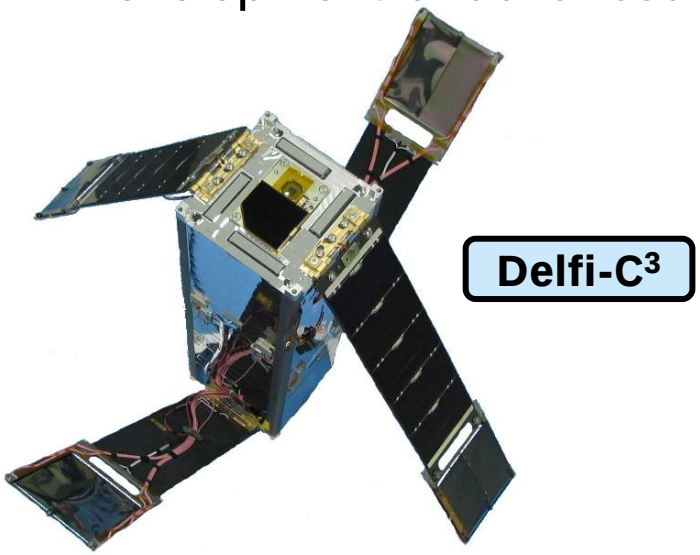
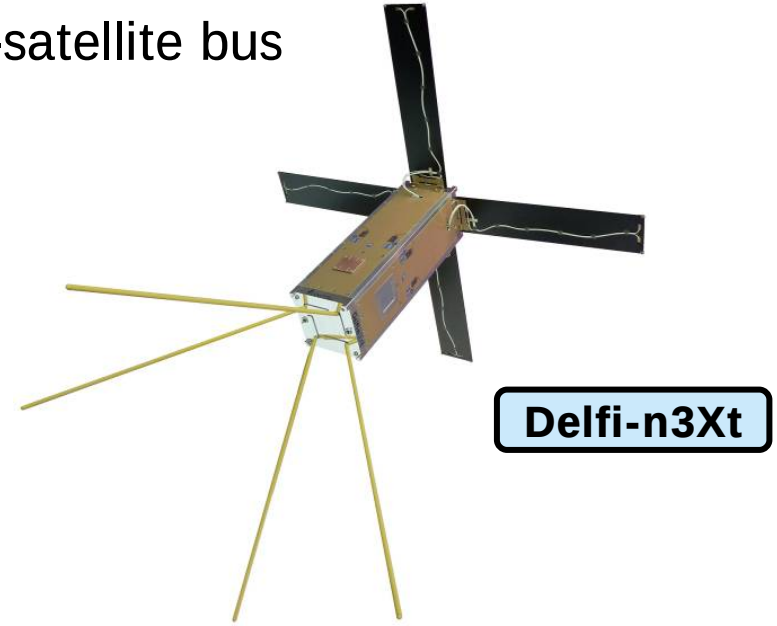
Delfi-program at TU Delft

- Delfi-C^3 nano-satellite launched in 2008 and a full mission success
- Delfi-n3Xt nano-satellite under development for launch in 2012
- Hands-on education for students in Master of Science program
- Demonstration of small satellite technology for Dutch space sector
- Development of advanced nano-satellite bus

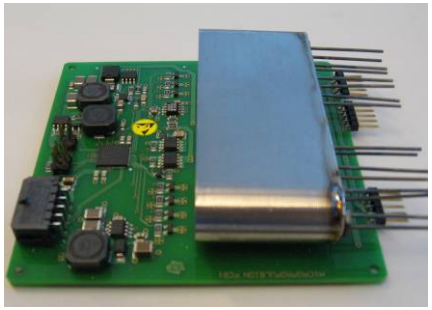


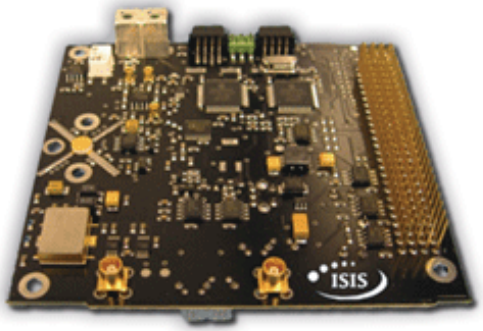
Delfi-C^3



Delfi-n3Xt

Delfi-n3Xt key characteristics





- Nano-satellite of size 340 x 100 x 100 mm
- Mass about 3 kg
- Power about 6.5 W
- Two payloads from Dutch space sector:
  - Micro-propulsion system (TNO)
  - High Efficient Transceiver (ISIS)
- Experimental amorphous silicon cells (DIMES)
- Advancement on all subsystems compared to Delfi-C^3

- Launch planned for early 2012

Delfi-n3Xt satellite ADCS

- The Delfi-n3Xt Attitude Determination Control Subsystem (ADCS) should be able to maintain sun-pointing along longitudinal axis

- The following hardware is envisaged:
  - 6 redundant coarse sun sensors (Silonex photodiode)
  - 1 fine sun sensor (TNO)
  - 1 3-axis magnetometer (Honeywell HMC5843)
  - 1 3-axis MEMS gyro (ST Micro-Electronics L3G4200DH)
  - 3 magneto-torquers (TU Delft)
  - 3 reaction wheels (TU Delft)

Development strategies for reaction wheel

- Three possible strategies:
  1. Buy Commercial Off-The-Shelf (COTS) reaction wheel
  2. Develop complete reaction wheel in-house
  3. Develop reaction wheel around a COTS motor

- The third strategy allows for
  - Low cost
  - Moderate development time
  - Educational experience for students

  Downside: Expected lifetime is uncertain

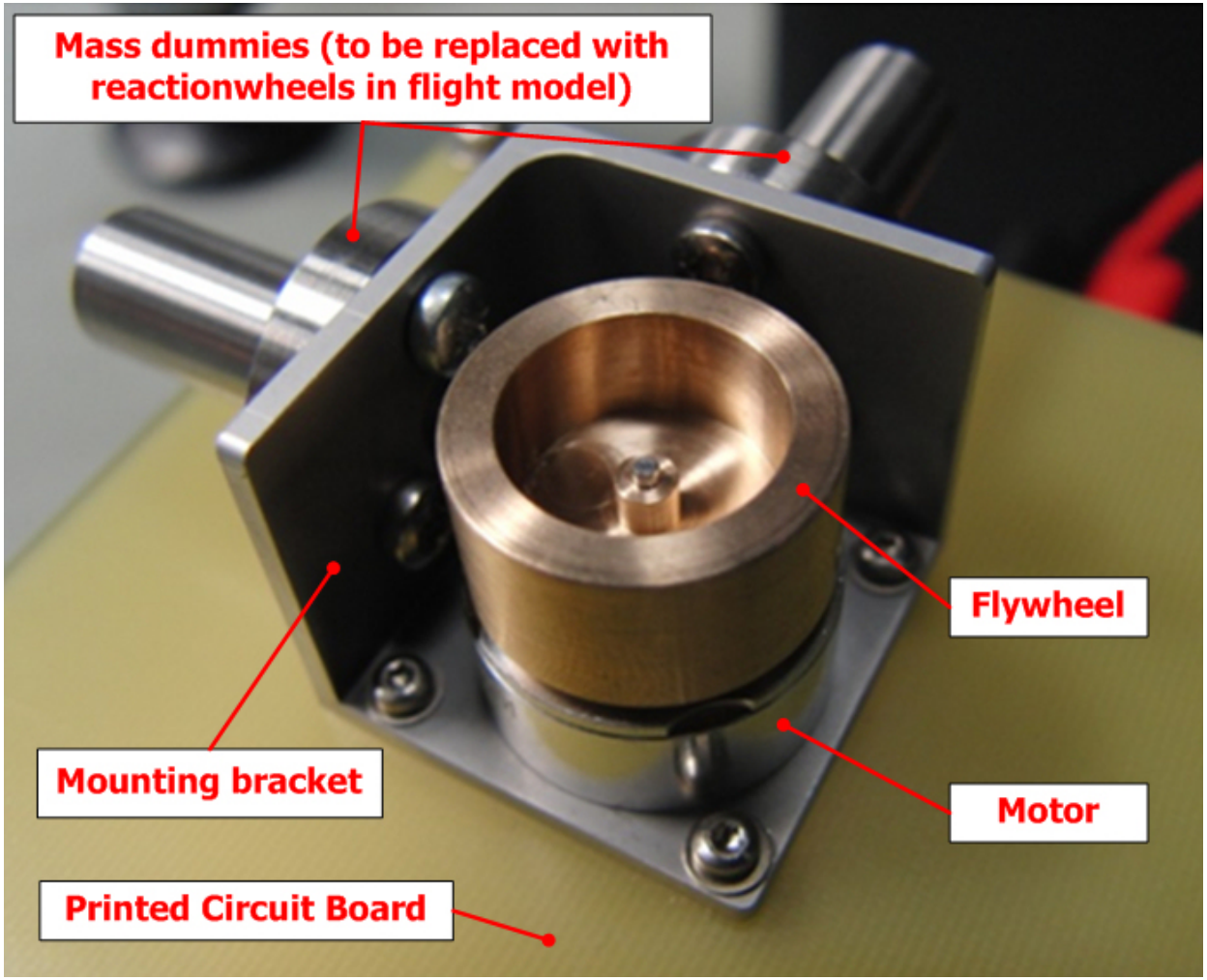
Choosing the motor

- Brushless Direct Current (DC) motors offer best performance
- Highest speed at which torque-level still meets mission requirement is a comparison basis for motor performance
- Ability to withstand space environment important, but usually nearly no data available from manufacturer (especially for mechanical load resistance)
- Integrated speed controller simplifies development (customizing controller often not possible however)

- Our choice: Faulhaber 2209T005BSC motor

Picture: Courtesy Faulhaber

Reaction wheel assembly design



Vacuum-proofing

- COTS motors are normally not suited for use in vacuum of space
- Two solutions:
  - Use hermetically sealed pressurized container
  - Modify motor to make it vacuum compatible
- Manufacturer replaced lubricant in our motor with vacuum-proof lubricant (Braycote)

Characteristics reaction wheel system

• Maximum torque:	0.09	mNm
• Angular momentum storage:	$1.5 \cdot 10^{-3}$	Nms
• Total mass (bracket + 3 wheels)	104	gram
• Max. peak power consumption:	± 400	mW

Development test program

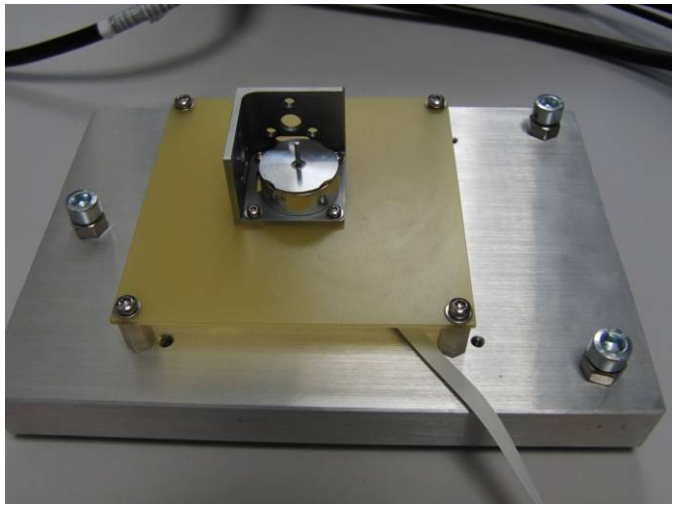
- Standardized electrical performance test for motor to be used for repeated characterisation
- Vibration test campaigns
  - 1st : In-house vibration test at Faculty of Mechanical Engineering
  - 2nd: Vibration test at NLR as passenger in ISIPOD qualification
- Thermal vacuum test (not performed yet)

Vibration testing

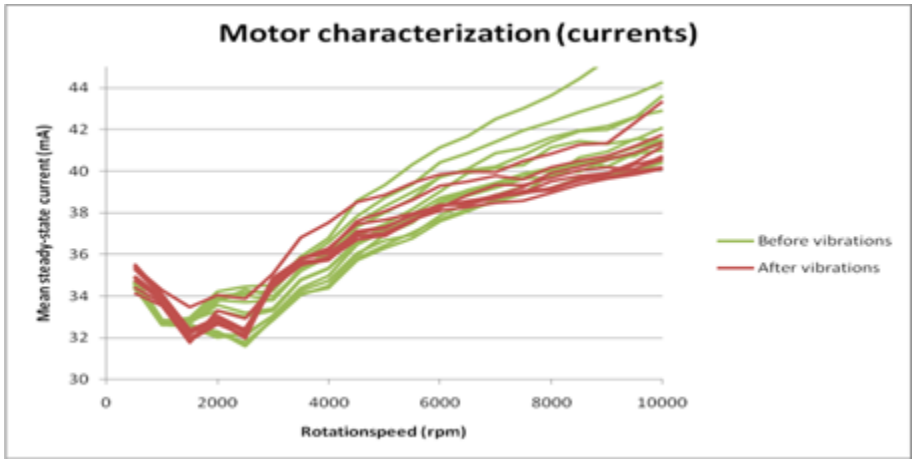
- Vibration testing is critical because of vulnerable motor axle with large unsupported mass attached
- Internal damage of motor (e.g. bearings) may cause performance degradation, but not necessarily catastrophic failure
- Steady-state current measured before and after vibration sessions
- Increased steady-state current after vibration test is an indicator of additional friction due to bearing damage

Standardized performance test for motor

- A standardized electrical performance test was made for the motor
- Test can be run in a automatic sequence with control parameters:
  - Variable voltage throughout the sequences
  - Duration of one sequence
  - Number of sequences
- Measured parameter is motor current

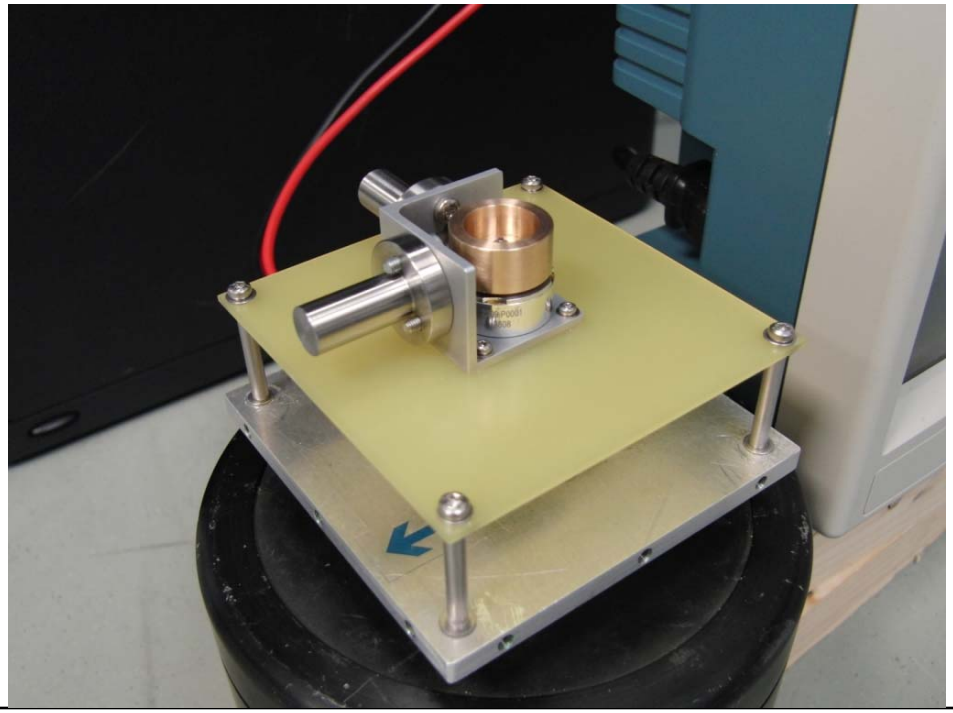


Graph shows steady-state current consumption before and after 1st vibration test campaign. No drastic changes are seen.



1st Vibration test campaign

- 1st Vibration test series at the Faculty of Mechanical, Maritime & Materials Engineering (3mE) at TU Delft
- A small shaker set-up was used

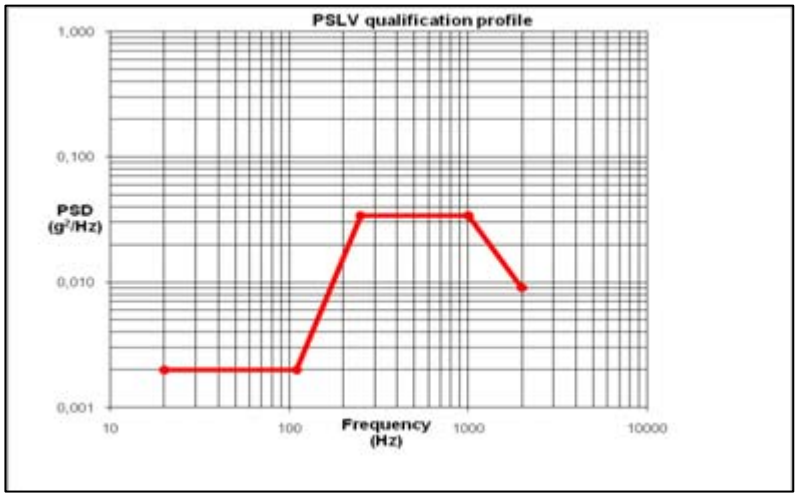


1st Vibration test campaign

- Qualification loads of a Polar Satellite Launch Vehicle (India) were simulated

Frequency range (Hz)	Amplitude
5 – 10	10 mm
10 -100	3.75 g
Sweeprate = 2 octaves/minute	

Sine vibration

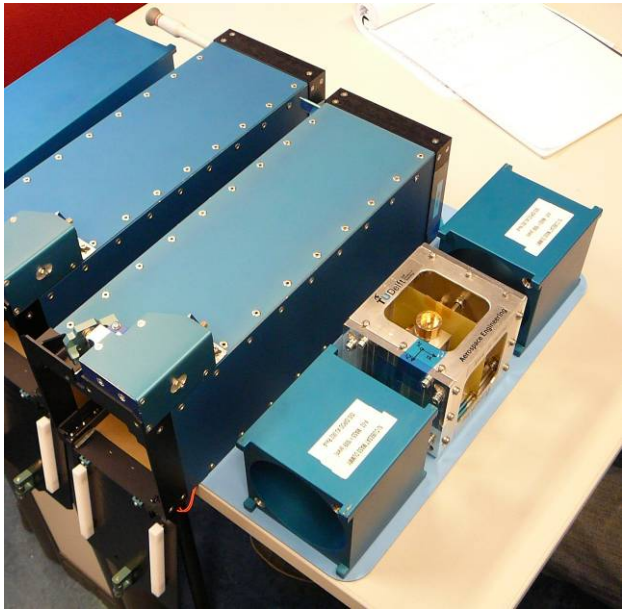


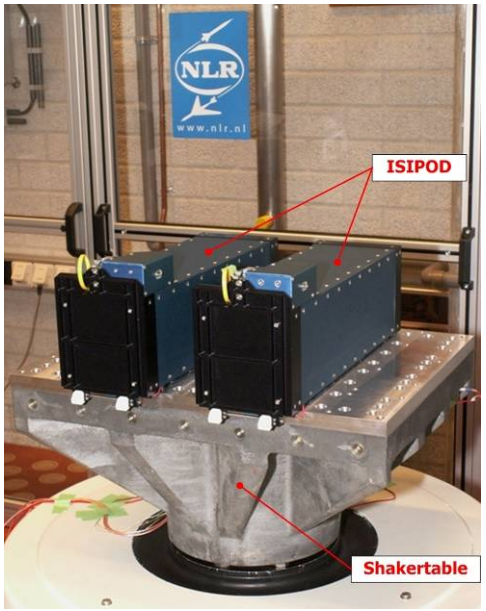
Random vibration

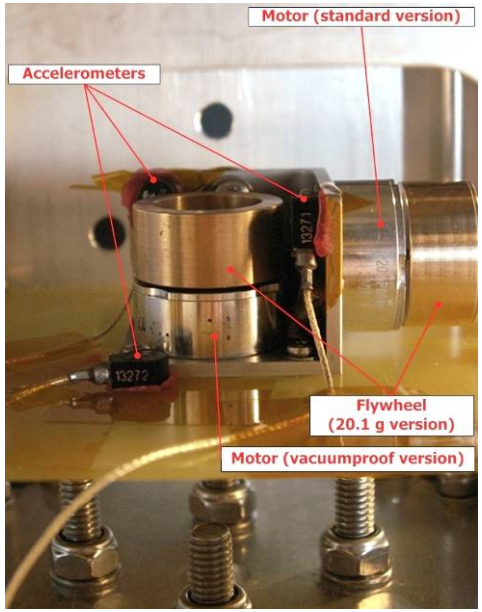
- Multiple vibration sessions were performed,
  (many runs needed to tune input profile to obtain required output)
- Electrical performance showed no detectable degradation
- Total added up vibration time was about one hour

2nd Vibration test campaign

- Piggy-back vibration test in ISIPOD launch canister of ISIS B.V.
- Test was done at the National Aerospace Laboratory (NLR)
- Two reaction wheels and one dummy on a PCB were installed in a 1-Unit CubeSat



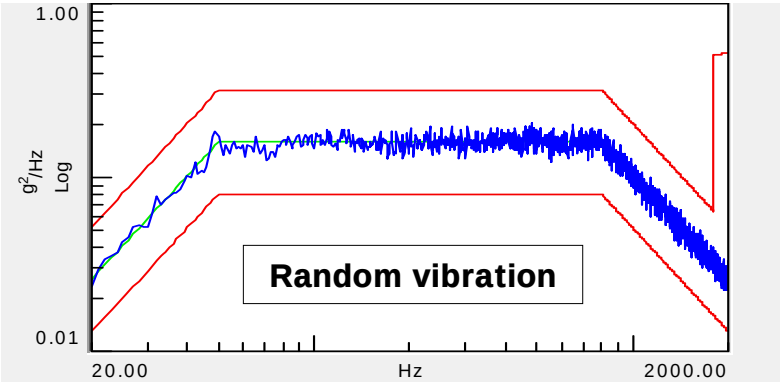


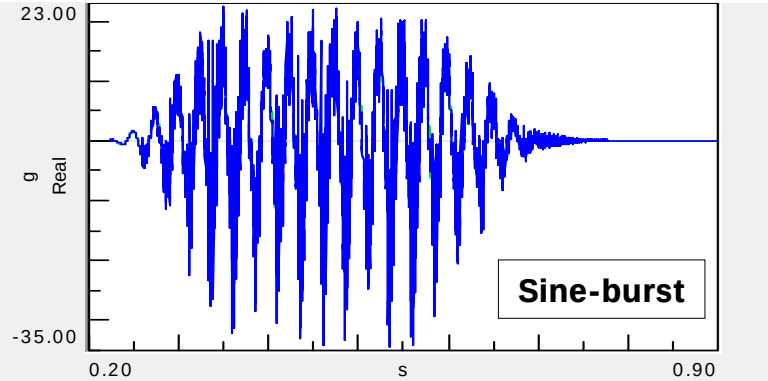


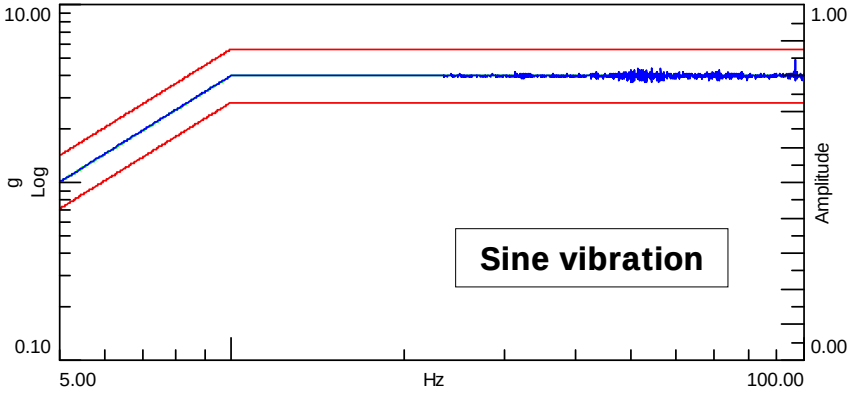
2nd Vibration test campaign

Test order

1. Resonance survey
2. Sine Burst
3. Resonance survey
4. Sine sweep
5. Resonance survey
6. Random vibration
7. Resonance survey





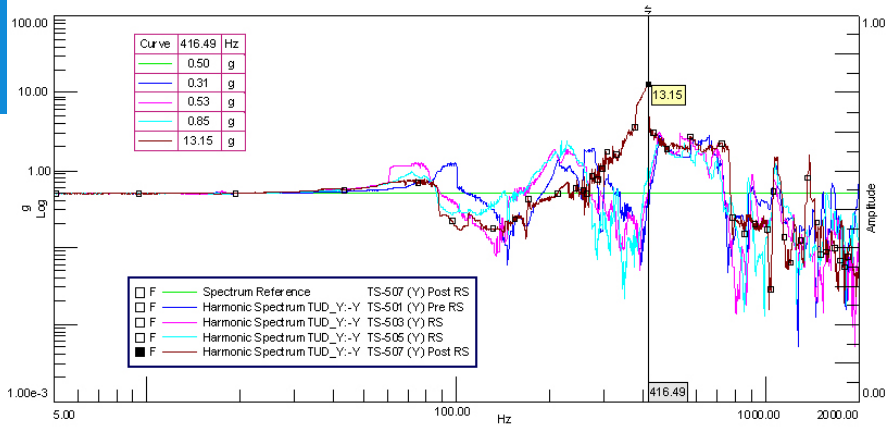


The qualification vibration test profile was an envelope for multiple launch vehicles.

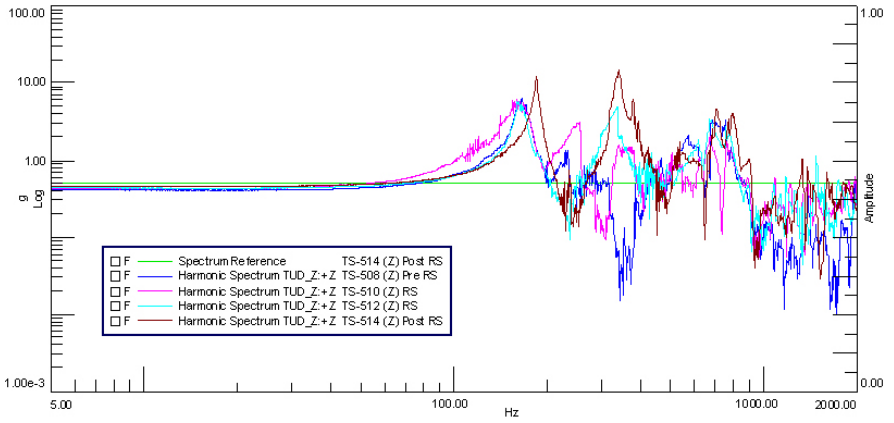
Pictures: National Aerospace Laboratory

Resonance surveys vibration campaign

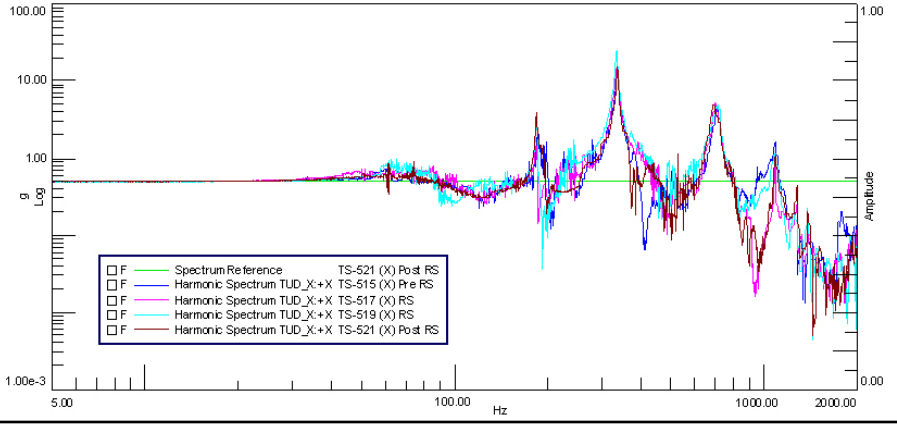
1st test: Y-direction



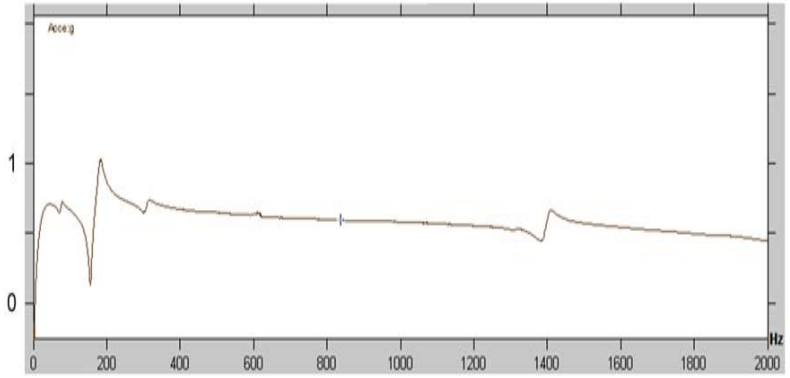
2nd test: Z-direction



3rd test: X-direction

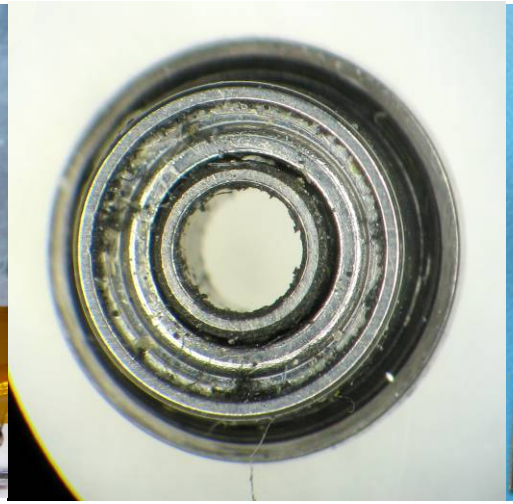


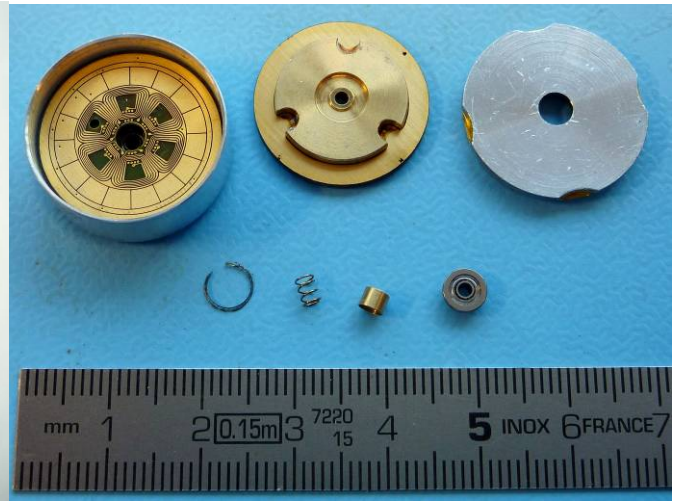
For comparison: Resonance plot 1st vibration test.
NOTE that the test configuration is not the same !



2nd Vibration test campaign – results & post test inspection

- Reaction wheel 1: Motor completely disintegrated; damage and debris was found inside the bearings (N.B. This motor has also seen test 1)
- Reaction wheel 2: Flywheel came from the motor axle; motor intact, no play on bearings found; electrically it does not run anymore
- It is suspected that the failures occurred during random vibrations





Conclusions

- So far the Delfi program has shown a high educational value
- (Vibration) testing of custom-built hardware should be done in an early design stage and preferably in-house
- The automated electrical performance test of the motors is a very useful tool during environmental testing
- Load levels during the 2nd vibration test levels were a bridge too far
- Current reaction wheel design could survive launch on a PSLV rocket, but the safety margin is small
- The eigenfrequency measured on the bracket was below 100 Hz, leading to large load amplifications

Outlook

- Development of reaction wheels for Delfi-n3Xt and successors is continuing
- The support structure around the reaction wheels should be modified to increase eigenfrequencies
- A new vibration test at more realistic load levels should be performed
- The desire is to upgrade the existing vibration testing facility at TU Delft to allow testing of higher masses with better control of load levels
- Thermal-vacuum testing will be performed after completion of a successful vibration test

Acknowledgements

- Faculty of 3mE at Delft University of Technology

  Prof. Dr. D.J. Rixen and M. Ozbek MSc for their extensive support with the 1st vibration test

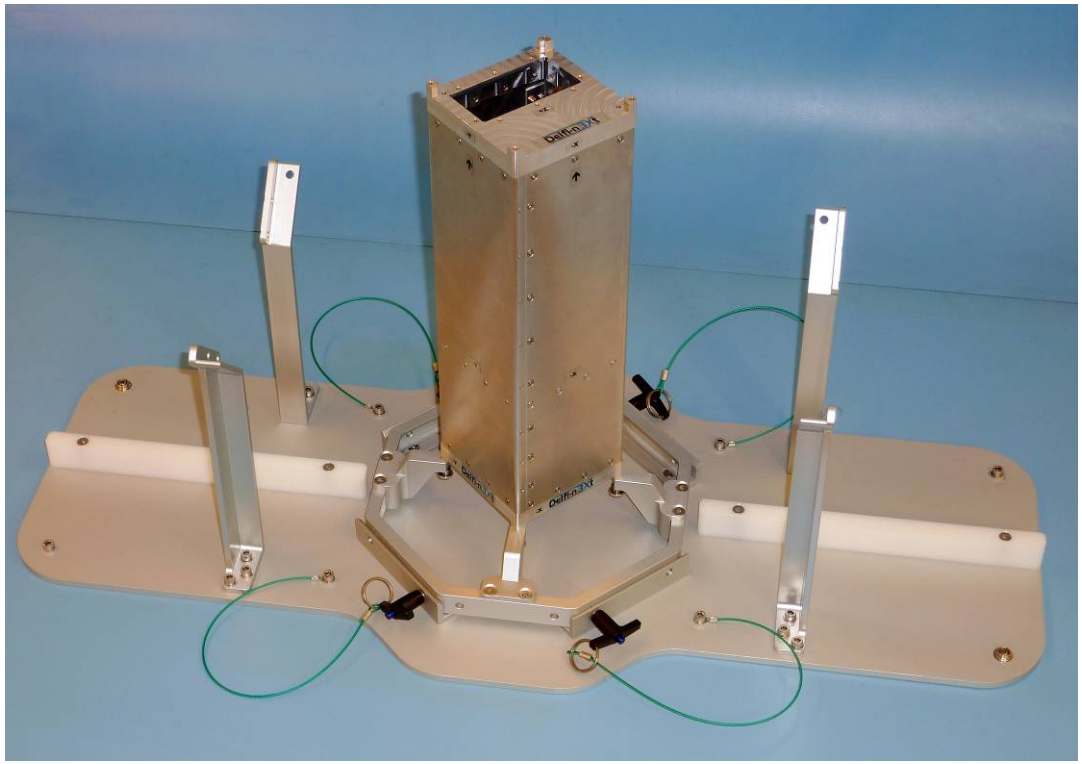
- Innovative Solutions in Space BV (ISIS B.V.)

  Mr. G. Lebbink for enabling and supporting the vibration test in an ISIPOD.

- National Aerospace Laboratory (NLR)

  for their support with 2nd vibration test

Questions?



Delfi-n3Xt Engineering Model Structure in integration jig