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NOTCHING DURING RANDOM VIBRATION TEST BASED ON INTERFACE FORCES - THE JWST NIRSPEC EXPERIENCE -

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ABSTRACT

Force limited vibration was used during the sine and random qualification tests of the NIRSpec instrument, to limit stresses in the brittle structure while demonstrating adequate qualification with regard to the environmental flight conditions. First, NASA provided a force limit curve based on their internal "Semi-Empirical Method". Then, strain gages were mounted on the legs of the kinematic mounts to recover interface forces during the vibration test. Two different methods were then used to determine the notches: one called the "Apparent Mass" method that is based on sine sweep signatures and another one based on direct force measurement in the time domain during random test. The second method resulted in the most effective notch determination, allowing the justification of the notches in real time with high accuracy. The resulting RMS forces are well below the forces corresponding to static design loads that is a more conventional method.

1. THE JAMES WEBB SPACE TELESCOPE (JWST) MISSION

1.1 Introduction

Since 1996, NASA, ESA and CSA have cooperated on designing and constructing a worthy successor to the Hubble Space Telescope. This project was named in 2002 the James Webb Space Telescope. Although in several aspects JWST represents a radical departure from its predecessor, the astronomical capabilities of the JWST telescope and its instruments are very much driven by the scientific successes of HST, especially concerning the exploration of the early Universe. Unlike its predecessor, it will be placed into orbit at the L2 point, some 1.5 millions kilometers from Earth.

The Observatory will be launched by an ESA provided Ariane 5 ECA launcher in 2014.

1.2 The Observatory

The JWST Observatory consists of a 6.55m diameter telescope, optimized for diffraction limited performance in the near and mid-infrared wavelength regions.

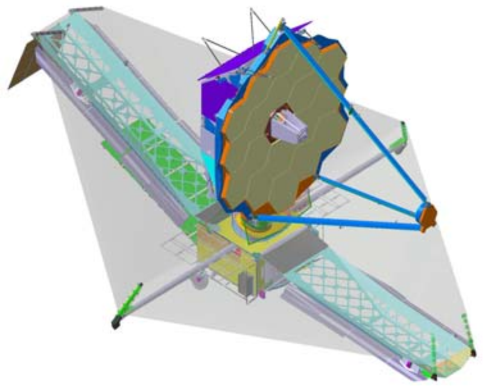

Fig. 1. JWST Observatory

Like HST, it will carry a suite of four astronomical instruments: MIRI, NIRCam, FGS/TF and NIRSpec. The four instruments are housed into the so-called Integrated Science Instrument Module (ISIM), in the back of the primary mirror. The telescope and its instruments are cooled to operate at around 35K.

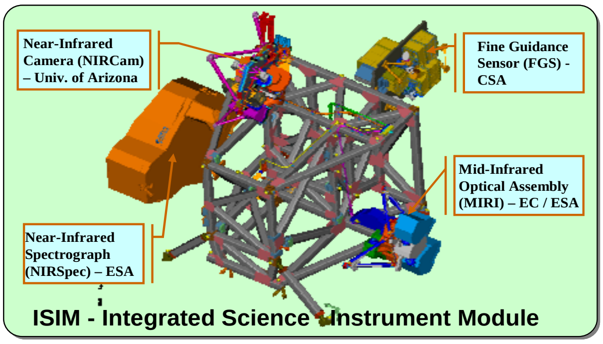

Fig. 2. ISIM – Integrated Science Instrument

2. THE NIRSPEC INSTRUMENT

NIRSpec is a wide field multi-object spectrometer and covers the 0.6 to 5 microns wavelengths at spectral resolutions of R~100, ~1000 and ~2700. It will measure red-shift, metallicity and star formation rate in first light galaxies. This instrument is provided by the European Space Agency, with EADS-Astrium GmbH as Prime Contractor. The performances of the instrument are further detailed in [1].

2.1 Overview of the NIRSpec Instrument

The overall instrument fits within 1.9m x 1.5m x 1.1m and weights about 200kg. It consists of a monolithic base plate that supports mirrors, four mechanisms, a calibration lamp and a detector. This base plate is interfacing the Observatory ISIM by three kinematic mounts. A two-foil cover assembly protects the optics from contamination and ensures the thermal insulation and stray-light protection.

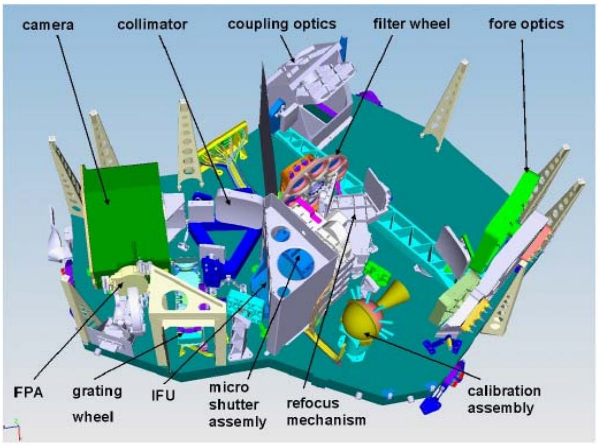

Fig.3. NIRSpec Overview

2.2 Driving specifications

The main design drivers are, as for all space missions, the mass (limited to 220kg), the stiffness (first mode shall be >50Hz) but above all the opto-mechanical performances, in particular the optical stability between the pick-off mirror of the coupling optics and the detector (FPA).

The static design loads are between 4.4g and 8.1g depending on the axis. Random vibration loads are relatively low (0.003g^2/Hz between 50 and 2000 Hz) but remain critical because of the size of the Instrument and the SiC-100 low damping, see 3.1.

2.3 Mechanical specificities

More than 60% of the overall Instrument mass is made of SiC-100. This ceramic was selected for its excellent stiffness to mass ratio and for its very low CTE.

Furthermore it can be used for structural components as well as for mirrors since it can be polished and coated. Fig. 4 gives an overview of the parts made out of SiC-100 (grey).

The 3 kinematic mounts ensure a decoupling of the thermo-elastic and mounting distortions. They constitute simple interface to the ISIM with well identified load transfer paths.

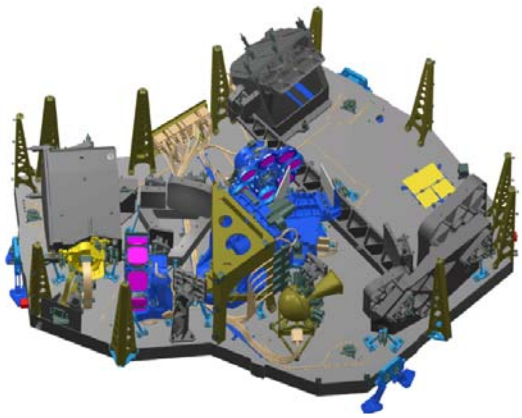

Fig. 4. Materials used for NIRSpec instrument

2.4 The Demonstration Model

The Demonstration Model (DM) is used for the qualification of the flight hardware. The build standard of this DM is close to the flight model one from a structural view point: all SiC parts were present –but most of the mirrors were not polished, the kinematic mounts are flight like, all bolted joints are flight like, the mechanisms and other metallic assemblies are representative in mass, CoG and first resonance frequency.

Note that all SiC parts have been individually proof-tested and sub-assemblies, like the 3 three mirror assemblies have been vibrated at assembly level before being integrated in the DM.

This DM was successfully submitted in January 2009 to vibration tests.

3. THE NIRSPEC INSTRUMENT DM VIBRATION TEST CAMPAIGN

3.1 Challenges

Despite a relatively high strength, the SiC-100 is brittle and over stressing has thus to be avoided with much more care than with metallic materials for which local overstress often results into local yielding but not into a complete failure.

Another point of attention is the alignment stability: the interfaces to SiC cannot be pinned but only bolted, relying on friction to transfer the loads. Since this instrument has stringent alignment stability requirements, overloading of the bolted assemblies shall be avoided.

The vibration specification for all flight assemblies (eg mechanisms, detector) shall be as low as possible due to the fragile components they support.

Finally, the SiC-100 has a very low intrinsic damping. Amplifications greater than 100 were recorded during the sub-assembly vibration tests.

Notching has thus to be applied to protect this delicate instrument. As for all missions, the loading shall however be sufficient to demonstrate the qualification. This was achieved through an original process.

3.2 Notching criteria for the random vibration test

The agreement with ISIM/NASA was to perform notching based on the “Semi-Empirical Method” [2]: the Instrument interface forces resulting from the hard-mounted Instrument can be limited such that the following force spectral density curve is not exceeded (but reached) at the frequencies where the notches are applied:

$$F(f) = \begin{cases} c^2 * m^2 * ASD(f) & \text{for } f < f_0 \\ c^2 * m^2 * ASD(f) / [f / f_0]^2 & \text{for } f > f_0 \end{cases} \qquad (1)$$

where: m total mass of the Instrument
f_0 fundamental frequency in excitation direction
c = 3 semi-empirical constant
ASD(f) is the acceleration PSD input

To ensure the validity of this semi-empirical curve, NASA calculated the force spectral density from their spacecraft FEM resulting from acoustic and random vibration excitations. Fig. 5 shows an example of the comparison between the semi-empirical FSD (green line) and the computed interface force from FEM coupled analysis (red line).

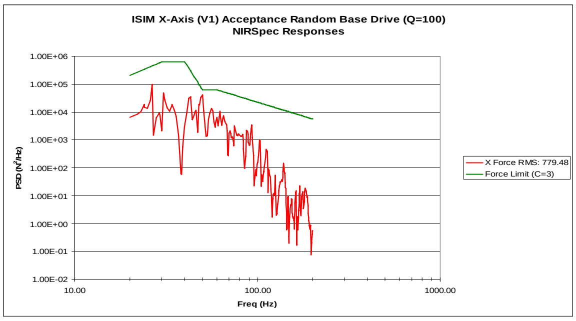

Fig. 5. Comparison between the semi-empirical FSD and the computed interface force from FEM coupled analyses.

Note that the semi-empirical curve is quite conservative, even with predictions assuming a very low damping (Q=100).

It shall be mentioned that the possibility of force limited vibration has been used from the start of the project, at the time of the definition of the environments to the sub-assemblies. Therefore the benefits of limiting overstress have been fully exploited for the development of the instrument and its sub-assemblies.

Secondary notches were also implemented based on stress allowable in the SiC-100 bench and on several large mirrors. The latter will not be discussed in more details in this paper since the method is quite standard.

4. NOTCHING IMPLEMENTATION

The proposed notching requires measurement of the interface force. Use of force measurement devices placed between the kinematic mounts and the shaker did not provide the necessary stiffness for adequate control of the shaker. Moreover, the necessity to acquire the interface force for each individual kinematic mount (used for sine notching), did not allow introducing a stiffening adapter between the force measurement devices and the NIRSpec bench.

The retained solution was to use strain gages glued on the blades of the kinematic mounts. Those strain gages allowed measuring the axial force in each of the kinematic mount legs and computation of the axial and lateral force at each interface. However, the global interface force has to be computed through linear combination of each measured strain, taking into account the phase between the signals (PSDs can not be used here). This need of post processing did not allow automatic notching, i.e. the force measurement is not used in closed loop to control the shaker, but in a step by step approach, using the previous random run at lower level or sine low level to define the acceleration input for the next level.

Two methods were developed, one called the “apparent masses method”, using low level sine results and the second one based on direct measurement of the interface forces at each interface during random test:

4.1 Apparent mass method

The Apparent Mass denoted $\underline{M}$ is the Frequency Response Function (FRF) defined as the ratio of interface reaction force to interface acceleration. This apparent mass takes into account the contribution at each frequency of the various modal masses. During testing, it can be determined as the ratio between the measured interface forces and the input from a low level run:

$$\underline{M(f)} = F(f) / a(f) \qquad (2)$$

With: F(f) = interface force, function of frequency
a(f) = input acceleration, function of frequency

This apparent mass is calculated per direction of excitation and in each one of the 3 axis.

Then, the force spectral density FSD at the Instrument interface can be determined before test as the product of the square of the apparent mass in test configuration by the random input acceleration power spectral density:

$$FSD = \underline{M}^2 \times ASD_{input} \qquad (3)$$

This FSD can be compared to the semi-empirical FSD limit specified by ISIM/NASA, see 3.2. The random vibration input has then to be tuned such that the resulting FSD does not exceed, but reaches this limit when notches are applied.

Note that this method uses force measurements from a low level sine. Extrapolation to higher levels is based on the hypothesis of a linear behavior, which is not always the case - damping may vary depending on the levels. This is the main limitation of this method, which otherwise is very straightforward to apply.

4.2 Direct measurement method

This method makes use of time responses of the strains in the kinematic mounts measured during a previous (lower level) random test. The interface forces on each leg, each kinematic mount and the global instrument interface force can then be reconstructed in the time domain and the force spectral density can be determined directly from test data.

Using appropriate signal processing software, the transient interface forces can be processed to give the corresponding FSDs which are then compared to the aforementioned ISIM/NASA limit.

$$FSD = f_{PSD}(F_i(t)) \qquad (4)$$

Note that this method cannot be used for the first low level random test, which is not an issue since notches are usually not needed for the low level. The “apparent masses” approach can then be used instead.

Note also that this method requires the possibility to acquire time responses during a random test. This was possible at IABG where the NIRSpec test was performed. Acquisition of time signals is anyway recommended since it allows investigating problems, if any, and checking the actual maximum instantaneous level reached, which most often exceeds significantly the 3 sigma value used as a standard.

4.3 Instrumentation

Strain gages were glued, as shown in Fig. 6 on each side of the blades, for each leg of each kinematic mount, resulting in a total of 12 strain gages. The signals from both sides of each blade were combined together to eliminate thermal and bending distortions. The acquisition system therefore provides 6 signals, two per kinematic mounts.

Conversion of the strain measurement to force measurement is performed using a pre-determined factor SF obtained using geometry and material Young modulus of the kinematic mount, and confirmed during the quasi-static load calibration:

$$F(t) = SF \times \varepsilon(t) \qquad (5)$$

From the geometrical layout of the kinematic mounts, each F(t) is decomposed into XYZ components which are then summed accordingly per axis to give the total interface forces $F_x(t)$, $F_y(t)$ and $F_z(t)$ of the instrument. This processing is performed in the frequency domain for the apparent mass method.

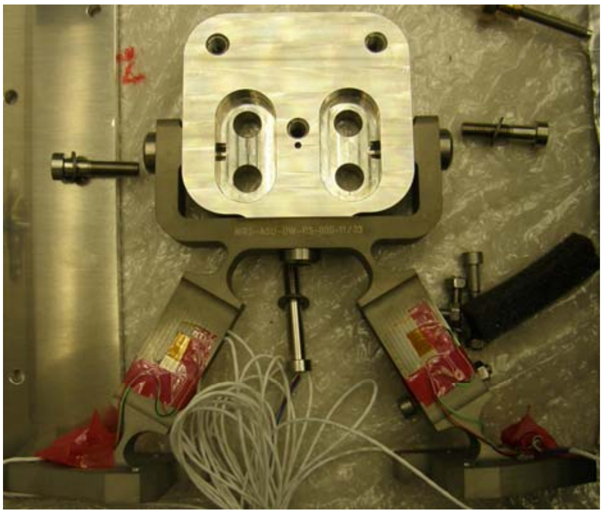

Fig. 6. Strain gages on the kinematic mount

The strain gages signals were checked and calibrated using the instrument measured mass under gravity as well as low vibration levels. Check of the calibration was regularly performed to insure quality of the force measurement.

Accelerometers were also mounted at the interfaces, and at response locations on the bench and on sub assemblies, to allow secondary notching and verification of the sub-assembly specifications. However, this will not be further discussed here, since emphasis is placed on force limited testing.

4.4 Automatization of the post processing

To allow a quick and reliable post processing of each test and preparation of next level, macros were developed in Dynaworks. These macros perform the complete post-processing of the test results, i.e. linear combination of signals for global FSD derivation, as well as predictions for next level, definition of the notched input profile and the extrapolated responses, using both proposed notching method.

In Chart 1 and Chart 2, the schematics of the apparent mass and direct measurement macros are shown respectively.

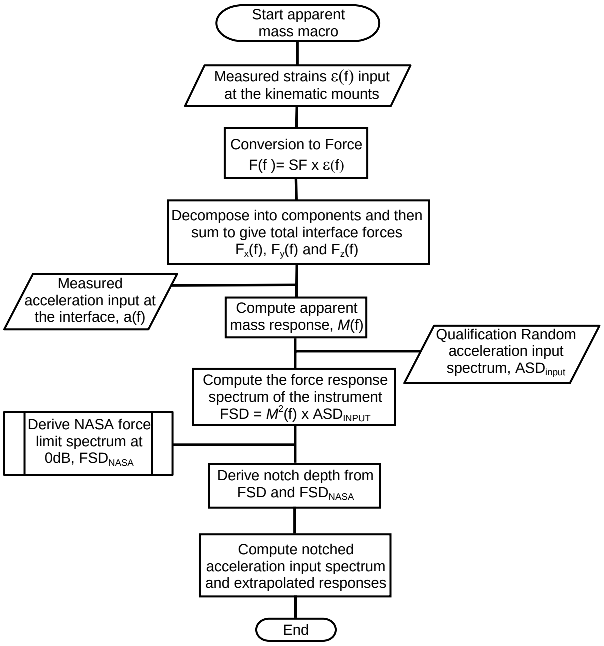

Chart 1: Flowchart – Apparent mass approach

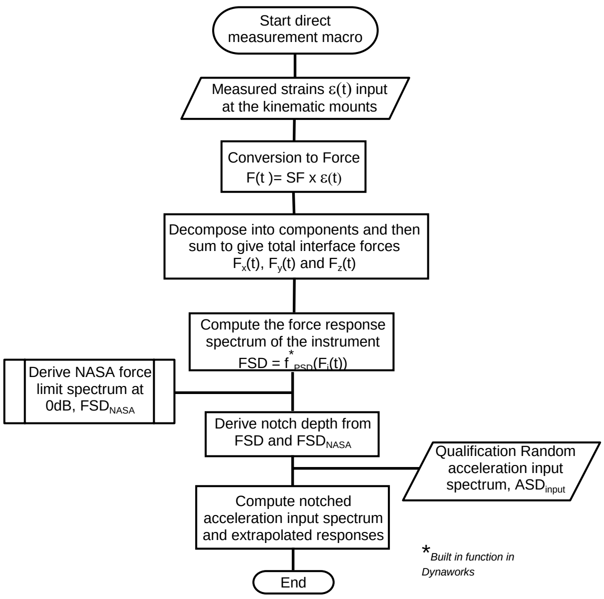

Chart 2: Flowchart – Direct Measurement approach

To verify the correctness and robustness of the macros, NASTRAN computations in the frequency domain as in the case for the apparent mass approach and in the transient time domain as in the direct measurement approach, were performed *a priori*. This step required a significant effort especially for the latter notching methodology since the NASTRAN computation was making use of a time varying noise signal (60 sec) to simulate the actual random vibration test input to the shaker. This noise signal corresponds to the qualification random vibration acceleration spectrum.

4.5 The practical application

As an example, Fig.7 and Fig.8 show respectively the results of the extrapolated unnotched FSD and the extrapolated notched ASD for the X axis 0 dB run. As can be seen, the two notching methodologies were found to give similar spectra:

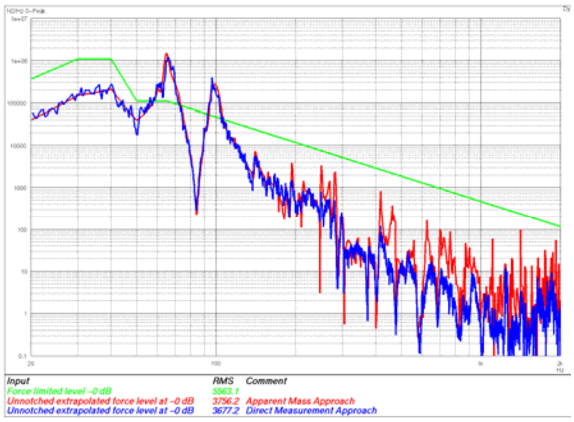

Fig. 7. Extrapolated Unnotched Force Spectral Density @ 0dB level in X axis

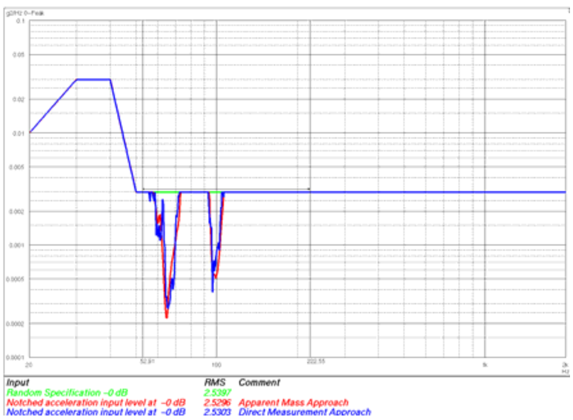

Fig. 8. Extrapolated Notched Acceleration Spectral Density input @ 0dB level in X axis

In Fig. 9, the usefulness of the Apparent Mass approach is clearly demonstrated. Prior to the first low level random vibration test @ -12dB, the extrapolated notched ASD input @ 0dB computed using the

Apparent Mass approach can be seen to be above the nominal ASD input @ -12dB. This means that the first run could be safely proceed without any implemented notch.

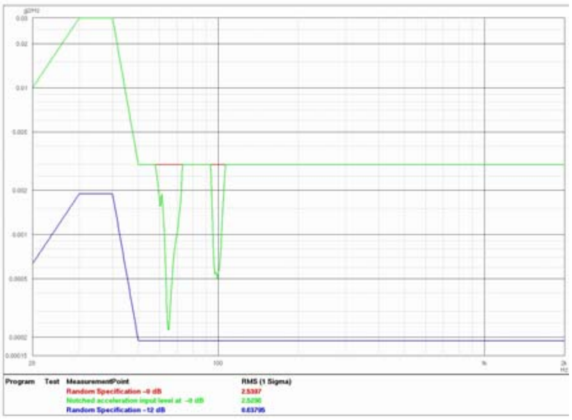

Fig. 9. Comparison of qualification notched limit level to low level run input in X axis

It should be reminded that the Apparent Mass approach is the only possibility before any low level random vibration test is performed. Thereafter, the Direct Measurement approach should be used since this method allows accounting for the change in damping when levels are increased. In the case of increasing damping in the tested structure w.r.t. an increase in input level, the qualification notched ASD input will thus be less conservative and should therefore minimize the possibility of under testing the instrument.

In Fig.10, Fig.11 and Fig.12, the achieved FSD at the interface of NIRSpec w.r.t. the global interface force spectral density limit by NASA is plotted for the qualification random test in the X, Y and Z axes respectively.

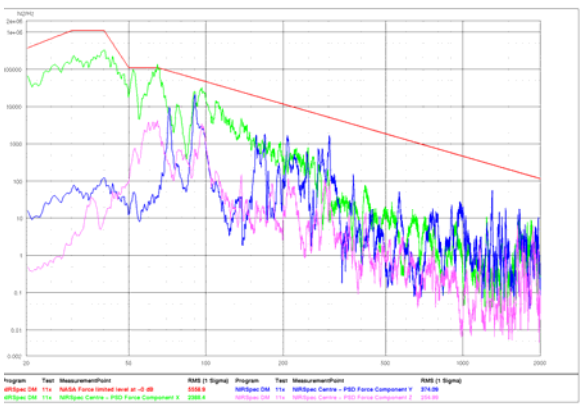

Fig. 10. FSD qualification level X axis

Note that the global force reached is 2388N RMS, i.e. 7164N at 3 sigmas, which is 20 % lower than the 8850N corresponding to the quasi-static load.

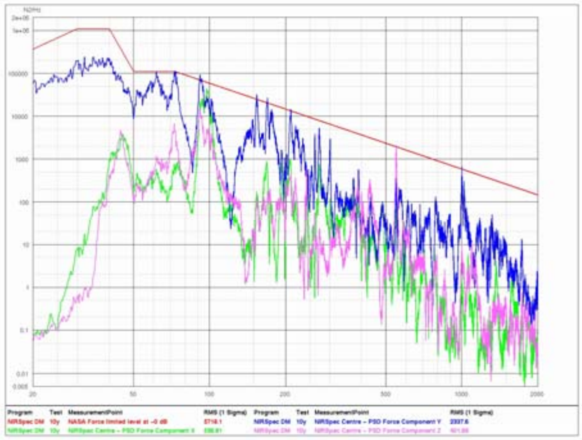

Fig. 11. FSD qualification level Y axis

Note that the global force reached is 2338N RMS, i.e. 7014N at 3 sigmas, which is 20% lower than the 8850N corresponding to the quasi-static load.

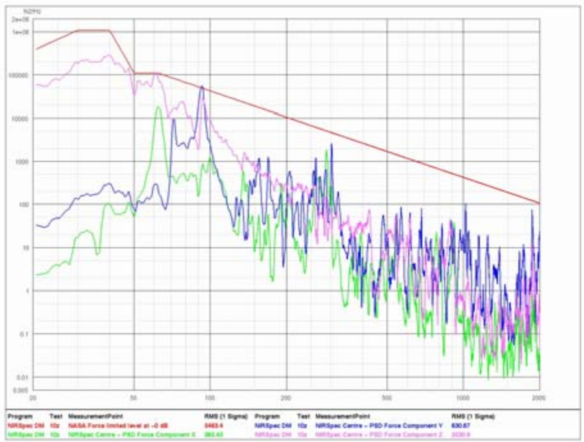

Fig. 12. FSD qualification level Z axis

Note that the global force reached is 2531N RMS, i.e. 7593N at 3 sigmas, which is significantly lower (54%) than the 16500N corresponding to the quasi-static load.

5. CONCLUSIONS & RECOMMENDATIONS

Force limited vibration testing has been successfully applied on NIRSpec demonstration model, both for sine and random environments, in an original way.

Strain gages on the kinematic mounts have been used to recover the interface forces, both in the frequency domain (FRF) during low level sine test and in the time domain during random test, allowing computation of the overall interface force from the individual strain measurements on each leg.

Predictions of the interface forces for the next level have been performed using both data, allowing the definition of the notch needed to reach but not exceed the FSD specified by NASA.

This notching method proved very efficient and accurate. The instrument qualification to vibrations was successfully obtained without over-stressing the fragile hardware. The use of semi-empirical FSD to limit the interface force led to lower interface forces - between 20 and 54% - than those corresponding to the specified design loads.

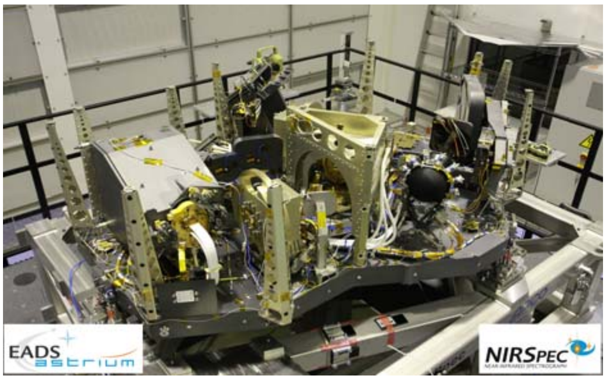

Fig. 13. NIRSpec Instrument without its cover

Out of this successful test campaign, the following recommendations can be proposed.

The first recommendation is to use force limited vibration for the development of space structures and instruments. To take full benefit of this method, it shall be applied from the very start of the project, at the time of definition of the specifications. In this way, it allows not only limiting over-testing, but also over-specifying and over-designing the structures.

The semi-empirical method has now been used for decades by NASA and years in Europe and showed to be reliable. Theoretical developments have provided some further justification of its robustness. It is however recommended to perform numerical coupled analysis at system level to predict the interface forces and compare them to the semi-empirical method. The numerical predictions shall be covered with sufficient margins, even using conservative assumptions in the predictions, e.g. low damping.

The use of a force limit curve in spectral density usually leads to lower interface forces than those corresponding to the specified design loads which cover all the mechanical environments. It therefore allows limiting overstressing and excessive internal responses, still demonstrating qualification. It is also a very straightforward notching method, compared to the use of design loads, for which the user has to arbitrarily decide the depth and width of the different notches to limit the global RMS of the interface force.

Practical implementation of force transducers or strain gages shall be prepared in advance of the test, as it may highlight difficulties. For NIRSpec, blank tests were performed with a dummy instrument to check the controllability of the shaker using force measurement devices at the interfaces. In the end, the force transducers had to be abandoned and strain gages used instead. In other cases where the mounting is not iso-static, force measurement may be difficult as interfaces forces might be influenced by the introduction of force measurement devices.

Use of strain gages during random test has proved to work very well. The signals were of good quality, allowing combination of time signals to reconstruct global forces.

Obviously, the phase information of the force measurement shall be recorded. The signs of the signals shall also be checked to allow their correct combination and extract global values.

Acquisition of the time signals during random allows to record phase information between channels and to reconstruct global forces from several measurements. It also provides a better knowledge of the real environment injected to the instrument, in particular to investigate possible problems, e.g. non linearities and check the maximum instantaneous levels reached. Indeed, the PSD calculation and averaging is a huge loss of information. The final PSD presented to the user may hide important variations of the signal in time.

Preparation and validation of post-processing tools allow significant gain in time during test and increase the confidence in the notch prediction. It is of primary importance to validate the tools with dummy data (e.g. produced by FEM runs) before the tests.

The use of the apparent mass method is possible with a low level sine test, and can be used in preparation of the first random test level. For subsequent random tests at higher levels, the direct measurement method shall be preferred as it allows accounting for change in damping with the vibration levels. It however requires measurement in the time domain.

6. REFERENCES

1. J.C. Salvignol, K. Honnen. JWST NIRSpec mechanical design of an ultra-stable cryogenic instrument. Proceedings of the 11th European Conference on Spacecraft Structures, Materials and Mechanical Testing. Toulouse, 2009

2. T.D. Scharton. Force Limited Vibration Testing Monograph. NASA RP-1403. May 1997

7. ACKNOWLEDGMENT

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