Development of Shock Test Fixture for a Heavy Rocket Valve

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Abstract

This article presents the technical challenges faced during the shock test of 84kg cryogenic valve for a liquid rocket engine and the counter measures implemented to tackle the issue. Aerospace valves are generally subjected to shock test in three orthogonal directional axes (x, y & z) as part of qualification test program to simulate the sudden accelerations occurring during transportation. The main challenge was posed due to high mass (153kg) and asymmetry of the Equipment Under Test (EUT) with respect to centre of gravity (CG) of the valve. The shock level for the test is 50g force in semi-sinusoidal waveform for duration of 10millisecond. The CG of EUT is located using 3D CAD model. The CG offset varied from 37mm to 94mm from shaker axis depending on mounting plane (XY, YZ & XZ) due to asymmetry of the EUT. The large mass, offset of CG from the vertical axis and the shock level called for a higher capacity shaker with a large displacement withstanding higher overturn moment. To counter this issue, a Shock Test Fixture (STF) is designed to keep the CG of EUT within a radius of 10mm from the axis of the available shaker of 290kN capacity. The STF is developed keeping the cumulative mass of EUT within the shaker limit of 230kg and acts as an intermediate test fixture between EUT and shaker table. The shock test of EUT is conducted successfully for the first time in the 290kN shaker using the newly developed STF. This approach shows that similar design methodology can be followed for the optimum utilization of available resources in an economical way

Keywords: *Cryogenic Valve, Shock Test, Centre of Gravity, Shaker*

1. Introduction

Liquid rocket valves are subjected to environmental test such as vibration, thermal and humidity test and the performance of the hardware is evaluated by conducting valve level functional tests. The vibration test for qualification hardware consists of random, sine and shock test. Random vibrations are the result of a number of events occurring by chance and may be characterized by any frequency spectrum [1]. Sine vibration testing involves subjecting the EUT to a swept sine input over a frequency range. Mechanical shock is a sudden, non-periodic disturbance occurring when environmental accelerations are applied for short but definite period of time [1].The different parts of a electrodynamic shaker is detailed in [2]. Testing of a component for any kind of vibration involves mounting it on a shaker with the help of an intermediate element called a Fixture [3].The fixture transmits the forces produced by shaker table to EUT. The most common material used for fixture fabrication is Aluminium alloy [3].

Generally, aerospace valves are subjected to vibration test in all three orthogonal axes. However, in cases of symmetric valves, the vibration tests are limited to only two axes, one in lateral direction and other in longitudinal direction. The EUT described in this article includes a cryogenic valve of 84kg and a box type fixture. This cryogenic valve is asymmetric in shape and hence the vibration tests are performed along all three orthogonal axes. The specification of the cryogenic valve is given in Table-1.The overall size and weight of the cryogenic valve and the multiple axes vibration requirement called for the development of a box type fixture. The EUT including cryogenic valve and box type fixture discussed in this paper is shown in Figure 1.

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Table 1: Specification of Cryogenic Valve

No.	Parameter	Spec.
1	Fluid medium	Liquid Oxygen (LOX)
2	LOX flow rate, nominal (kg/s)	443
3	Fluid temperature, nominal (K)	117.3
4	Operating pressure (MPa)	45.6
5	Command fluid	Ambient GHe
6	Overall size of valve (mm)	460x381x300

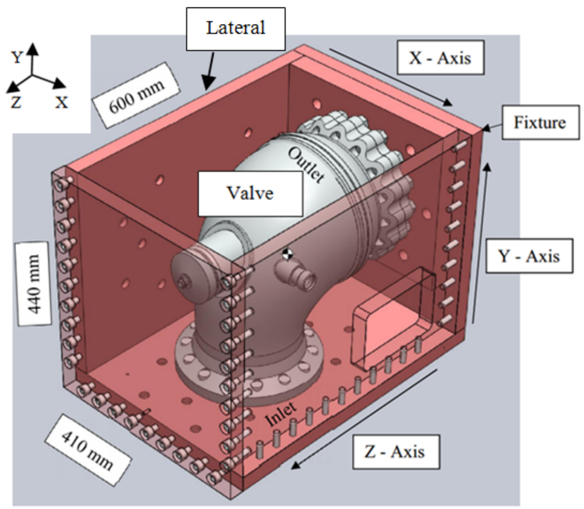

Figure 1: 3D model of EUT

1.1. Sine and Random Vibration Test

The test specification of sine vibration test and random vibration test is given in Table-2 and Table-3 respectively.

Table 2: Sinusoidal Vibration Test Level

Frequency, Hz	Z-Axis	X & Y-Axis	Sweep rate
10-16	20 mm DA	12 mm DA	2 Octaves/min
16-100	10g	6g	

Table 3: Random Vibration Test Level

Frequency (Hz)	PSD (g^2/Hz)	Acceleration (g_{rms})	Duration (sec)	Axes
20	0.002	13.5	120	All three orthogonal axes
60	0.002			
250	0.138			
1000	0.138			
2000	0.034			

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The overturn moment of EUT estimated for sine and random vibration tests are 1415Nm and 2703Nm against shaker capacity of 1765Nm. Additional counter masses are used accordingly to limit the overturn moment within the maximum limit of the available 160kN shaker as shown in Figure 2. As the overturn moment of random vibration test is higher compared to sine vibration test, the counter masses are estimated for the maximum requirement case of random vibration level. The details of counter mass estimated, is given in Table-4. The resultant overturn moment estimated is within the maximum capacity of shaker. As the force requirement of EUT including armature mass in sine and random vibration tests are lower (28.5kN and 54kN respectively) compared to the shock test level (229kN), the sine and random vibration tests were conducted initially with the box type fixture in 160kN shaker. The responses of pre and post-test resonance survey are comparable which ensures the mechanical integrity of EUT. The frequencies of peak responses in the resonance survey are observed within the range of 156Hz to 488Hz.

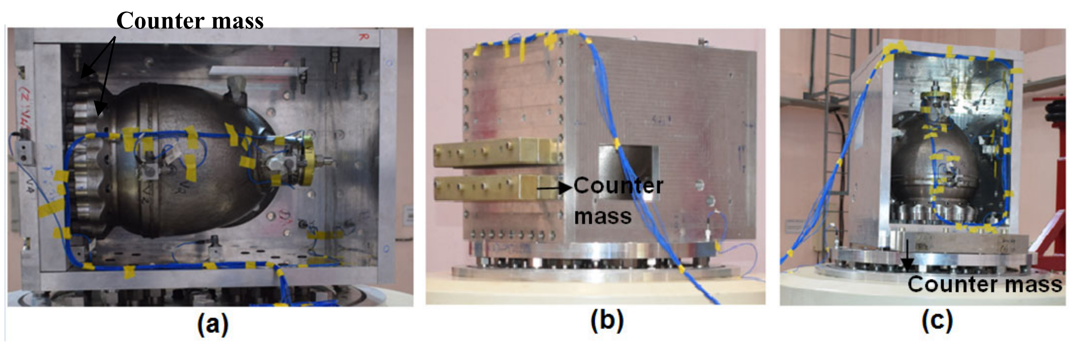

Figure 2: EUT mounted on shaker table for Sine and Random vibration test along (a) X-Axis, (b) Y-Axis and (c) Z-Axis.

Table 4: Details of counter mass used in sine and random vibration test along each axis

Vibration direction	CG offset (mm)	Over Turn moment (Nm)	Counter mass used	Resultant overturn moment after using counter mass (Nm)
X-Axis	36.9	1057	Nil	1057
Y-Axis	94.35	2703	30kg@300mm&180°	1017
Z-Axis	68.35	1958	8.2 kg@215mm&180° 8.2kg@275mm&180°	1206

1.2. SHOCK TEST

As part of general load capacity checks before the test, the overturn moment of EUT is estimated for the Shock test for 160kN shaker. The maximum turning moment of EUT for 50g shock test is 7080Nm and is above the overturn moment capacity of 160kN shaker. As a result, the feasibility study for conducting shock test in another higher capacity shaker of force rating 290kN is carried out. Towards this, a new STF was designed and realized from Aluminium alloy AA2219-T87 plate which can cater for the shock testing along all the three axes and for meeting the interface requirements of the shaker and EUT. The first section of the paper explains the design procedure followed for the development of STF. A comparison of natural frequency of STF between analytical and finite element analysis method are presented to validate the finite element model. The lowest natural frequency of STF is

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estimated and sufficient margin is available to avoid resonance with EUT. Finally, the cryogenic valve was subjected to shock test using the newly developed STF and the performance of the cryogenic valve post shock test is verified by conducting functional tests.

2. Design Procedure

The major parameters considered for designing the STF is given below.

i. EUT
   a) Mass of EUT = 153kg
   b) Overall size of EUT = Cuboid of size 600mm x440mm x410mm
   c) Mounting holes = Minimum number of mounting holes in EUT required for shock test is finalised based on the estimate given below.

Mass of component	=	153kg
Shock level	=	50g
Size of bolt	=	M12
Total force experienced by bolts	=	153x50x9.81
	=	75047N
Total force experienced by each bolt	=	75047/6
	=	12508N

Considering higher load transfer, the bolt selected is A286 (1100MPa Class). The Factor of Safety (FOS) for the fasteners is estimated and is given in Table-5.

Table 5: Estimation of FOS for fastener

S.No.	Parameter	Value
1	Yield Strength, YS (MPa)	827
2	Tensile area, A (mm^2)	84.3
3	Load (Max) capacity of each bolt, Fmax = YS x A	69716
4	Nut Factor, k	0.16
5	Torque, T (N-m)	60^{+10}
6	Load due to torque, Ft = T/(k x d) , (N)	36458
7	Percentage of external load transfer	38%
8	External load due to vibration, Fv2, (N)	12508
9	Total load, FTOT = Ft + 0.38 x Fv2, (N)	41211
10	FOS = Fmax/FTOT	1.69

Based on the estimation, 6nos. of M12 bolts are sufficient to withstand the shock load.

ii. Specification of shaker
   a) Force rating of Shaker = 290kN
   b) Overturn moment of Shaker = 10kNm. In order to keep the overturn moment of EUT well within the shaker limit of 10kNm, the CG offset of EUT from the centre is required to be kept minimum. The maximum limit for CG offset is finalized as 10mm to ensure safe operation of shaker.
   c) PCD of mounting holes in shaker table = 8nos. of M12x1.75-6H holes are available in the shaker table at PCDs Ø203.2mm, Ø406.4mm, Ø558.8mm and Ø711.2mm and one number at the centre.

iii. Material for STF fabrication = The material selected for the fabrication of STF is aluminium alloy AA2219-T87.

iv. Assembly sequence: The assembly sequence of EUT is given below.

   a) Mounting STF to shaker table using 33nos. of M12x1.75 bolts.
   b) Mounting EUT to STF using M12x1.25 bolts in orientations as per shock test direction.

2.1 DESIGN OF STF

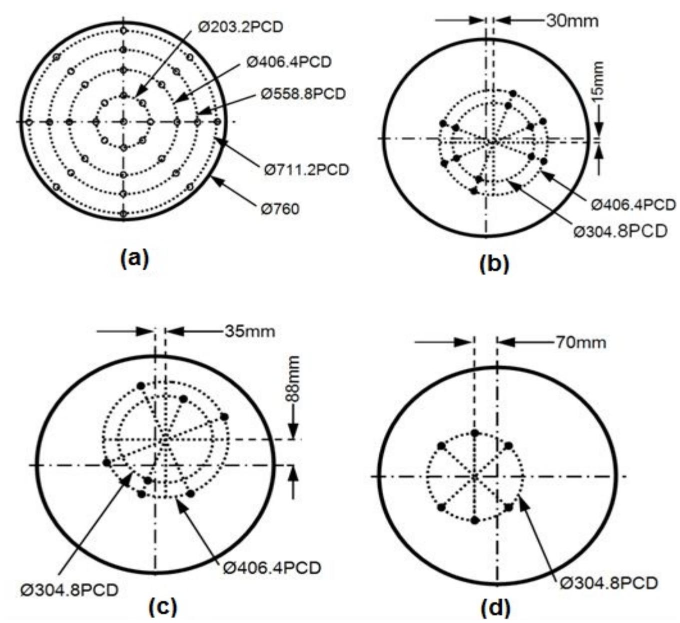

Figure 3: PCD and hole location in STF for (a) fastening to shaker table, (b) shock test along X-axis, (c) shock test along Y-axis, (d) shock test along Z-axis.

The outer diameter of STF is selected as Ø760mm based on envelope size of shaker table. The thickness of plate selected is 33mm considering the available plate size. 8Nos. of Ø13mm through holes with Ø31.5mm counterbore to a depth of 18mm at PCDs shown in Figure 3(a) is provided in STF to mount it to shaker table. The details of PCD in box type fixture are given in Table-6. In order to fasten box type fixture to STF, being an aluminium alloy, thread inserts are installed in STF. The locations of thread inserts in STF are established by ensuring the CG offset is within 10mm from shaker axis. Towards this, the centre of PCDs for thread inserts is shifted from the geometrical centre of STF.

Table 6: Details of PCD in box type fixture

Vibration direction	Mounting side in Box type fixture	PCD of holes in mounting side	No. of bolts per PCD
X-Axis	Lateral side	Ø304.8 & Ø406.4	6
Y-Axis	Inlet Side	Ø304.8	2
		Ø406.4	5
Z-Axis	Outlet side	Ø304.8	6

The mounting hole features shown in Figure 3 are superimposed on a single plate to configure STF. The 3D model of EUT assembled to STF is shown in Figure 4.

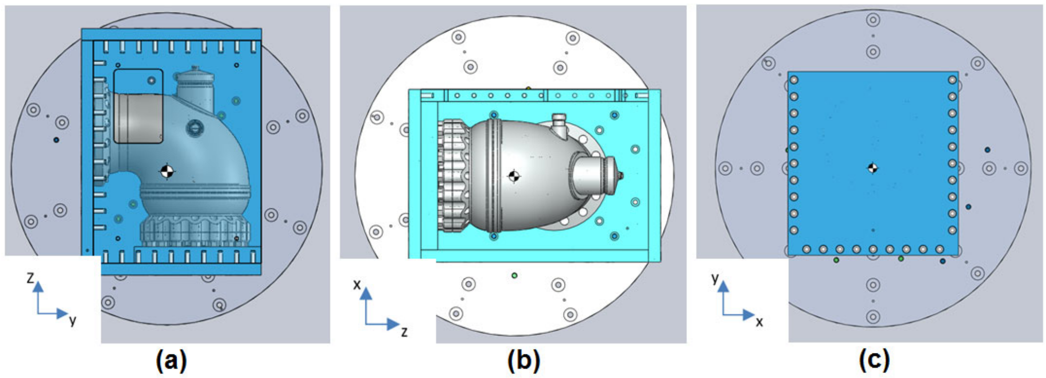

Figure 4: 3D model of EUT mounted to STF for shock test along (a) X-axis (b) Y axis (c) Z axis.

Table 7: CG offset of EUT with STF

Direction of Vibration	G offset of EUT from Shaker axis after mounting on new STF (mm)
XX	7.10
YY	1.90
ZZ	1.86

The new CG offset of EUT mounted on STF estimated using 3D model is given in Table-7 and is within the requirement of 10mm. The CG offset values in Table-7 is finalized as the attempts made to further reduce the offset in CG resulted in overlapping of thread insert hole with the counter bore. The mass of STF estimated using 3D CAD model is 40kg. The overturn moment with the maximum estimated offset of 7.1mm is 0.682kNm and is within shaker specification of 10kNm. The force rating estimated for 290kN shaker with EUT along with armature, fasteners and STF is 229kN, which is within the shaker specification. The factor of safety of fasteners for mounting STF to shaker table is estimated to be 1.85.

3. Design Verification

3.1. Modal Analysis

The natural frequency of newly designed STF for clamped condition along the contour is estimated by FEA and compared with analytical result to validate the finite element model. The natural frequency of the first vibration mode of a round plate clamped along the contour is given by the Equation (1) [5]:

$$f = \frac{10.21}{R^2 \times 2\pi}\sqrt{\frac{D}{\rho \times h}} = 575Hz \tag{1}$$

where, the density $\rho = 2840 kg/m^3$, thickness of material $h = 0.033m$, radius of circular STF $R = 0.38m$, Flexural stiffness of the plate $D = Eh^3/12(1-\nu^2)$, Young's modulus $E = 0.73E+011Pa$ and Poisson's ratio $\nu = 0.33$ (UNS A92219).

The fundamental frequency estimated by FEA is 551.68Hz and is very close to the value obtained by analytical method. Further, modal analysis of STF is conducted by setting boundary condition as fixed geometry at 33Nos. of mounting holes in STF and the result is given in Table 8. The different mode shapes of STF are shown in Figure 5.

Table 8: Modes of STF

Mode	Frequency (Hz)
1	1655.1
2	1728.3
3	1729.4
4	1909.3
5	1909.5

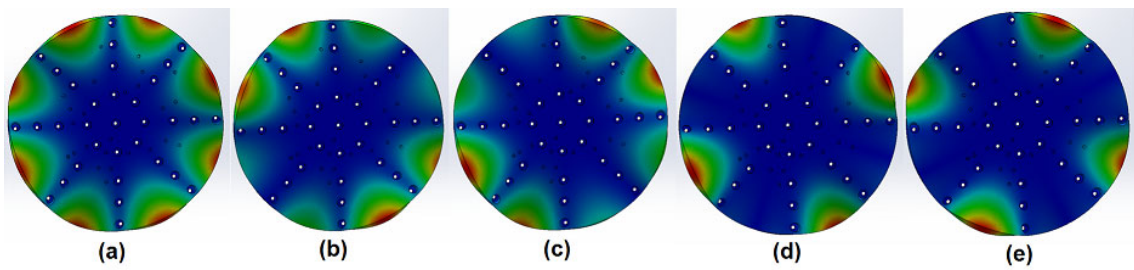

Figure 5: (a) First mode (b) Second mode (c) Third mode (d) Fourth mode (e) Fifth mode

The lowest frequency of STF is higher than the frequencies of peak responses of EUT in resonance survey and hence the design is safe.

4. EXPERIMENT AND DISCUSSION

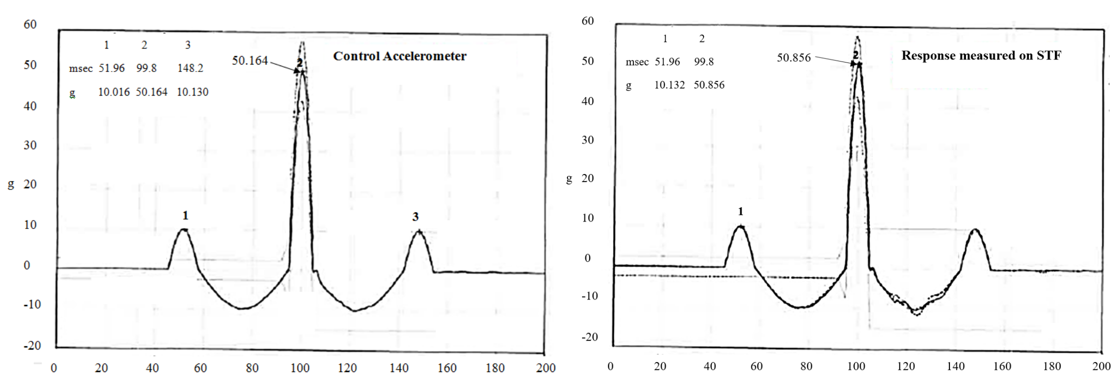

Figure 6: Validation test result

Before carrying out the full level 50g shock test on EUT, a validation test on newly fabricated STF is conducted. STF was mounted on the shaker table by using 33 Nos. of

M12x1.75 of 75mm length bolts and 70Nm torque was applied. Validation test to simulate the standalone performance of STF in shock test was carried out by starting with -18dB level. The shock level is increased in steps of 3dB until 50g is achieved. The plot of validation test at 50g shock level is given in Figure 6. The response measured on STF showed good match with control signal. EUT is then mounted on STF after the validation test.

4.1. SHOCK TEST OF EUT AND RESULT

As the shock test of this magnitude on such a large EUT is planned for the first time in the 290kN shaker, the test is conducted along all three orthogonal axes by starting from a lower level of -18dB. The shock level is then increased in steps of 3dB until 0dB to achieve the full level. The condition of EUT was checked after each shock and found satisfactory. The shock levels achieved is given in Table-9.

Table 9: Shock Test Result

Level	Peak Acceleration Achieved (g)		
	Test-1 (Z Axis)	Test-2 (Y Axis)	Test-3 (X-Axis)
-18dB	6.4	6.529	6.3
-15dB	8.92	8.879	8.936
-12dB	12.55	12.5	12.72
-9dB	17.67	17.721	17.68
-6dB	24.8	24.956	24.882
-3dB	35.31	35.307	36.344
0dB	49.89	49.75	50.217

The achieved shock levels are within the specification of 50g (+ 0 dB/ -3 dB). Post shock test health check of shaker is evaluated and found normal. The fasteners used for mounting was checked post shock test and are found to be in tight condition. Also, the performance of the cryogenic valve post shock test was verified by conducting functional test. Various functional tests include seat leak test, minimum command pressure to start open the valve and external leak test. The performance of the cryogenic valve in post shock functional test is satisfactory.

5. CONCLUSION

Design of STF is primarily controlled by various factors such as overall size and weight of EUT, shaker capacity, CG offset, natural frequency of EUT etc. A STF to meet the test requirement of an 84kg asymmetric cryogenic valve is designed and realized. The large mass, offset of CG distance from the vertical axis and the shock level called for a higher capacity shaker with a large displacement withstanding higher overturn moment. The major constraint of CG offset is addressed by adjusting the location of thread inserts suitably in STF using CAD software. The STF is designed to keep the CG of EUT within a radius of 10mm from the axis of the available shaker of 290kN capacity. The STF is developed keeping the cumulative mass of EUT and STF within the shaker limit of 230kg (excluding armature mass) and it acts as an intermediate test fixture between EUT and shaker table. Modal analysis is conducted on newly designed STF to verify the design. STF mounted on shaker is initially subjected to 50g shock test and the responses are verified. Shock test is initiated by subjecting EUT with STF to lower shock levels. This helped in gaining confidence for proceeding to higher shock levels by gradually increasing the levels. The shock test of EUT is conducted successfully to 50g level for the first time in the shaker using the newly developed STF. The fasteners are found to be intact after the shock test, which proves that the torque applied is adequate. Also, the performance of the shaker and cryogenic valve was satisfactory post shock test. This approach shows that similar design methodology can be followed for the optimum utilization of available resources in an economical way.

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