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HYDRA, A NEW TOOL FOR MECHANICAL TESTING

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ABSTRACT

The introduction outlines the verification concept for programmes of the European Space Agency (ESA). The role of the Agency in coordinating the activities of major European space test centres is summarized.

Major test facilities of the environmental test centre at ESTEC, the Space Research and Technology Centre of ESA, are shown and their specific characteristics are highlighted with special emphasis on the 6-degree-of-freedom (6-DOF) hydraulic shaker. The specified performance characteristics for sine and transient tests are presented. Results of single-axis hardware tests and 6-DOF computer simulations are included.

Efforts employed to protect payloads against accidental damage in case of malfunctions of the facility are listed. Finally the operational advantages of the facility, as well as the possible use of the HYDRA control system design for future applications are indicated.

INTRODUCTION

Verification Concept for Spacecraft

In view of the very high cost of developing and launching satellites, it is essential to ensure that the design fulfils all specified requirements and that hardware and software are free from workmanship failures before the spacecraft is placed in orbit. The verification of space systems, however, cannot be limited to a series of environmental and functional tests at the end of the development programme after the integration of the flight models. The identification of problem areas and in particular of design deficiencies at a late stage in the programme would lead to significant schedule delays and cost overruns. Efficient verification consequently needs to start with the design and must continue throughout all project phases confirming at each phase that the programme objectives will be met. Hence the verification concept must deploy a series of verification steps including tests, which lead to satisfactory system performance without undue risks. Its purpose is to:

- qualify the design already in the early development phase of a project;
- permit timely selection of suitable materials and processes;
- ensure proper functioning of components, units, subsystems before final flight model integration;
- guarantee the integrity of system performance and identification of workmanship failures before launch.

Design verification requires the provision of computer models as well as breadboard or full scale satellite models, which are sufficiently representative with respect to the performance to be verified (e.g. structural, thermal, electrical models). Tests on satellite models are generally performed to update and qualify the corresponding mathematical models. Confidence in functional performance is built up by tests at different hardware levels, starting at component level and terminating with system performance verification. Therefore performance characteristics of the test facilities are regularly reviewed and adapted to the needs of future Agency programmes. In this context the Agency has recently decided to extend its satellite test facilities by implementing a 6-degree-of-freedom (6-DOF) hydraulic shaker until 1996.

Facility Coordination

The European Space Agency has developed and maintains major environmental test facilities. Similarly some ESA member states have established test centres to support their national programmes. The facilities are at the disposal of industry, scientific institutes and projects to support Agency programmes as well as space programmes of ESA member states; but these can also be made available for non-ESA projects, when not utilized for Agency purposes.

Therefore European industry and scientific institutes do not have to procure those environmental test facilities, saving not only extensive investments but also significant costs for operation and maintenance. In order to avoid duplication of facilities and subsequent underutilization of facilities in Europe, ESTEC has established a close co-operation with its partners CNES/INTESPACE (France), IABG (Germany) and CSL (Belgium). This co-operation is not limited to operational aspects, but also includes consultation with respect to identification of requirements of future programmes and coordination of investments for new test facilities. This improves the utilization of facilities in Europe and avoids unnecessary redundancies or over-capacities. Whilst the national test centres are equipped for environmental tests on small and medium satellites, the ESTEC facilities are compatible with the requirements of the large spacecraft to be launched on Ariane-4 and Ariane-5. The test facilities of all centres are compliant with the stringent product assurance requirements of ESA for tests on space hardware.

THE MAIN TEST FACILITIES IN THE ESA TEST CENTRE

The cut-out view in Fig. 1 illustrates the most important test facilities of the ESTEC Test Centre. The illustration already includes the test hall for the 6-DOF vibration facility, which is presently under construction.

The facilities shown in Fig. 1 are briefly described hereafter. All facilities are located in one building, which also contains integration halls, data handling and support facilities, such as meeting rooms, customer offices and storage areas. Hence, test campaigns involving various test disciplines can be efficiently executed with low transportation and handling effort.

Facility for Thermal Balance Tests

The Large Space Simulator (LSS) at ESTEC with a solar beam diameter of 6 m is the largest solar simulator within the ESA member states with unique performance characteristics. Fig. 2 illustrates the LSS and shows the main dimensions.

During the tests the pressure inside the test chamber is reduced to levels below 10^{-6} mbar with oilfree high vacuum pumps. For simulation of the deep-space heat sink, the vacuum chambers are lined with stainless steel shrouds, which are cooled down to temperatures of about 100 K by liquid nitrogen. In GN_2 mode they can be operated in the temperature range from + 80°C to - 100°C for thermal cycling. Simulated solar radiation is produced by 25 kW xenon-arc lamps and associated optics. Motion systems make it possible to simulate the spacecraft orientation with respect to the impinging solar beam.

Electromagnetic Test Facilities

- EMC facility

The EMC chamber has a surface area of 7.1 m x 6.1 m and a height of 5 m.
All emission and susceptibility tests in the frequency and time domain are fully automated. They are computer-controlled with online data reduction, narrow and broad-band identification. All evaluated data are corrected for probe factors, etc.

The facility is particularly well adapted to carry out electrostatic discharge tests on spacecraft and to verify the effects of the discharges. A high voltage unit, generating up to 30 kV, with a maximum discharge capability of 500 joules, is used for this purpose. A separate, multi-channel data acquisition and measurement system is used to verify the effects of electrostatic discharges on the test subject. The system, which has an overall dynamic range of 160 dB, includes active sensors for measurements of the magnetic and electric fields and of the surface current.

- Compact Payload Test Range (CPTR)

The CPTR permits the testing of the radiation links between ground stations and satellites. The CPTR is illustrated in Fig. 3. The overall size is about 25 m x 11 m x 10 m with a plane wave zone of 7 m x 5 m x 5 m. The reflector dimensions are 9.2 m x 8 m with a surface accuracy of 70 microns peak-to-peak. It permits measurements of critical system parameters such as EIRP (Equivalent Isotropic Radiated Power, PFD (Power Flux Density), beam steering, link budgets, etc. One of the facility's main features is its low cross-polar performance. The frequency range is from 1.5 to 40 GHz.

Facilities for Mechanical Tests

- Vibration facilities

The test centre at ESTEC is equipped with electro-dynamic vibrators, which operate in a frequency range from 5 to 2000 Hz and can perform sinusoidal, random and shock tests sequentially along the main orthogonal axes of the specimen.

The main vibration system consists of two 140 kN shakers which can either be used individually or in multishaker configuration. In the latter configuration, the two shakers are coupled to a dual-head expander for tests in the longitudinal (vertical) axis and to a large slip table for "lateral tests". Fig. 4 illustrates the multishaker configurations.

- Acoustic facility

The ESTEC facility is the largest one in Europe with a volume of approx. 1600 m^3. It operates with GN_2 and can produce noise levels of up 158 dB ($P_{ref} = 2 \times 10^{-5}$ Pa). During the test liquid nitrogen is evaporated and temperature controlled in two serial heat exchangers. The thermal energy is provided from a hot water reservoir fed by the central heating system of the plant.

THE 6-DOF HYDRAULIC SHAKER

Considerable effort has been expended during the last decade in studying the possibilities for improvement of dynamic structure qualification in general and for system acceptance of Ariane-4 and Ariane-5 payloads in particular. These investigations have led to the concept of the 6-DOF hydraulic shaker (HYDRA), which is distinguished by the following improved features as compared with conventional electrodynamic shakers:

a) actuator force and stroke
b) frequency range extended below 5 Hz
c) active control of orthogonal motions
d) controlled excitation in 6-DOF permitting realistic flight load testing
e) improved test operations and safety

The design and engineering phase for HYDRA and the associated building has been performed during 1992/1993. The procurement, installation and acceptance phase of the building started in 1993, while the start of the shaker procurement has been delayed until August 1994 for budgetary reasons. The facility shall become operational in the second half of 1996 for tests on the structural model of the PPF/Envisat satellite (mass approx. 7000 kg). This ESA satellite is currently planned for launch in 1998 by Ariane-5.

Performance Characteristics

System configuration and forces

The geometry of the table and actuator arrangements was optimised by detailed trade-offs early in the design phase. These were based upon finite element models calculating the rigid body modes and the elastic modes of the loaded and unloaded table, taking into consideration stiffness, masses and the geometric configuration of all actuators. The actuator force requirements were calculated with a dedicated computer programme taking into account the kinematics of the loaded table. The results of the trade-offs (reported in Ref. 1) and subsequent engineering have led to an octagonal table with a span of 5.5 m and a mass of 22000 kg. The first flexible mode in loaded configuration, is 22% above the upper operational frequency limit of the shaker, which is at 100 Hz. According to DIN standard 4024 and taking into consideration the damping ratio for such a table, the first elastic mode will not have a remarkable influence on the table acceleration up to 100 Hz. The table is driven by 4 actuators in the vertical direction and 2 actuators for each lateral direction. Each of the 8 actuators has a stroke of ± 70mm, a maximum piston velocity of 0.8 m/sec and a force rating of 630 kN. The high force levels are required to accommodate the "overturning moments" created by the table and payload assembly during dynamic testing. In conventional testing with electro-dynamic shakers these need to be compensated for using bearing assemblies, i.e. passive elements. The 6-DOF hydraulic shaker counteracts these moments by the active control of the motions in all translational and rotational axes. In this way it will be possible to actively attenuate the parasitic orthogonal motions (often referred to as "cross-talk") for sine tests of large payloads. The cut-out view (Fig. 5) illustrates the PPF/Envisat satellite being tested on the HYDRA facility.

Operational test modes

HYDRA has been designed for sinusoidal testing along each translational axis. Besides testing at selected discrete frequencies (sine-dwell), it is possible to perform sine sweeps with sweep rates in the range of 2 to 4 octaves per minute. Furthermore transient excitation signals in 6-DOF can be generated in addition.

Dynamic performance

The dynamic range of HYDRA is shown in Fig. 6 and Fig. 7. The upper acceleration limits of the performance diagrams are applicable for a test article mass of 7000 kg with a centre of gravity 5 m above the table surface. The acceleration limits will increase as the test article mass decreases and vice-versa. The Ariane-5 qualification levels for sinusoidal vibration tests are indicated hereafter for comparison and show that margins exist even for payloads with higher masses.

Ariane-5 (Ref. 2)	Frequency range (Hz)	Qualification levels (0-peak) recommended
Longitudinal	4-5 5-100	12.4mm 1.25g
Lateral	2-5 5-25 25-100	9.9mm 1g 0.8g
Sweep rate		2 oct/min.

The specified performance tolerances are as follows:

a) Signal distortion for sine test mode
(differences between measured and reference signal)

peak values:
≤ 1.5 dB
or
≤ 0.025g, whichever is larger

RMS values:
≤ 1.0 dB
or
≤ 0.025g, whichever is larger

b) Parasitic cross-axis excitation in sine test mode in the unexcited orthogonal axes

≤ 10% of nominal excitation level
or
≤ 0.025 g, whichever is larger.

c) Signal distortion for transient test mode
(differences between measured and reference signal)

peak values (all maxima and minima):
≤ 1.5 dB
or
≤ 10% of the max. amplitude in all other degrees of freedom, whichever is larger

RMS values (difference between measured and reference signal):
≤ 1.0 dB
or
≤ 10% of the max. amplitude in all other degrees of freedom, whichever is larger

Total signal duration:
≤ ± 5%

Signal quality

Hydraulic exciters cannot reproduce acceleration signals free from distortion, mainly because of non-linearities of the hydro-dynamics in servovalves and actuators (Ref. 3). An example of this phenomenon is shown in Fig. 8. The graph shows the distorted acceleration at the table centre during a sine test at 4 Hz with an existing 6-DOF hydraulic shaker.

In order to reduce these distortions to an acceptable level, special effort has been put into the careful design of servovalves, actuators, and bearings and particularly into the actuator control system of HYDRA. The digital control system (Ref. 4) uses detailed mathematical models of the shaker system with the following features:

- non-linear control algorithms for servovalve/actuator
- on-line prediction of actuator motions
- on-line prediction of system kinematics

The functioning of the actuator control algorithm was verified by tests with an available actuator and a simplified control system. A typical result of these tests is shown in Fig. 9. Subsequently a 6-DOF computer model was set up, and initial investigations were performed at discrete frequencies from 0.5 Hz up to 100 Hz without yet employing table acceleration feedback and oil pressure feedback of the servovalves. Fig. 10 illustrates a typical result of these simulations, which shows good coincidence between the nominal and actual waveform; it also shows that the orthogonal motions ("cross-talk") are well below 10% of the nominal excitation. The 6-DOF simulations will be continued in order to perform sensitivity analyses and to test various feedback options for the final optimisation of the control software. Due to the delayed start of the implementation phase of the project, these results cannot be presented in this publication.

Transient Testing

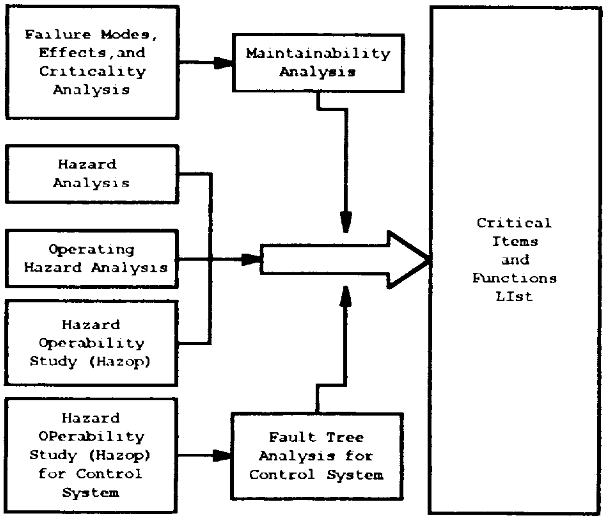
The introduction of a test method that reflects a more realistic representation of the space flight environment has been a major objective for the development of HYDRA. In preceding studies it has been concluded that the simulation of the multi-directional transients at the interface of launcher and spacecraft produces more realistic structural responses. In contrast, traditional sine tests lead to unrealistic responses and therefore involve an inherent risk of over- or under-testing (Ref. 5, 6, 7). Multi-degree-of-freedom hydraulic shakers designed for earthquake simulation have been used in the past to demonstrate that the reproduction of transients is feasible after several iterations (Ref. 8). Recent advances in computer technology permit the control system of HYDRA to simulate transients in 6-DOF without iteration. Fig. 11 shows the simulation results of a representative transient for Ariane-5 at lift-off. The quasistatic portion of the transient signal as well as its frequency contents above 100 Hz have been filtered out to become compliant with the dynamic range of the facility.

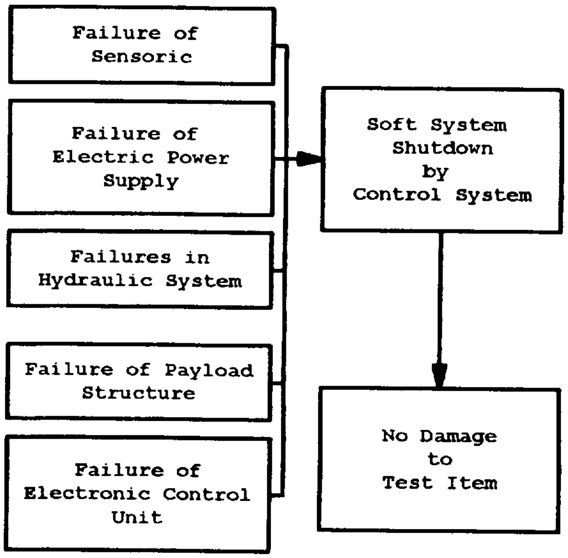
Operational Aspects

The 6-DOF hydraulic shaker allows the specimen to be tested along both the vertical and the lateral axes with one single test setup. It is therefore no longer necessary to dismount, re-locate and re-instrument the payload for the different excitation directions. This not only reduces the effort involved in handling and instrumentation, with consequent reductions in test durations and risk, but it also provides flexibility in the sequencing of tests. In particular, x-, y- and z-signature tests can be performed without particular effort before and after each single-axis test run.

The large octagonal test table is flush with the test floor. It facilitates the mounting of heavy and/or geometrically large specimens (e.g. appendages such as solar arrays). Due to the wide span of the table the complexity and mass of the adaptors can be kept low. All shaker equipment and supplies are located in the basement of the building, mechanically isolated from the clean test area (class 100.000 Fed.Std. 209). The gap between the aluminium test table and the test floor is closed by a flexible seal. This provides mechanical separation of the clean test area from the hydraulic equipment located below the table.

Detailed reliability and safety analyses were made during HYDRA's design, as outlined in the following diagrams. The control system has been designed in such a way that the failure events identified in the various analyses will not lead to a hazardous situation for facility or payload, because it will trigger a "soft facility shutdown" in time.





CONCLUDING REMARKS

The installation of the hydraulic shaker will ensure that the ESA test centre at ESTEC, Noordwijk, remains compliant with the testing requirements evolving from the ongoing launcher developments, which lead to larger satellites with higher masses.

However, the new facility will not only extend the performance for applying traditional test methods, it will also provide ESA with the tool to verify the advanced test method of "transient testing" after more than one decade of intense theoretical study work and subsequently to apply this method for the qualification of satellite structures.

The control system design, once verified in practical application, will certainly have the potential to improve the performance characteristics of other machines and simulators driven by hydraulic actuators. In fact, the control algorithm for the HYDRA hydraulic system has already been successfully used for the control of the horizontal moving system of the 6-DOF driving simulator at Daimler-Benz, Berlin, Germany. Both the acceleration control accuracy and the time behaviour could be improved drastically compared to the previous analogue feedback control.

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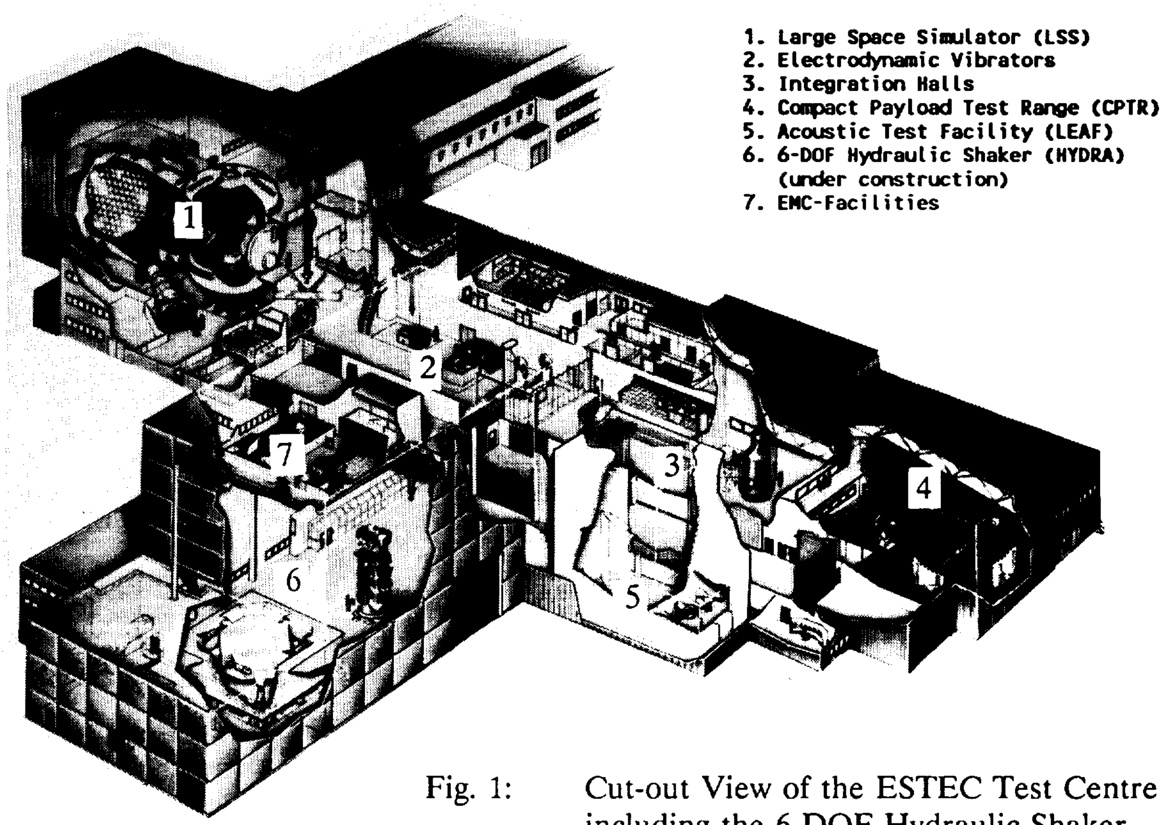

Fig. 1: Cut-out View of the ESTEC Test Centre including the 6-DOF Hydraulic Shaker

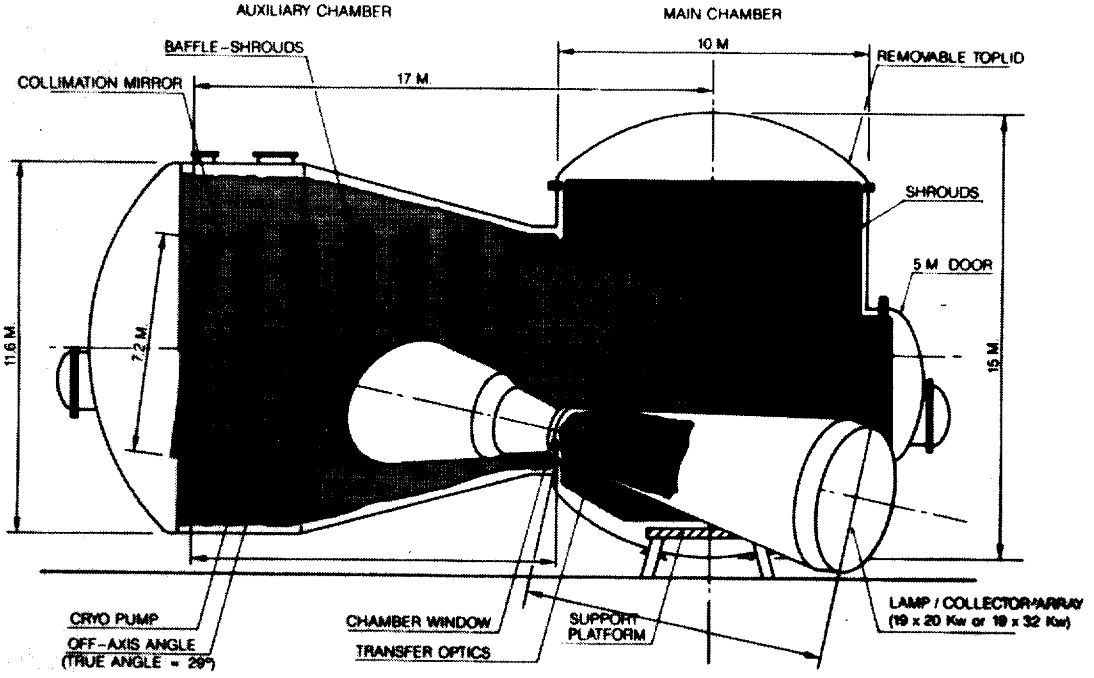

Fig. 2: Schematic of the Large Space Simulator (LSS) at ESTEC

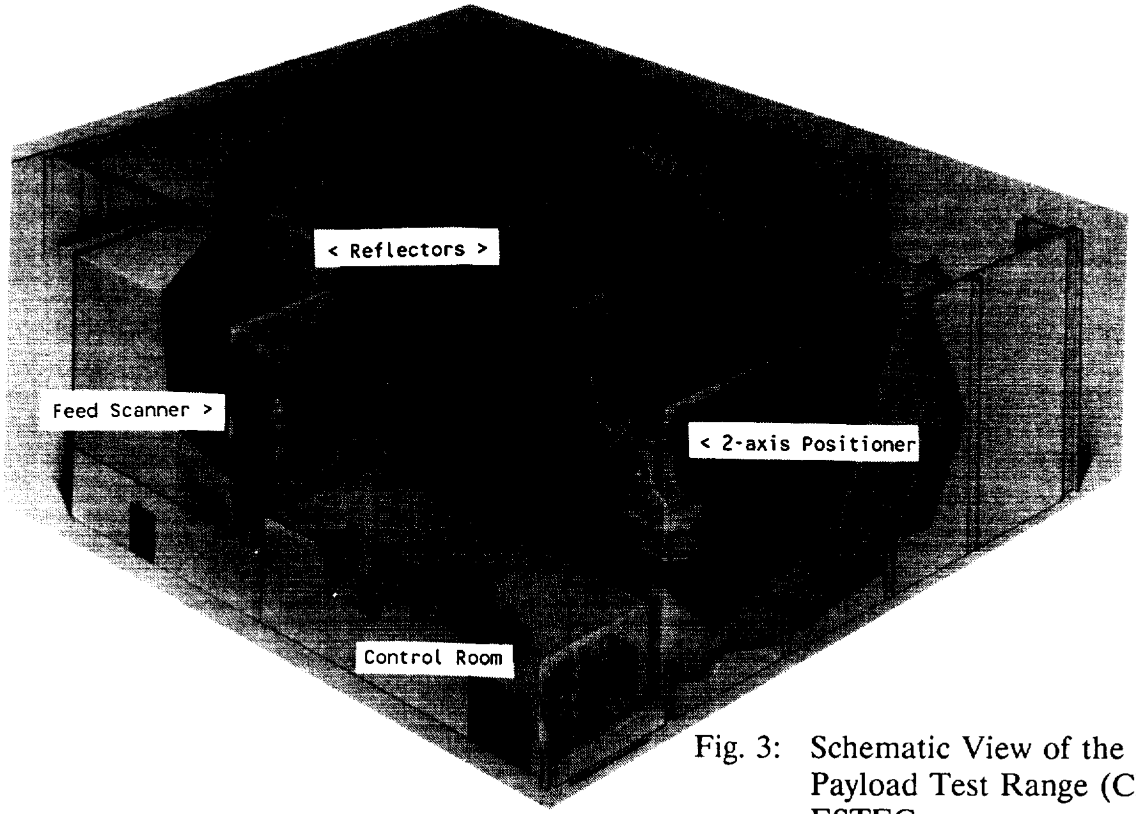

Fig. 3: Schematic View of the Compact Payload Test Range (CPTR) at ESTEC

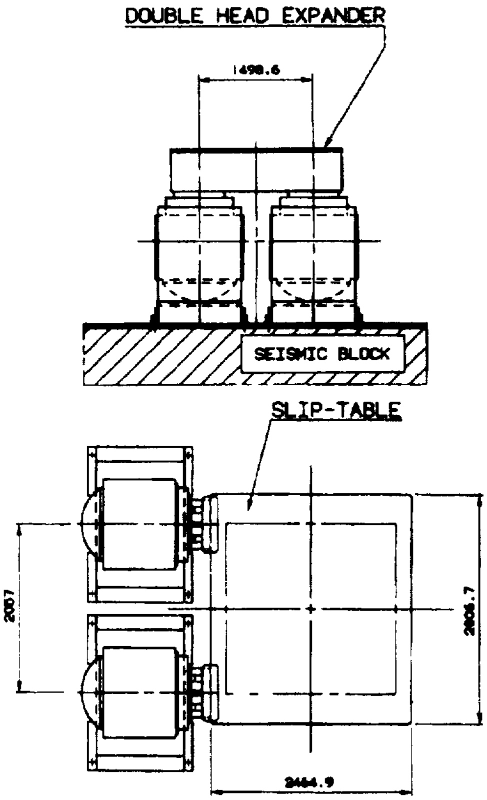

Fig. 4: The 280 kN Multi-axis Shaker in Vertical and Horizontal Configuration

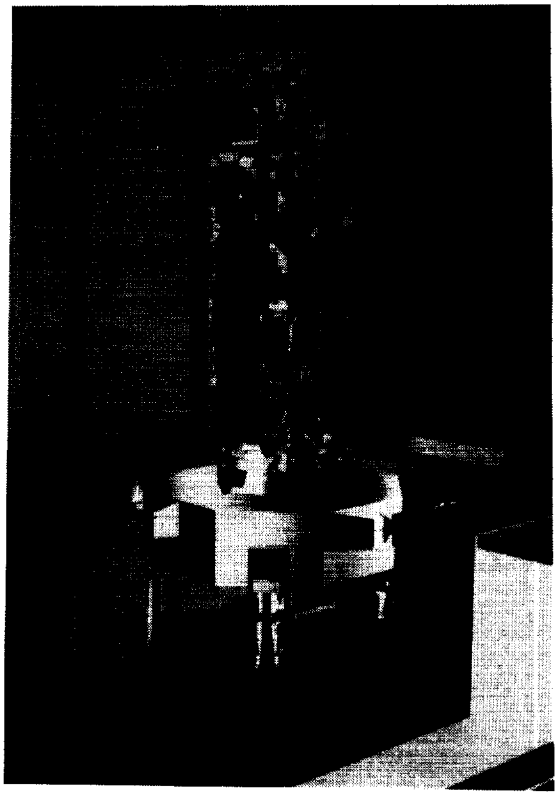

Fig. 5: HYDRA Test Configuration with the PPF/Envisat Satellite

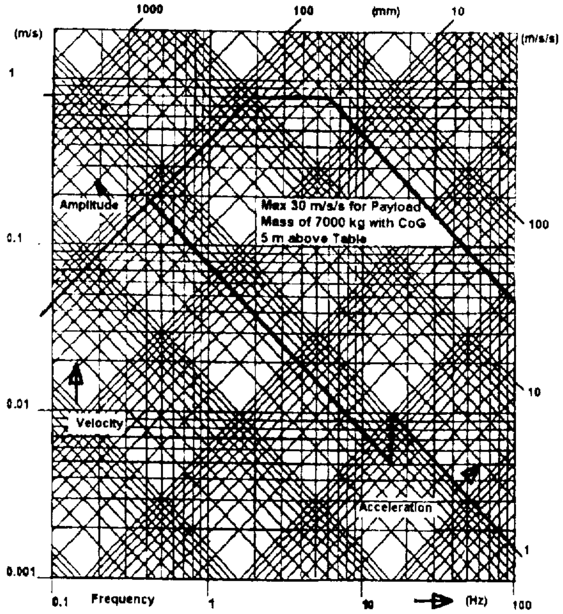

Fig. 6: HYDRA Performance for Lateral Excitation

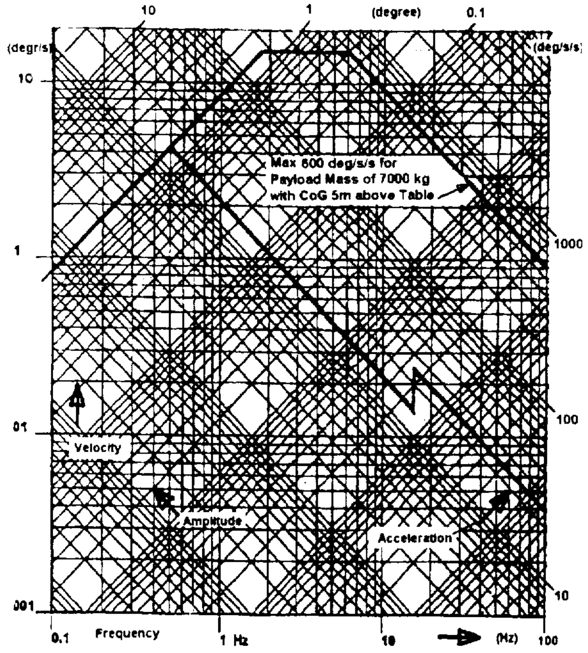

Fig. 7: HYDRA Performance for Rotational Excitation

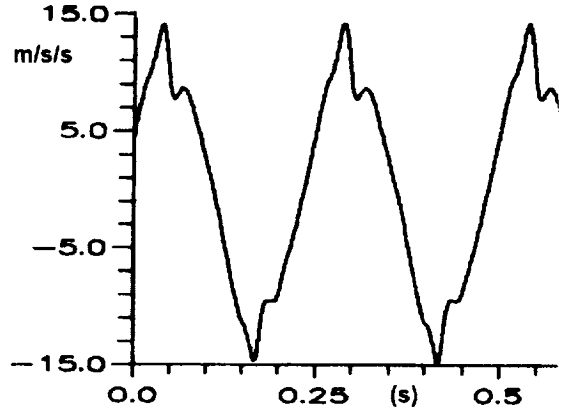

Fig. 8: Acceleration Time History with 4 Hz Sinusoidal Input of an Existing 6-DOF Earth Quake Simulator

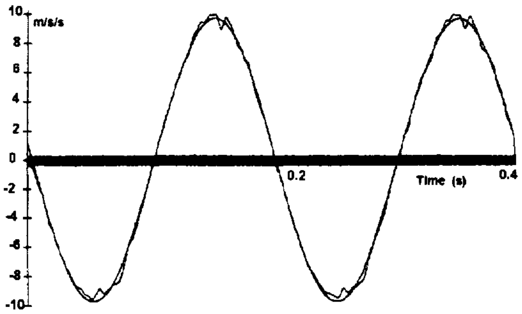

Fig. 9: Acceleration Time History Measured with Single Axis Test Rig Using a Simplified HYDRA Control (Input 5 Hz Superimposed)

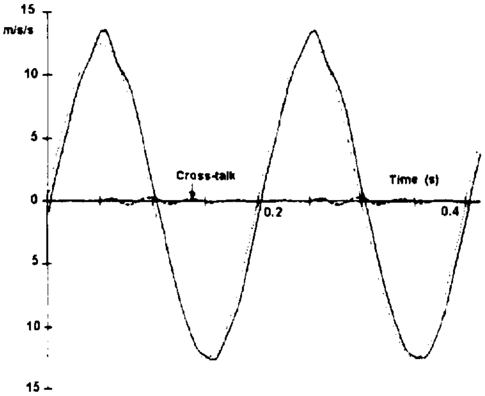

Fig. 10: Acceleration Time History simulated with the 6-DOF HYDRA Computer Model without Feedback Loops (Input 5 Hz Superimposed)

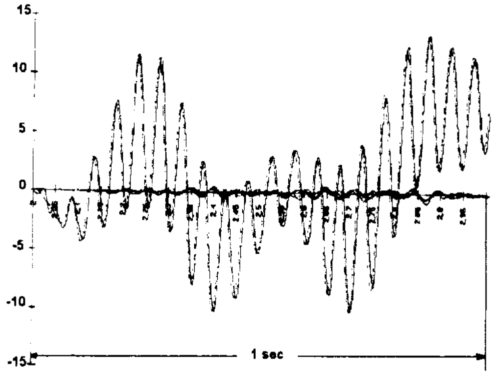

Fig. 11: A Transient Simulated with a HYDRA Mathematical Model (Input Superimposed)