DESIGN CRITERIA AND APPLICATIONS OF MOTION SIMULATORS USED IN RESEARCH AND TESTING OF INERTIAL SENSOR PACKAGES FOR SPACE APPLICATIONS

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ABSTRACT

Accurate attitude orientation and trajectory planning of spacecrafts and satellites in free space is typically realised using inertial navigation and star tracker sensors. ACUTRONIC Switzerland Ltd designs and builds high-end motion simulator that make it possible for the system engineer to accurately reproduce roll, pitch and yaw motion in the laboratory. To accurately reproduce the real environment, a temperature or vacuum chamber is often a requirement. Thereby all motion sequences can be tested with the conditions the test article is likely to experience in space of during launch of the spacecraft. This helps significantly in accelerating the development and testing phase for new products and lowers the overall research and development costs.

ACUTRONIC presents typical examples of motion simulators delivered to the space industries in Europe and Asia, thus highlighting the special needs of the space community. Furthermore, research institutes and equipment manufacturers will obtain information and guidance to define the requirements of a motion simulator. They will be able to understand the crucial factors designing a motion simulator. Among these factors, the following can be identified:

- Number of rotational axes needed to be tested simultaneously
- Size and inertia of the Unit Under Test (UUT)
- Static accuracy requirements, for example positioning accuracy or axis orthogonality
- Dynamic accuracy requirements, for example achievable frequency response or acceleration. Obviously the testing of launch vehicles inertial navigation units requires a motion simulator with higher dynamical capabilities than one for the testing of a star tracker device.
- Accuracy and stability of rotational speed, especially at low rates.
- Combination of the rotational motion sequence with an environmental condition, such as temperature or even vacuum. ACUTRONIC's motion simulators are designed to accommodate thermal or vacuum chamber on the rotating axes.
- Field of view from the device under test towards other optical measurement equipment for the testing of optical devices

INTRODUCTION

Accurate attitude orientation and trajectory planning of spacecrafts and satellites in free space is typically realized using inertial navigation and star tracker sensors.

Inertial navigation relies on Inertial Measurement Units (IMU) and Inertial Navigation Systems (INS) consisting of accelerometers and gyroscopes. The sensor's principles are based on the measurement of rotational and linear movements along up to three input axes.

Throughout an IMU's product life cycle it needs to be exposed to reference movements and excitations. Starting from the conception and development phase of the sensors, towards the production launch, followed by their start of operation and potentially being transferred to periodical calibration, the IMU requires a source of excitation on all input axes that it is supposed to measure.

For different purposes different IMUs are needed. For a space launcher high dynamic motions are key, while a Star Tracker Sensor uses accurate optical systems to point to fixed stars.

For the latter low dynamic rotational movement will be applied, but also extremely accurate positioning is required.

ACUTRONIC Switzerland Ltd designs and builds high-end motion simulators that make it possible for the system engineer to accurately reproduce all kind of roll, pitch and yaw motion in a laboratory environment.

To accurately reproduce the real environment of IMUs and other sensors, controlled temperature or pressure differences can be combined with the mechanical motion.

Therefore motion simulators can optionally be fitted with temperature or thermal vacuum chamber. For devices requiring a line of sight to other measurement equipment, e.g. an autocollimator or a star simulator, the chambers can be fitted with optical windows to allow optical measurement, throughout the climatic testing.

Thus, all motion sequences are tested with the conditions that the test article is likely to experience in space, or during the launch of a spacecraft.

This helps significantly to accelerate the development and testing phase of new products, and lowers the overall research and development costs, no matter for short or long periods of tests.

Some industries examples will highlight the special needs of the space community, prior to detailing further the main design criterions of such motion simulators.

INDUSTRY EXAMPLES

Five examples from the industry give an overview over the different design aspects to be covered for different applications.

2-Axis Motion Simulator for Star Tracker Sensor

Figure 1: 2-Axis Motion Simulator (top) and Star Tracker Sensor (below)

The 2-axis position and rate table depicted above is specifically designed to test satellite star tracking navigation platforms, for payloads up to 30kg.

The system is configured with an inner, elevation axis and an outer, azimuth axis. The large offset of the table top keeps the optical sensors of the star tracker at the required axis intersection.

The table is designed to be mounted on a marble block together with the star simulator, therefore its specific low height dimension. It guarantees that both optical axes of the star tracker and star simulator are collinear.

The inner axis table top has a threaded hole pattern for the mounting of the star tracker. Electrical and hydraulic access to the unit under test (UUT) is handled through twist cables and flexible couplings passing through the hollow axis shafts.

Both axes of the table are supported by high precision, angular contact bearings, giving the axes high wobble performances, even loaded. The achieved wobble are generally below 2 arc-seconds peak.

Star Tracker motion simulator are high accuracy positioning tables, therefore specific attention is given to the position accuracy of this system.

Thanks to its controller, and encoder selection, not only the coarse positioning error (full position range) is corrected, but also the fine positioning error. Even for a small range of displacement angles, the fine positioning error remains within the specification of 2 arc sec peak-to-peak for any position. The combination of a positioning repeatability below 0.5 arc sec, and of a position resolution of 0.036 arc sec, gives this motion simulator one of the highest position accuracies.

The combination of all these mechanical specification give the simulator a pointing accuracy of less than 5 arc sec.

Construction materials are treated for long term dimensional stability. As such, the error induced by the test equipment, and measured error of the star tracker optic, can be reduced to a minimum and offers a great stability.

Protective coatings are used to prevent corrosion; outer surfaces are painted with a specific black mat to avoid light reflections. All components, lubricants, paints have been specifically defined for having as less gaseous emissions as possible. As a result, star trackers motion simulators Series8800 can be used into clean room class 1000, testing “open” star tracker optics, while having the guarantee of no contamination of the optics tested.

3-Axis Motion simulator with Temperature Chamber

Figure 2: Three Axis Simulator with Temperature Chamber

The 3-axis position and rate table Series AC3367-TCC is designed for the development and testing of IMUs and optical devices.

It has three degrees-of-freedom. The middle gimbal (pitch axis) has an open frame and supports the temperature chamber. The inner axis consists of a table top that rotates inside the temperature chamber.

The system is specifically designed with two different removable chambers, in accordance with the different payloads to be tested (height of units optical focal point). Both chambers are fitted with special optical windows.

Power and signals from and to the device under test are transferred by sliprings through all three axes. Rotary joints for GPS signals and MIL-Bus 1553 data lines are also available.

The system has medium range dynamic specifications, with the following rate and acceleration capabilities:

- Inner axis: 1000°/s, 4000°/s^2
- Middle axis: 600°/s, 500°/s^2
- Outer axis: 400°/s, 500°/s^2

Despite the big inertia and massive structure of the axes, the system offers high mechanical performance in terms of position accuracy (below 3 arc sec peak-to-peak for each independent axis) and wobble (+/- 2 arc-seconds).

The mechanical structure is designed to achieve position measurement bandwidth of 50Hz, 20Hz and 30Hz on the inner, middle and outer axis respectively.

The system has different inertia configurations, due to the two different chambers. Different servo setting files are stored in the controller, guarantying the same performance independently of the mechanical configuration. The different settings are reloaded within seconds.

Combined with high rate stability capabilities (below 0.0005% of commanded rate, measured over 360°), the system specifications offer the best possible platform for high-end IMU testing.

2-Axis Motion Simulator with Thermal Vacuum Chamber

The Series AC2267-VTCP is a high precision, two-axis motion simulator that is designed to test space grade inertial systems and star trackers.

The simulator is configured with an inner, azimuth axis that carries the device under test and the thermal vacuum chamber. The horizontal outer, elevation axis supports the inner axis. A stiff, welded steel base secures the simulation system to the isolated pier.

Figure 3: Two Axis Simulator with Vacuum Dome

The thermal vacuum chamber is fitted with optical viewing windows. As the chamber is installed on the inner axis, the optical windows are aligned with the UUT optics under all motion conditions.

The system is evacuated prior to simulation run by an external turbomolecular pump. Once the desired vacuum is reached the pump is sealed off and removed. Ion pumps fitted to the chamber maintain the vacuum during simulation.

The vacuum range achieved on this system reaches 10^{-7} millibar (or 7.5e^{-7} Torr), and can be maintained only using the ion pumps during more than 27 hours.

The thermal vacuum chamber is fitted with a temperature controlled hot/cold-plate. A heat shroud surrounding the UUT is designed to uniformly absorb the controlled temperature of the plate. The temperature of the plate is controlled using a combination of water and Peltier elements.

The temperature range covers -20°C up to +60°C, within the vacuum chamber, with a mean gradient of 1.5°C/min and a stability of +/-1°C.

<u>3-Axis Motion Simulator with embedded vacuum and temperature Chamber</u>

Figure 4: Three Axis Simulator with Thermal Vacuum Chamber

The AC3380-VTCP 3-Axis Motion Simulator has three degrees-of-freedom, and is equipped with a thermal vacuum chamber.

The performance specification of the system are similar the system described above. The main differences are the third rotating base axis, the missing optical window and higher dynamic specifications. The latter are as follows: Inner axis: 1200°/s and 2300°/s^2, middle axis: 900°/s and 500°/s^2, outer axis: 500°/s and 300°/s^2

This system is used for IMU testing, requiring higher oscillation excitation.

The middle gimbal (Pitch Axis) and inner gimbal (Roll Axis) are closed frames offering high torsional stiffness, and therefore higher bandwidth (30Hz for the middle axis) than an open gimbal systems.

<u>3-Axis Motion Simulator High Dynamic</u>

The Model AC3361-450 Flight Motion Simulator (FMS) is a high dynamic and high precision test instrument.

The Three Axis Motion Simulator is configured with a horizontal outer (pitch) axis, a middle (yaw) axis, which is orthogonal to the outer axis and an inner (roll) axis supported by the middle axis gimbal. The inner axis table top is the payload mounting area.

The system is designed for the development and test of a space launcher's IMU during all flight conditions of the spacecraft. Typical payloads of this kind weigh up to 50kg.

The system is designed to simulate both high dynamic vibrations and precise slow motion while maintaining high pointing accuracy in both cases.

Despite its large and robust design, the wobble specifications and position accuracies remain excellent, with a maximum of 3 arc sec wobble on every axis, and a position accuracy below 2 arc sec RSS.

The vibration capabilities requires large amplitude and high frequency oscillations, over a period of more than 30 minutes.

To better illustrate these requirements, here some key figures of the AC3361 series:

Accelerations with load on the inner axis 18000°/s^2, on middle axis 13000°/s^2 and on outer axis 5000°/s^2.

The system can be exited with a large signal bandwidth at its peak torque during 10 minutes.

For a typical input signal of 1 degree peak-to-peak the maximum phase lag at 10Hz for all axes in simultaneous operation is below 10 degrees for both inner and middle axis and below 25 degrees for the outer axis.

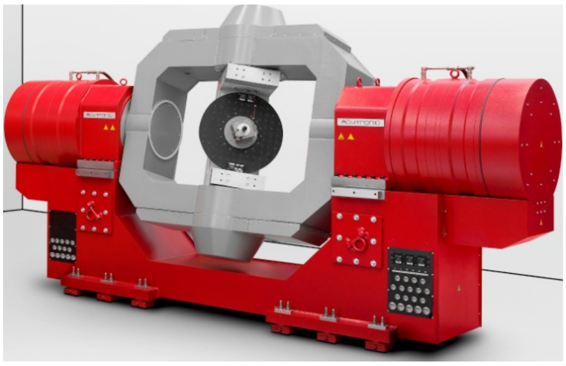

Figure 5: High Dynamic Three Axis Motion Simulator

The high dynamic tests require high continuous power motors. The system is equipped with large, water cooled electric actuators in all axes. The motor housings are jacketed for the water cooling. Protective coatings are used to prevent corrosion .

Despite its massive mechanical structure the achieved position bandwidth is 50Hz, 30Hz and 30Hz on the inner, middle and outer axis respectively.

All axes have continuous rotational freedom. Sliprings connect the power and signals circuits from the device under test to instrument test hardware.

DESIGN CRITERIA

In the following crucial design criteria are discussed, when it comes to the specification, design and manufacturing of a motion simulator. Clearly in the limited framework of this paper major design drivers only are discussed. Depending on the details of the application other aspect have to be considered.

Axis Configurations

Different applications require different axis configurations. The axis sequence, balancing, north alignment and field of view are discussed.

Axis Sequence

For testing optronic devices it is beneficial to have the yaw axis as the most inner axis of the motion simulator. This ensures that the mechanical gimbal structures of the middle and outer axis do not obstruct the field of view when the system is rotating around yaw.

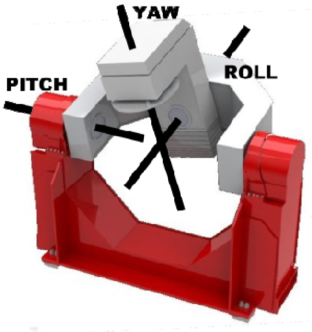

Figure 6: Axis Sequence for Optronics Testing

The figure above shows a typical axis configuration. The pitch and the roll gimbal are further designed to offer a large field of view (FoV) to the device under test.

For classical IMU testing the yaw axis is arranged as the most outer axis of the motion simulator. Pitch is middle and roll is inner axis. The pitch axis gimbal can be designed as an open frame gimbal, thus giving the device under test a reasonable field of view towards external measurement equipment.

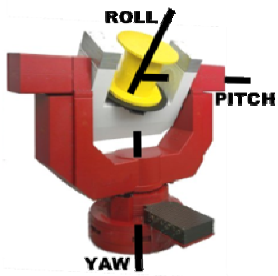

Figure 7: Classical axis orientation for IMU testing

North Alignment

With an unlimited yaw rotation as the most outer axis the motion simulator can easily be aligned with respect to the northern direction by simply setting the right axis offset (zero position) in the controller software.

System with horizontal outer axis need to be north-aligned at the time of mounting it on the pier. North alignment kits (optional equipment) facilitate this procedure.

Axis Balancing

Electrically direct driven axes are statically balanced using steel counterweights. There is typically a trade off between axis balancing and the required field of view from the device under test.

Alternatively different drive solutions with gear drives or hydraulic systems are considered.

Field of View

For testing of optical devices, like star tracker cameras and gimbal stabilised optronics, the needed field of view (FoV) from the unit under test is an important design criteria. Depending on the field of view of the optical device the field of view out of the simulator is determined.

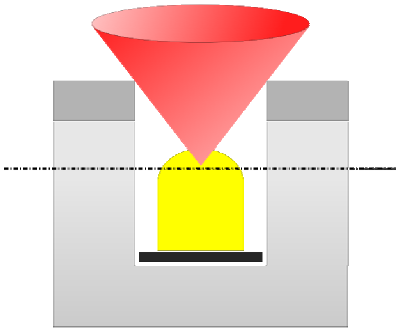

Figure 8: Field of view out of a gimbal structure

Number of rotational axes needed to be tested simultaneously

The number of installed axes on a motion simulator drive the number of axes of an inertial measurement unit (IMU) that can be tested simultaneously. Simultaneous testing is, however, not always mandatory.

A two axis system is able to excite all three IMU-axes sequentially, thus eliminating the need for a third axis in certain cases. The inner axis excites the Z-axis of the three axis rate gyro. The outer axis can excite the other two axes sequentially with the inner axis being stable at zero or ninety degrees. For rate linearity calibration and rate linearity calibration over the temperature range, a two axis simulator with temperature chamber is the logic choice.

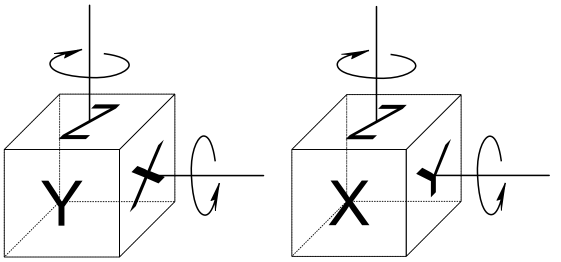

Figure 9: Excitation of three directions with a two axis system

In a development phase, when more information of the IMU characteristics is needed, only two axis can be exited simultaneously.

The availability of a three axis motion simulator gives the development engineer fullest flexibility in testing and evaluation of IMU characteristics. The effects of all three axes can be separated: Rate linearity, cross coupling errors, static error between the axes. Ultimately a 3-axis motion simulator fitted with temperature chamber, to investigate effects over different temperatures and at different temperature rate of change.

Accelerometer testing

Accelerometer can be tested on motion simulators in two different ways. Simple calibration procedures for +/- 1G can be tested on a horizontally aligned table axis, similar to a static dividing head.

To induce accelerations larger than 1G the unit under test can be mounted on the table top in a distance away from the axis of rotation. The rotation speed then induces a centrifugal acceleration on the unit.

$$F = m \cdot a \cdot \omega^2$$

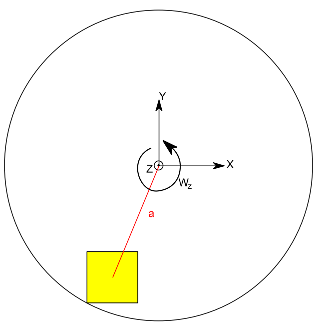

Figure 10: Centrifugal Force

Specially designed two axis systems can sequentially perform all both of the above explained functionality. With the outer axis at 90deg position, the inner axis positions the UUT with respect to +/-1G or any value in between. With the outer axis at 0deg position, the inner axis can be used like a small centrifuge. Testing values of up to 150G can be used in this configuration. High speed slipring devices and a firm fixation of the outer axis ensure save operation.

Also such a system can be equipped temperature chamber.

GNSS Augmentation Simulation

Global Navigation Satellite Systems (GNSS) are often used to augment the signals of the three axis IMU

For an integration simulation the artificial GPS signal can also be induced to the unit under test. This is made possible by means of high frequency sliprings that run through the axes of the motion simulator.

Size and inertia of the Unit Under Test

Motion simulator usually are driven by special designed, high-end direct drive motors. The motor design is determined by the axis acceleration and rate requirement.

The axis' acceleration is linked by Newton's law with the motor torque and the axis inertia. The inertia of the unit under test directly influences the axis inertia.

Consider the number of UUTs to be tested at the same time: The off-axis distance increases the inertia seen by drive train. See the example below for one single UUT or four UUTs respetively.

$$J_{tot} = 4 \cdot m \cdot a^2 + 4 \cdot J_Z$$

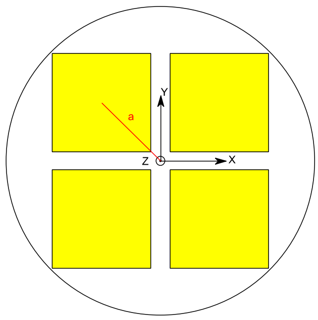

Figure 11: Inertia calculation for four units under test

Static Accuracy Requirements

When performing cross axis coupling tests like described above. Zero position and 90 in the inner axis to excite different senor axes of the unit under test, then errors like position accuracy go directly into the cross coupling error of the device cannot be distinguished.

Alignment of the sensing device within the sensor package, alignment of the sensor package on the motion simulator and position accuracy of the motion simulator all of those cannot be distinguished and separated easily.

Axis Orthogonality

Axis Orthogonality means how accurate the angle between two axes is close to 90degrees. Typically error values around 90 degrees nominal are considered. Non Orthogonality induces rate cross coupling effects periodically with the full rotation of an axis.

Axis Wobble

Wobble means the tumbling of an axis or bearing system. Precision machining and high quality, preloaded bearing systems reduce the wobble and ensure that conditions are repeatable. The wobble is typically measured in indicating the maximal runout of the axis

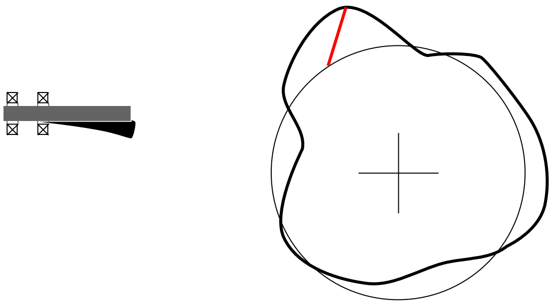

Figure 12: Axis Wobble

Position Accuracy

Position Accuracy is indicated as error between the true position from the measured axis position as given by the used position transducer. The combination of a coarse transducer, that produces position signals over a full axis turn with a incremental transducer, providing exact position information over fractions of a full axis turn, give always an absolute position signal of the axis. No homing or indexing procedure is necessary at the beginning of the test.

Typical position accuracy figures indicate maximum error values or combined calculated error measures of the incremental errors as well as the full rotation errors.

By mounting the transducer directly on the axis shaft, coupling errors and hysteresis effects are reduced.

Pointing Accuracy

Pointing Accuracy is a calculated as a mathematical combination of Orthogonality, Position Accuracy and Axis Wobble.

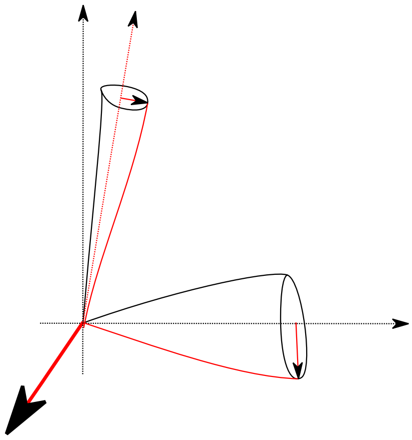

Figure 13: Wobble-, Orthogonality- and Position error constitute the pointing accuracy

In a first order approximation, the error values from the single measurements are combined using a RMS formula:

$$Pointing = \sqrt{W_{IA}^2 + W_{OA}^2 + PA_{IA}^2 + PA_{OA}^2 + O_{IA-OA}^2}$$

Dynamic accuracy requirements

Dynamic requirements, for example achievable frequency response or acceleration and rate capabilities drive the mechanical stiffness of the design as well as the dimensioning of the motors.

Rate and Acceleration Capabilities

The acceleration requirement is the primary driver of the motor power to be installed. The motor power is by Newton’s law directly linked with the acceleration and the inertia.

The requirements of the three axes are linked together by the design. A high acceleration requirement on an inner axes leads to a big motor on the inner axis. This in return increases the inertia of the following axis, again driving the need for a bigger motor on the middle axis and so forth.

Acceleration requirements therefore need to be chosen with care as they have exponential consequences on system size, performance and price.

The maximum required rate is the second design driver for dimensioning an electric motor and the power amplifiers. Given the physics of an electric motor the maximum torque (acceleration) cannot be achieved at the maximum rate.

Special use cases of the system, such as highly dynamic and long term frequency oscillations have to be considered and analysed in details for the design of a motion simulator.

Special measures like water cooled motors or design criterias are applied to accommodate almost every scenario required for a successful system testing

Frequency response testing

The frequency response of the motion simulator is tested by applying a sinusoidal motion. A sine wave generates time varying commands for all three motion states (position, rate and acceleration), therefore characterizing a real dynamic motion. The bode plot depicts the amplitude ratio and the phase shift in decibel between position command and position feedback on a logarithmic scale. Below is a typical measurement of a position bandwidth measurement, the example has a 25Hz closed loop bandwith.

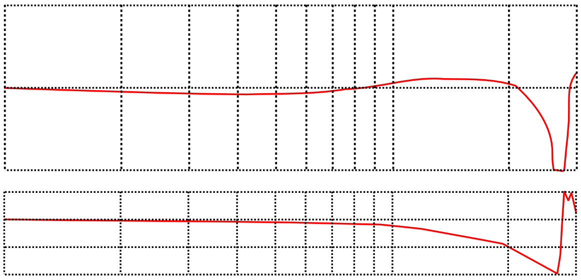

Figure 14: Sample Bode Plot

The bandwidth capability of a motion simulator is influenced by the structure's Eigen frequencies. State of the art controller, including multi-state observer and feedforward techniques can tune the frequency response close to the natural frequency of the system.

The servo settings are optimized for minimal phase lag at low frequency and virtually no overshoot in the passband of the system.

Instantaneous Rate Performance

An improved instantaneous rate performance can reduce the testing time significantly. For rate linearity measurements for example, fewer numbers of full simulator turns are necessary for data collection.

The controller's ability to model and compensate deterministic error models, such as the transducer error and ripple torque compensation allows to keep the rate at precisely controlled values.

Temperature Chamber

Typical gyroscopes and accelerometer show varying characteristics under different temperatures. Almost all types of motion simulators can optionally be equipped with a temperature chamber, allowing the system engineer to characterise the sensors at different temperatures.

Rate linearity correction factors for arbitrary temperature set points are determined without changing the unit under test. Temperature gradients are fully controlled and can be set to the needed level.

Temperature ramp rates, operating range and running cost will determine the type of cooling applied. The out-gasing of liquid nitrogen or carbon dioxide provides steep ramp rates and very low temperatures.

Mechanical refrigeration units are best suited for series testing and long time cooling periods; over the product live cycle the operating costs are much lower and there is no gas supply needed.

Vacuum Chamber

Vacuum or combined temperature and vacuum chambers over a wide pressure range can be fitted on a motion simulator. Depending on the level of vacuum, different approaches of cooling come into place. Air convection has reduced cooling capacity as the level of vacuum increases.

For high vacuum type systems, radiation and heat conduction are used to cool the unit under test. For a uniform temperature distribution a metallic shroud surrounds the device under test.

CONCLUSIONS

Simulation and test systems most effectively save time and money in the development and calibration of sensors and the development of algorithms for navigation, guidance and control systems. Both the inertial test instrument and the simulation system must be transparent to the user, but in somewhat different ways.

The test engineer insists that the test instruments are a magnitude better in position accuracy and precise motion than the sensor under test. Under these conditions test instruments are truly used as a reference: Test instrument’s errors can be ignored.

The simulation engineer demands excellent dynamic characteristics, supported by an efficient real-time motion controller. Such systems allow simulation of real-life scenarios with high fidelity. Under these conditions the main interest concentrates on the observation of the sensors or control algorithm ignoring the quasi-static errors of the simulator.

The variety of applications for both groups of test instruments and simulation systems is reflected in the instruments developed to reproduce the required real-life situation: the differences are visible in the mechanical design.

The design criteria discussed in this paper are limited to major design drivers. Nevertheless, they represent the main factors and interactions with the highest cost impacts.

Motion simulators are investment goods, therefore present as well as potential future applications for the system have to be considered. A cross check of design criterion versus application is highly recommended to optimize the motion simulator specifications.

Naturally, definition of requirement specifications at an early stage of the project is difficult. Motion simulators remain tailor made products for most space application, allowing the system engineer to incorporate extra performance reserves for potential future programs.