Design and development of the Nozzle Deployment Mechanism for the Vinci Cryogenic Engine

Sigmunn Strøm[(1)], Johan Krabberød[(1)], Olivier Condaminet[(2)]

[(1)]*Kongsberg Defence and Aerospace, Kirkegårdsveien 45, 3610 Kongsberg, Norway*

Email: sigmunn.stroem@kongsberg.com; johan.krabberoed@kongsberg.com

[(2)]*Snecma, Foret de Vernon, Vernon, France. E-mail: olivier.condaminet@snecma.fr.*

ABSTRACT

Snecma Space Engine Division in Vernon, France is developing a new cryogenic upper stage rocket engine, VINCI, for future version of the Ariane 5, the A5ME (Ariane 5 Midlife Evolution). Kongsberg Defence and Aerospace, Norway are responsible for the design, development and delivery of the Nozzle Extension Deployment Mechanism (MDD = Mécanisme Déploiement Divergent).

The deployment mechanism is a complete new design functionally and structurally and includes use of novel components and materials.

The paper describes the design principles, analysis methods, test campaigns and general information about obtained performance, electrical architecture and the integration cycle of the MDD on the Vinci Engine.

1. INTRODUCTION

Snecma Space Engine Division in Vernon, France is developing a new cryogenic upper stage rocket engine, VINCI, for A5ME future version of the Ariane 5. Kongsberg Defence and Aerospace, Norway are responsible for the design, development and delivery of the Nozzle Extension Deployment Mechanism (MDD=Mechanism Deployable Divergent).

Astrium is responsible for the development of the CRIUS stage, and ESA/CNES is project manager of A5ME.

The introduction of a deployable nozzle extension on the Vinci engine provides a 5 % increase in engine thrust with a corresponding payload increase. The Vinci engine with the nozzle stowed and extended is shown in Fig. 1.

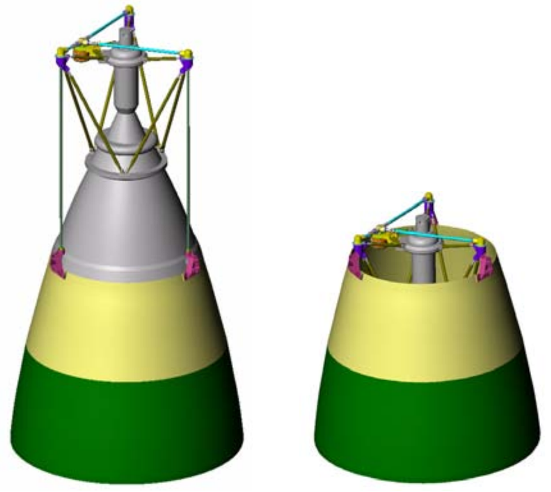

Figure 1. Vinci with MDD – shown in Stowed and Deployed position

2. REQUIREMENTS

2.1 Main Requirements.

Three main functional requirements determined the architecture of the MDD. They are:

The nozzle extension is to be deployed 1830 mm and latched in < 10 s.

Latching resistance is defined by a statistical distribution.

Kinetic Energy at latch must be < Ecmax to avoid damage of the nozzle by the final impact.

To satisfy these requirements a deployment sequence as shown in Fig. 2

Other design driving requirements were:

- Electronic speed control could not be used
- Limited battery capacity for deployment and sequencing.
- Endurance of vibration loads during launch of the first stage of the launcher.
- Minimum mass
- Dynamic behaviour of the deployment mechanism - nozzle extension system

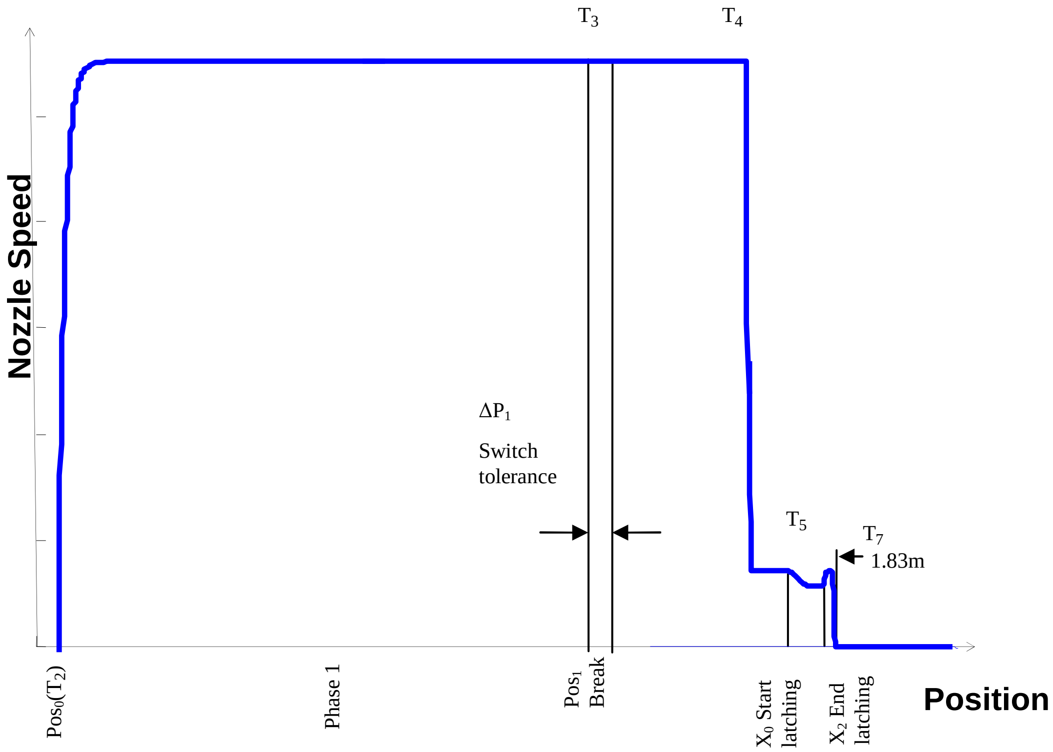

Figure 2. Principle deployment sequence at Hot and Cold conditions

2.2 Design Restrictions

The three main functional requirements are in conflicting with each other.

High deployment speed is required to meet the deployment time target, while requirement for low kinetic energy requires a low speed.

Sufficient latching force is required to guarantee latching for worst case conditions, but limited in order not to damage the fixed or the extendable nozzle.

The speed of deployment could only be controlled by the equilibrium between the speed torque characteristic of the motors and the frictional and inertial resistance in the gears and ballscrew system.

3. DEPLOYMENT MECHANISM CONCEPT EVALUATION

Several system concepts were investigated attempting to satisfy all requirements. Initially a concept using two identical brush motors, one acting as a brake/generator and one driving through the same gears was proposed. One of the motors was short circuited to a generator/brake a short distance from the latching point. The required combination of high deployment speed, low latching speed and the required latching force was not obtainable.

It became clear that two different motors with different gearing ratio were required.

The selection of the two motors torque-speed curves and the motor to ballscrew gear ratio and ballscrew pitch was an essential and critical part of the system design. To minimize the effect of the variation in friction in the deployment system the motors had to be specified to operate at approx. 60 to 80% of the no load speed.

The ESA rules for mechanism torque margin calculation (ECSS-E-30-8A) could not be used to stay in the allowed latching force. The requirement for a safety factor of 3 on friction and a motorization factor of 2, leads to a motor torque capability 6 times that theoretically required. This "oversizing" of the motors to satisfy the ESA rules for the latching effort led to low or negative margins on deployment time and kinetic energy specifications.

A probabilistic design approach was therefore used. The most significant variables in the deployment analysis were assigned a mean value and a range of variation. Depending on the type of variable a normal distribution with a standard deviation or a uniform distribution was used.

A Monte Carlo method was used to make up to 1 million draws to calculate the mean value and the standard deviation and then to demonstrate the level of reliability for meeting the requirement specifications.

4. MDD DESIGN DESCRIPTION

4.1 General

The MDD design consists of three ball screws, 120° apart, supported by struts at the upper end and by the fixed nozzle at the lower end. The ball nuts are attached to the extendable nozzle via flexible couplings. Each ballscrew is driven through a gear chain consisting of a 90º gearbox, a transmission shaft, a "three shaft" main gearbox, and two electrical motors. A block diagram of the MDD is shown in Fig. 3 and a drawing of the complete MDD is shown in Fig.4.

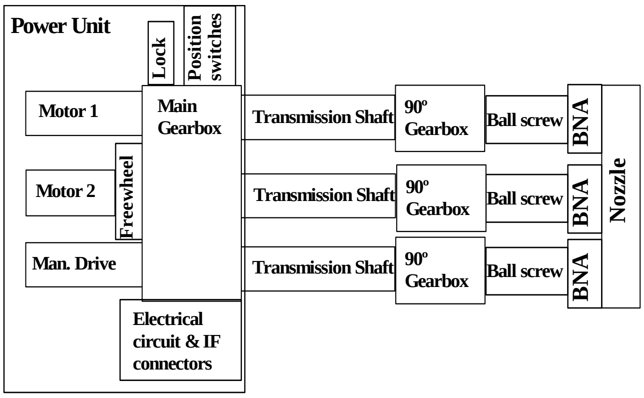

Figure 3 MDD block diagram

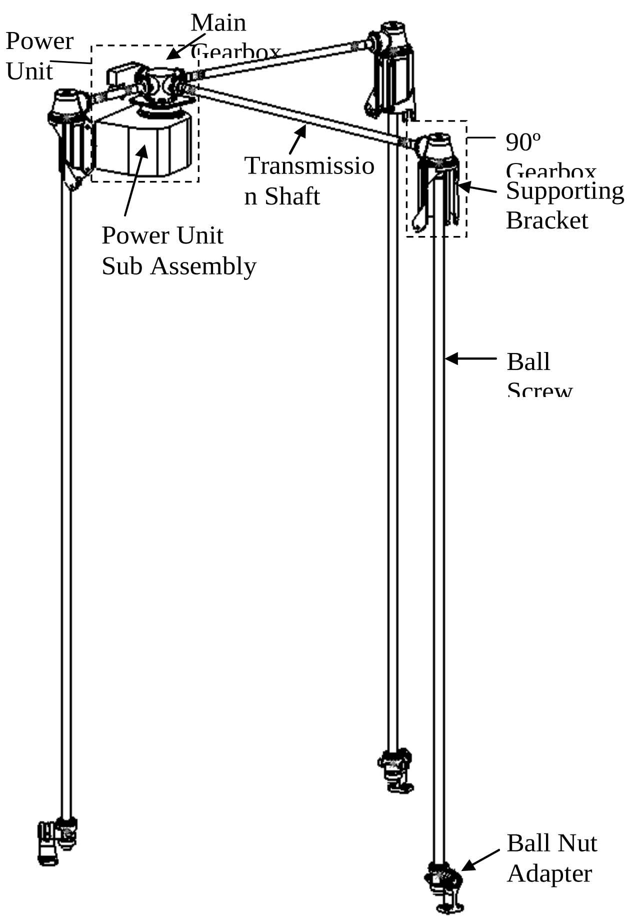

Figure 4 MDD components

The central Power Unit contains:

- Motor 1 driving through a spur gear.
- Motor 2 driving through a geared freewheel and a spur gear.
- Main gearbox with three output drive shafts
- Locking Mechanism with manual operation access.
- Position Sensor
- Electronic circuits with sequencing and switching relays

4.2 Mode of operation

During EAP-EPC flight phase of Ariane 5 the nozzle is locked in stowed position by a locking arrangement in the power unit.

The deployment is initiated by command from the Ariane 5 control unit (SEL). The MDD is from this moment fully autonomous and controls the deployment sequence.

The sequence starts with the release of the locking mechanism by operating a memory alloy pin puller before powering the motors.

Motor 1 is driving in high speed phase of the deployment, while Motor 2 is idling via a free-wheel. The brake-position, at approx 95 % of the deployment distance, is detected by the Position Sensor integrated in the Power Unit. At this moment Motor 1 is switched off and short-circuited by the sequencing electronics to provide dynamic braking before the latching phases.

In the latching phase Motor 2 provides the driving force.

4.3 Component design

4.3.1 Motors

KDA identified three suppliers of aerospace/launcher qualified brush motors. Two US suppliers, Kollmorgen and MPC and one French supplier, Artus.

Based on KDA's simulation for the MDD system for a range of ball screw pitch, gear ratios and motor characteristics a requirement specification for the motors were developed in cooperation with Artus. To limit cost, both motors were built with identical external dimension and common internal parts to the extent possible.

Motor 1 was specified with low torque constant and low winding resistance for the high speed low torque deployment duty.

Motor 2 was specified with high torque constant and high winding resistance for the slow speed high torque latching duty.

Figure 5 Motor 1 (deployment motor) with pinion.

4.3.2 Gear Chain

Several variables determine the ratio between the motor speed and the linear deployment velocity and latching force.

Motor 2, the latching motor, need a large ratio from the rotational speed to linear nozzle velocity, this can be obtained by a small pitch ball screw and relatively large gear ratio. Motor 1, the deployment motor, needs a small ratio from rotational speed to linear nozzle velocity, this can be obtained by large pitch ball screw and smaller gear ratio. The difference in gear ratio is obtained by engaging Motor 2 to the external diameter of the freewheel, in that way a two stage parallel gear is obtained for Motor 2 as shown in the drawing in Fig. 6. Motor 1 is engaged directly to the crown wheel. This solution in combination with a compromised ball screw pitch provided the right combination of speed and torque in the different phases of the deployment.

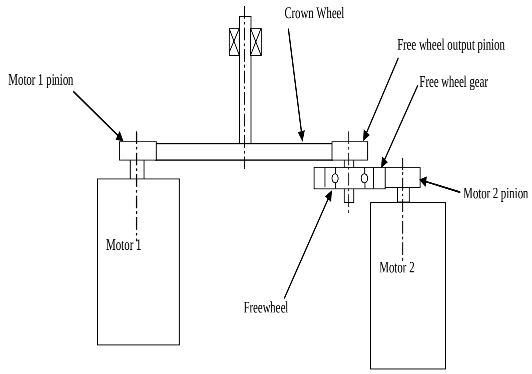

Figure 6 Motor1 and Motor 2 gearing arrangement

The torque from the motors is turned from vertical to horizontal and split to the 3 ballscrews in a gearbox with 4 output shafts as shown in Fig.7. The 4th shaft is used for the manual drive and the locking mechanism.

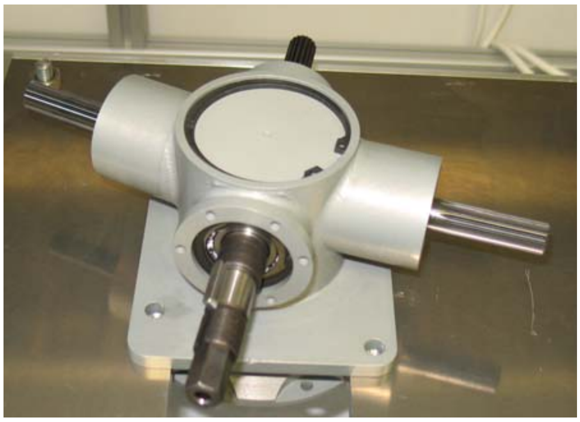

Figure 7 Gearbox with 4 output shaft.

The drive torque is connected to the ballscrews via 3 slender transmission shafts with universal joints and 3 90ºgearboxes, as shown in Fig.8. The arrangement on the Vinci engine is shown in Fig 9 and the 90ºgearboxes.in Fig 8.

Figure 8 90ºgearboxe

The main driving requirement for the gearboxes is the dynamic loads during launch which transmitted through the gearboxes to the Locking Mechanism and the need to limit the variation in efficiency and the no load frictional torque over the operating range.

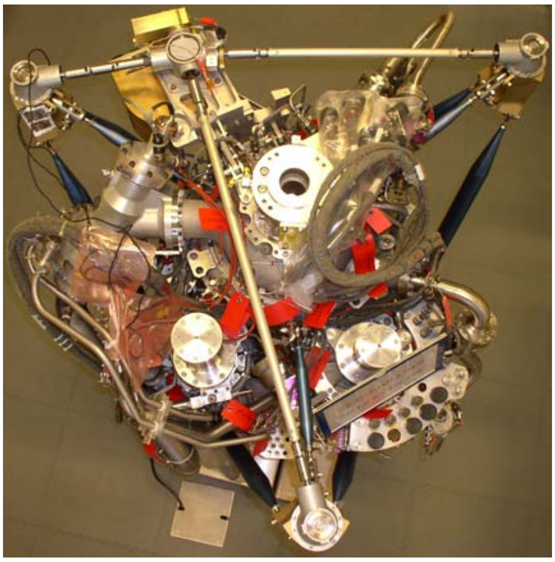

Figure 9 Vinci engine seen from the top with the MDD installed.

Lubrication: Due to the low life requirements wear or loss of lubrication is not a critical factor. One of the main criteria for selection of lubrication was to have a low variation in viscosity with temperature to reduce the variation in frictional torque.

4.3.3 Ballscrews

During the design selection, ball and roller screws from Thomson Saginaw (Danaher), SKF Transrol and Rollvis were considered.

To satisfy the thermal, strength and mass requirements hollow titanium ball screws was selected. The only supplier with space heritage was Thomson Saginaw in the US/UK. The upper end of the ballscrews with the ball nut is shown in Fig.10.

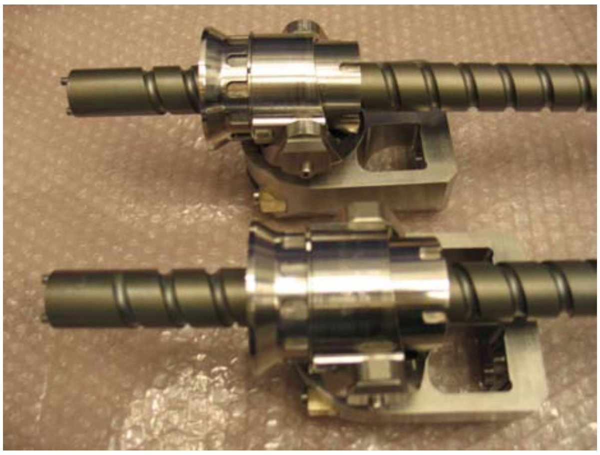

Figure 10. Titanium ballscrews attached to the nozzle connection bracket.

Possible vibration of the ball screw during Launch and nozzle deployment has been a major concern, and the rotational speed range of the ballscrews during deployment must not excite a fundamental mode of the ball screw-nozzle dynamic system. Modal analysis and forced response analysis were performed for the system both for the stowed situation and during deployment. After dedicated analysis, no excitation was predicted.

Lubrication: As for the gearboxes, due to the low life requirements wear or loss of lubrication is not a critical factor. Dry lubricant was therefore considered for the ballscrews mainly.

4.3.4 Locking Mechanism

The purpose of the locking mechanism is to secure the position of the nozzle in stowed position.

In the locked mode the locking mechanism is designed to hold extendable nozzle in stowed position. The locking Mechanism is shown installed on the Power Unit in Fig.11

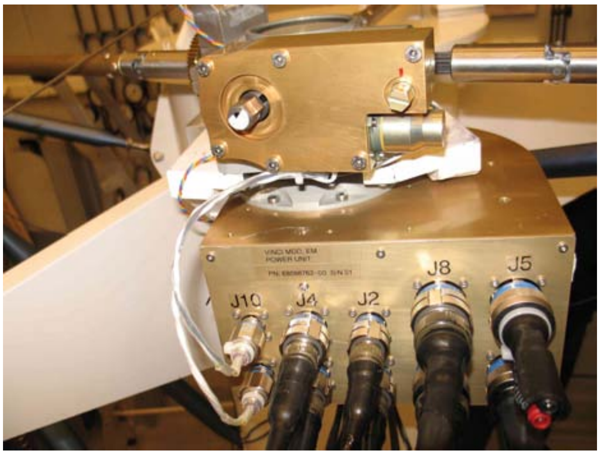

Figure 11. Locking *Mechanism installed on the Power Unit*

The locking is achieved by locking the gear shaft which goes through the gearbox and is directly attached to one of the transmission shafts.

At deployment a pinpuller is activated to release the locking mechanism. The pinpuller has a redundant electrical circuit. Once energised (released), manual reset will be required to lock.

The pin puller and its reset tool are shown in Fig.12.

Figure 12. The pin puller and its reset tool

4.4 Performance Prediction

The Vinci MDD power and transmission system is modelled in Matlab/Simulink software. The Simulink model consists of a “Top Model” and several “sub models” as shown in Fig. 13. The top model’s main function is to switch between Motor 1 and Motor 2 as the drive torque provider after the braking point. The sub models for the two brush DC-motors solves the differential equations using a standard graphical modelling approach. In addition, battery supply, latching resistance force, bearing friction gear efficiencies and data acquisition are important aspects of the Simulink model.

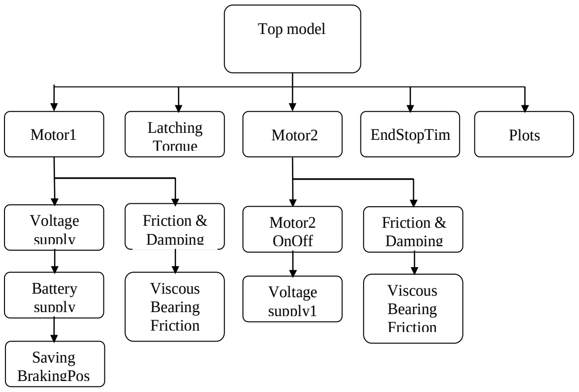

Figure 13 Simulink model hierarchy

The Monte Carlo simulation using the Simulink model is run from a Graphical User Interface (GUI) which runs the different Matlab scripts and the Simulink model for each simulation.

The simulations were performed at expected operating conditions for the Vinci engine. Values for 10 variables were randomly drawn within a specified distribution. The number of runs for each simulation varied from a few hundred for initial analysis to several 100 thousands for final results of the analysis. Fig. 14, 15 and 16 gives examples of the output from the simulation program.

As an example would zero violations of the requirement within a sample of 230000 draws, represent a single event probability of less than 10^{-5}

From this analysis we were able to assign probability numbers for compliance to the three main functional requirements.

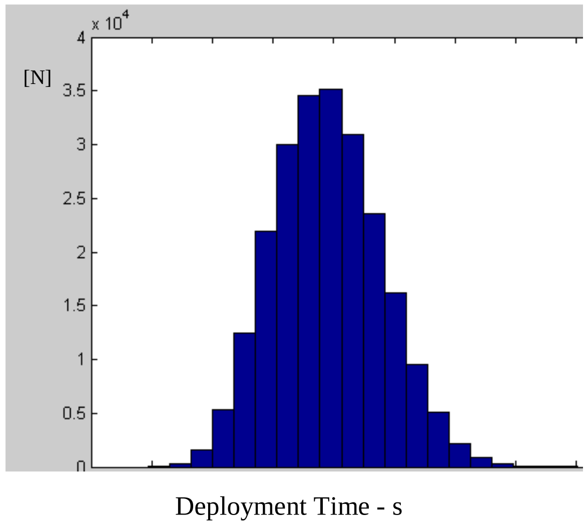

Figure 14 Histogram of predicted Deployment Time.

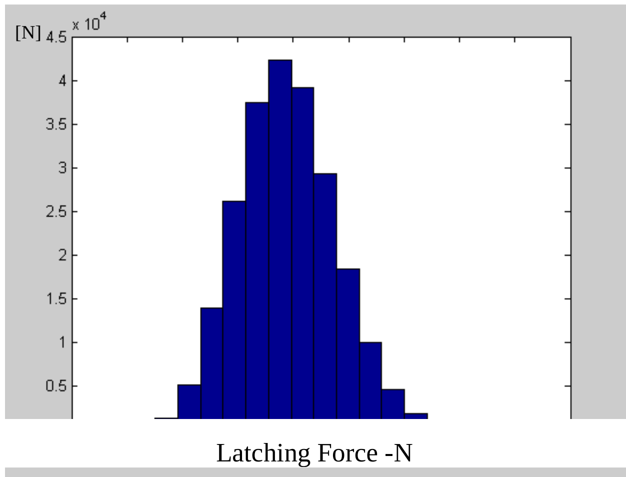

Figure 15 Histogram of predicted latching force:

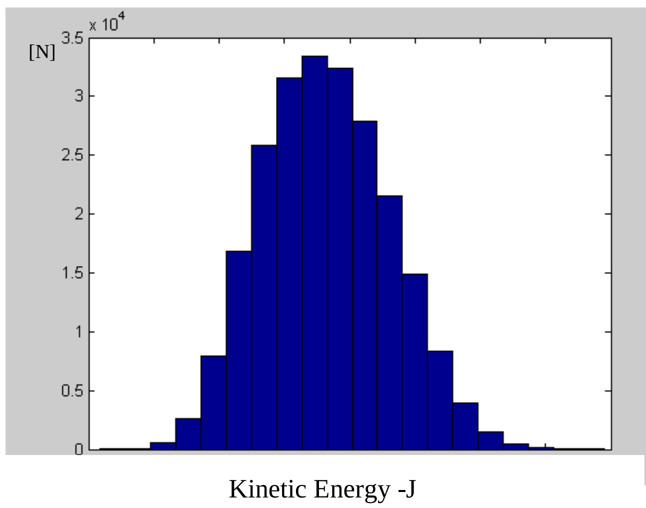

Figure 16 Histogram of predicted Kinetic Energy at latch.

5. TEST CAMPAIGNS

Two test campaigns have been performed; one at KDA where a MDD Engineering Model has been tested and one at Snecma where the 1st development Model of the MDD has been tested installed on the Vinci engine.

5.1 MDD -EM Testing

KDA has manufactured and tested an Engineering Model of the MDD. A test jig simulating the interfaces attachment points on the Vinci engine has been designed, built and used for testing of the MDD-EM (Engineering Model) at Kongsberg. The nozzle was represented with a ring with the correct mass and attached to the ballscrews nuts with a representative radial stiffness. Micro gravity was simulated by a mass and pulley arrangement.

The rig was used to establish assembly procedures, in particular for the assembly of the ballscrews challenging in order to obtain the required parallelism between them.

Deployment tests were performed over a range of input voltage and temperatures.

Figure 17. MDD-EM installed on the Test-Jig at KDA.

In total approximate 70 powered deployments have been made under different conditions.

Good agreement has been obtained between prediction and test values for the 3 main functional requirements; deployment time, latching force and kinetic energy at start of the latching phase. Both the analysis and the tests values are within the requirements.

5.2 MDD within Vinci engine:

A sensitive specification:

Due to the high level of interconnection of the MDD, with the others VINCI sub-systems, the VINCI engine system, and the launcher system as well, the MDD specification has to make a complex synthesis of everybody's needs:

- For the electrical system, it has to specify relevant electrical interfaces and an acceptable electrical architecture as well.
- For the ESC-B stage, it has to specify the relevant values of voltage and the maximum deployment time.
- For the VINCI engine, it has to specify the relevant load cases, thermal and interfaces specification.
- For the other VINCI sub-systems, it has to specify the necessary effort for latching the nozzle extension and also to specify a maximum level of kinetic energy at the end of the stroke.

Complex test conditions:
Lessons learned on previous development have highlighted the importance to perform tests on the basis on the "Test as you fly" logic.

Applied to the MDD, this logic requires performing deployment tests in vacuum and in cold conditions as well.

Moreover, as operating on an upper stage engine, the MDD has to demonstrate its capability to operate a deployment after withstanding loads applied during the 1st part of the flight.

Dynamic characterization
A complete engine experimental modal analysis was performed at the end of 2008 in Snecma-Vernon facilities. It provides the knowledge of the overall dynamic behaviour of the engine and leads to the identification of locations of the structure where an excessive dissipation of vibratory energy may result fatigue damage or local fretting. The modal analysis is performed with the engine hanging from a support frame in a free configuration using dynamic actuators in several excitation points. In addition to the modal characterization based on low level sine sweeps, higher excitation levels are applied at specific frequencies in order to observe possible non-linearities. Special attention was paid to the support structure of the nozzle deployment mechanism which is a large low frequency structure prone to be excited by the dynamic environment of the booster ascent phase. As an example of a design consolidation activity, stiffening rods were added to the nozzle deployment support frame in order to increase its level of robustness and increase its natural frequencies.

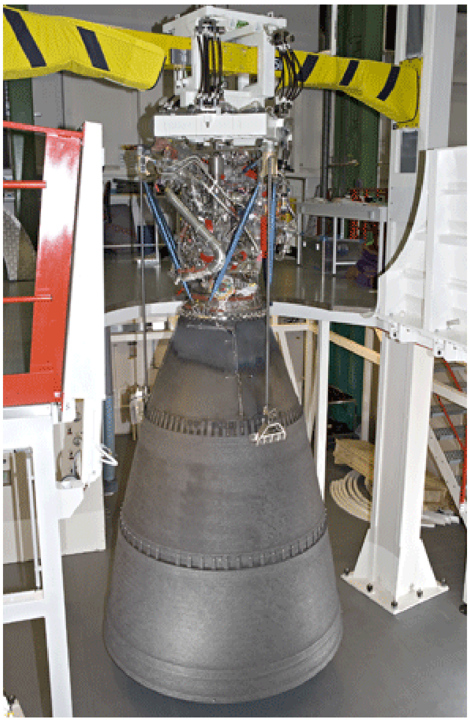

Figure.18 shows the Vinci engine with the nozzle extension during dynamic characterization and deployment tests at Snecma

6. CONCLUSIONS

Performing the design using a probabilistic approach has proven to result in a sound design where a good compromise between conflicting requirements is obtained.

Results from development tests on the 2 initial hardware of the deployment mechanism are encouraging.

The present status forms a good basis for further development and qualification in time for the introduction on Ariane 5ME in 2015.

7. ACKNOWLEDGEMENT

The authors like to thank the management at Snecma and Kongsberg Defence & Aerospace for their support and confidence our ability to provide solutions to the challenging tasks.