IBDM ELECTRO-MECHANICAL LINEAR ACTUATOR

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ABSTRACT

This paper presents the design process and the description of the verification campaign of the Linear Electro-Mechanical Actuators (EMA) for the International Berthing and Docking Mechanism (IBDM) soft docking capture system. The actuators will be the driving elements of the hexapod mechanism that is the key capture system for the docking and berthing mechanism developed with ESA fundings. It is described the design process from the definition of the actuator needs, the selection procedure of the main components, the design of the mechanism configuration and the final design of the actuators. The validation campaign is also described to show the way the key performance parameters are being verified.

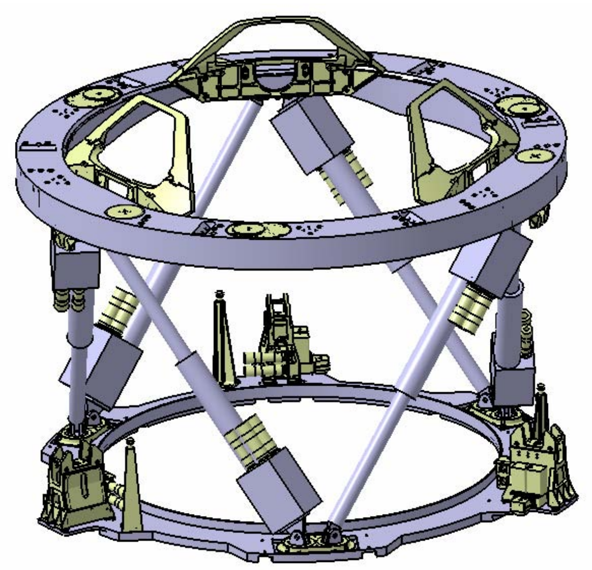

Figure 1 IBDM soft docking/berthing platform

1. INTRODUCTION

The Linear Electro-Mechanic Actuators (EMA) are the link between the base ring and actuated ring of the IBDM mechanism. Six actuators are setup in hexapod parallel cinematic mechanical configuration. The aim of the actuators is the correct positioning of the IBDM intermediate ring.

The actuators provide positioning and force accuracy with low backlash, back-driving force, as well as high linear speed.

These performances are required to have a robust control of the platform which is controlled in a closed loop by measurement of contact forces at the guiding rings and by driving the actuators to maintain these forces within a given range to avoid any rebounds during the capture process.

The linear speed of the actuator shall be comparable to that of the approaching vehicles during docking in order to be able to match the alignment ring velocity with the vehicles velocity both linear and angular.

Force capability is less important than how this force is applied to the system. The force increments need to be provided accurately and rapidly, in order to react to the contact forces which profile is short in time. The accuracy of this force is related to the back-driving force, which defines the force “noise” of the actuator that is directly linked to the control loop performance.

The actuators include a lead screw, a gear train and brushless motors. Position feedback is provided by an absolute encoder which provides absolute position feedback to the controller.

The development and verification process includes one validation actuator and six additional ones for integration in the hexapod. The validation model will be extensively tested to verify all requirements by testing while the six additional units will be verified by either testing or similarity.

The main functions of the linear actuators are:

- To withstand launch and in orbit environment
- To provide linear movement for positioning the six degrees of freedom table, with a computer controlled kinematics
- To provide command interface to the six dof table controller
- To provide feedback of the actuator parameters (length, status of end stops) to the EMA controller

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- To provide controlled stiffness in orbit during docking/berthing operations
- To drive the six dof table with the speed characteristics required to perform capture
- To provide push/pull force enough to attenuate the impact between the two mating parts

2. REQUIREMENTS DEFINITION

The requirements for the IBDM Linear EMA were defined initially according to preliminary analyses of the IBDM. System analyses run parallel to this actuator development, including the mechanism, avionics and control. It was found that the initial requirements covered the system requirements, but additional ones would be implemented to achieve a robust control and system performances.

2.1 Key Requirements

- Length of the actuator between 444mm retracted length and 737mm extended length (293 mm stroke).
- Linear accuracy of the absolute position monitorization better than 0.25mm over the full stroke (better that 0,1%)
- Speed from zero to 0.125 m/s peak speed.
- Back driving force less than the maximum trust capability.
- Nominal thrust of 900 N in either tension or compression along the entire stroke and a peak thrust of 2200 N.
- The actuator linear stiffness in the direction of thrust/motion higher than 5e5 N/m
- Backlash lower than 0.075 mm
- Mass less than 5 kg including harness.
- The maximum external diameter of the housing tube surrounding the thrust output tube shall be 44 mm.
- The motor-sensor-gearbox cluster maximum envelope dimension of 80 x 90 x 132 mm.
- Mechanical connection by a through hole on a lug.
- Actuator output with free rotation around the longitudinal axis.

2.2 Environmental requirements

- On ground ambient:
  - Non operational temperature: From 0ºC to 50 ºC.
  - Operational temperatures: From 15ºC to 30ºC
- Launch, In orbit and TV environment:
  - Non operational temperature: From -55ºC to 85ºC.
  - Operational temperatures: From -40ºC to 80ºC
- Quasi-static acceleration of 40 g in any direction.
- Random vibration environments of 16.9 grms in any direction.

2.3 Updated performance requirements

As a result of the system activities, additional requirements were identified:

- Minimization of friction losses in the actuator
- Improvement of the accuracy of the position monitorization
- Improvement of speed with reduced load capability

3. IBDM LINEAR EMA TRADE-OFF

The analysis of alternatives was divided in two parts: The first part focused in the arrangement of the different components of the actuator. The second part is the selection of the actuator components to better fit the requirements.

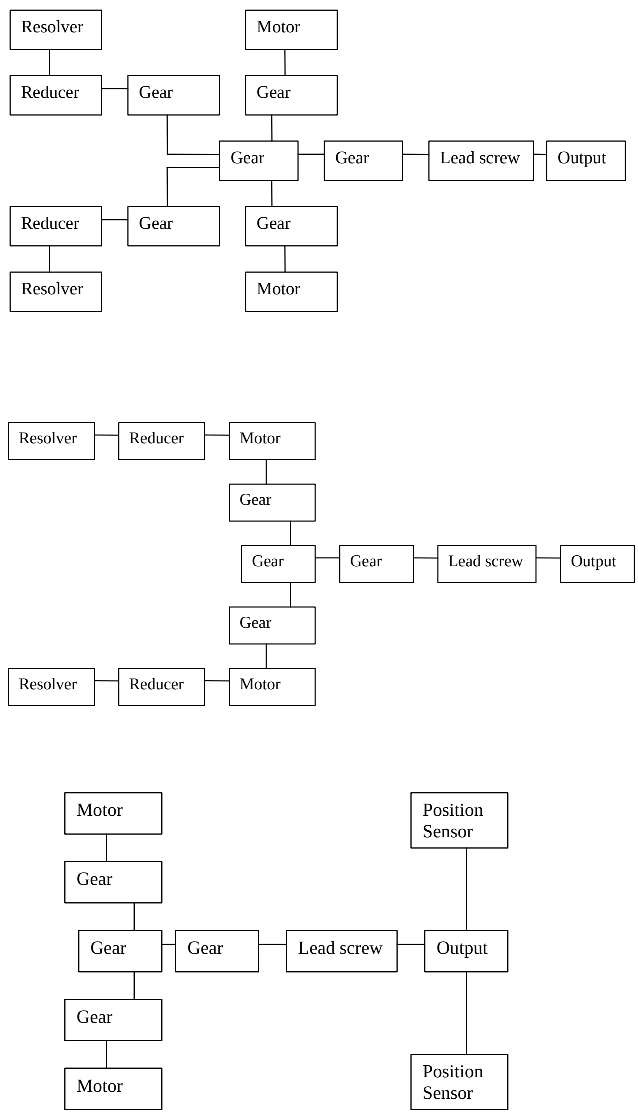

Figure 2 Components arrangement options

3.1 Components arrangement trade off

In the study of the alternatives for the disposition of the components, three main architectures were studied:

- One arrangement in which the position sensor is mounted independently to the motor. The monitorization of the position is taken from a free wheel that connects the motor gear with the lead screw gear.
- A second arrangement in which the position sensor is mounted directly in the motor shaft through a gear. The monitorization is taken from the motor position.
- The third configuration includes the implementation of the position sensor directly on the lead screw output, in such a way that linear displacement is measured with a LVDT.

The main evaluation criteria were implementation difficulty, efficiency (and friction losses) and sensor accuracy. Figure 2 shows the alternatives considered.
The third configuration was rejected because any implementation of linear sensors requires the constraining of the rotation of the output thrust in the longitudinal rotation axis. In addition, the inductive sensors require a length that is double the available length of the actuator. Other linear sensor concepts investigated had several implementation disadvantages.

The second option was not good for volume and accuracy reasons. The implementation of the sensors in the same axis of the motors needs a lot of longitudinal volume. In addition, the connection between the sensors and the lead screw is very large, with several gears and the motor between both. And the necessity to reduce the high speed of the motor to low rotations of the sensor makes necessary the introduction of a very high reduction ratio between them.

Finally, the chosen option was the first one, in which the volume necessity is the minimum, and the used gear ratios are not so high. For accuracy reasons, is the second best configuration from the three analyzed options with two gearing steps between the lead screw and the sensor.

3.2 Actuator components trade off

- **Lead screw**

Several lead screws have been studied and identified as potential constituent of the actuator.
The main parameters defining a lead screw are:
- Type of lead screw that can be based on rollers or balls. The roller screw in principle has better resolution and load capability but also more wear and reduced life. Ball screws provide higher efficiency.
- Pitch of the lead screw define the displacement of the output versus rotation of the screw. Having a linear speed requirement defines a rotation speed as a function of the pitch.
- Rotation speed of lead screws is a limiting factor for the selection. Roller screws have lower speed limit than ball screws.
- Load capability of nut is higher in the roller screws. For the same size of screw the ball screw have also deeper grooves for the ball tracks thus reducing the buckling capability.
- Efficiency of the ball screw is higher than the roller screws at high speeds. Efficiency is an important factor for defining the force-speed curves with a given motor.
- Axial play and stiffness is also a factor for the selection, however in this application play is allowed and the lead screws either ball or roller meet the 0.075 mm play requirement. Preloaded ball screws or roller screws are also available with increased stiffness and zero play but with a reduced efficiency and speed limitation.

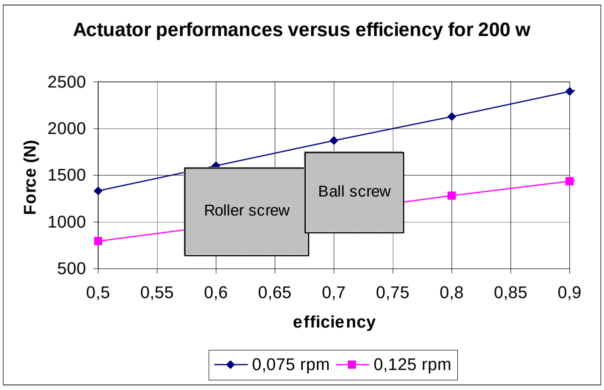

Figure 3 Lead screws performances

- **Motor:**

A Motor characteristic curve is already defined in the specification and the trade off is really a screening of the available motors in the market that can fit with the requirements and can provide the desired performances.
Different motor speed-torque curves means different actuator design in order to achieve similar output characteristics in terms of speed-force. Three European manufacturers have been investigated and the characteristics of several motors have been compared to identify the best option. They have been selected considering:
- Product range for the sizes of 200 w motors
- Heritage or experience in Space or Military programs
- Performances of torque versus speed

Figure 9 shows the comparison between the motors identified and studied in the trade off, which are all in the range of 200 w brushless motors:
- Faulhaber motors based on commercial model 4490. Depending on the winding arrangement in star or delta

it gives two operating speeds: 5000 or 10000 rpm. It has a mass of 750 g and a size of 44mm diameter and 90 mm length

- Muirhead motor have the same characteristics of torque-speed than Faulhaber motor but is larger in size (45 mm diameter and 100 mm length). It is a custom design.
- Maxon motor operates at 17000 rpm and its mass is 270 gr being its size 30 mm diameter and 64 mm in length. It is based on commercial EC-powermax 30 serie.
- MPC motor size D which operates at 20000 rpm. This size means a diameter of 27 mm and the length is adapted to provide the desired power.

The selected motor is the Maxon one.

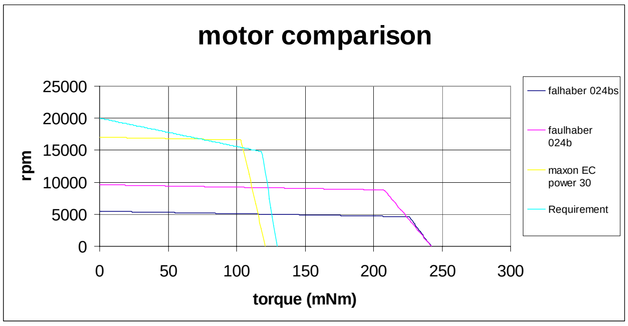

Figure 4 Motor options characteristics

- **Absolute position sensor**

Several alternatives have been investigated all with non contact feature as required in the Specification. Due to the volume requirements and the sensors characteristics, only rotary sensors can be implemented of limited size. The rotary sensors for absolute non contact position feedback and with some flight heritage are:

- Absolute encoder
- Resolver

All other position sensors are either incremental and/or with contact.

Absolute encoders are digital devices that provide the position as a digital word. The number of bits of the absolute encoder define the number of positions that it can provide. For our application it is required a 11 bit encoder that provides a resolution along the stroke of 0.15 mm. It is available a size 9 (diameter 22,35 mm) of 13 bits absolute optical encoder from CODECHAMP having a operational temperature from -45 ºC.

Absolute resolvers put the complexity of the sensor in the electronics instead than on the sensor itself. However the sensor itself is more robust and reliable. Resolvers provide resolutions in the range of arc minutes with small sizes (from 20 mm diameter). It is available, from HAROWE, a model of size 11 with a resolution of 7arcmin. The unit requires a specific driver I/F in order to provide position feed back.

The selected sensor is the encoder CODECHAMP due to the constraints in the electronics. That was an electrical I/F requirement imposed by the avionics. However the implementation of a resolver is still a valid option for the design of the actuator

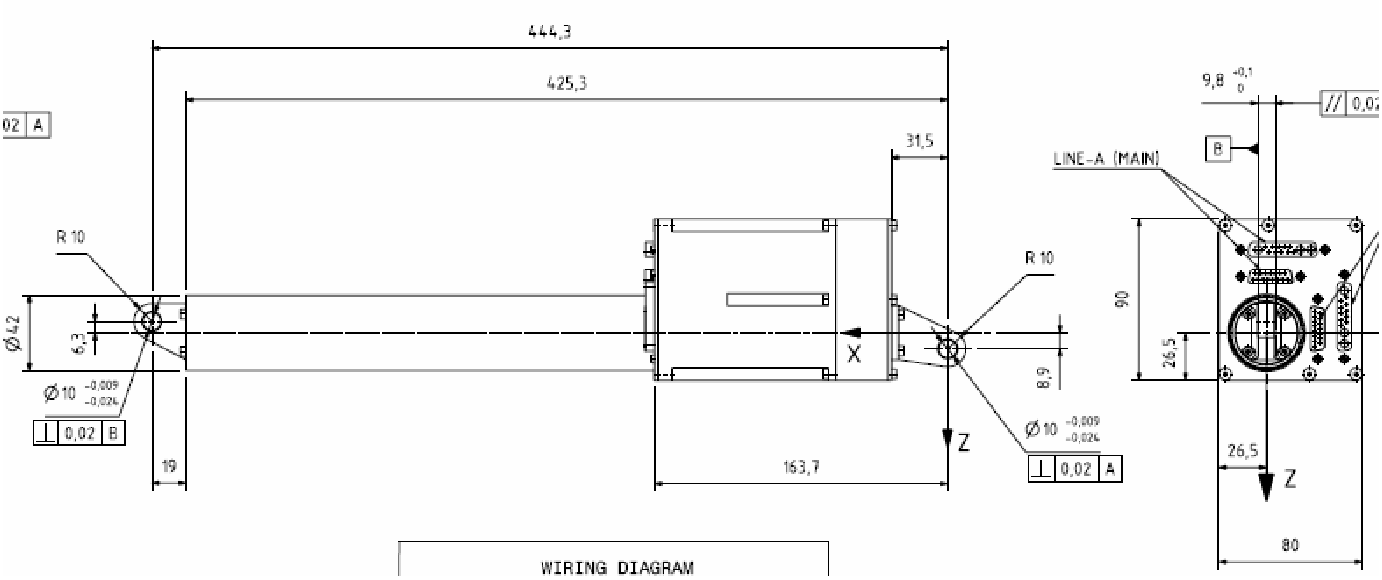

Figure 5 IBDM Linear EMA Interface Drawing

4. DESIGN DESCRIPTION

4.1 General Configuration

The linear actuators are composed of the following main components:

- Two independent brushless DC motors working in cold redundancy. Therefore the active one is dragging the passive one increasing friction losses.
- A gear train to couple the motion of motors, sensors and lead screw.
- A lead screw drive, to transform the angular motion to a linear motion.
- Two independent contact-less sensors for position monitorization.
- A base structure to attach the main components, motors, sensors and gears.
- A guiding telescopic structure to guide the linear motion and provide mechanical output interface.
- Redundant end switches to detect both ends of travel. They are magnetic reed switches to maintain the contact-less feature for all sensord
- A base fitting to provide mechanical interface between the base structure and the external I/F
- Redundant electrical connectors to provide electrical interface to the control unit with power and signal in separate harness

Figure 6 shows a general view of the actuator.
All components have been selected to be compatible with the required environments (non operational temperatures from -55ºC to 85 ºC and operational temperatures from -40ºC to 80ºC).

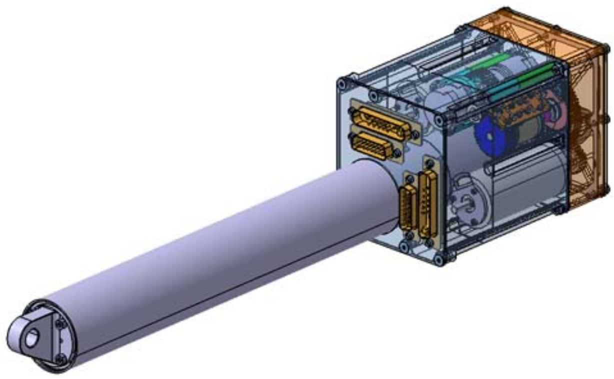

Figure 6 actuator general configuration

Actuator Operation

The brushless motor (main or redundant) actuates with an angular velocity and torque. The motor output shaft is connected to a two-stage gear train, which transmits the torque and velocity up to the lead screw.
The output shaft of the 2nd stage gear drives the lead screw that transforms the rotation movement to a translational movement of the telescopic tube that provides the required push/pull force and motion.
The actuator absolute position motorization is performed via two encoders which are connected througn an Harmonic Drive (HD) to the first stage of the gear. The HD output shaft is connected to each of the encoders via two independent gears. In this way the redundancy of the position motorization system is ensured. The encoders are single turn encoders: one turn of the HD output shaft represents the total translational stroke of the telescopic cylinder. The selected encoders have 13 bits, which provides the required resolution along the total stroke. In the same package of the encoders there are one magnet and two pairs of reed switches. One pair of the switches will monitor the initial position of the telescopic tube and the second one the end position.

4.2 Description of components

Lead screw

Lead screw baseline coming out form the Trade-off is a ball screw of 16 mm diameter and 5 mm pitch made of AISI440C. The lead screw has been selected considering the following criteria:

- Buckling capability
- Natural frequency versus rotation speed to achieve maximum speed.
- Minimization of friction losses

Lead screw manufacturer is KORTA.

Motor

Each actuator includes two brushless motors (main and redundant).
The selected for the IBDM linear actuator is a Maxon Brushless DC-200 w EC-powermax 30 with hall sensors commutation.

Position Sensor Package

The position sensor group is an independent package including the encoders, the contact less end position switches and a reducer (harmonic drive) to transform the input rotations to a single rotation at encoder level.

The Harmonic Drive is part of the position sensor package. The HD is connected to the lead screw via an intermediate free wheel, and it serves to transform the input rotations to a single rotation at encoder level.
The selected Harmonic Drive model for the IBDM Linear actuator is HDUC-5-100-SP size 5, which has a reduction ratio of 1:100. The Absolute Position Sensor is a CODECHAMP Encoder FPCOA09-01

Gear Train

The gear train is made with spur gears.
The spur gear train connects all the elements of the linear actuator. Motors are connected to the lead screw through an intermediate free wheel. This free wheel connects both the lead screw and the sensor package .
Spur gear is selected to have the maximum efficiency and the teeth are coated with Nituf to reduce friction losses as much as possible to provide a gear efficiency of 97 %.

During system level activities the load capability and speed requirements were revised and therefore different gear ratios were studied to improve speed and to reduce friction losses. Different arrangements were analysed and implemented in the design.

Total gear ratio	Maximum no load speed (mm/s)
I=11.46	110
I=9.14	137.5
I=6.47	194
I=3.04	409.5

Table 1 Gear options and speed preformances

Bearings

Bearings of the gear train are mounted with soft preload in order to minimize the friction at these stages which have a major impact in friction losses.
Lead screw is mounted in angular contact ball bearing with hard preload in order to avoid any backlash from the bearings and to provide stiffness as the only support of the lead screw which defines the first natural frequency and the maximum speed at which the lead screw can rotate.

Mechanical End Stops

The mechanical end stops ensures the linear movement of the linear actuator inside dimensions of the stroke. It can stop the motion from the maximum speed to zero without any damage of the actuator parts. Specification indicates specifically to have endstops in radial direction so the limitation is done in the rotation motion of the lead screw. The limitation of envelope and the high rotation speed of the lead screw showed very early that the dimensioning of such end-stop would require the implementation of flexibility in the end-stop in order to reduce the shock loads to affordable levels. Therefore the final design is composed by 4 pieces:
a) One torsion bar which has an end fixed to the shaft of the ballscrew, and the other free end serves as support for the rotating end stop. This bar is turning together with the ballscrew and provides sufficient flexibility in the contact to reduce the shock loads.
b) One piece denominated rotating radial stop (see Figure 7) that is fixed to the free end of the torsion bar turning with it..
c) Other 2 pieces, denominated actuator end stops, are inserted inside the telescopic tube; they have a linear movement and will be used to stop the linear actuator when the rotating radial stop contacts with them at the full deployed position or at the starting position.

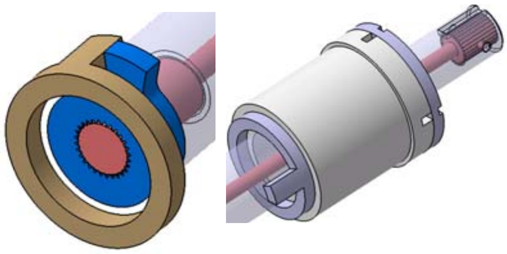

Figure 7 mechanical end stop parts

Thrust tube

The thrust tube is screwed to the nut of the ball screw. It is machined internally with some teeth in order to support the endstop bushings.

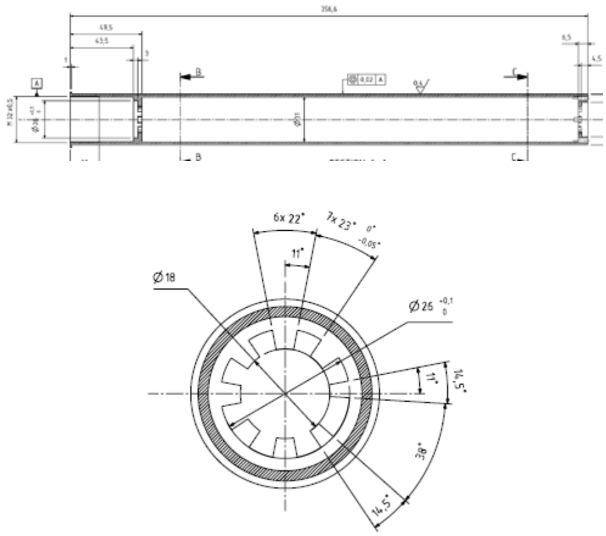

Figure 8 Telescopic tube

5. ANALYSES OF PERFORMANCES

5.1 Motorizing margin

Early in the project it was found that dragging one motor produces a reduction of performances that is proportional to the gear ratio between the output and the motor axis. In addition the compliance to motorization margin rules implies the assumption of increased losses that provides a ratio between output power-input power

of less than 50%. Therefore for a 200 w motor and 125 mm/s speed it is not possible to get 890 N output load.
In addition, as a result of the system level study it was found that force was over-specified, while the maximum speed increase improves the capture capability of the system. Thus, four different gear ratios has been analyzed. For all of them a functional simulation has been performed with a mathematical model in SIMULINK/MATLAB obtaining speed vs output force curves for different gear ratios of the actuator.

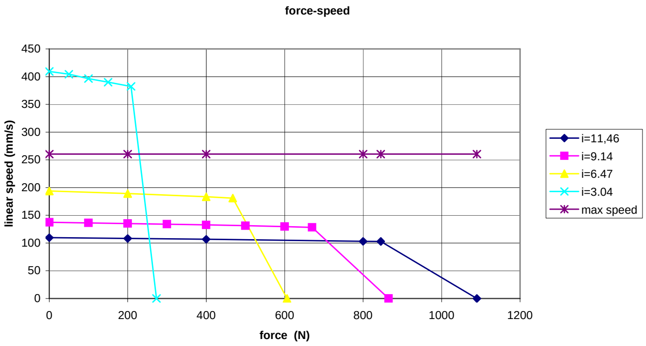

Figure 9 different gear ratios comparison

In this last figure can be seen that using the gear ratio of 3.04 the actuator exceeds the maximum permitted speed for resonance reasons in the lead screw bending mode.

6. VERIFICATION APPROACH

6.1 Test matrix

The teststo be performed on EMA linear actuators are described in Table 1

IBDM EMATest Matrix	
Physical properties	x
Mechanical Tests	
Life test in ambient	x
Sine vibration	x
Random vibration	x
Thermal tests	
Life test in TV	x
Functional test in TV	x
Functional Tests	
Stroke, Speed & acceleration	x
Stiffness and Backlash	x
Back driving force, Stiction	x
Thurst Capability	x
Absolute position and End stop detection	x
Torque margin	x

Table 2 Test matrix

6.2 Test description

The different tests of the actuator will be performed in specific test setups as shown in Figure 10 and Figure 11

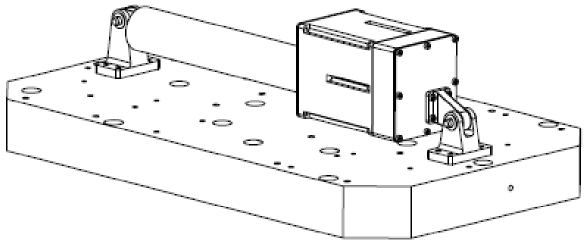

Figure 10 Vibration test setup

The first actuator is currently under assembly process. Functional test will be performed in both ambient and vacuum. Preliminary data will be available at the presentation. All parameters affecting the performances of the actuator will be measured in full assembled configuration and in steps during the assembly process.

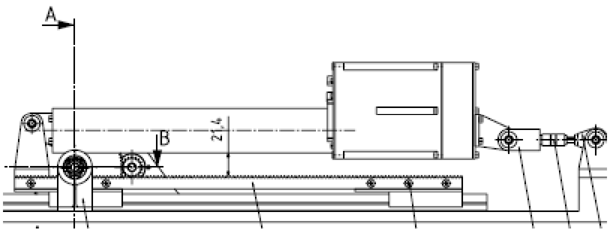

Figure 11 Functional test setup

7. ACKOWLEDGEMENTS

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