LANDING LEG AND AERODYNAMIC CONTROL SURFACE MECHANISMS AND FUNCTIONAL DEMONSTRATORS FOR THE RETALT1 LAUNCH VEHICLE

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ABSTRACT

Within the framework of the EU Horizon 2020 project RETALT (RETro propulsion Assisted Landing Technologies), mechanisms for the RETALT1 reference launch vehicle configuration are investigated. Almatech has studied the actuation of aerodynamic control surfaces, thrust vector control and landing leg mechanisms.

This paper presents an overview of activities, scaled demonstrator design and test of the landing legs and aerodynamic control surfaces. A scaled functional demonstrator of a single leg is built to verify the leg deployment mechanism function and its kinematics. Another scaled leg demonstrator is constructed and tested in a drop tower to verify the leg shock absorbing function, energy dissipation during touchdown. In addition, functional test of the aerodynamic control surfaces is carried out with a scaled fin demonstrator to verify kinematics of deployment from stowed to nominal position, as well as operation, and axis locking functions.

Index Terms – *mechanisms, landing leg, shock absorber, deployment, drop test, deployment, aerodynamic control surfaces, fin*

1. INTRODUCTION

The RETALT project aims to foster competitiveness of the European industry in the global launcher market by building up technologies for Vertical Takeoff Vertical Landing (VTVL) launch vehicles. These technologies are investigated through reference configurations, the main of which being RETALT1, a two-stage-to-orbit (TSTO) reusable launch vehicle. An overview of the key technologies is presented in [1].

The reusability of the launch vehicle necessitates specialized components to return the vehicle and carry out safe landing. The design of these components is addressed in a work package dedicated to the structures and mechanisms of landing legs, aerodynamic control surfaces and thrust vector control (TVC). Almatech is responsible for the design of mechanisms, works closely with MT Aerospace who is responsible for structures, and takes inputs from other disciplines of the consortium: aerodynamics, aerothermodynamics, flight dynamics and guidance, navigation, and control (GNC), as well as thermal protection.

This paper specifically focuses on the mechanism demonstrators developed for the RETALT project, for the functional verification of aerodynamic control surfaces and landing legs. The paper is organized as follows. First, an overview of the mechanism development methodology is provided along with an overview of the mechanisms themselves: their concept of operation and design description. This section is followed by the presentation of the mechanism demonstrators, after which the test setup and status of tests are discussed. The paper then closes with a discussion on the remaining activities – test activities on the landing leg demonstrators and result synthesis are in progress as of the submission of the present paper.

2. RETALT1 MECHANISMS OVERVIEW

2.1. The RETALT1 configuration

RETALT1 is a heavy lift launcher with a configuration similar to that of the SpaceX launch vehicle: Falcon 9. Its first stage is powered by nine engines. Depending on the mission scenario, the RETALT1 first stage can return to the launch site, or it can perform down-range landing. In either case, aerodynamic control surfaces are deployed before the first stage reenters the denser atmosphere. Then, a first braking maneuver is performed followed by the main engine cut-off and a ballistic phase. Finally, the first stage is decelerated further with the landing burn of the central engine until touchdown. TVC is used for low-speed maneuvering and the landing legs deploy shortly before touchdown with attenuation mechanisms to dissipate the landing energy. The reference configuration is discussed in detail in [2], and the mission scenario is elaborated on in [3] and [4].

2.2. Methodology of mechanism concept development

The mission concept of RETALT1 necessitates specialized mechanisms to operate the deployable fins and the landing legs.

First, main requirements and key design drivers were identified answering functional requirements of the descent phase of the RETALT1 launch vehicle. Concept generation was carried out working closely with structures and with inputs from other disciplines of the consortium. Concepts were traded off, and the down-selected solutions then were developed to a sufficient level such that representative scaled test articles could be made. The most promising solutions for aerodynamic control surfaces and landing leg systems were carried forward to manufacture and demonstration. The goal of the mechanism demonstrator tests is to verify functionality and produce information that can facilitate manufacture, assembly, integration and further testing of the technologies.

2.2.1. Aerodynamic control surfaces

The main functional requirements of the aerodynamic control surface mechanisms are:

- retainment of the control surfaces until their deployment,
- deployment before the first breaking maneuver,
- and operational actuation of the control surfaces to provide pitch and yaw inputs to the launcher during the aerodynamic descent phase.

Three types of aerodynamic control surfaces have been explored for RETALT1: petals, grid fins and planar fins. Structures and mechanisms design specifically addresses petals and deployable planar fins. Concept feasibility checks were aided by simplified motorization analysis considering the main components of forces/torques seen by the actuators for the aerodynamic control surfaces [5].

Due to the large hinge moment requirements of the petals, induced requirements on the structures involved, as well as GNC and other system considerations, deployable planar fins were chosen as a baseline configuration for the aerodynamic control surfaces. [6]

2.2.2. Landing legs

The main functional requirements of the landing legs are:

- full leg deployment and locking in deployed position,
- providing stability of the launcher, withstanding loads and conditions imposed by the environment,
- and protection of the launcher against landing shocks by dissipating the impact energy at touchdown.

Three candidate architectures were identified for the landing legs: inverted tripod, parallel linkage, and cantilever configurations. Architectures were screened using preliminary analyses, considering a two-dimensional, vertical landing onto a uniform, flat surface. Required leg dimensions were determined by assessing static stability of the launcher after landing. A preliminary mass estimation for each configuration was established based on the frame structure of struts. Static loads at landing were estimated, and strut cross sections chosen such as to obtain a positive margin of safety for the loading and buckling. Such preliminary sizing then allowed for mass estimation of the strut structure. Based on this assessment, the inverted tripod configuration was deemed to be most promising, in addition to its heritage.

Upon choosing the architecture, two main deployment mechanisms were considered: telescoping leg and folding leg. Due to its design flexibility, modularity and reliability, the folding leg configuration was selected. For the selected concept the articulated legs deploy with the aid of linkage mechanisms, assisted by gravity. The concept selection is summarized in Figure 1, and further details can be found in [4].

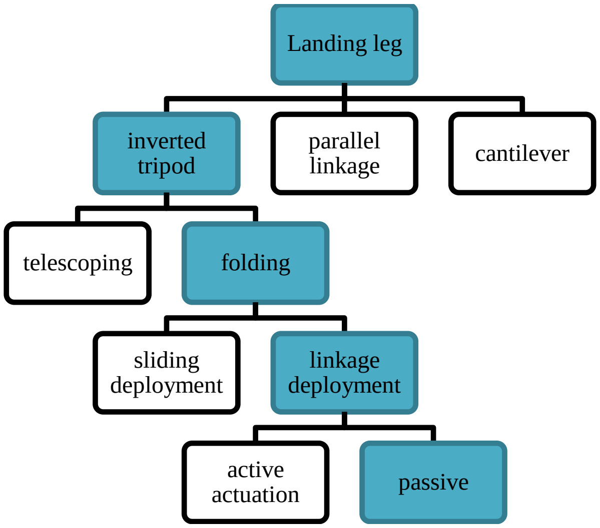

Figure 1: Landing leg architecture evolution

Several models were established to aid the leg design. Landing dynamics was modeled by MT Aerospace, who provided the required damping performance to Almatech. Kinematic models of the deployment and landing event were established by Almatech to ensure that the stowed configuration has a minimal encumbrance, deployment is possible and positive locking is achieved, as well as that the landing is feasible, and suitable attenuation mechanisms can be found, as well as detailed requirements can be derived for the damping subsystem.

2.3. Overview of down-selected mechanism concepts and concept of operations

2.3.1. Aerodynamic control surfaces

The control surfaces are stowed for launch and during ascent along the launch vehicle main axis. The fins are deployed following stage separation, in the descent phase of the first stage, but still at high altitude, as to minimize aerodynamic loading at deployment. At this altitude, the hold-down mechanism (HDRM) is released, and the control surfaces are driven to nominal position, then actuated at demand.

Control surface deployment and drive into nominal position require large rotations (90 deg), with the loads at this phase being low on the fin. The operational actuators, while only need to rotate the fin by ±20 deg from its nominal position, are to work against very large aerodynamic loads. Therefore, it was deemed important to decouple load paths for different phases of actuation to avoid having to size all components for large loads and choose actuators to cater to large rotations at different speed requirements. [5]

The control surface mechanism overview is presented in Figure 2. The fin deploys from the stowed configuration by a rotation of 90 degrees around Axis 1 with the help of a linear actuator housed in the Fork Assembly. To bring it into nominal position, the fin is turned by 90 degrees around Axis 2 by a small rotary actuator at the Belt Assembly. Fins are operated around their nominal position by a rotation around Axis 2 by ± 20 degrees. This rotation is carried out by a pair of large linear actuators.

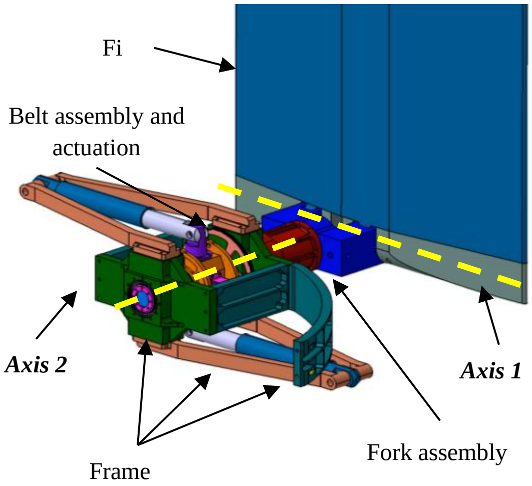

Figure 2: Fin mechanism overview

2.3.2. Landing legs

Landing legs are stowed against the launcher body and retained in this position during the ascent and descent phases, until deployment by the HDRM. When commanded, the tip of each leg is pushed away from the launcher body. When the legs are fully deployed, they are locked in their final position. Upon touchdown, leg attenuation mechanisms protect the vehicle by dissipating the impact energy: the damper struts stroke and the footpad slides slightly outward.

The main leg components are presented in Figure 3. The lower legs interface the launcher on one side and support the footpad on the other. The footpad also interfaces the damper strut that houses the shock attenuation mechanism. The primary strut consists of the damper strut and upper strut, this articulation allows for unfolding. The locking struts integrate an end stop for the deployment and secure the landing leg structure once deployed. [5]

The attenuation mechanism is integrated into the bottom section of the damper strut, consisting of a pneumatic-hydraulic shock absorber and a crushable cartridge assembly. The shock absorber is fully reusable under nominal landing, while the cartridge is engaged in case of an off-nominal landing event, to protect the vehicle from the additional loads induced. [5]

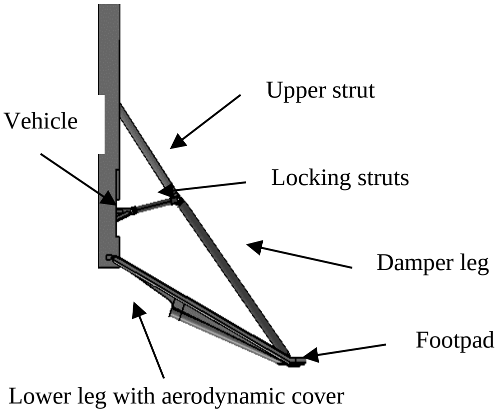

Figure 3: Schematic of the landing leg main components

3. DESIGN OF MECHANISM DEMONSTRATORS

3.1. Fin mechanism demonstrator

A fin mechanism demonstrator is built to validate critical mechanism roles: to test the actuation chain and locking of main axes. The mechanism demonstrator is built to accommodate the 1/5th scale, 1 m span fin designed by MT Aerospace and is shown in Figure 4.

Actuation and locking functions, as well as component roles, are identical to those of the full-scale mechanism. The fin interface and Axis 1 actuation are slightly modified for the demonstrator, as pure geometrical scaling would have resulted in a very small level arm for the actuator, and very high forces at the interface. The mechanism is manually actuated, and a single large actuator is implemented rather than the dual configuration of the full-scale model.

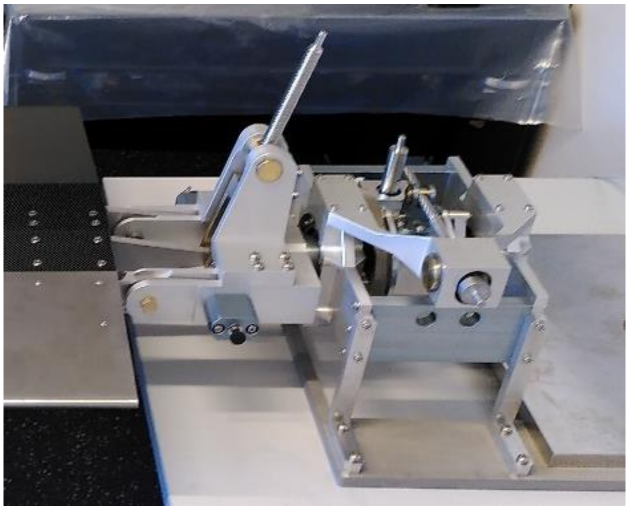

Figure 4: Control surface mechanism functional demonstrator assembly

3.2. Landing leg demonstrators

To demonstrate the landing leg main function, two scaled demonstrators are prepared. A model of the damper leg with the main shock absorber is attached to a 1/5th scale lower leg assembly. The configuration is tested in a drop tower to verify structural integrity of the leg and functionality of the attenuator mechanism. In addition, a 1/10th scale deployment demonstrator is built to demonstrate feasibility of the deployment concept under 1g loading and verify the deployment kinematics. The setup consists of a single leg with mechanisms suspended on a supporting structure.

Furthermore, several models are established to aid the design and evaluation of demonstrators. The leg geometry definition is defined with the help of kinematics models, addressing deployment and landing kinematics.

The main functions of the deployment kinematics module are:

- unfolding feasibility check,
- vehicle interference check,
- kinematics deployment sequence,
- and encumbrance check when folded.

The main functions of the landing kinematics module are:

- feasibility check with incorporation of stroke requirements of the shock absorber,
- and Kinematics of landing i.e., evolution of footpad and folding knee location.

Additionally, a model of the damping leg – shock absorber is established, incorporating the landing kinematics module that can evaluate that shock absorber performance. A multiphysics model is also established to aid deployment definition.

3.2.1. Drop test demonstrator

Damper leg scaling for the demonstrator considered representativeness in terms of dynamic performance compared with the full-scale mechanism, within the limits of the drop tower. During the demonstrator design, however several scaling limitations were encountered. Some of the constraints of the drop tower were: (1) the landing leg could not be wider than 960 mm at the point where it enters the gauge section of the drop tower, (2) the drop mass is adjustable from 150 kg with 60 kg increments. Drop tower dimensioning could accommodate a 1/5th scale landing leg. Predicted structural integrity of the lower legs and geometry of the interface could not accommodate the original shock absorber choice, thus its selection has been adjusted accordingly, taking into account geometry and volume envelope available at the interface with the lower leg. Finally, the absorber selection was limited by geometry and volume envelope available at the interface with the lower leg. In turn, the induced loads in the lower legs are limited by the rod end eyelet performance with extra heavy duty rod ends rated to 81.5 kN static load.

The demonstrator shock absorber performance is summarized below:

- peak force 81.5 kN,
- stroke: 50 mm,
- energy absorbed: 3.2 kJ.

The absorber performance is characterized by a damping coefficient matrix as a function of absorber stroke and stroke speed.

Test predictions were carried out with the damping leg analytical model where test conditions were varied with the following assumptions:

- friction (no friction, realistic friction, high friction scenarios),
- drop mass (150 kg, 210 kg, 270 kg, 330 kg),
- drop mass height (0.30 m, 0.90 m).

Energy to be dissipated and predicted maximum shock absorber force were tracked and the ‘design point’ condition identified, based on the shock absorber force limitation.

3.2.2. Deployment demonstrator

The deployment demonstrator is equipped with tension dampers to limit the deployment-induced shock, as indicated on Figure 5. Demonstrator scaling was adjusted to commercially available off-the-shelf hydraulic dampers with 100 mm stroke. Furthermore, demonstrator mass and mass properties were adjusted to enable the deployment. Center of mass height of the model was tracked to assess the energy to be dissipated.

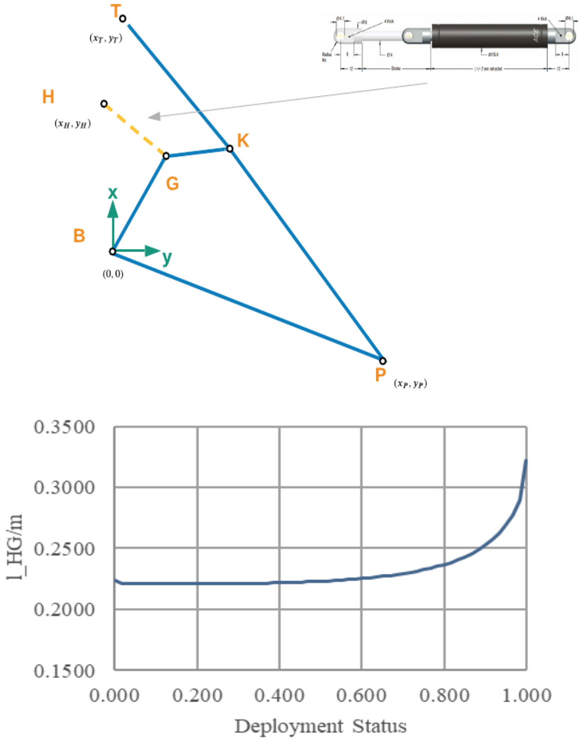

Figure 5: Top: schematic of deployment demonstrator kinematics setup. Below: predicted evolution of the HG segment during leg deployment as a function of the deployment status.

To further evaluate deployment with the tension dampers, a 2D multiphysics COMSOL model of the landing leg was established. The tension damper is modeled with a spring-damper element that allows the definition of a force function to model constant extension rate independent of the force applied. Gravity load was applied to the model, the deployment simulated, and parametric studies were carried out with a range of damper saturation speeds and forces applied by the tension damper. The model allows for evaluation of the deployment status and time as indicated in Figure 6.

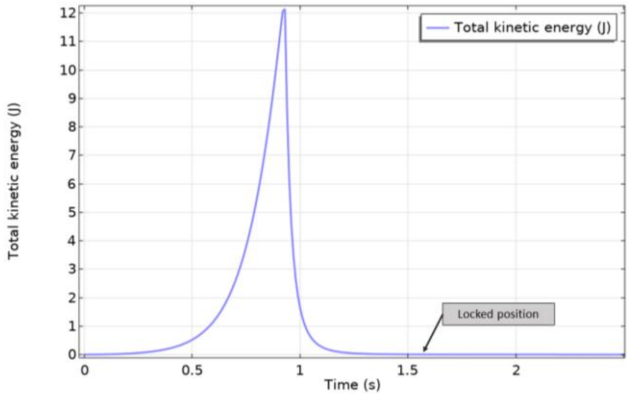

Figure 6: Kinematic energy vs time for a case with damper saturation speed, v0 = 0.2 m/s force applied by the tension damper F0 = 0.981 N.

4. DEMONSTRATOR TESTS

4.1. Control surface mechanism functional test

The test was carried out at Almatech facilities, with the Almatech mechanism demonstrator and MT Aerospace scaled fin assembled, shown on Figure 7.

The main mechanism functions were successfully verified with the following observations:

- movement from stowed to deployed position was smooth,
- Axis 1 locking was achieved,
- actuating the gearbox, movement from the deployed position was achieved,
- the Axis 2 locking pins latched successfully,
- the fin could be smoothly rotated in the operational configuration.

Interference was observed between the fin lugs and the tilting fork due to a manufacturing issue on the fin lugs. This resulted in the stowed fin position not being fully vertical. The issue did not affect mechanism function.

Figure 7: Control surface functional demonstrator test. Left: stowed configuration. Right: in operation in fully deployed configuration

4.2. Landing leg demonstrator drop test

The test campaign was carried out at LZS in Dresden, Germany. The landing leg was installed upside-down in the test facility, and a mass was dropped on the leg footpad. The test rig is shown in Figure 8. An optical measurement system and strain gauges were used to collect information on the leg performance, as well as an accelerometer on the damper leg. Detailed test setup is discussed in [7].

The test was carried out with the shock absorber functioning nominally, and the structural integrity of the leg not compromised. Following a sequence of sanity check tests aimed at verifying the proper assembly of the test unit and integration of sensors, a series of drop tests were executed with progressively increasing energy levels. These levels were obtained by releasing the drop mass of 368.5 kg from different heights, starting from 0.10 m up to 0.90 m, with repetition of intermediate test cases to enable further data output comparison. Accounting for the kinematics of the demonstrator and the associated vertical displacement of the footpad during the impact, a maximum total energy of 4 kJ was successfully absorbed without visible damage or degradation of the test unit.

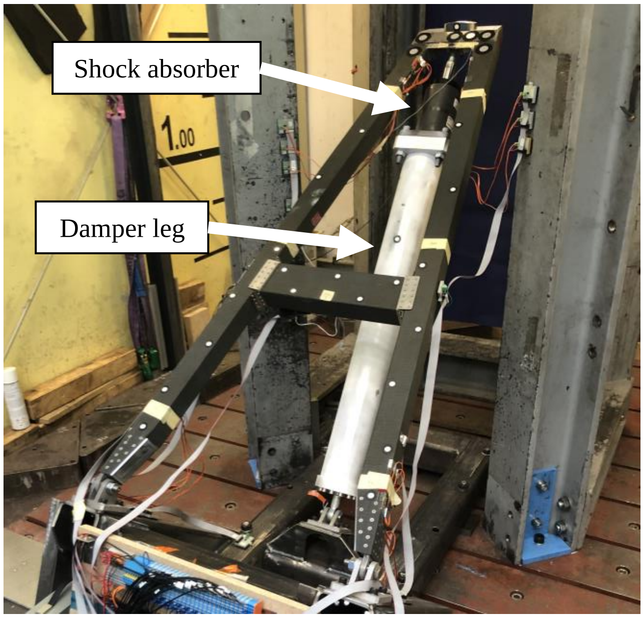

Figure 8: Drop tower leg demonstrator test rig

4.3. Deployment demonstrator functional test

The functional test is carried out to verify:

- uninterrupted movement from folded to deployed configuration,
- no interference between components or with launcher body during deployment,
- tension damper function,
- end stop function,
- manual refold,
- system behavior – comparison with model predictions.

The test campaign will be carried out at Almatech facilities, with the demonstrator in a vertical configuration and gravity assisted deployment, as shown in Figure 9.

Following the demonstrator assembly, the COMSOL model is to reproduce landing dynamics behavior to characterize the initial angle and friction loss effects. This characterization is to be done in the 'damper independent' phase, about the first 90° rotation. During the test the leg is retained in the stowed (folded) configuration, then released in free fall, without push off. After completed deployment, the leg is refolded, then the test setup is adjusted – by adjusting the initial release angle and/or change of the test setup inclination.

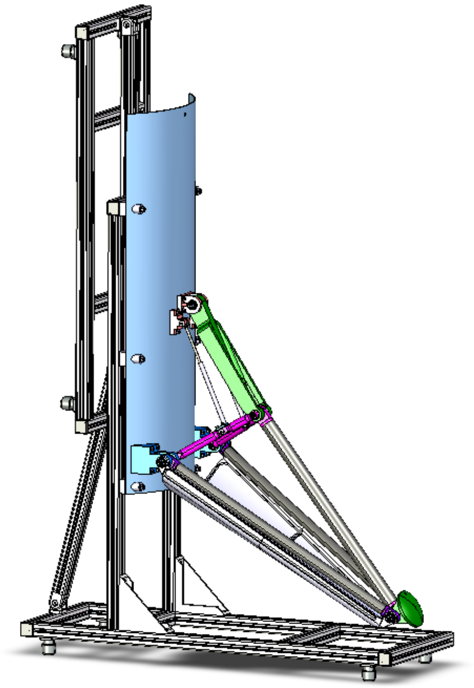

Figure 9: Model of the deployment demonstrator test rig

5. CONCLUSIONS AND OUTLOOK

Almatech activities in the RETALT project on mechanism demonstrator development for the aerodynamic control surfaces and landing legs have been reviewed.

Key design drivers were identified, several concepts generated and traded off, and the down-selected deployable fins and articulated landing legs were carried forward to produce large scale demonstrators used for functional verification.

Activities on the aerodynamic control surfaces have been completed with success, including functional verification of the scaled demonstrator.

The landing leg drop tower demonstrator has also been built and the test successfully carried out verifying the damper leg functionality and leg kinematics. A large amount of test data was generated and is being delivered by the test facility as of writing this paper. The data will be post-processed and used to further assess the damping mechanism behavior. The deployment demonstrator assembly is in progress, and testing is scheduled in the near future to verify the deployment kinematics.

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