A motorized and remotely controlled Horizontal Tailplane for efficient WT testing

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Abstract. The H2020-Cleansky 2 project EULOSAM II supports the development and assessment of an innovative natural laminar aircraft wing by integrating innovative aerodynamic control surfaces and high lift technologies. The project focuses on the modification and completion of a WT-model to enable robust and efficient testing. EULOSAM II is a project funded by the EC through the Clean Sky 2 JU and carried out in cooperation with Dassault Aviation. In order to ensure efficient testing a key element of EULOSAM II was to develop and validate a solution to improve the WT test productivity, which was achieved by designing, manufacturing and testing a remotely controlled, actuated HTP which significantly reduces the time needed in the WT for model-configuration changes. The model under review is a business jet half-model, test will be performed in the ONERA F1 Wind Tunnel, at high Reynolds numbers and low Mach Numbers typical of high-lift conditions. This paper presents the outcome of the whole development process of the actuated solution. This development includes the mechanical design as well as the control-solution to be applied in the WT. Pre-Tests have been performed in order to show that the implemented solution is working well and is robust enough to enable smooth and productive testing operations. In this paper, details on the design as well as explanations on why specific solutions were down-selected and found to be most effective ones are presented. During the final development phase, to investigate the functionality and robustness of the system, ground tests have been conducted with the assembled model on test benches to save WT time and to enable faster troubleshooting. Actuating WT models are seen as key to increase WT test efficiency, therefore this is in particular interesting for WT-test which have high hourly test-costs. Lessons learned for future applications therefore will be given to discuss if solutions found so far can be extrapolated to other, comparable applications.

Keywords: EULOSAM II, motorized movables, efficient WT testing, remotely controlled

1. Introduction
The general scope of the EULOSAM II project (see Figure 1) is to integrate innovative high lift devices and laminar wing technology in an already existing wind tunnel model (WTM). Another aspect of the project, and main focus of this document, is to develop a motorized HTP mechanism for the WTM.
Actuated mechanisms in WTM are desirable as WT time is expensive and time is rather used for measurements than for setting changes (especially in pressurized WTs).

Therefore, the research community take on this problem to solve it via remotely controlled movables. When looking through the published research reports and industrial innovations, it can be seen that the focus is on flaps, ailerons and rudders.

The National Aerospace Laboratory (NLR) developed a family of RC systems to drive ailerons, elevators and rudders of low speed WTM’s (1).

In the CleanSky2 Project POLITE also a complex remotely controlled motorized flap mechanism was developed (2).

Nevertheless, these named innovations could not help to met the special challenges of the remotely motorized HTP. Firstly the hinged mechanism is not applicable to the rotary movement. Secondly the POLITE approach is to filigree to cover a huge torque with simultaneously high required precision. However, a redefinition of the POLITE worm wheel approach was deemed useful and investigated.

The major concern of this project is to meet the technical requirements and at the same time to develop a robust system compliant with the wind tunnel environment.

2. Objectives, requirements and challenges

2.1. Objectives and requirements

The HTP configurations are:
-14°, -12°, -10°, -6°, 0°, +3° (motorised and non motorized), with a requested angular accuracy of < 0.04° without aerodynamic forces and < 0.08° with aerodynamic forces.

The configuration change time must be less than 1 min. The motorized HTP configuration change is performed at wind off conditions. Therefore, there is no aero load on the HTP during the configuration change.

According to the wind tunnel regulations (3) the given loads have been increased by factor 1.3 to take into account also dynamic effects. Therefore the design loads provided by the aircraft manufacturer Dassault Aviation have been amplified accordingly. The load application point on the HTP is shown in Figure 2.

2.2. Project challenges

The design for the motorized HTP (see Figure 3) has been very challenging. The main faced challenges are summarized in the following:

1. Ideally the rotation axis at the interface VTP to HTP should have a circular cross section to minimize gaps between VTP and HTP if the HTP configuration changes. As the available space at this interface is very small, and the loads are very high, it was not possible for structural reasons to keep a circular HTP shaft. It had to be changed to an elliptical one, with the side effect that the gap size between VTP and HTP varies in different configurations, which is a challenge for the sealing at the shaft region (to ensure no airflow through the model).

2. To prevent an airflow between the upper and the lower surface of the HTP, a sealing had to be developed, that works on movable parts in all configurations with varying distances between VTP and
HTP in chordwise direction.

3. The stringent requirement in terms of accuracy of the rotation results in a backlash-free actuation, a high precision positioning and position stability under WT conditions.

4. The distance between WT control room and HTP motorization is relatively large—this requires a remote-control wire length of at least 80m with challenges to signal quality and robustness.

5.Fallback solutions on the motorized HTP need to be simple to implement and adjust, so that the possible manual actuation of the HTP is possible in short time and with minimum effort when functions like self-blocking, motorization or positioning are not working properly.

3. Design Solution

The HTP consists of two parts. The HTP-Root (the smaller silhouette in Figure 2) that transmits the motion to the HTP and the HTP outer shape (outline in Figure 2) that gives the actual required aerodynamic shape. To transmit the motion, the HTP-Root is rigidly fixed to the worm wheel. The worm is mounted under the worm well and directly connected to the actuator. The rotation of the actuator directly connected to the worm transmits the motion to the worm wheel and therefore the HTP. The actuator control logic compares the required position to the position signal provided by the encoder(s) and adjusts the actuation until the required position is reached.

The required position of the HTP is set in the control room. During the WT test the position of the HTP remains unchanged, as the mechanism is self-blocking and the control logic supervises only the encoder signals.

3.1. Continuous adjustment capabilities

In Order to guarantee the tight rotational tolerance the motorized mechanism needs to be backlash free. But it also needs to be blocked in the desired position guaranteeing that the set angle does not change under load (i.e. at wind-on conditions). As the HTP is highly loaded, and the available space is tight, a brake (meaning a dedicated extra part) is not the best solution. An electrical brake via the holding torque of the electric motor would require a very high gear transmission or a “big” actuator to cover the required brake moment. It would also have an impact on the model safety, as electric current is always required, posing possibly also problems of electro-magnetical interference with sensors measurements.

All these requirements led to the choice of a high-performance duplex worm gear:

It has high accuracy (to cover the tolerance requirements), a high transmission (good for precision and to reduce the required actuator torque moment leadin to the smaller actuator possible) and is self-blocking, so a brake is not necessary to ensure that the mechanism does not move under load.

In addition to the necessary fine adjustment in the axial direction of the worm, high-precision manufacturing of all affected components is necessary.

The transmission of the chosen worm gear is 1:75.

The worm is mounted with two plain bearings between two bearing blocks (see Figure 4), the finetuning (to make it backlash free) is performed with adjusted shim washers – see Figure 5. With duplex worm drives, this is achieved by the axial displacement of the worm on which slightly different modules are located. Figure 5 shows also the actuator (on the right side) that is aligned and directly

Figure 3. Whole HTP Trim assembly including VTP Peniche.
coupled to the worm via feather key connection. The worm-wheel has a fixed connection to the HTP. All surfaces of the HTP that glide on surfaces of the VTP are lubricated with silicone spray.

3.2. High precision position measurement
The HTP-Mechanism must meet the position tolerance of 0.04°. To meet this requirement, not only a high-performance worm gear with no backlash and self-blocking is necessary, but also a high precision position measurement for position control and to regulate the actuator. There are two different encoders implemented in the system. One encoder is directly mounted to the actuator and gives the actuator position (later referred as “indirect encoder”), the other encoder measures directly the position of the HTP root (later referred as “absolute” encoder).

The indirect encoder provides the exact movement of the actuator. On the other hand, it gives only indirect information (via the mechanical chain) on the movement of the HTP. This movement can be calculated with the gear transmission. The disadvantage of this indirect measurement is that, it does not consider possible free play, backlashes or unintended sliding (i.e., between shaft and coupling). This means, without a second encoder (that allows direct measurement of the HTP position) it is not possible to find out if there is some free-play/ error/ unintended behaviour or other inaccuracies in the system.

Therefore, a second (absolute) encoder is implemented to directly measure the position of the HTP. The required accuracy would be met best by an optical encoder system. But optical systems have stringent requirements in terms of clean environment that is not always given in a WT. Furthermore, the available space did not allow housing an optical encoder, so it was decided to implement a high-performance magnetic encoder system. To meet the requirements in terms of robustness, accuracy and space, IBK, in concurrence with NHOE, developed a customized solution with a segment magnetic encoder together with the supplier.

The signal of the absolute encoder is given to the control device as well as the information from the actuator’s (relative) encoder. To bring the HTP via the motorized HTP in position, the absolute encoder (measuring the HTP movement directly) is set in the control software as the master for the position measurement. The software on the control device controls the actuator so that the HTP motion is stopped if the absolute encoder measures the correct HTP position. The signal of the relative encoder provides an indication to the human controller in the WT control room about the “health status” of the mechanical chain (no or negligible difference to absolute encoder indicates good system health, conversely significant difference to absolute encoder indicates the presence of backlash or other transmission failures).

3.3. Remotely controlled actuation
To reach the necessary torque, a DC motor is used. As the motor is only turned on or off, it is combined with an encoder (and a controller) to have a feedback and control logic on the position. To reach the required torque it is also necessary to have a planetary gear attached to the actuator.

3.3.1. Actuation control logic for WT tests. Thanks to the control unit, the actuator can be driven to the desired position. The encoder signal from the absolute encoder (measuring directly the HTP-root position), is also plugged into/ connected to the control unit. The control unit can cope with both signals.
and makes sure the position is accurately reached. The software can be set up in a way that both encoders can be in turn master or slave. The default setting will be that the absolute encoder is the master and the indirect encoder is the slave because the absolute encoder measures directly the HTP position. As fallback solution only one of the encoders can be used.

The control software works in a way that the set position will hold automatically (closed loop) if the software is in the “controller connected mode”. To avoid a possible correction during the WT test (i.e. vibration induced “wrong” measurement) the control software for the HTP must be run in “controller disconnected mode” during the WT test. In this mode only position monitoring is possible, but no position setting. Otherwise, vibrations could lead to “fake motion measurement” and result in an actuator that is constantly trying to correct the position.

3.3.2. Motorized HTP wiring. The wiring arrangement is shown in Figure 6. The absolute encoder is connected with one sensor cable to the control unit transmitting current for the encoder and the signal back to the control unit. The control unit is powered directly from the control room via the power supply converter (230V to 24V) with a 24V power cable, only interrupted by an emergency-stop button installed in the control room. Between control unit and actuator there are two cables, one transmitting the signal from the encoder, the other giving power to the actuator.

The slave control unit is connected with a CAN-CAN cable to the master control unit stored within the WT but outside the test section. This control unit is powered by a 24V power cable directly from the control room via power supply in the WT, with the possibility to be interrupted by an emergency-stop button as a mitigation measure in case of failure. The connection to the master control unit must be done via USB. As USB has a maximum signal length of 3-5m (but better below 1,50m), it is necessary to convert from USB to Ethernet Cable and in the control room back to USB-Cable to bridge the distance of roughly 80m in total to the control room. This is also the reason why two control units are necessary (after finishing the design, the controller supplier informed that now it can also be implemented with only one Ethernet connection).

3.3.3. In-house developed user interface. A high-level in-house user interface was developed for easy operation in the wind tunnel. The control window (Figure 7) is explained in the following points.

1 - The header lists the name of the actuator as well as a target position to be specified by the user. If the continuous positioning mode has been selected in the setup, a freely editable input box is shown. For the discrete positioning mode, a dropdown menu with all available values is given instead.

2 - This section contains the current output values as send by the controller which will be continuously updated, independent on whether the actuator is currently moving or not.

3 - Below the current values, a fine-tuning of the position is available. The central input defines the movement step for one fine-tuning increment and the buttons beside it applies said movement forwards or backwards, relatively to the current position.

4 - Setting the reference position will store the current value as an internal offset and use it as the zero-position. All further movements as well as the given output will be offset by that value.

5 - The speed control defines the velocity with which the actuator performs any movements.

6 - This section defines the acceleration used to increase or decrease the velocity of the actuator. Note: ramp types are not available for Maxon actuators.

7 - The plot window displays a time history (with a range as stored in the settings) of all output values provided by the actuator. By default, all parameters are visible at the same time while individual curves can be hidden/shown by clicking their entry in the plot legend. Specific values of measurement points can be shown by hovering the curves, highlighting the closest point respectively. Furthermore, the plot can be expanded into its own window via the expand-label in the top right of the plot (only visible when hovering). This will also show axis labels but otherwise provide the same functionality. An expanded plot can be collapsed again via the same icon or by closing the dialog window via the x-icon.

8 - Starting and stopping the actuator movement is performed via the buttons at the bottom of the block. Starting a movement will disable the respective button and start to continuously check for movement completion. If detected, the button will be enabled again.
Both default and brake ramp acceleration as well as a correct velocity value should be selected before any movement is started to prevent a value range error.

3.4. Fallback solutions to ensure operational capability

In order to guarantee the operational capability in the WT, three fall back solution were developed to secure the function and dimensional accuracy of the HTP trim mechanism in case of failure.

1. In fallback solution one, shown in Figure 8, the HTP configuration can be set manually by using an Allen key (on front side of the worm) in case the drive train doesn’t work.

2. If the self-blocking mechanism of the worm gear does not work well enough, it is possible to clamping device by fixing the screw in the position 2, Figure 8. Note: the clamping plate is installed to the model only if fall back solution 2 occurs. Fallback solution 1 and 2 can be combined if required.

3. If the function of the worm gear fails/ is blocked for some reason, fallback solution 3 is adopted. In this case the worm wheel must be released/ removed by unlocking the screws and “covers” on the axial bearing blocks. Then the desired HTP position is set by adding suitable jigs onto the latch/ tongue above the HTP (see Figure 9).

This mechanism is also used to define the 0°-position on the WTM and for the encoder calibration.
Due to internal software calculation processes, it was not possible to extract the absolute zero position of the encoders or transfer functions. Nevertheless, it is possible to create a zero position in the internal software, but the value of the absolute encoder is not influenced by this. The zero value also was defined by using a “zero” jig. The required positions were reached correctly, so the other jigs fit as well.

4. Test and Validation
The developed system complies with structural as well as functional and accuracy requirements. This compliance has been demonstrated by tests, whose purpose and results are discussed hereinafter.

4.1. Structural safety with regard to WT requirements
The VTP-HTP assembly is gradually loaded up until the maximum design load (including safety factors) is reached. The test rig is shown in Figure 10.

The gradual loading is realized with a weight which is slowly lifted up. The full lifted weight represents the maximum test load level. Lifting the weight stepwise allows for an intermediate (visual – i.e. by camera) inspection of the mechanism for different load levels.

The static load test has been performed three times. The collected values show that the bending level is practically the same (see Figure 11), showing repeatability. In summary, the assembly resists the maximum expected load and there is no trend to increase the bending. The bending at max. load was in line with numerical analysis results gathered in the design process.

On the basis of the repeatability and accuracy tests carried out after the static load test, it can be concluded that the system works very good after more than one cycle reaching the maximum load.

4.2. Repeatability and high precision
The comparison of different test runs, shows a very good repetition of each required angle. The closed loop positioning works really well. As the jigs fit over all tests, the accuracy as well as the repeatability is given.

Finally, it can be noted that the adjustment times are very short. From 0° to -14°, only 30 seconds are needed between each step, less than 6 seconds.

5. Stress investigation
The design was accompanied by stress analyses (Figure 12) to ensure that the developed mechanism can also fulfill the special structural requirements of the wind tunnel. For this purpose, calculations were carried out for all load-bearing parts and interfaces.

The stress analysis is performed with following verification concepts (see Table 1).
The structural verification for the demonstrator plays out with following reserve factor level approach:

1. All loads are applied as they are (without additional safety factors); this allows for the structural analysis to obtain the induced stresses, reactions and deformations directly.

2. Because the safety factors are not being used on the load side, the limit (ultimate, elastic limit, contact…/) stresses for each material are being reduced by all safety factors (according to (3)) to “allowable” stresses.

The ratio “allowable stress” to “real stress from structural analysis” defines the reserve factor; therefore, a reserve factor equal to or higher than 1 means that all reserve factor requirements are fulfilled.

| HTP root | Stress analysis and deformation via FE model |
|----------|---------------------------------------------|
|          | Screws and pins design by hand calculation  |
| HTP root | Stress analysis and deformation via FE model |
|          | Screw and pin design by hand calculation    |
|          | Support stresses by hand calculation        |
|          | The worm gear is a customized design, therefore not part of this stress analysis |
| VTP      | Stress analysis and deformation via FE model |
| Worm     | Hand calculation of worm gear support       |

**Figure 12.** Result of HTP-root analysis.

In summary, all parts are safe as they have a reserve factor higher than one.

The lowest reserve factor is located at the HTP-root shaft (Figure 12) with RF=1.04 (4% above the ONERA reserve factor requirements) considering – as required - a factor for dynamic effects of 1.3, prescribed for hinged surfaces. However, considering the high stressed shaft area (which is from the structural point of view a cantilever and not a hinge) the “hinged surface” hypothesis can be questionable, therefore it is arguable that the real reserve factor is 1.13 instead of 1.04, obtained by considering a dynamic factor of 1.2 instead of 1.3.

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