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# The UHURA project at a glance – motivation and objectives

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**Abstract** The European H2020 project UHURA is focusing on the unsteady flow behaviour around high-lift systems and will first time deliver a deeper understanding of critical flow features at new types of high-lift devices of transport aircraft during their deployment and retraction together with a validated numerical procedure for its simulation. UHURA performed detailed experimental measurements in several wind tunnels to obtain a unique data set for validation purposes of Computational Fluid Dynamics (CFD) software, including detailed flow measurements by Particle Image Velocimetry (PIV) and other optical measurement technologies. Advanced CFD methods promising significant improvements in the design lead time are validated against this database to obtain efficient and reliable prediction methods for design.

## 1. Introduction

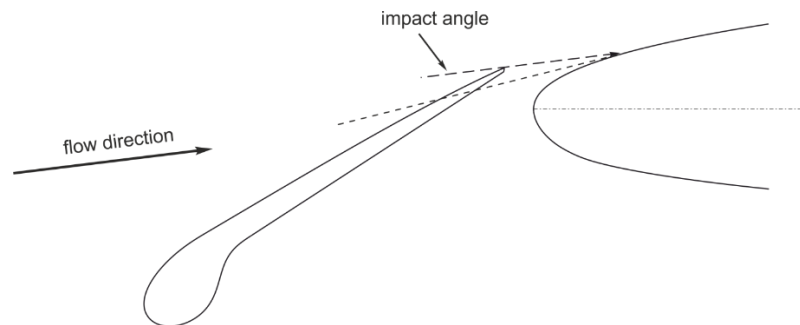
The ‘nose split flap’ was first defined by Werner Krüger in Göttingen [1], which would later be solely known by his name as ‘The Krueger flap’. It is a high-lift device at the leading edge of the wing and thus intended to increase the stall angle, thereby increasing the maximum lift coefficient and reducing the flight speed at take-off, approach and landing. The specialty about the Krueger flap is that it deploys from the pressure side of the wing against the flow direction. The Krueger flaps were extensively used by Boeing at the beginning of the age of jet airliners and used them on all transport aircraft from B707 to B747. While the original Krueger flap was simply a hinged panel, on the B747 already a small slot was introduced to improve the aerodynamic performance. Nevertheless, in the past the Krueger flap even at Boeing aircraft was subsidized with slats as they offer a higher aerodynamic performance, especially during take-off.

Krueger flaps gained attraction again in the course of laminar wing technology development. Laminar wing technology offers the highest potential in aerodynamic drag reduction by keeping the wing boundary layer flow in a laminar state and thus reducing frictional forces.

One of the critical requirements for a leading edge high-lift system for a laminar technology wing, is to avoid any steps and gaps on the upper side of the wing, as slats do. Such disturbances would spoil laminarity and are therefore excluded for aircraft application in this context. The Krueger flap, due to



its unique motion from the lower wing side, prevents such disturbances on the critical upper suction side of the wing. The Krueger flap also offers an additional functionality that other leading-edge stall protection mechanisms, like e.g. a smart droop nose or active flow control means cannot provide: When positioned with the trailing edge above the wing leading edge, see Figure 1, the Krueger flap can shield the wing against contamination by insects, dirt or other pollutants.



**Figure 1.** Shielding functionality of the Krueger flap.

Krueger flaps are therefore currently the high-lift system of choice at the wing leading edge. The first laminar wing flight test conducted by NASA on a Boeing B757 implemented such a Krueger flap [2]. Later investigations in European projects like DeSiReH [3], AFLoNext [4] or CS2-HLFC-Win [5] incorporated similar devices.

## 2. Motivation and Setup of the UHURA project

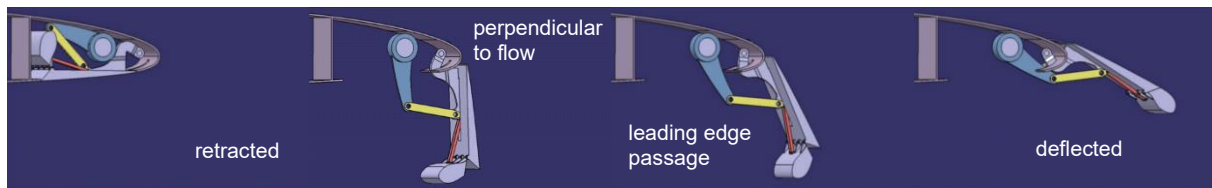
The unique motion of the Krueger flap served as the motivation for the UHURA project. The Krueger flap deploys from the lower side against the flow around the wing leading edge. It thus, on its path, is perpendicular to the flow and produces large area of flow separation. Therefore, it is beneficial to pass this position as fast as possible and the risk of jamming on the full span must be prevented. In conclusion this requires a scheduled deployment, either individually – like on the Boeing B707 – or in groups – as on the Boeing B747 – where the wing inboard of the engines is deployed first, and the outboard wing after.

This requirement introduces new challenges on the high-lift system design. Given an overall lift time for a complete deployment, operating Krueger flaps in sequence reduces the time available for a single panel and increasing the deployment speed. At some point it must be accepted, that unsteady transient effects are likely to occur. To predict these effects, a validated simulation technology is needed.

### 2.1. Challenges

In order to properly simulate the aerodynamics associated with the Krueger flap motion, the challenges for the simulation method must be considered. First, the extent of large-scale separations must be covered including its dynamics of built up and vanishing. This must be achieved at relatively fast deployment speeds. First estimations led to a time available for overall deployment on a targeted model scale of 1:6 of about 1 second in total for an approximately 140 deg. deflection angle. Therefore, large transient effects are to be expected. Beside the ability of the simulation method to handle both – the large deflection and the significantly high motion speed deg./s, the simulation method has to predict the impact correctly, especially in the phases when the Krueger is perpendicular to the flow or passes around the leading edge, thus shielding the wing against the flow, see Figure 2.

To verify that the simulation methods are capable to simulate this challenging aerodynamics, a validation with experimental data was needed. Unfortunately for this kind of flow, no experimental database was available before the project. All wind tunnel tests data available concentrated on steady behaviour with the Krueger deployed to fixed positions. Only few tests were previously performed with the Krueger flap at intermediate positions, but even those in static condition only.



**Figure 2.** Critical aerodynamics during Krueger deployment.

This encouraged creation of an appropriate validation data base to validate the simulation technologies for such cases, and to use both the test data and the simulation data to fully understand the impact of the unsteady effects of a moving Krueger device to de-risk its implementation on an aircraft and to enable the high-lift solution for the laminar wing.

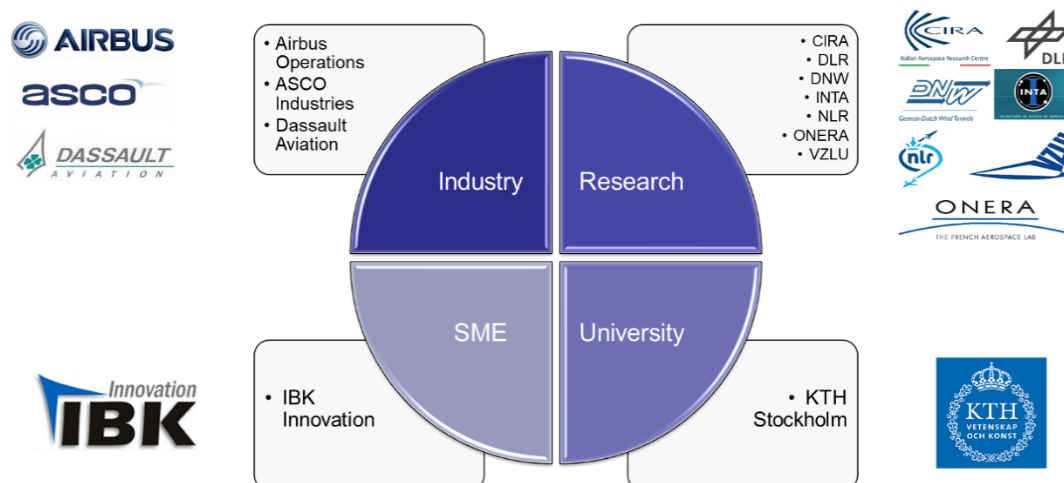
### 2.2. Project Goals

According to the motivation, three specific project goals were formulated. First, the validation the numerical simulation methods for predicting the unsteady aerodynamics and dynamic loads during the deployment and retraction phase of high-lift systems. We aim at predicting the unsteady aerodynamic and corresponding forces with an accuracy better than 1% in lift, drag, and pitching moment coefficients.

Second, we want to understand and to quantify the aerodynamic characteristics of a slotted Krueger flap during deployment and retraction, which was completely unknown before the project. With this knowledge we can quantify the differences to state-of-the-art approaches, like slats. We hope to support a reduction of system complexity, which in worst case is driven by using single actuators at every Krueger flap kinematics station. Validating the assumptions, both on loads and on overall aircraft-level impact will provide a better scaled actuation system – up to the option of returning to centralized drive systems. And, with the improved load prediction, we want to show that such a Krueger flap system can be built at or below the weight of a state-of-the-art slat device.

Third, we want to characterize the impact of the unsteady flow behaviour on the overall aircraft in terms of handling qualities and certification. Mapping the obtained unsteady data to deployment schedules on a full wing will help to understand the criticality and its mitigation of different sequences, in best case relaxing the requirements for a safe operation of the aircraft.

### 2.3. Consortium



**Figure 3.** UHURA Project consortium.

The consortium for the UHURA project consists of 12 partners of the European aeronautics research community. With Airbus Operations and Dassault Aviation, two major European aircraft manufacturers and with ASCO Industries one major supplier for high-lift system mechanical parts demonstrate the

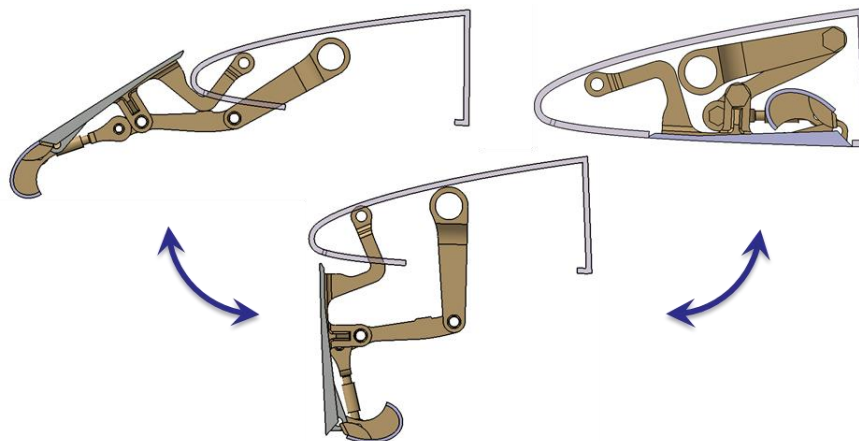
industrial interest in this research topic. Almost all major European aeronautic research centers – CIRA, DLR, INTA, NLR, ONERA and VZLU – and one wind tunnel operator – DNW – are cooperating for the purpose of this project. The consortium is completed by a university- KTH Stockholm – and IBK Innovation – a small-to-medium enterprise (SME) offering engineering services, see Figure 3.

### 3. Results of the UHURA project at a glance

The UHURA project is organized in five work packages acting in three subsequent phases. At the beginning of the project, the first phase deals with the specific design of the test object. Here the aerodynamic shape of the specific Krueger flap and the corresponding kinematics are designed. From aircraft perspective, design requirements and operating conditions are specified. In the second phase, the CFD simulations capabilities are established in parallel to the preparation and conduction of the wind tunnel experiments. The last phase is dedicated to the validation of the CFD methods and the assessment. The latter is aimed for both, the simulation technology as well as the dynamic characterization of the Krueger flap based on the experiments and the then validated simulation results. The management as last work package was running permanently at the side and only of minor importance

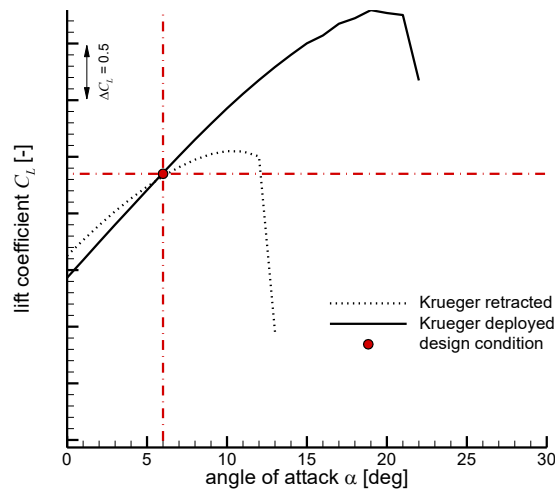
#### 3.1. Aero Design and Definition

As mentioned, the first work package had the purpose to design the aerodynamic shape and the mechanical geometry to fully define the motion path of the Krueger flap. This was achieved by a collaborative-concurrent design by integrating the kinematical constraints into a Krueger flap design for an existing airfoil, the DLR-F15 airfoil [6] with a natural laminar flow leading edge, as designed by Dassault Aviation in the frame of the CleanSky Joint Undertaking [7]. At the end we obtained a fully operational Krueger flap with kinematics on both scales, wind tunnel model and full aircraft scale, see Figure 4.



**Figure 4.** Kinematics of fully functional Krueger flap.

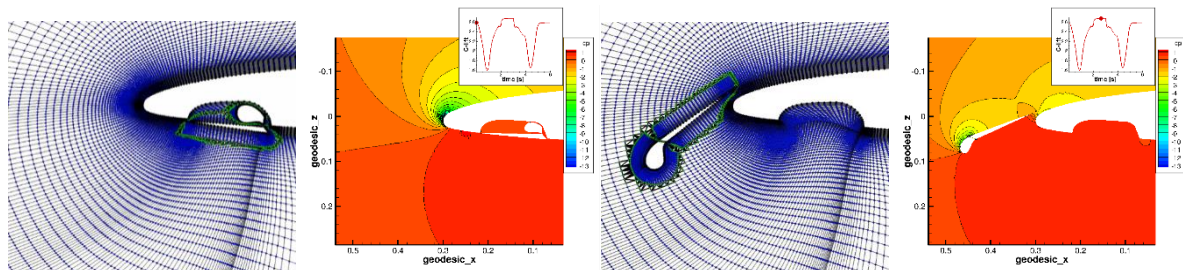
In order to obtain reasonable results for the assessment of the Krueger flap at the aircraft level, it was further necessary to properly define the operating conditions. For the operation of the Krueger, a safe condition must be met where the airfoil is not stalled, either in retracted or deflected position. Comparing the lift curves of the airfoil for both states, see Figure 5, established a condition of an angle of attack of 6 degrees to be suitable for the further motion analysis within the project. The design phase is further detailed in [8].



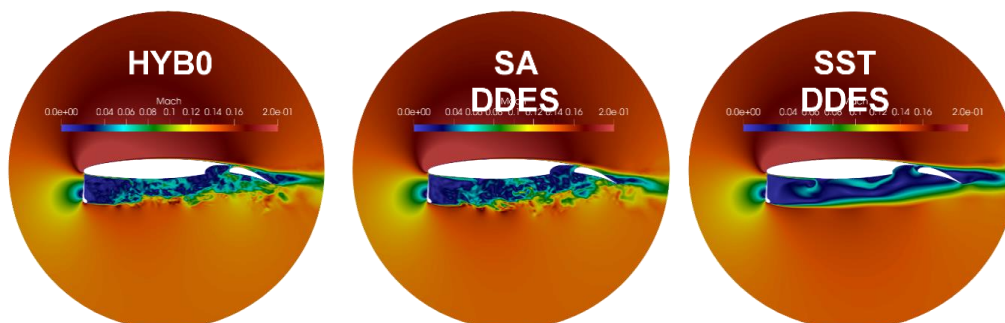
**Figure 5.** Design condition for Krueger at Aircraft level.

3.2. Numerical Simulations

Having a look at the different CFD methodologies incorporated into the project, of course a major emphasis was given on the today's standard RANS/uRANS approaches, see Figure 6. In order to simulate the very large deflections out of scope for any mesh deformation technique, most widely the overset mesh – or Chimera – method would be a standard approach that needs to be validated for the designate purpose of High-lift system deflection. Within the project we addressed improvements in mesh technology as well as assessing the proprietary solver technology of the different partners.



**Figure 6.** RANS – uRANS by Chimera simulation method.



**Figure 7.** Hybrid RANS/LES simulation method.

Apart from the RANS/uRANS, of course scale resolving methods like hybrid RANS/LES method may be seen as more appropriate CFD strategies for such a highly dynamic problem incorporating large scale separations. For this some hybrid RANS/LES methods were applied too, see Figure 7.

In order to widen up the spectrum, even less-standard methods have been investigated. Immersed Boundary Method, see Figure 8, promises to eliminate the Chimera typical challenge of conservative interpolation schemes. Due to the underlying cartesian mesh technology and the solution adaptivity it is expected to provide also computational time benefits. Thus, it was also tested in the combination with a structural model for fluid-structure-interaction (FSI) simulations. Further on, the emerging Lattice-Boltzmann method was investigated as an alternative to uRANS or hybrid RANS/LES methods, see Figure 9. Further details on the investigated methods are given in [9].

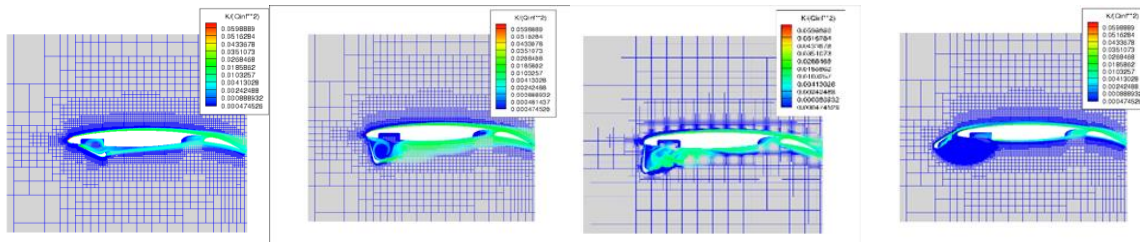


Figure 8. Immersed boundary method.

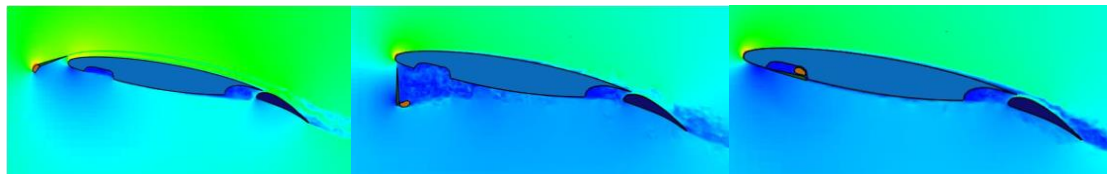


Figure 9. Lattice Boltzmann method.

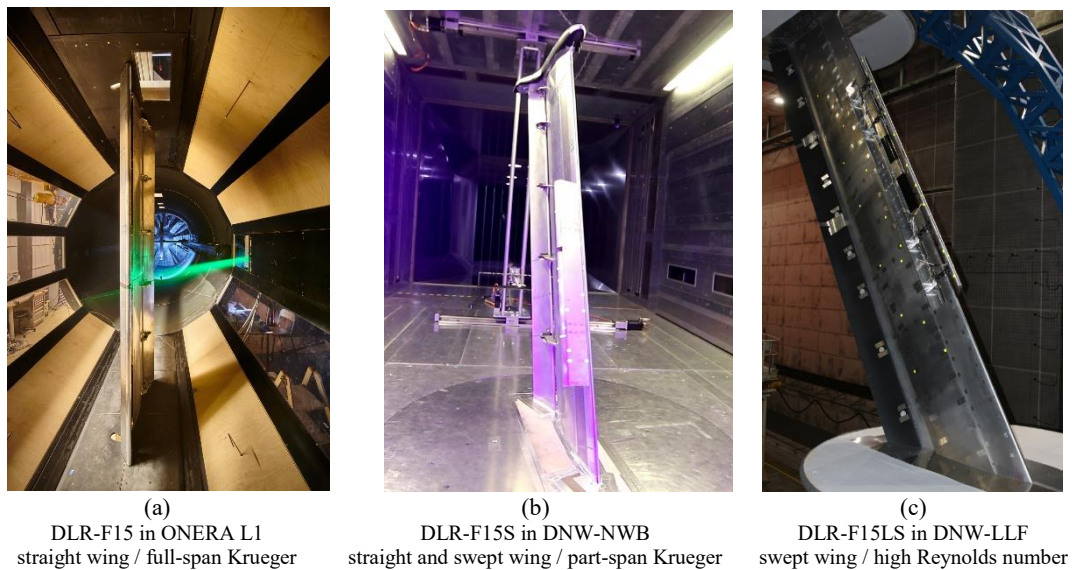
### 3.3. Experiments–Wind-tunnel Testing Strategy

The second major block of activity in the second phase was the preparation and the execution of a series of wind tunnel tests to create a data set on the unsteady aerodynamics of the Krueger flap deployment. We tested with two wind tunnel models of the DLR-F15 family in three facilities.

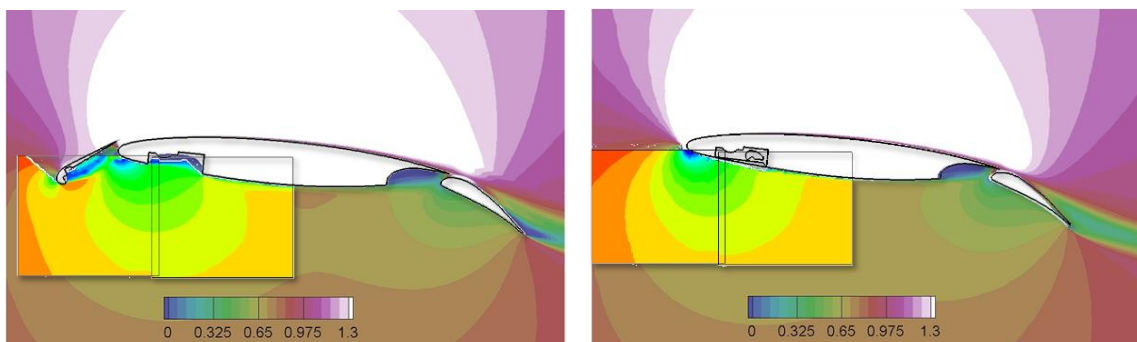
The smaller model – the standard DLR-F15 model with 600 mm clean wing chord – was first setup as a 2D straight wing with a full span Krueger flap in the ONERA-L1 wind tunnel facility in Lille, France, see Figure 10 (Left). Here we focused on a check-out of the mode technology, the setup of the synchronization of the different applied measurement techniques and on inspecting the flow field by Particle Image Velocimetry PIV. After this, the model was reconfigured to a part-span Krueger flap and measured in a cantilever setup in the DNW-NWB facility in Braunschweig, Germany, see Figure 10 (centre). Here, the emphasis was on the impact of wing sweep – we measured a straight and a 23 deg swept wing configuration – as well as the variation of deployment profiles in terms of time, speed and acceleration.

Finally, the Krueger flap was implemented on the large-scale model DLR-F15LS, which is an exact 2:1 upscale of the DLR-F15 model with 1.2 m clean wing chord and a span of 7 m. This model was measured as a 30 deg swept wing in the DNW-LLF facility at Marknesse, The Netherlands, see Figure 10 (Right). Emphasis here was to obtain data at even higher Reynolds number and higher wing sweep. In addition, the larger model size allowed for the implementation of more pressure sensors thus giving additional information on the spanwise variation. Further details can be found in [10].





**Figure 10.** Wind-Tunnel set-up at three facilities.



**Figure 11.** Comparison of CFD results and Experimental data.

### 3.4. Validation and Assessment

At the end of the project, it was attempted to qualify whether the CFD simulations are reliable. For this, a coordinated validation activity was implemented into the last phase of the project. Here, all partners used established methods and attempted to simulate the exact measured wind tunnel conditions. Some aspects investigated include the wind speed, angle of attack and wing sweep, impact of wind tunnel walls, usage of measured deployment profiles, etc.

At the end, the simulation data was compared to the obtained experimental data in terms of pressure distributions. From PIV images the velocity field is derived and can be compared to the field slices of the CFD solution. More specifically and quantitatively better to evaluate are velocity distributions at a certain line extracted both from PIV data and CFD. Solely as a first comparison, a static condition is shown in the image. For the fully retracted position and the fully deflected position, the image shows the velocity magnitude obtained from time-averaged PIV images in bright as an overlay on top of the more faded 2D CFD solution with steady RANS at the same iso-contour scale, see Figure 11. It can be seen that the flow fields at the interfaces match extremely well. This is highlighted by the well captured increase of the boundary layer thickness on the lower side of the wing with deflected Krueger flap. The entire validation effort is detailed in [11].

#### 4. Summary

To summarize, 5 wind tunnel campaigns were conducted with two wind tunnel models in three different wind tunnel facilities. It is to highlight that all were performed strictly under COVID-19 restrictions. This meant no onsite support for model handling, fully remote trouble shooting with the dynamic drives and measurement equipment. Given the complexity of the tests, it can be said that the activities were very skilfully managed and a vast and unique data-set was generated for unsteady Aerodynamics as a result– 34GB of transient data overall with the PIV and SPR images not counted.

On the simulation side, 9 partners produced results using five different approaches of CFD (e.g. all Chimera counting only as one). In total, 16 static and 44 different dynamic cases were simulated (varying deployment sequences, wind speed, wing sweep, etc.). It is also to be noted that the full CPU hours used were not accounted for – which indicates that the total effort was much more than we expected at the planning of the project.

Regarding the first objective, a concrete process was established to achieve reliable results with all the different methods investigated. Exceptional relation between experimental and numerical simulation data was established, especially when looking at pressure distributions. Which in turn makes it possible to confidently provide solid load estimates, although a direct measurement of force components was not feasible in this experiment. With the insight provided by both methods, it was possible to obtain a sound understanding of the flow physics that appear on this special case of a deploying Krueger flap. All the necessary unsteady characteristics have been obtained along with critical factors for further maturation of such systems. The system architecture has been finalised that is appropriate for the full aircraft development based on the criticality of certain flow features for flight safety. And, the tools for more accurate load assumptions have also been studied, which in turn provide improved weight estimations and requirements for actuator sizing. Last but not least, this database also helped identify ways to achieve improved deployment schedules that minimize the aircraft response, de-risk jamming cases and thus increase the passenger comfort in the end.

#### Acknowledgments

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