Please cite at this link: https://ieeexplore.ieee.org/document/8014172

Development of a reliable electro-mechanical actuator for primary control surfaces in small aircrafts

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***Abstract*— This paper lays the foundation for the development of an innovative electro-mechanical actuator for flight-control surfaces. The main features of the enhanced system will be the introduction of new sensor types and health monitoring capabilities. A dedicated test bench has been developed in order to perform endurance tests, leading the mechanical components to failure. In this view, a Condition Monitoring (CM) algorithm is expected to assess the progressive faults degradation, estimating their progression and the Remaining Useful Life (RUL) of related subsystems. Based on the development of new hardware and software components, the REPRISE project is expected to deliver a significant contribution to the More Electric Aircraft mission.**

I. INTRODUCTION

Over the last few decades, several industrial programmes have started the concept of a More Electric Aircraft [1]. Many subsystems that previously used hydraulic, mechanical, and pneumatic power for primary and secondary surface control, braking, landing gear and many other important functions, have been fully or partially replaced with electrical systems. Examples of early adoption of the Power-by-Wire (PBW) technology include Airbus A320 [2], Boeing B777 [3] and Dassault Falcon 7X [4]. The replacement of hydraulic systems can lead to advantages in terms of reduced operational costs and weight savings [5]. By reducing the overall aircraft fuel consumption, removing oil leakage and recycling, this contributes to the birth of a greener aviation [6]. The aero-equipment industry has in particular launched studies for a more extensive electrical actuation, replacing traditional hydraulic systems [7] with Electro-HydroStatic Actuators (EHSAs) [8] and Electro-Mechanical Actuators (EMAs) [9]. This trend has found application in the 2-Hydraulic/2-Electric (2H/2E) power distribution architecture [10]. In this scheme, flight controls are powered in backup mode by EHSAs using a local hydraulic reservoir, and the use of EMAs is reserved for specific systems (spoilers, brakes and engine starters).

Both EMAs and EHSAs require an electric motor and an inverter, see Figure 1. In a self-contained unit, EHSAs are based on a closed-circuit hydraulic transmission, composed by a bidirectional pump driven by an electrical motor, that regulates the oil movement and the pressure difference in the chambers of an hydraulic cylinder. This technology has been applied in the aeronautic sector, mainly in safety critical applications [11]. Conversely, EMAs do not use any hydraulic power, but instead leverage on a gearbox and a mechanical system to translate rotary motion into linear motion. As a result, EMAs are more efficient than EHSAs and provide a better option for leak-free operation and reliability [12].

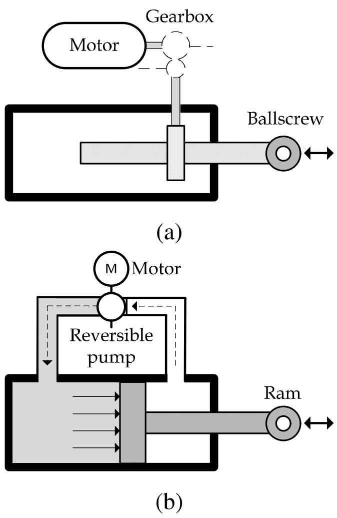

Fig. 1: (a) EMA system. (b) EHSA system [9]

Several collaborative research and development projects have also been launched, in order to develop the All-Electric Aircraft [13]. The Power Optimised Aircraft (POA)−FP5 [14] and the More Open Electrical Technologies (MOET)−FP6 [15] projects have demonstrated on specific flight platforms the effectiveness of electrical actuation. More recently, Actuation2015−FP7 has been focused on developing standardized modular EMA technologies. Electro-mechanical actuators are consequently viewed as the best candidate for the aircraft of the future. However, a major drawback of EMAs is the potential of mechanical jamming. For this reason, an actuator needs to be equipped with a Health Monitoring (HM) architecture, which is able to recognize if a component deviates from its healthy condition, thus preventing a potential failure.

Fault Detection and Isolation (FDI) algorithms aim at identifying the location and harshness of the damaged components [16]. The process of Condition Monitoring (CM), conversely, aims to identify when a particular machinery is wearing out. Such a procedure permits to reduce the down time caused by planned inspections, moving from a scheduled maintenance program to a Condition Based

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Maintenance (CBM) strategy [17]. As a by-product of the method, the Remaining Useful Life (RUL) of the component can be estimated.

The *main contribution* of this paper is to present the Reliable Electromechanical actuator for PRImary SurfacE with health monitoring (REPRISE) – H2020 project. The purpose of this research activity, currently in its early stages, is to support the improvement of the Technological Readiness Level (TRL) for a Flight-Control System (FCS) of small aircrafts, bringing it to TRL 5. This will be achieved by developing a new electro-mechanical actuator architecture, in combination with a health monitoring software able to perform condition assessment on its mechanical components.

The remainder of the paper is organized as follows. Section II presents an overview of the project scopes and main activities. Section III discusses the performed failure analysis, in order to assess the degree of fulfillment to the safety requirements. In Section IV, the developed test bench is described, along with the acquisition hardware and software stack. Lastly, Section V is devoted to concluding remarks and future developments.

II. PROJECT DESCRIPTION

A. Main activities overview

The REPRISE project, a 30 months lasting activity, is articulated into two main parts:

1) *Test bench development and endurance tests*. In this phase, a specific test bench is developed in order to stress the EMA until a failure occurs. Data are collected and a first issue of the condition assessment strategy is provided. In this paper, a description of the rig and related measurements is given.
2) *Design of a new EMA layout and health monitoring software*. Based on the results of the first phase, this second part will be devoted to: i) possible modifications in the EMA and Electronic Control Unit (ECU) layout, ii) develop a health monitoring system, iii) envisage mechanical solutions to allow recovery strategies, in case of major or hazardous failures of the system.

The design of an innovative electro-mechanical actuator for flight-control surfaces needs to be endowed with reduced spatial envelope and weight, in order to permit the installation inside thin wings. In this view, the importance of materials and overall assembly goes along with the sensors types adopted for control and monitoring. Inductive and contactless linear encoders (Zettlex UK Ltd) have been deemed suitable for possible inclusion in the project, due to their lightweight volume, accuracy and reliability. Relying on trusted measurements is fundamental for online condition assessement. The health monitoring capability will be based, at first, on the sensors strictly required to comply with the EMA requirements. If the analysis suggests that more variables need to be acquired, the evaluation of new sensors will be made. As in the FDI framework, the condition monitoring approach to assess the health of a physical system can be pursued through different paths. Some of them rely on knowing precisely the model of the system to preserve, for example in a transistor [18]. If the model is not well known, or too difficult to identify precisely, some different approach can be realized: in [19] the vibrations of the structure are analyzed, in time and in frequency in order to identify if something is changing. Others approach aim to evaluate how the system is working differently from the initial or typical condition, for example the current signature analysis in motors [20]. Specific works have been done regarding electro-mechanical actuators in the aerospace environment. In [21], the authors developed a model-based approaches to prognostics and health management, for actuator fault detection and failure progression. A combined model-based and data-driven prognostic health management software for EMA is presented in [22], using gaussian processes for estimating the RUL of the component that is faulted. Furthermore, authors in [23] present various algorithm to overcome different actuator faults, proposing also a prognosis method.

Summarizing, the main activities addressed in the framework of this research consist of:

1) To test an available EMA on a developed test rig until mechanical failures occur
2) To develop a HM system able to detect degradations of the mechanical components before they will evolve into failures. The HMS will be made of hardware and software to be installed into the ECU of the EMA
3) To redesign the tested EMA in order to improve its reliability, reducing at the same time weight and envelope
4) To design innovative sensors (linear, rotary and load cell), in order to reduce weight and increase system reliability
5) To test the redesigned EMA and ECU, which incorporate the HM system, to demonstrate that the degradation of the mechanical components is detected before it evolves into a failure.

Results from the test campaigns and the health monitoring application will help to fulfill all requirements specified for the actuator. In order to quantify this specifications, a detailed failure analysis has been performed on the designed EMA for testing.

III. FAILURE ANALYSIS

The design and development of more reliable electromechanical actuators needs to follow specific guidelines, to comply with requirements on fabrication, performances and testing of the EMA. In order to assess the specifications laid out by the REPRISE topic manager Piaggio Aero Industries S.p.A Italy, a Fault Tree Analysis (FTA) has been performed. Results from a Failure Mode Effect and Criticality Analysis (FMECA) have been used as input to the FTA.

A. Failure Mode Effect and Criticality Analysis

The FMECA procedure has identified a total of 1950 failure modes, in term of their effect, severity and criticality. The main information about each failure mode consist of:

- *Potential failure mode*: failure mode description
- *End effect*: failure effect at actuator level
- *Item failure rate* (λ): Mission Failure Rate associated to the examined item, expressed in failures per milion hours (fpmh)
- *Mode percentage* (α): percentage of the item failure rate λ related to the particular failure mode in subject
- *Failure mode rate*: the failure rate applicable for the failure mode considered, derived as $\alpha \cdot \lambda$

The Failure Mode Effect Summary (FMES), see Table I, presents summary of the identified failure modes grouped for *end effect*. For each end effect identified, the equivalent failure rate has been evaluated as sum of the corresponding failure mode rates.

TABLE I: Failure Mode Effect Summary

End effect	**Failure per milion hours [fmph]**
Actuator jam	$3.647 \cdot 10^{-2}$
Actuator runaway	$6.000 \cdot 10^{-6}$
False Alarm Signal	$7.859 \cdot 10^{-2}$
Loss of actuator	6.152
Loss of capability to engage the static brake	$3.664 \cdot 10^{-1}$
Loss of service communication	$5.748 \cdot 10^{-2}$
No Functional Effect	$1.039 \cdot 10^{1}$
No functional effect. The failure could become critical in presence of other failures	$1.777 \cdot 10^{-1}$
No significant effect	$4.366 \cdot 10^{-2}$
Possible loss of actuator	$1.550 \cdot 10^{-4}$
Static brake always engaged	$6.660 \cdot 10^{-2}$

B. Fault Tree Analysis

The safety requirements, related to the actuator, that the FTA has taken into consideration are:

- *Loss of control/function*: this event refers to the case where the actuator is lost and cannot be controlled anymore
- *Free floating*: this event refers to the case where the actuator results in free floating or excessive backlash resulting from structural failures
- *Runaway*: this event refers to the case where the actuator results in free floating, hardover, uncommanded movements or oscillations
- *Jam*: this event refers to the case where mechanisms related to the movement of the actuator fails, leading to the actuator inoperability

For each FTA basic event, that represents a specific component failure mode, the relevant failure mode rate (expressed in fpmh) has been used, in accordance with the FMECA. The computation of the risk likelihood $0 \leq Q(\lambda_0, t) \leq 1$, originated from an equipment failure during its mission, is performed as:

$$Q(\lambda_0, t) = 1 - e^{-\lambda_0 \cdot t} \quad (1)$$

where λ_0 represents the component failure rate, and t is the operating time, expressed in Flight Hours (FH). A summary of the FTA results are reported in Table II.

The design of a new EMA, with health monitoring functions embedded, will help to fulfill the constraints currently not satisfied, such as the "actuator loss of control/function" and the "actuator jam" events.

TABLE II: Fault Tree Analysis summary

Top FTA event	**Risk likelihood** [$^1/_{FH}$]	**Requirement** [$^1/_{FH}$]
Actuator loss of control/function	$6.218 \cdot 10^{-6}$	$< 10^{-7}$
Actuator free floating	$6.000 \cdot 10^{-9}$	$< 10^{-7}$
Actuator runaway	$2.0709 \cdot 10^{-12}$	$< 10^{-8}$
Actuator jam[2]	$3.648 \cdot 10^{-8}$	$< 10^{-9}$

IV. EXPERIMENTAL SETUP

A. Electro-mechanical actuator

The electro-mechanical actuator deployed for the REPRISE project consists of a Mechanical Actuator (MA) with incorporated the ECU, directly assembled on the MA housing, see Figure 2. The EMA is usually connected to each primary control surface kinematics and is commanded by one Servo Interface Unit (SIU). The ECU uses a duplex 28 Vdc power supply to power a single internal bus: thus the system is able to operate even if one supply is missing. The digital control unit implements the position control loop for the three-phases Brushless DC motor, with 5 pole pairs. The position measurements come from three Hall sensors and a Meggit Simplex LVDT with ± 37 mm of stroke. The ballscrew transmission consists of 8 circuits with 1 turn each and 28 balls per turn. The actuator can be installed with three different configurations: aileron, elevator and

[2] The required risk likelihood for the Actuator Jam event is 10^{-9} 1/FH since there is a single point of failure leading to this fault. Otherwise, it would have been 10^{-8} 1/FH. The same reasoning applies to the Actuator Runaway event, for which there is not a single point of failure.

rudder. The EMA nominal load is 1346 N, 1405 N, 1494 N respectively. The nominal speed is 36 $\frac{\text{mm}}{\text{s}}$, 79.4 $\frac{\text{mm}}{\text{s}}$, 60 $\frac{\text{mm}}{\text{s}}$ in the three position configurations. In Figure 3, it is possible to observe the experimental magnitude Bode diagram of the EMA closed loop position system. It can be noticed how, incrementing the movement stroke, the system becomes less reactive.

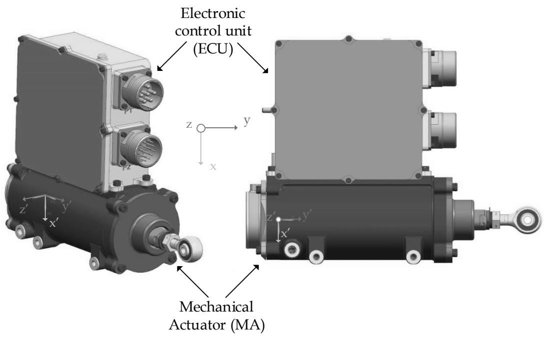

Fig. 2: REPRISE's EMA general view

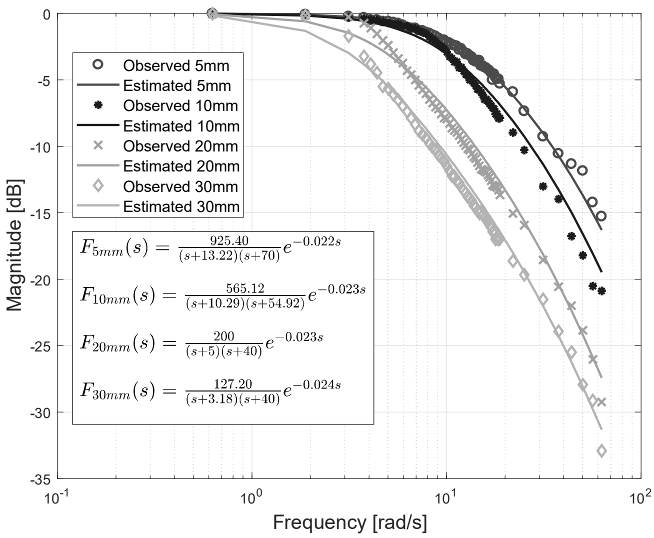

Fig. 3: Magnitude Bode diagram of the REPRISE's EMA closed loop position system

B. Test bench

In order to perform the endurance tests, the test bench employes a Parker Ironcore R16-3A-HS linear motor to generate the aerodynamical load to which the EMA is subjected, Figure 4. The linear motor is able to generate a constant load of 2230 N with a peak of approximately 7400 N for less than 5 s. The piezoelectric Kistler 9321BU load cell, able to measure a range of ± 10000 N, returns the load feedback to the motor drive. A Siko MSK5000, in combination with a magnetic strip Siko MB500/1, is used to measure the position of the linear motor. The Renishaw Resolute optical encoder, located after the load cell, is used to estimate the EMA absolute position, considering the transmission as rigid.

C. Measurements

A schematic, which represents the variables acquired, is depicted in Figure 5. These variables have been regarded to provide meaningful information from the health monitoring point of view, based on the literature and authors previous experience with the HOLMES project[3]. Variables which are stored by the cRIO internal to the test bench are:

- *Temperature*: this variables refers to the air temperature in the proximity of the EMA housing
- *Load sensor*: this signal is the measurement done by the load cell, mounted between the EMA and the linear motor, and it is used to close the force loop of the linear motor
- *Linear optical encoder*: this variable is used to measure the absolute position of the EMA, considering the transmission as rigid
- *Linear motor load reference*: this signal is the load reference that the linear motor has to supply to counteract the EMA motion

Additional measurements, with respect to those acquired internally by the test rig, have been drawn from the sytem. The added variables include:

- *EMA phase currents*: as notice in [24], via a Lem AT-B420L sensor
- *EMA torque*: via a Kistler 9349A Torquemeter, used to validate the torque estimation from the phase currents
- *EMA position reference*: this variable is acquired both by the bench and by the external cDAQ in order to eventually synchronize the measurements
- *Acquisition trigger*: this signal is sent from the PC bench to the external cDAQ in order to trigger the acquisition of its measurements. This will help to maintain the two sources of saved data synchronized
- *Drive current*: this signal refers to the current supplied by the linear motor drive to the linear motor
- *Siko MSK500 linear encoder*: this measurement is related to the position of the linear motor

In Figure 6 are reported some measurements taken from the test bench. As stated in Section II, the health monitoring software will be based upon variables already acquired by the

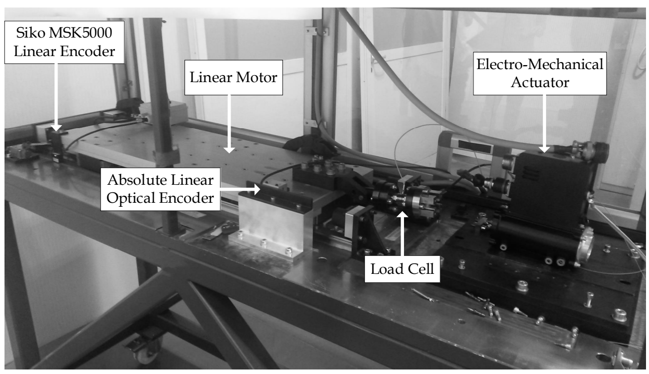

Fig. 4: Test bench with main components

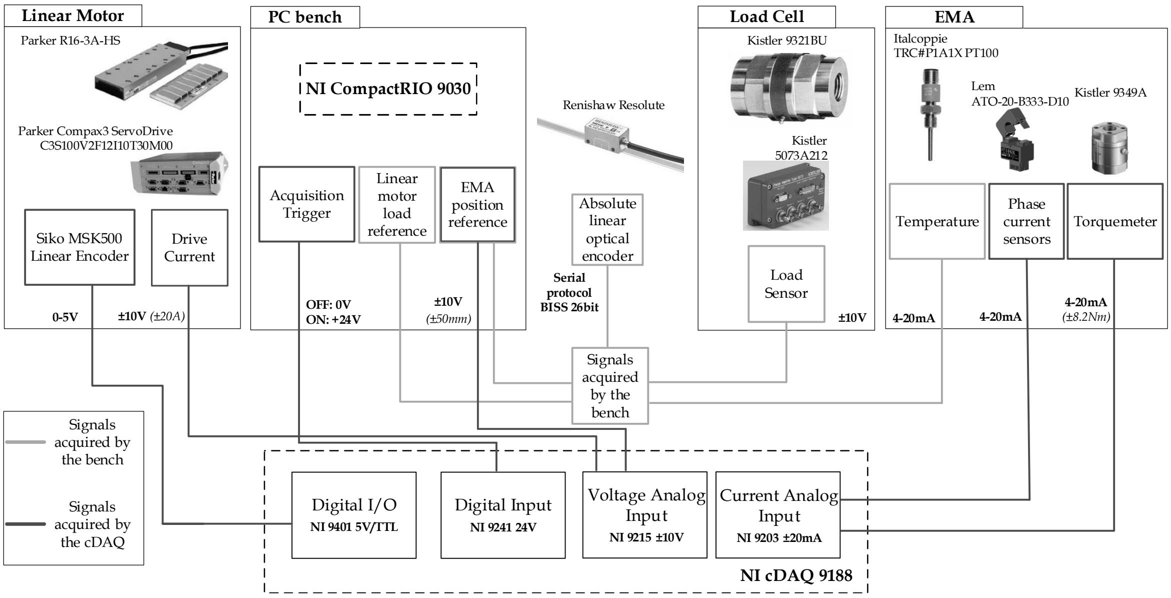

Fig. 5: Schematic of the test rig components, with interactions and measurements system information. (Red) Measurements acquired by the NI cDAQ. (Green) Measurement acquired directly by the NI cRIO inside the test bench. In italics, between brackets, is reported the measurement range of the sensor, reported to the physical variable.

electro-mechanical actuator system. If necessary, new sensors will be investigated and installed.

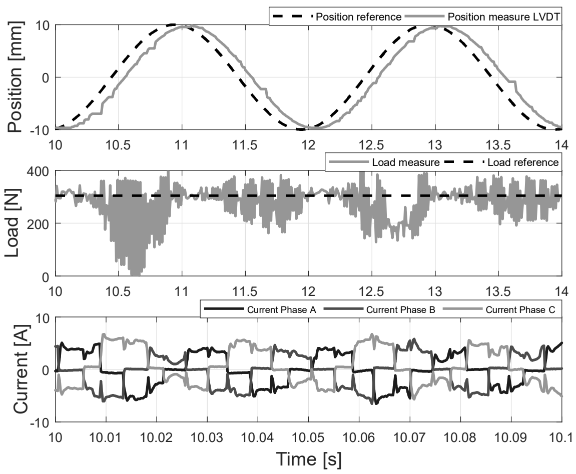

Fig. 6: Examples of measurements from the test bench. Sine frequency: 0.5 Hz. Position amplitude: 10 mm. Load: 300 N. The time on the currents' plot has been zoomed in order to see the currents behaviour

D. Test conditions

The test conditions envisaged for the presented program have been preliminary defined by focusing on the possibility to induce progressive degradation on an otherwise extremely robust and fault-tolerant electro-mechanical actuator. For this reason, the EMA will be tested with 3 ballscrew ball circuit, instead of the EMA design configuration which foreseen 8 balls circuits. This will increase the contact pressure on the balls and on the ball tracks, allowing a faster degradation of the parts. Furthermore, not only an axial load will be applied, but also a radial load. This will result in even higher pressures, above the allowable design, on a certain number of balls in the ballscrew, which could lead to an accelerated degradation of the mechanical parts. From Piaggio's specification, the radial load component will be the 17% of the axial load. After that a FEM analysis has been conducted, it has been observed that loading conditions are still within design allowables, when the the axial load is at most 300 N and combined with a radial load. In order to effectively over-stress the ballscrew components, an axial

TABLE III: Test conditions

Condition	Axial load [N]	Radial load [N]	Additional factors
Condition 0	300	51	-
Condition 1	800	136	-
Condition 2	300	51	Poor lubrication
Condition 3	800	136	Poor lubrication

[3]The HOLMES project, funded by European Union's Framework Programme 7, had the scope of testing and developing fault detection algorithms for EMA's mechanical parts in primary control surfaces

load of 800 N will be used. This will produce a maximum stress of about 3800 MPa on some balls. The load profiles consist then of a constant load. The constant value of the load profile is reached though a ramp, from zero to the set value in 5 s. Then, position profiles are executed and the movement of the EMA is achieved. Once the position profiles have been completely executed, the value of the load profile reaches zero in 5 s with constant negative slope. Additional faults that will be tested regard the removal (partial or complete) of lubricant. This is a situation that is considered most likely to occur, and that could lead to actuator jamming. The initially envisaged test conditions are summarized in Table III. The rationale is to continously monitor the system, starting from Condition 0. Then, Condition 1 is tested. In order to assess if detected deviations are due to a fault or only to the different applied loads, Condition 0 will be retested. This procedure will be carried out iteratively, and the same reasoning can be applied to Condition 2 and Condition 3.

V. CONCLUSIONS AND FUTURE DEVELOPMENT

In this paper, the initial phases of the REPRISE project have been laid out. The aim of this European research program is to design a more reliable electro-mechanical actuator for aerospace systems. This can be accomplished by means of new sensors, design solutions and the supplement of a health monitoring capability. In this view, the condition assessment declination of the monitoring approach is taken into consideration. The aim is to develop indicators that estimate the current health state of the system, providing also an estimation of the residual useful life. After a FMECA and FTA analysis, the main safety requirements have been identified. In order to fulfill these specifications, a test bench has been developed in order to perform endurance tests on an a defined electro-mechanical actuator. The entire measurement chain has been designed in order to acquire relevant information for health monitoring. Following initial test campaigns, the results of the software development will aid to identify additional needed sensors and ECU requirements, leading to a final prototype of a more reliable EMA. A second test phase is envisaged to test condition assessment solutions and added sensors.

ACKNOWLEDGMENT

This project has received funding from the the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 717112 (project acronym: REPRISE)

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