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ASSESSING FORMATION FLIGHT BENEFITS ON TRAJECTORY LEVEL INCLUDING TURBULENCE AND GUST

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ABSTRACT

Within this paper two methods to estimate the aerodynamic benefits of a two-aircraft formation will be compared. The first model calculates the average up-wash velocity at the follower's wing resulting from the leaders wake and superimposes it on the aircraft speed during the trajectory calculation. The second model uses a vortex lattice method to model the aerodynamic interactions between the leader and the follower for a set of specific flight states beforehand. This database can be used by the trajectory calculation to interpolate the actual benefits for the given flight. In this paper for a specific aircraft type and an example mission both methods will be compared and it will be shown, that they can be used to derive surrogate models to predict the formation benefits based on general formation data. To further improve the prediction of the aerodynamic benefits, the influence of gust and turbulence will be assessed by simulating the aircraft reaction on the disturbances and deriving a reduction factor degrading the aerodynamic benefits creating a database and corresponding surrogate models. The occurrence of turbulence and gust can then stochastically be imposed during the trajectory calculation and the sensitivity of the aerodynamic benefits will be examined.

Keywords: formation flight, wake surfing, energy harvesting

1 INTRODUCTION

The aerodynamic formation flight also known as wake surfing can be considered as one of the most promising operational procedures in aviation enabling substantial fuel and cost savings, and bearing the potential to reduce climate relevant gaseous emissions and contrail induced cirrus. Several studies show, that the potential of this procedure can be realized not only under experimental conditions but also in realistic traffic scenarios. However, in order to evaluate such scenarios the aerodynamic interaction between the leading and the trailing aircraft needs to be modeled precisely. Therefore, the work presented in this paper compares two methods of aerodynamic modeling (*advanced model* and *simple model*) and presents a method to account for the influence of turbulence and gust on the fuel saving benefits.

1.1 State of the art

The aerodynamic modelling is one of the key elements to assess formation flight benefits. *Marks* [6] uses a simple aerodynamic horseshoe model to calculate the aerodynamic interaction between leader and follower. *Liu* [5] adapted a potential flow solver to investigate the potential drag reduction in formation flight. Validations with wind tunnel experiments and theory shows a good agreement with the used Athena Vortex Lattice method (AVL). Other work related to the influence of turbulence and gust on the formation benefits are not known to the authors.

1.2 Approach

In this section, the basic approach to assess the aerodynamic benefits estimated by the *advanced model* and the influence of turbulence and gust as followed in this paper is presented (see figure 1).

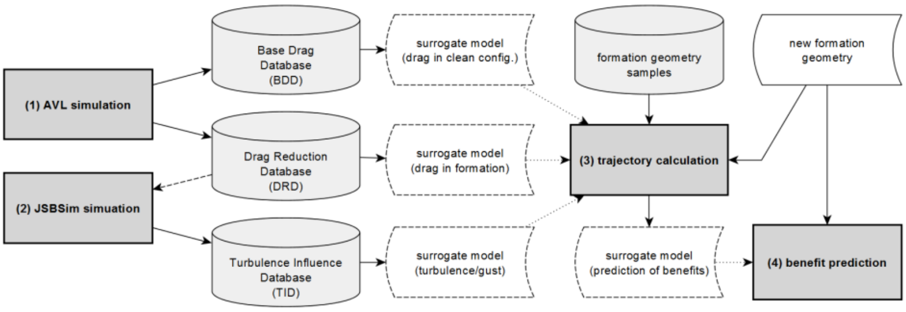

Figure 1: Schematic approach to assess the aerodynamic formation benefits

Based on the Athena Vortex Lattice Method (AVL) (1) and the flight dynamics model software JSBSim (2) three databases are set up containing information about the drag of a trailing aircraft in solo flight (Base Drag Database; BDD), in formation flight (Drag Reduction Database; DRD) as well as the relative change in drag due to the influence of turbulence and gust (Turbulence Influence Database; TID) for a set of different operating points and positions behind the leader. For all these databases surrogate models are generated that can be used to interpolate the values for any operating points that occur during the trajectory calculation (3) of the formation mission. The trajectory calculation is done by the in-house tool Trajectory Calculation Model (TCM) that is based on the Base of Aircraft Data (BADA version 4) flight performance models provided by EUROCONTROL and can be used to calculate the overall benefits for a formation mission and thus to create surrogate models to predict the overall formation benefits (4) based on a set of formation parameters. In section 3 the results of the *advanced model* will be compared to the *simple model*.

1.3 Assumptions and scope

Within this paper several assumptions concerning the conduction of formation flights are made (see table 1). First, only two-aircraft formations will be considered with a follower (index *f*) flying in an extended formation flight (EFF) at about 30 wingspans behind a leader (index *l*). It is assumed, that there are no positional changes and the formation operates at the same altitude and Mach number throughout the formation segment. The aircraft type was chosen to be the Boeing 777-200 as one of the most prevalent aircraft on the North Atlantic corridor. Here also the example mission is located represented by a double Origin-Destination pair (DODP) with the leader flying from LHR to JFK and the follower from CDG to YUL (see figure 5c). The passenger load factors of both aircraft are set to 0.80 representing an average value on the North Atlantic corridor. In order to set up the parameter limits of the DRD, BDD and TID the constraints given in [8] were used. The values for each parameter, lead to a model data set of about 15625 samples for the DRD, 61 for the BDD and 28632 for the TID. For the validation of the models additional samples were randomly generated.

number of aircraft	2	formation Mach number	0.84 (fixed)
AC-type leader	B777-200	formation altitude	39000ft (fixed)
AC-type follower	B777-200	passenger load factor	0.8 (both)
OD pair leader	LHR-JFK	streamwise separation	30 wingspans
OD pair follower	CDG-YUL	spanwise position of follower (y_t)	variable

Table 1: Summary of reference mission parameters

2 METHODS

In this section two methods to model the aerodynamic interactions between the leader and the follower as well as the modelling approach for the influence of turbulence and gust will be presented.

2.1 Simple aerodynamic model

The *simple model* as it is used in [6] uses two parallel infinite vortices representing the wake of the leader (see figure 2a, not to scale).

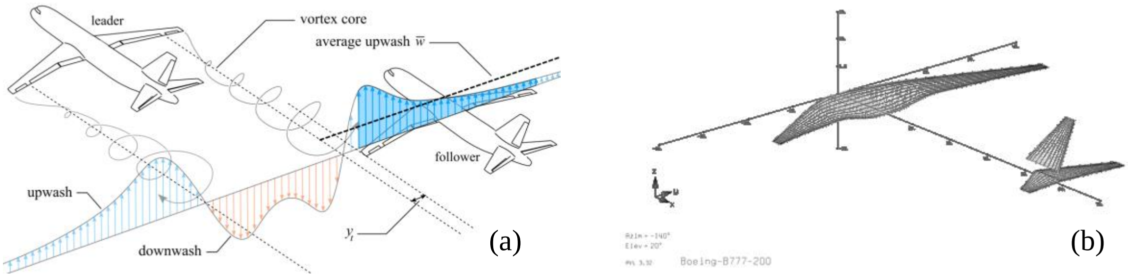

Figure 2: Schematic model used for the simple aerodynamic assessment (a);
screenshot of Boeing B777-200 in AVL (b)

In order to model the upwash w(y) at the follower's position the Hallock-Burnham vortex model is used as presented in equation (1). Here Γ_l represents the circulation of the vortex created by the leader, y the distance to the vortex core and r_c the core radius of the vortex that can be estimated to $r_c = 0.035 \cdot b_l$ with b_l as the wingspan of the leader [3]. The average upwash $\overline{w}$ at the follower's position is calculated by integrating the upwash of both vortices over the follower's wingspan b_f according to equation (2).

$$w(y) = \frac{\Gamma_l}{2\pi} \frac{y}{y^2 + r_c^2} \quad (1)$$

$$\overline{w} = \frac{1}{b_f} \int_{y_t}^{y_t + b_f} w(y)\, dy \quad (2)$$

With the spacing between wingtip and vortex core y_t (see figure 2a) the change of the velocity vector $\overline{\varphi}$ can then be estimated by equation (3) resulting in a thrust reduction of the follower ΔF_f for a stationary flight according to equation (4). More details on the *simple model* can be found in [6].

$$\overline{\varphi} \approx \frac{\overline{w}}{v} \quad (3)$$

$$\Delta F_f = A_f \overline{\varphi} = m_f g \overline{\varphi} \quad (4)$$

2.2 Advanced aerodynamic model

2.2.1 Vortex lattice method and simulation

The *advanced model* calculates the induced loads at the trailing aircraft due to the vortices of the leading aircraft using a vortex lattice method (VLM). Additionally, empirical methods estimate the viscous and wave drag at the trailing aircraft. In the Athena Vortex Lattice Method (AVL), a distribution of horseshoe vortices calculate the aerodynamic loads of the lifting surfaces and their trailing wakes, which are generated by the superimposed horseshoe vortices [1]. As the source and doublet distribution for the fuselage is not well validated, the fuselage is omitted in AVL and replaced by a rectangular surface between the two half of the wing. Figure 2b illustrates the generated aircraft geometry of a Boeing B777-200 in AVL. A detailed description of the methodology can be found in [8]. The VLM is limited to thin profiles, small angles of attack and sideslip and cannot capture flow separation. However, in a stationary cruise flight, this limitation should not affect the results. A Prandtl-Glauert correction considers the transonic flow at cruise flight. To calculate the viscous and the wave drag of the aircraft, the developed calculation environment around AVL uses the aerodynamic functions of the in-house conceptual aircraft design tool MICADO, which are based on semi-empirical functions of Raymer and Mason.

2.2.2 Surrogate modelling of drag

The databases created by the *advanced model* can be used to create surrogate models to predict the expected drag in solo (BDD) and formation flight (DRD) for any operating point. In this work the Kriging method is used to create the surrogates as this method generates highly accurate representations. For a set of different Kriging models originating from varying parameters used in the model creation the root mean square errors of the prediction (RMSEP) were calculated and the model with the lowest RMSEP was selected. To create the Kriging models in the first place the Matlab© toolbox DACE Kriging was used.

2.3 Modelling turbulence and gust

2.3.1 Autopilot and simulation

To assess the influence of turbulence and gusts together with the induced forces created by the leading aircraft, a simulation environment was developed. As the external forces lead to a movement of the follower away from the desired optimal position behind the leader, the simulation includes a simplified autopilot. The dynamic derivatives of the trailing aircraft are determined by the program DATCOM+ Pro, which is based on the United States Air Force stability and control data compendium (DATCOM) [2]. The program interpolates the induced drag, roll and yaw moments from the previously described *advanced model* (see chapter 2.2) for the initial flight condition (flight speed, altitude and aircraft masses). In order to avoid errors due to the different drag estimation methods in AVL and JSBSim, the relative change of the induced drag at the trailing aircraft ΔC_{Di} is calculated according to

$$\Delta C_{Di} = C_{Di,form} - C_{Di,solo} \tag{5}$$

Here, $c_{Di,form}$ represents the induced drag coefficient in formation flight and $c_{Di,solo}$ in solo flight respectively. This generates look up tables for different vertical and spanwise separations of the aircraft. The atmospheric model in JSBSim is based on the military specification MIL F-8785C [7] and includes discrete gusts, that have a “1-cos” shape, and continuous turbulences, which are described by a Dryden spectrum.

Turbulence degree	**Wind speed [ft/s]**	**Gust degree**	**Gust magnitude [ft/s]**
1	25.0	1	10.0
2	50.0	2	20.0
3	75.0	3	35.0

Table 2: Turbulence and gust severity levels (MIL-F-8785C [7])

Table 2 lists the three different turbulence and gust severities with the corresponding wind speeds or gust magnitudes. In the simulation, the gust acts in positive y direction towards the right wing tip. The autopilot function consists of an altitude and a position hold. The position hold determines the required aileron deflection ξ_{ap} and consists of two PID controllers. For the altitude hold, one PID controller is used. The coefficients K_P, K_I and K_D of the PID controllers are estimated with the tuning method by Chien, Hrones and Reswick. Further explanations about the autopilot can be found in [8]. To further improve the flight trajectory the proportional parameter of the PID controller 1 and 3 in table 3 were adjusted.

	PID 1 (Position Hold)	PID 2 (Position Hold)	PID 3 (Altitude Hold)
K_P	0.001496	21.96	-0.00006886
K_I	0.00000009163	22.875	-0.000003146
K_D	0.004034	3.689	-0.0001554

Table 3: PID controller parameters

2.3.2 Surrogate modelling of turbulence and gust

The results of the JSBSim simulation showed in some cases an unrealistic behaviour. This can be explained by the fact, that the station keeping in the JSBSim simulation is not optimal, so that aperiodic amplifications of the vortex offset can occur. The corresponding values were omitted during the interpolation and the nearest neighbour interpolation (NNI) was chosen for the interpolation of the TID. For each gust/turbulence combination the corresponding drag reduction values are extracted from the TID, normed and the average value of the nearest neighbour is used for the prediction.

2.3.3 Imposing on trajectories

The probability of turbulence and gust occurring during a flight is a random process. Several assumptions concerning the probability of exceeding a certain turbulence/gust level exist (see [7]). However, in order to give a first estimate of the influence of turbulence and gust on the formation benefits on trajectory level a single discrete gust is imposed during the trajectory calculation degrading the aerodynamic benefits of the follower for the time interval of 300s as defined in the turbulence and gust simulation. A first indication of the magnitude of the gust/turbulence influence on the formation benefits is given in section 3.

2.4 Overall benefit estimation

It was shown by the author, that the benefits of a formation mission can be estimated using a set of 11 mission parameters describing the formation geometry, speed, altitude and load factors [6]. In order to create such surrogate models for the benefit prediction, for a set of example missions detailed trajectory calculations are performed. The simple aerodynamic model shows that very high accuracies can be obtained using multiple linear regressions (MLR) or a Kriging approach. The Kriging approach was used in this paper to generate surrogate models for the formation benefits based on the *advanced model*.

3 RESULTS

In this section the results for the creation of the surrogate models for the drag databases (BDD, DRD) and turbulence database (TID) as well as a comparison of the simple and advanced model will be presented. Using the example mission described in section 1.3 the results of an exemplary trajectory calculation will be presented and discussed and a first guess of the influence of gust on the formation benefits will be given.

3.1 Surrogate modelling of drag and turbulence

The results for the surrogate models calculated for the B772-B772 formation shows for the BDD and DRD interpolation that a very good fit of the data is obtained. The quality of the TID interpolation depends on the turbulence/gust level. The values obtained during this work are summarized in table 4. Especially for the gust level 3 the prediction quality showed to be rather poor. An improvement of the autopilot or a finer resolution of the database could help to improve the prediction quality.

database	RMSEP	mean
BDD	2.0379e-09	0.0226
DRD	8.6951e-06	0.0188
TID (gust: 0-2 / turb: 0-3)	0.0159 – 0.0177	0.9699 – 0.9812
TID (gust: 3)	0.0585 – 0.0920	1.0923 - 1.3045

Table 4: Validation results for the surrogate models

3.2 Aerodynamic model comparison

To compare both aerodynamic models, trajectory calculations of the example mission were performed using different values of y_t. Figure 3a shows the estimated drag coefficients in solo flight calculated by the BADA total energy model $c_{D,\text{bada}}$ as it is used in the trajectory calculation against the *advanced model* $c_{D,bdd}$ by interpolation of the BDD during the formation segment. It can be found, that the *advanced model* is slightly underestimating the drag. This can be explained by the fact, that AVL does not consider the effect of the fuselage on the induced drag. Therefore, the relative drag fraction

$$\Delta D = \Delta c_D = \frac{c_{D,form}}{c_{D,solo}} \tag{6}$$

of the drag coefficient in formation $c_{D,form}$ relative to the drag coefficient in solo flight $c_{D,solo}$ is used for the benefit estimation during the trajectory calculation. Figure 3b shows Δc_D of the *simple model* $\Delta c_{D,simple}$ against the *advanced model* by interpolation of the DRD $\Delta c_{D,drd}$. It can be observed, that the estimations of both models can be compared and are depending on the relative tip spacing $k_t = y_t/b_l$. In this example a k_t of about 0.075 shows a good match of both models. For lower k_t the *advanced model* shows a lower drag reduction than the *simple model* whereas a higher k_t leads to higher values. Generally it can be observed that the drag reduction $1 - \Delta D$ is reduced as k_t is enlarging with the aircraft moving further out of the vortex. In figure 3c the overall relative fuel saving benefit for the formation mission λ_F as defined in [6] is presented for the *advanced model* and the *simple model*. As expected, both models yield the same λ_F for $k_t \sim 0.075$.

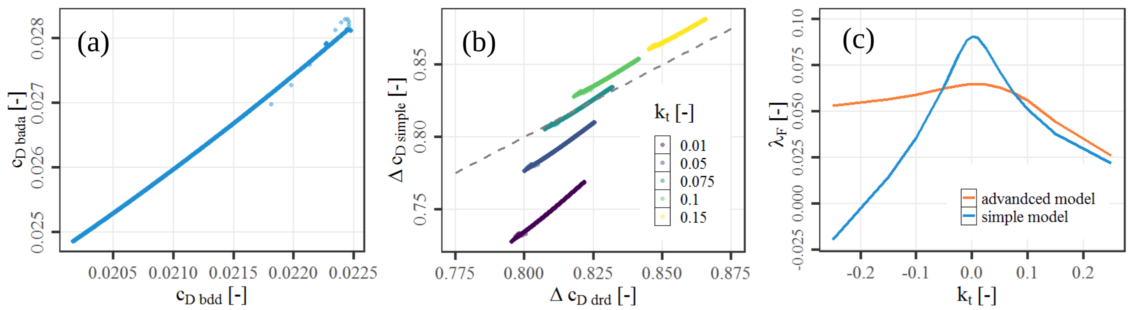

Figure 3: Comparison of simple and advanced aerodynamic model; estimated drag coefficient in solo flight (a); relative drag fraction due to formation flight (b); variation of tip spacing k_t and overall mission benefit λ_F (c)

3.3 Influence of turbulence and gust

In this section the example formation is investigated exemplarily. The simulation starts with a Mach number Ma_{init} of 0.80, an altitude h_{init} of 43000ft, weights of both aircraft of 172000kg and the wings overlapping by 15 percent of the half span. The vertical distance is zero. During the simulation of the trailing aircraft, the simulation includes the induced loads from the *advanced model* (DRD) after 20s. After 60s discrete gusts and continuous turbulence with a severity of two, act on the aircraft. Figure 4 shows the resulting variation of the altitude (a) and lateral displacement (b) during the simulation period of 500s.

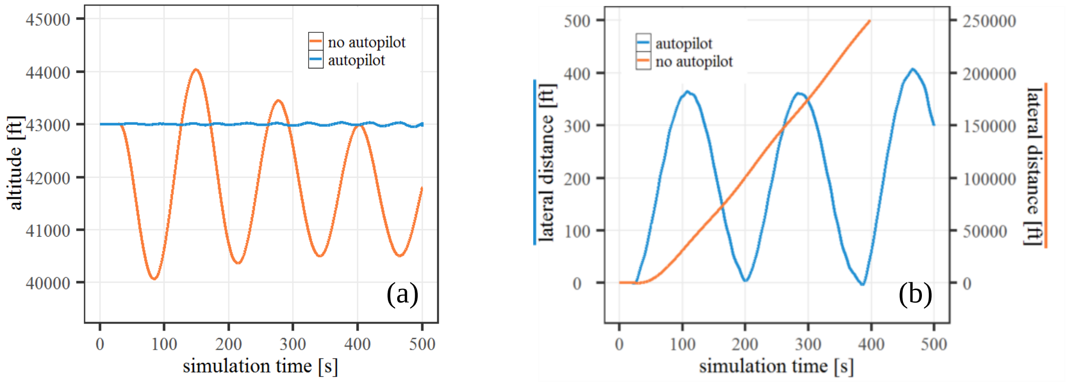

Figure 4: Variation of the altitude (a) and lateral displacement (b) without and with activated autopilot

Without an autopilot, the flight altitude oscillates between 40000ft and 44000ft. The reason for this oscillation can be the increase of the induced drag outside of the wake vortices, which leads to a lower velocity and consequently lift. When the autopilot is switched on, this oscillation is reduced and the altitude changes between 50ft above and below h_{init}. Due to the induced roll moment, the trailing aircraft moves out of the wake vortices of the leading aircraft. The lateral gust from the left enforces this movement. Thus, the lateral distance increases strongly after 500s. When the autopilot is activated, the lateral distance oscillates between 0ft and 400ft. The average relative drag fraction $\overline{\Delta D}$ (see equation 7), determines the decrease of the potential drag reduction due to the offset from the optimum position. Here, the averaged total drag coefficient $\overline{C_D}$ is the mean drag coefficient between 100s and 400s and $C_{D,ref}$ the total drag coefficient at 19.5s, when no formation influence and atmospheric disturbance exists.

$$\overline{\Delta D} = \frac{\overline{C_D}}{C_{D,ref}} \tag{7}$$

When the autopilot is switched on, the average drag fraction $\overline{\Delta D}$ varies between 0.915 and 0.919 for different turbulence and gust severities. Hence, the average drag reduction $1 - \overline{\Delta D}$ in formation flight and atmospheric disturbances is between 8 and 9 percent.

3.4 Trajectory analysis and prediction of formation benefits

The results of the trajectory calculations for the example mission are presented in figure 5a. It can clearly be seen, that during the formation beginning at the formation start point (FSP) and ending at the formation end point (FEP) the drag reduction $1 - \Delta D$ decreases as the weights of the aircraft change during the course of the mission. Depending on k_t these reduction is smaller and decreases less as the follower moves out of the leader's wake. Figure 5b shows the drag reduction for the example mission showing the influence of a gust (level 2) encounter during the formation segment. The reduced benefit level is maintained for 300s of the simulation. Caused by this single disturbance, the overall relative mission benefits λ_F decrease from 0.06295 to 0.06204 representing a decrease of about 1.5%.

The prediction of the relative formation benefits λ_F using the formation parameters as described in [6] shows a very good fit to the calculated data if the *advanced model* is used to determine the aerodynamic effects during the trajectory calculation. For the validation data a very good fit was obtained resulting in a RMSEP of about 5.4279e-04.

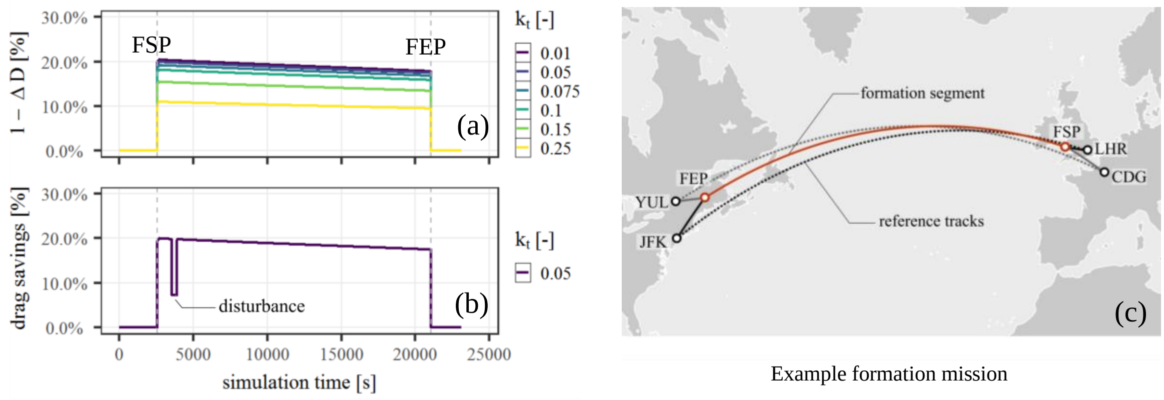

Figure 5: Results of the trajectory calculation for the example mission; drag reduction dependent on lateral position (a); influence of single disturbance (b); example formation mission used in this paper (c)

4 CONCLUSIONS AND OUTLOOK

The work presented in this paper shows, that the prediction of the formation benefits by the simple and the advanced approach are both applicable if relative values are used and yield a comparable prediction for a tip spacing of about 7.5% of the wingspan of the leader. The prediction of the overall formation benefits based on the mission parameters using the advanced model was found to be very accurate. Furthermore, it was shown, that atmospheric disturbances have a significant influence on the formation benefits as the follower is moved out of the vortex and loses the aerodynamic advantages. A method to induce the turbulence and gust influence on trajectory level was presented and it was indicated, that depending on the occurrence of such events the influence on the formation benefit cannot be neglected. However, further improvement must be done on the flight dynamic model (including the autopilot), the turbulence interpolation method and the modelling of the occurrence of atmospheric disturbances during the flight to achieve more accurate results. An expansion of the research to more formation missions and aircraft types has to prove the universality of this approach in the future.

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