

Effects of En-route Wake Vortex on RPAS Operations

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Abstract—Compared with common airliners, High/Medium Altitude Long Endurance (HALE/MALE) RPAS are lighter and have larger wingspan. Therefore RPAS will be extremely sensitive to vortex interactions with larger airliners, not only during departures and arrivals, but also at medium and high altitudes during the en-route phase. The extent of this sensitivity shall be investigated in order to determine safe levels of separation and come up with feasible maneuvers to avoid the effect of wake vortex under the assumption that the RPAS may become unrecoverable by the autopilot. For this reason, the objective of this paper is to model the generation of en-route vortex and quantify its impact into the airworthiness of a potentially conflicting RPAS. To accomplish this objective, a wake vortex generation and encounter model will be created as a first step to define the airliner-RPAS separation requirements due to the airliner's vortex. Then, vortex separation requirements will be compared to those usually employed for separation assurance.

Conclusion will show that some current separation standards are not conservative enough when the RPAS faces an airliner wake vortex.

Index Terms—RPAS, vortex, impact

I. INTRODUCTION

During the last decade, the interest of using RPAS for civil missions and applications has increased significantly. However, the lack of regulations concerning certification, airworthiness and operations is still confining RPAS to segregated (most likely uncontrolled) airspace. Among all possible RPAS applications, surveillance missions will be perhaps the most common. In these missions, RPAS will not operate as current commercial aircraft, which fly point-to-point missions. They will possibly stay over certain areas performing different types of non-conventional maneuvers (such as scans, perimeter loops, etc.) that will change dynamically during the flight according to the mission needs. Moreover, most RPAS will have flight performance different to that of commercial airliners (in terms of cruise speed and climb/descent performance, for instance) but will likely operate at very similar altitudes, effectively introducing additional complexity into the separation assurance tasks.

Nowadays, separation in controlled airspace is typically the responsibility of the *air traffic controller* (ATC), which issues clearances to the aircraft in order to maintain minimum separation values. Some systems, however, have been proposed to increase the automation levels of these manual separation assurance processes (e.g. *short-term collision alert* (STCA),

medium-term collision detection (MTCD)). Previous research on separation management and collision avoidance for RPAS already demonstrated that certain aspects related to the RPAS particularities should be taken into account to maintain the efficiency and safety of the separation assurance.

Even though RPAS maneuvering is not seen as a practical mechanism from the point of view of ATC, in some situations, vectoring the RPAS may be unavoidable. Potential encounters with lower-end airliners (like turbo props) in which the relative performance dissimilarity is minimal, or with aircraft in distress and/or with a high priority level will require the RPAS to perform separation maneuvers.

In addition to separation, the additional factor of en-route vortex will influence RPAS maneuvering. The impact of en-route vortex on extensive RPAS operations has never been considered in previous investigations. En-route vortex has been seen just as an inconvenience to passengers until recent years. The increasing number of incidents between airliners has caused a much deeper analysis of the implications of vortex encounters. RPAS susceptibility to en-route vortex adds further complexity to the scenario, along with the increasing number of (super) heavy aircraft, which are powerful wake vortex generators.

Both *medium altitude long endurance* (MALE) and *high altitude long endurance* (HALE) RPAS may experience a larger number of vortex encounters due to their extensive flight time and higher speed differential with airliners. Moreover, the mass dissimilarity and large wing spans will generate vortex encounters that RPAS should avoid at all costs. Therefore, both separation encounters and vortex encounters motivate an in depth investigation of the RPAS maneuvering capabilities and implications. Hence, both from the RPAS pilot and the ATC point of view, new tools need to be envisaged in order for them to determine the most appropriate separation maneuver at each scenario, taking into account RPAS-specific factors that are generally neglected when managing airliner to airliner separation provision.

As a result of the RPAS sensitivity, wake vortex encounters may not only results into hazard situations near airports, but may also cause a significant threat in the upper airspace. For this reason, the objective of this paper is to model the generation of en-route vortex and quantify its impact into the airworthiness of a conflicting RPAS. To accomplish this

objective, a wake vortex generation and collision model will be created as a first step to define the airliner-RPAS separation requirements due to the airliner's vortex. Then, vortex separation requirements will be compared to those usually employed for separation assurance.

The remainder of the paper is organized as follows. The vortex generation model is profusely described in Section II. Section III presents the evaluation of the severity of vortex encounters taking into account the model of the generating aircraft, the atmosphere characteristics and the RPAS particularities. An assessment on the applicability of current separation standards on RPAS wake vortex encounters is presented in Section IV. Finally, conclusions and some identified further work are presented in Section V.

II. VORTEX GENERATION MODEL

This section will review the most relevant existing results on en-route wake vortex that are required to build the vortex models required to address the creation of the RPAS vortex model. The analysis will be developed based on these existing results by separating the vertical and lateral behavior of the airliner's vortex.

A. Previous work

Many studies regarding wake vortex generated by aircraft can be found in the literature. Most of them address the minimum separation that has to be maintained between two aircraft when they are within the take-off or landing phases. For instance, in [1], [2], [3] it is evaluated the wake vortex separation minima required during the final approach, intermediate approach, departures, landings, crossing and parallel runways.

Current wake turbulence separation is defined by ICAO in [4], which only considering the aircraft's MTOW. However, recent studies like [5] introduced another wake vortex categorization which takes into account not only the aircraft mass but also its wingspan. The new model will provide more accurate and efficient spacing between sequential aircrafts, increasing airport capacity, but taking always into account the safety factor. Wingspan consideration play an important role in the analysis of the impact of wake vortex on RPAS. Existing RPAS not only present significant lower masses than typical airliners but also wider wingspan than typical aircraft of similar MTOW.

Little or no research can be found in the literature about the impact of en-route vortex encounters on RPAS. However, some related studies have been carried out to investigate en-route vortex encounters between airliners. For example, [6] describes the vortex generation and the factors that influence intensity and duration. Authors state that vortex stabilizes 1000 ft under the generating aircraft and it can be active from 10 up to 40 NM. In [7] authors focused wake vortex encounters in en-route phase. They defined the so-called *vortex habitation area* as the area where the generated vortex could be active taking into account not only the aircraft dimension but also

several uncertainties such as position inaccuracies. In [8] authors define a simple way to compute a wake vortex encounter severity metric: the *rolling moment coefficient* (RMC). This metric only depends on vortex total circulation and several structural parameters of the follower aircraft. In [9] authors propose three different models to quantify the vortex intensity decay with time: the Sarpkaya, D2P and TDAWP models and compare them with real circulation data in different atmosphere conditions. Conversely, in [7] authors present a study about the effects of wake vortices on commercial aircraft. They examine the risk of penetrating into a wake vortex quantifying the strength of the induced rolling moment and determining if the aircraft is able to compensate such perturbation.

The presented vortex generation model is based on the contributions presented in [6], [7], [8]. A separated dimension analysis will be performed thus splitting the model into two different submodels; one for the horizontal dimension and the other for the vertical one.

The lateral dimension model will take into account a subset of dynamic characteristics of the generating aircraft plus along with the effects of the horizontal wind velocity to calculate the hazard area in which the wake vortex is active. Conversely, the vertical dimension model will focus on the vortex natural behavior as described in [7] but also taking into account the vertical component of wind velocity. This way, the vertical displacement of the hazard area is determined. Moreover, to determine the intensity of the vortex in every location of such area, the vortex intensity model presented in [8] will be used. Doing so, the wake vortex will be fully characterized.

B. Lateral dimension

As a starting point the lateral dimension model will be defined based on [7]: a straight line behind the trajectory of the generating aircraft. Nevertheless, this line will not be rigid fixed following the direction of the trajectory of the aircraft but will vary its position depending on the velocity with which the wind is blowing. Therefore, the vortex will not follow the same trajectory of the generating aircraft except in case of no crosswind. In this particular situation, the wake vortex will be strictly behind the generating aircraft.

To determine the trajectory the vortex will perform, the proposed model will be constructed under the following assumptions. On one hand, as stated in [6], the most important cause of wake vortex turbulence behind a flying aircraft lies in the formation of aerodynamic trailing vortices which are consequence of the circulation around the airfoils. Nonetheless, the air mass from the jet which is behind the engine also contributes on the wake generation but it can be neglected. Therefore, aircraft wakes are, in fact, two parallel, rapidly rotating, spiral tubes of air up to 35 feet in diameter, trailing downstream.

Regarding the extension of the vortex, in [6] is stated that vortex can be considered active from 10 up to 40 NM behind the generating aircraft. Typical airliners cover 40 NM in 5 minutes at cruise altitudes so the model will consider the vortex to stay active those 5 minutes. Nevertheless, this time

refers to the total time the vortex needs to disappear due to the viscosity of the atmosphere. The effects on the following aircraft shall take into account the vortex strength and its structural characteristics.

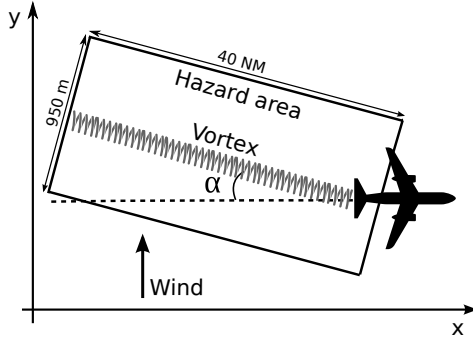


Figure 1. Wake vortex hazard area

Taking into account all the stated assumptions, Figure 1 depicts the lateral extension of the wake vortex and the involved hazard area based on [8]. α is defined as:

$$\alpha = \arctan\left(\frac{\omega_y}{\omega_x + v_{x_{airliner}}}\right) \quad (1)$$

Where:

- α is the wake vortex deviation angle [rad]
- ω_x is the wind speed in the x direction.
- ω_y is the wind speed in the y direction.

C. Vertical dimension

To define the trajectory the vortex will perform in the vertical plane, the proposed model will be based on the following assumptions. In [8] is stated that the wake vortex descends with respect to the trajectory of the aircraft and that it decays with an average speed of 400-500 ft/min. At cruise altitude, vortices usually level off at about 1000 ft below the altitude of the aircraft as their density comes into equilibrium with that of the surrounding air.

Moreover, from [6] is extracted that the rate of circular motion around every vortex acts on the trailing vortices and causes downwash with a velocity determined by:

$$w = \frac{\Gamma_0}{2\pi L_v} \quad (2)$$

Where:

- w is the downwash velocity [m/s].
- Γ_0 is the vortex circulation [m²/s].
- L_v is the span between vortex axes.

Conversely, Γ_0 can be computed as follows:

$$\Gamma_0 = \frac{W}{\rho V L_v} \quad (3)$$

Where:

- W is the weight of the generator [N].
- ρ is the density of air [kg/m³].

- V is the airspeed of the generating aircraft.

The span between the vortex axes is determined by the layout of airflow along the wing span, which depends on the shape of the wings and angle of attack. In free air the factor that relates the wingspan (b) and the span between the vortex axes is $L_v = 0.8 \cdot b$ [6]. This way, the rate of descent of the wake vortex depends on structural and dynamic characteristics of the generating aircraft.

Finally, similarly to the lateral dimension, the hazard area has been defined as in [7]. Figure 2 shows the hazard area of the wake vortex.

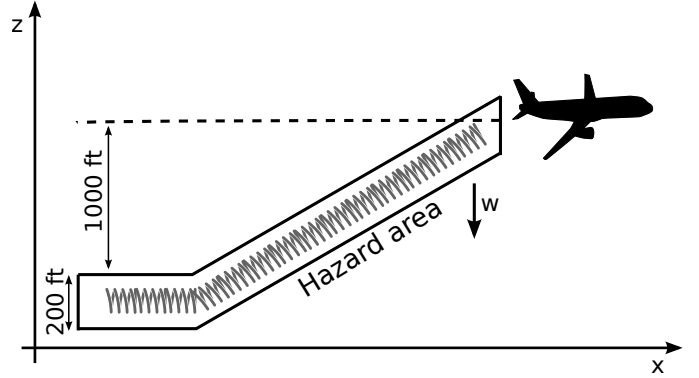


Figure 2. Wake vortex hazard area

D. Vortex strength

Once vortex extension is determined, the vortex strength along the hazard area shall be determined through the calculation of the RMC based on [8]. Equation 4 defines RMC as:

$$RMC = \frac{\Gamma_{tot}}{V_f b_f} \frac{AR_f}{AR_f + 4} F\left(\frac{b_l}{b_f}\right) \quad (4)$$

Where:

$$F\left(\frac{b_l}{b_f}\right) = 1 - 2\left(2r_c \frac{b_l}{b_f}\right) \left(\sqrt{1 + \left(2r_c \frac{b_l}{b_f}\right)^2} - \left(2r_c \frac{b_l}{b_f}\right) \right) \quad (5)$$

Where:

- Γ_{tot} is the vortex circulation [m²/s].
- V_f is the follower speed [m/s].
- b_f is the follower span [m].
- b_l is the generator span [m].
- AR_f is the follower wing aspect ratio.
- r_c is the core parameter ($r_c = 0.035$) [8].

Most of the variables need to calculate the RMC depend on the follower and generator aircraft characteristics and speed which are considered constant. However, Γ_{tot} decreases with time thus also making the RMC to decrease. Several Γ_{tot} decrease models exist in the literature. In [9], [10], [11], [12] the following models are defined: Sarpkaya, Deterministic 2-phase (D2P) and TASS Driven Algorithm for Wake Prediction (TDAWP).

Both D2P and TDAWP account for 2-phased vortex decay, which correspond to semi-empirical wake prediction models that have been formulated from guidance provided by *large eddy simulations* (LES). The Sarpkaya is also a semi-empirical wake model and it predicts wake vortex decay as a function of atmospheric turbulence and stratification. Moreover, unlike models developed from LES, they predict a rate of decay that is initially large and diminishes with time.

Although linear models such as Sarpkaya have an advantage of simplicity, theoretical justification for a linear circulation decay is weak when applied to aircraft wake vortices. D2P has been chosen as vortex intensity decay model because it gives a vortex circulation similar to reality (see figure 3). Moreover, in [13] it is affirmed that D2P is the most accurate model.

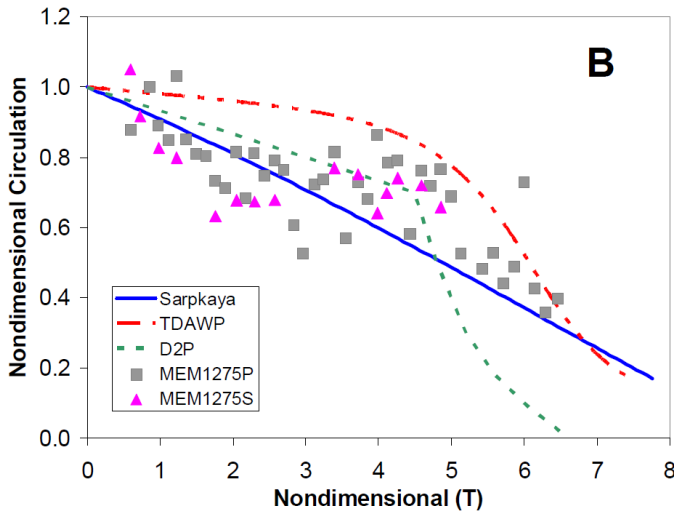


Figure 3. Wake measurements obtained by pulsed lidar

Once RMC is calculated, we are in a position to quantify the impact on the following aircraft. In [14], researchers propose to compute what they call the RMC of control, this is, the amount of roll moment that the control system of the following aircraft can generate. This gives an idea of the ability of the aircraft to compensate the RMC caused by the wake vortex. This is defined as follows:

$$RMC_{ctrl} = -RMC_p \left(\frac{pb}{2U_0} \right) \quad (6)$$

Where:

- RMC_p is the roll damping coefficient [-].
- $\left(\frac{pb}{2U_0} \right) = 0.07$ is the roll rate [-] [14].

The roll damping coefficient is computed using the following equation:

$$RMC_p = -\frac{C_{L_\alpha} [1 + 3\lambda]}{12 [1 + \lambda]} \quad (7)$$

Where:

- C_{L_α} is the finite wing lift curve slope [-].
- λ is the taper ratio $\lambda = c_{tip}/c_{root}$

Finally we can define r as the ratio between RMC and RMC_{ctrl} , this is, the amount of moment generated by the wake vortex divided by the amount of roll that the following aircraft can compensate.

$$r = \frac{RMC}{RMC_{ctrl}} \quad (8)$$

If $r > 1$ the follower aircraft will not be able to compensate the roll moment generated by the vortex thus producing a hazard situation. Conversely, if $r < 1$ the vortex roll can be compensated by the follower aircraft thus generating a safe situation.

III. EVALUATION OF THE IMPACT OF VORTEX ENCOUNTERS

Once the vortex generation and impact quantification model has been defined, this section will evaluate the vortex encounters between an airliner (the wake vortex generator, an aircraft from the Airbus family) and two different RPAS types (the follower aircraft an Northrop Grumman RQ-4A Global Hawk and a General Atomics MQ-9 Ikhana operated by NASA). The A320 is in the Medium class regarding the ICAO wake vortex categorization. Conversely, the Global Hawk is considered a HALE RPAS type while the Ikhana is a MALE one. Table I summarizes the considered airliner characteristics that are needed to calculate the wake vortex intensity.

TABLE I
CHARACTERISTICS OF CONSIDERED AIRLINERS

Model	MTOW	Span	Cruise airspeed	Cruise altitude
A320	64.5 t	35.8 m	Mach 0.79	FL390
A333	230 t	60.3 m	Mach 0.81	
A343	275 t	60.3 m	Mach 0.82	
A388	560 t	70.75 m	Mach 0.85	

Up to four Airbus models have been considered. The smallest one, the well-known A320 is a short medium range single aisle airliner. It has been identified as Medium within the ICAO *wake turbulence category* (WTC). The next bigger one is the A330-300 (A333), a twin engine wide body airliner identified as Heavy within the ICAO WTC. Moreover, two four engine Airbus models have also been considered both of them identified as Heavy within the ICAO WTC. On one hand, the A340-300 (A343) a wide body airliner similar (regarding aircraft dimensions) to the A333. On the other hand, the biggest one, the A380-800 (A388), that will likely generate the biggest wake vortex.

TABLE II
CHARACTERISTICS OF CONSIDERED RPAS

Model	MTOW	Span	λ	Cruise airspeed	Max altitude
RQ-4A	14.6t	39.9 m	0.333	TAS 343 kt	FL640
MQ-9	4.7t	20.1 m	0.384	TAS 150 kt	FL500

Table II summarizes the necessary characteristics of the considered RPAS to compute the impact of the wake vortex on themselves. The RQ-4A is bigger and faster than the MQ-9 so it will likely be less affected by wake vortices.

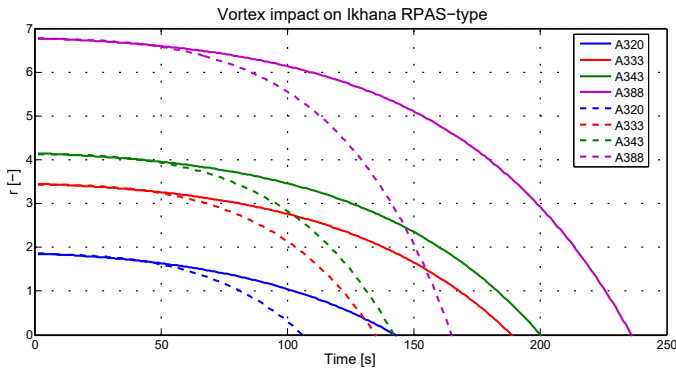


Figure 4. Impact of wake vortex on Ikhana RPAS type

Considering the whole set of aircraft characteristics of airliners, we are in a position to calculate the strength of the wake vortex that they generate and the impact of that vortex on the RPAS airworthiness.

For the sake of clarification, we define the *time to encounter threshold* (t_e^{th}) as the instant of time when for a specific generated vortex, makes the severity metric $r = 1$.

Figures 4 and 5 depict, respectively, the impact of wake vortices in the Ikhana and the Global Hawk platforms, its dependence with time to encounter (t_e), the generating aircraft and the atmosphere conditions. t_e is defined as the lapsed time when the vortex is generated until the moment the RPAS faces it. As it can be expected, when t_e is short, the RPAS will be more affected by the generated wake vortex. conversely the y-axis represents the non-dimensional r parameter, the definition of which was presented in Section II. When $r > 1$ the RPAS will not be able to compensate the generated roll moment by the wake vortex and, hence, RPAS will face a hazard situation. A pair of lines represent each considered airliner. As expected, the A388 is generating the more impact given the same t_e . The impact decreases with airliner mass and wingspan until the A320, which is the lightest and smallest considered airliner. However the impact of the latter cannot be neglected as r is greater than one until 50 seconds after the moment the vortex is generated. Regarding the atmosphere considerations, the solid line represents an atmosphere with neutral stratification while the dotted represents an stratified atmosphere. As it can be seen, these effects cannot be neglected as they significantly affect to the duration of the wake vortex.

Table III summarizes t_e^{th} per RPAS and airliner model. Thresholds are bigger for the MQ-9 than for the RQ-4A for the same generating aircraft. However, these differences are reduced for the biggest airliners.

IV. IMPACT ON SEPARATION MINIMA

In section III the vortex impact has been calculated by quantifying the time to encounter threshold (t_e^{th}). In this section, this time will be compared to current separation assurance standard to check whether the latter is conservative enough when an RPAS faces an airliner wake vortex. This analysis will consider both the vertical and horizontal dimensions.

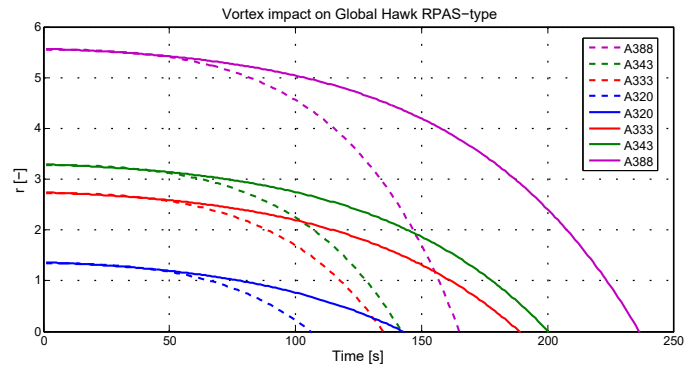


Figure 5. Impact of wake vortex on Global Hawk RPAS type

TABLE III
TIME TO ENCOUNTER THRESHOLDS PER RPAS AND AIRLINER MODELS.

RPAS model	Airliner model	t_e^{th}
MQ-9	A320	80 - 100 s
	A333	120 - 170 s
	A343	130 - 180 s
	A388	160 - 220 s
RQ-4A	A320	60 - 80 s
	A333	120 - 160 s
	A343	130 - 170 s
	A388	160 - 220 s

A. Vertical separation

Current vertical separation minima is set to 1,000 ft when both aircraft all involved aircraft equipment is sufficiently certified and aircraft operators have a specific approval to conduct operations in RVSM airspace. As stated in Section II, the wake vortex decays 1,000 ft until it gets stabilized as its density comes into equilibrium with that of the surrounding air. Therefore, it may be the case that two aircraft that are vertically well separated the one that is below may face the wake vortex generated by the one above. Few studies, like [15], [16] have addressed this issue. However they have not take into account what if the aircraft that faces the wake vortex is an RPAS. In this case, the issue that we are addressing is the following: when it gets stabilized, is the wake vortex strong enough to negatively impact on the RPAS airworthiness?

As defined in Section II the downwash speed can be written as follows:

$$\omega = \frac{\Gamma_0}{2\pi L_v} \quad (9)$$

It depends on the initial circulation (Γ_0) and the span between the vortex (L_v). Table IV summarizes the calculated downwash speeds and the time the vortex takes to stabilize (t_s). The time to encounter thresholds are also depicted to facilitate the comparison. The only case that the generating vortex will not overcome the danger threshold is the A320 case. In all other cases, ω is too big thus making the vortex to stabilize before it becomes enough attenuated.

There is no significant differences between the two RPAS types. Both of them are able to overcome a wake vortex

TABLE IV
DOWNWASH SPEEDS AND TIME TO STABILIZATION PER AIRLINER

Model	A320	A333	A343	A388
ω [ft/min]	586	737	880	1303
t_s [s]	102.4	81.4	68.2	46
t_e^{th} (MQ-9A) [s]	80 - 100 ✓	120 - 170 X	130 - 180 X	160 - 220 X
t_e^{th} (RQ-4A) [s]	60 - 80 ✓	120 - 160 X	130 - 170 X	160 - 220 X

generated by an A320. Nevertheless, the RQ-4A has much more time margin than the MQ-9A.

B. Lateral separation

Horizontal separation minima in radar control has been established taking into account the radar accuracy. Generally speaking these values are: 3 NM in terminal areas; 5 NM en-route to limiting range of 160 / 200 NM; and 10 NM beyond that. In this case, the issue to be addressed is to determine if the wake vortex is still strong enough to negatively impact on the RPAS airworthiness.

Table V summarizes the results. First, the time that each considered airliner type spend to fly 3 NM, 5 NM and 10 NM at cruise altitude. As the A320 is the slowest aircraft, the times to cover those distances are the highest ones. Nevertheless, there are no significant differences among these times since cruise speeds are relatively similar.

TABLE V
TIME TO ENCOUNTER FOR DIFFERENT SEPARATION MINIMAS PER EACH AIRLINER VERSUS TIME TO ENCOUNTER THRESHOLD PER EACH RPAS

Minima \ Model	A320	A333	A343	A388
3 NM	24 s	23 s	23 s	22 s
5 NM	39 s	39 s	38 s	37 s
10 NM	79 s	77 s	77 s	74 s
t_e^{th} (MQ-9A) [s]	80-100	120-170	130-180	160-220
t_e^{th} (RQ-4A) [s]	60-80	120-160	130-170	160-220

The two last rows represent the danger thresholds for both considered RPAS models as a reference. In general, the times that airliners need to cover the considered distances are smaller than the danger threshold. Hence the strength of the wake vortex is still high enough to consider the RPAS to be in a hazard situation even without considering wind effects that may worsen the whole situation. There is, however an exception for the RQ-4A when facing an A320 wake vortex in a 10 NM lateral separation minima scenario. In this specific case, the danger threshold is smaller than the time the airliner needs to cover that distance thus ensuring a safe situation.

V. CONCLUSION

Wake vortex encounters have been subject of study for decades. Novel studies addressed those encounters in en-route phase, where it was believed that current separation standards were restrictive enough to ensure that they will

not occur. However, the introduction of new airspace users such as MALE/HALE RPAS that are lighter than conventional airliners may pose additional risks on en-route wake vortex encounters.

Taking as starting point the well-known wake vortex generation models and novel severity metrics from the literature, a quantification of the vortex impact on RPAS have been performed over the RQ-4A Global Hawk and MQ-9 Ikhana platforms thus specifying a danger threshold above which both aircraft may compromise their airworthiness. Results showed the strong dependence on the generating aircraft type, the atmosphere conditions and the time the vortex was generated.

Finally the current stasis of separation minima has been reviewed to check if current separation standards preserve the RPAS from en-route vortex encounters that may compromise their airworthiness. Results showed that, regarding the vertical separation both considered RPAS models were enough well separated of the smallest considered airliner, the A320 while was not the case of the rest of airliners. The situation is even worse in the case of horizontal separation as, in most of the considered cases, the standard separation was not big enough to permit the RPAS to avoid the effects of the vortex encounter.

As further work, the presented study can be applied to re-analyze the data from real-time simulations of RPAS operations in non-segregated airspace such the ones obtained in [17] to check whether vortex encounters between airliners and RPAS has occurred to quantify the number of occurred vortex encounters, if any. Moreover, this work can also be adapted to assess the specification of *vortex aware* collision avoidance strategies for RPAS.

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