

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.

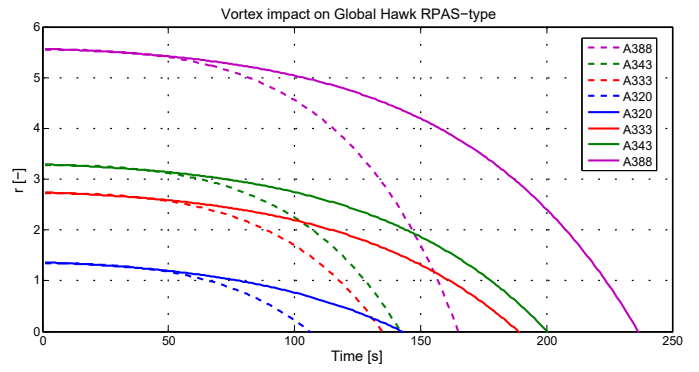


Figure 5. Impact of wake vortex on Global Hawk RPAS type

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

Model Minima	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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REFERENCES

- [1] NATS, "Aeronautical information circular. wake turbulence," NATS Services, Tech. Rep., 2015.
- [2] FAA, "Advisory circular. aircraft wake turbulence," Federal Aviation Authority, Tech. Rep., 2014.
- [3] Airbus, "Flight operations briefing notes. operating environment. wake turbulence awareness/avoidance," Airbus, Tech. Rep., 2005.
- [4] D. ICAO, "8643 aircraft type designators," *Latest Version*, 2015.
- [5] F. O. of Civil Aviation, "European wake turbulence categorisation and separation minima on approach and departure," Federal Office of Civil Aviation, Tech. Rep., 2016.
- [6] B. Galović, B. Grozdanić, and S. Steiner, "Influence of wake-vortex turbulence on the flight safety," *PROMET-Traffic&Transportation*, vol. 9, no. 1-2, pp. 1-14, 2012.
- [7] M. Hoogstraten, H. G. Visser, D. Hart, V. Treve, and F. Rooseleer, "Improved understanding of en route wake-vortex encounters," *Journal of Aircraft*, vol. 52, no. 3, pp. 981-989, 2014.
- [8] I. De Visscher, G. Winkelmanns, and V. Treve, "A simple wake vortex encounter severity metric," in *Eleventh USA/Europe Air Traffic Management Research and Development Seminar, Lisbon, Portugal*, 2015.
- [9] F. H. Proctor, N. N. Ahmad, G. Switzer, and F. M. Limon Duparcmeur, "Three-phased wake vortex decay," *AIAA Paper*, vol. 7991, 2010.
- [10] F. Holz-aring and pfel, "Probabilistic two-phase wake vortex decay and transport model," *Journal of Aircraft*, vol. 40, no. 2, pp. 323-331, 2003.
- [11] F. Holzäepfel and R. E. Robins, "Probabilistic two-phase aircraft wake vortex model: application and assessment," *Journal of Aircraft*, vol. 41, no. 5, pp. 1117-1126, 2004.

- [12] F. Holzäpfel, "Probabilistic two-phase aircraft wake-vortex model: further development and assessment," *Journal of Aircraft*, vol. 43, no. 3, pp. 700–708, 2006.
- [13] F. H. Proctor and D. W. Hamilton, "Evaluation of fast-time wake vortex prediction models," *AIAA paper*, vol. 344, 2009.
- [14] T. Economon, "Effects of wake vortices on commercial aircraft," *AIAA Paper*, vol. 1428, 2008.
- [15] V. Rossow and K. James, "Overview of wake-vortex hazards during cruise," *Journal of aircraft*, vol. 37, no. 6, pp. 960–975, 2000.
- [16] R. C. Nelson, "Trailing vortex wake encounters at altitude—a potential flight safety issue?" *AIAA Paper*, vol. 6268, p. 2006, 2006.
- [17] E. Pastor Llorens, M. Pérez Batlle, P. Royo Chic, R. Cuadrado Santolaria, and C. Barrado Muxí, "Real-time simulations to evaluate the rpas integration in shared airspace," in *Conference Papers*, 2014, pp. 1–10.