Wind Resistance Evaluation Technology for Air Mobility Utilizing Free Flight in Wind Tunnel

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Air mobility vehicles such as drones, eVTOLs (Electric Vertical Take Off and Landing aircraft), and unmanned aerial vehicles are used in various service businesses, which include infrastructure inspection, surveying, and pesticide spraying. Their market is expected to expand further in the future as legislation that enables package delivery by out-of-sight flights is currently being developed. Mitsubishi Heavy Industries, Ltd. (MHI) Research & Innovation Center develops wind resistance evaluation technology through free-flight testing of air mobility vehicles in a wind tunnel in order to contribute to the development of aerial vehicle bodies by aerial vehicle manufacturers and the verification of wind resistance by air mobility service providers. This report presents an overview of the equipment/devices developed for free-flight testing, case examples of fundamental wind resistance evaluation required for the development of aerial vehicles, and a case example of preliminary verification of infrastructure inspection that simulates the operating environment of an aerial vehicle and enables preliminary training of users.

1. Introduction

Air mobility vehicles contribute to improving operational efficiencies in a wide range of fields, including safely surveying inaccessible areas such as cliffs and landslide sites, significantly reducing the cost of inspecting building exterior walls that requires scaffolding and other preliminary preparations, and unmanned spraying of fertilizers and pesticides on large-scale land according to the growth of crops. We are also working on the automation of pipeline patrols using autonomous unmanned aerial vehicles(1) and on-site security operations around dams and power plants(2) using drones. It is predicted that the scale of the drone-related market in Japan, including the service market using drones and the drone body market, will increase to more than 900 billion yen in 2028 from 308.6 billion yen in 2022(3). For the drone market, which is expected to expand further as described above, MHI Research & Innovation Center is developing wind resistance evaluation technology through free-flight testing, which allows air mobility vehicles to fly in a wind tunnel, to contribute to the development of aerial vehicle bodies by aerial vehicle manufacturers and to the verification of wind resistance by air mobility service providers. This report first summarizes the flight rules and wind resistance evaluation items required for unmanned aerial vehicles, and then introduces equipment/devices developed to enhance flight safety and simulate natural environments such as gusty winds, in order to realize wind resistance evaluation through free-flight testing of air mobility vehicles in a wind tunnel. After that, there are case examples of wind resistance evaluation using a small drone including evaluations of "time-to-flight performance against payload", "wind resistance", and "takeoff/landing performance", which are necessary for the development of aerial vehicle bodies, and also a case example of "preliminary verification of infrastructure inspection" using a partial model of a bridge placed in the wind channel to simulate a bridge inspection service using a drone.

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2. Necessity of wind resistance evaluation of unmanned aerial vehicles

2.1 Flight rules required for unmanned aerial vehicles

Rules for the safe operation of unmanned aerial vehicles include (i) rules for aerial vehicle bodies, (ii) rules for no-fly zones, and (iii) rules for flight methods[4]. In rule (i), it is stated that airplanes, rotorcraft, gliders, and airships, which are structurally impossible to be boarded by humans and can be flown by remote control or autopilot (excluding those weighing less than 100 grams (the sum of the weight of the main body and the weight of the battery)) are subject to Chapter 11 of Law Civil Aeronautics Act. Rule (ii) stipulates that permission is required for flights in the vicinity of airports, at altitudes of 150 m or more, in populated areas, and the like. As for (iii), flights involving night flights, out-of-sight flights, dropping objects, etc., require approval from the director general of the regional civil aviation bureau, except when a person with a technical certificate flies a certified unmanned aerial vehicle. While the above-mentioned rules are in place, in December 2022, the Ministry of Land, Infrastructure, Transport and Tourism launched new rules for unassisted out-of-sight flights (Level 4 flight) in inhabited areas (above third parties air space) in order to further expand the use of unmanned aerial vehicles[5]. The rules require that owners obtain Class 1 UAS Certification for their aerial vehicles, and that manufacturers obtain Class 1 UAS Type Certification for mass-produced aerial vehicles they design and manufacture.

2.2 Wind resistance evaluation items for unmanned aerial vehicles

The type certification of unmanned aerial vehicles to achieve Level 4 flight requires clarification of the concept of operation and proof of safety and reliability through flight tests and other means. While specific test details need to be determined in consultation with the Ministry of Land, Infrastructure, Transport and Tourism, as a reference guideline for test methods, there is the "Guidelines on Performance Evaluation of Unmanned Aerial Vehicles" (hereinafter referred to as "Guidelines")[6] published by the Ministry of Economy, Trade and Industry and New Energy and Industrial Technology Development Organization. The Guidelines are based on regulatory documents and standards of other countries, set performance evaluation criteria for safety and reliability of unmanned aerial vehicles for out-of-sight and above-third-parties air space flights, and compile test methods and test equipment/devices. The Guidelines are intended to provide a uniform evaluation of the performance of unmanned aerial vehicles and to serve as a basis for making decisions in the development and introduction of unmanned aerial vehicles. In addition, the Guidelines rank the performance of unmanned aerial vehicles in detail, which is considered to be a performance indicator for air mobility vehicles in the future. **Table 1** shows the performance evaluation items specified in the Guidelines and the results of the compliance evaluation of the wind tunnel owned by MHI Research & Innovation Center with them. Our wind tunnel covers the basic performance evaluation items specified in the Guidelines, and has the feature of being able to evaluate flight stability during gusty winds by utilizing a variable wind generator that has been used to simulate natural winds (atmospheric boundary layer turbulence) in the civil engineering and construction fields.

Table 1 Compliance of our wind tunnel with wind resistance evaluation specified in the Guidelines

Objective	Application	Performance evaluation item		Test method	Wind tunnel		Compliance of wind tunnel
					Steady wind	Gusty wind	
In-sight and out-of-sight flights edition	Common	Time-to-flight performance against payload		Estimate the endurance by measuring the current and voltage values while the aerial vehicle is hovering for 1 minute, using the onboard payload and wind velocity (flight speed) as parameters.	✓	—	○
		Wind resistance performance		Determine if the aerial vehicle can withstand crosswinds based on flight stability when the aerial vehicle is exposed to (a) a crosswind at a constant wind velocity for a fixed period of time (about 5 minutes) and to (b) a gusty crosswind (change of wind velocity of 10 m/s/s).	✓	✓	◎
	Logistics	Payload performance	Long-distance flight performance and payload performance	Estimate the flight duration by measuring the current and voltage values while the aerial vehicle is hovering for 1 minute, using the onboard payload and wind velocity (flight speed) as parameters.	✓	—	○
		Takeoff/ landing performance	Basic takeoff/ landing performance	Measure the maximum deviation distance when the aerial vehicle lands and takes off with wind velocity (up to 10 m/s) as a parameter.	✓	—	○
			Takeoff/landing performance in narrow space	Evaluate interference by walls when the aerial vehicle takes off and lands in a narrow space in which a ceiling, walls, and a takeoff/landing spot are reproduced.	—	—	○
Above-third-parties flights edition	Above-third-parties flights	Flight stability		Measure the air resistance coefficient on aerial vehicle with attitude angle as a parameter using its fixed model at a constant wind velocity in a wind tunnel.	✓	—	○
		Guidance accuracy		Evaluate the difference between the flight setting position of the hovering aerial vehicle in autonomous flight and the motion-capture position.	✓	✓	◎
		Prevention of contact during fall		Measure the attitude characteristics (terminal velocity and attitude stability) of the aerial vehicle during a fall by applying wind to it from vertically below.	✓	—	○

◎: The test can be conducted by utilizing a variable wind generator. ○: The test can be conducted by our wind tunnel.

3. Overview of wind tunnel

3.1 Wind tunnel

Figure 1 shows the specifications of the large multi-purpose wind tunnel at MHI Research & Innovation Center Nagasaki District. The features of this wind tunnel include: (i) the world's largest measurement area of 30 m^2 and the possibility of being used as a 10m-wide or 10m-high wind channel by rotating the air outlet by 90°, (ii) the possibility of simulating large inspection targets, walls, and ceilings inside by being used as an open-type wind channel, and (iii) the possibility of simulating various natural winds by using a variable wind generator.

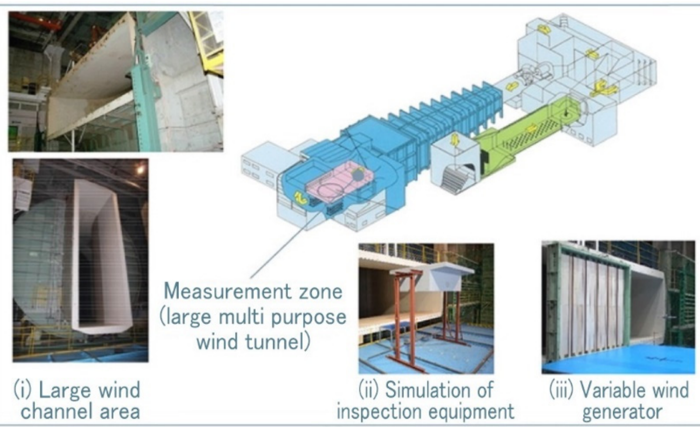
Overview	
Maximum wind velocity	28m/s
Size	10m(W) * 3m(H) * 6m(L) 3m(W) * 10m(H) * 6m(L) Air outlet can be rotated by 90°

Figure 1 Specifications of wind tunnel

3.2 Free-flight testing equipment

(1) Safety devices

The testing equipment is equipped with a tether system to prevent the aerial vehicle from falling in the event of loss of control, and safety catch nets to capture flying objects such as the aerial vehicle body, propeller, etc., in case the tether ruptures. **Figure 2** shows an overview of the safety devices. The tether system consists of a fall prevention wire attached to the aerial vehicle body, an electric winch that adjusts the length of the wire according to the flight conditions, and a spring damper that allows the system to withstand shock loads. The safety catch nets are installed to enclose three sides: both boundary sides of the flight area and the downwind side.

Figure 2 Safety devices (Left: Tether system, Right: Safety catch nets)

(2) Measuring devices

To measure the behavior, (i) image analysis software and (ii) a total station are used depending on the purpose of measurement, as shown in **Figure 3**. The former is software that detects the LED light-emitting part of the drone in the video image captured by the video camera and converts the pixel shift amount in the image into distance. Errors may occur due to detection errors caused by image capturing conditions, correction methods for pixel displacement due to lens distortion, etc., so in the evaluation case presented in this report, this image analysis software was used for wind resistance evaluation in which different air current conditions were relatively evaluated. The latter, a total station, is surveying equipment that emits a laser beam to measure the distance and angle to a prism attached to the drone. When the distance between the prism and the total station is 6 m, the vertical and horizontal distances can be determined with an accuracy of 0.1 mm. The total station was used for the takeoff/landing performance evaluation for ranking in the Guidelines, which requires quantitative displacement evaluations.

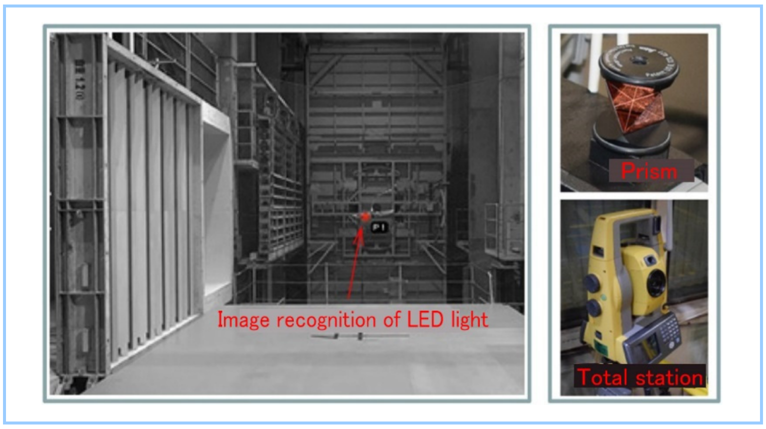


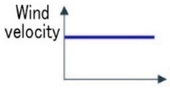
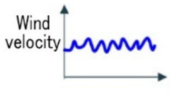
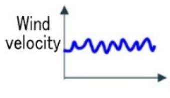
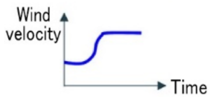
Figure 3 Behavior measurement method
(Left: Image analysis software, Right: Total station, https://www.iwasakinet.co.jp/rental/ts/ps/)

(3) Variable wind generator

This report assumes **Table 2** as variable winds (turbulence and gusts) required to verify the wind resistance of air mobility vehicles. The specific target values for boundary layer turbulence were set from the turbulence intensity and scale in the AIJ Recommendations for Loads on Buildings(7), and the target values for gusty winds were set from the ranks in the Guidelines.

Boundary layer turbulence can be reproduced with existing equipment, and sudden crosswinds can be reproduced by having the drone enter an ordinary open wind channel. So, this report presents a verification case in which gusty winds were reproduced by modifying existing equipment.

Table 2 Assumed wind environments for evaluation of wind resistance

Air current type		Schematic diagram of air current	Target value
UAV Flying in still air – Cruise flight	Uniform air current (equivalent to wind resistance test of the Guidelines)		
Air moving around steady UAV – Boundary layer turbulence	Boundary layer turbulence		(i) Mountainous area (Roughness classification IV) (ii) Flat land (Roughness classification II to III) (iii) Offshore (Roughness classification 0 to I) Based on turbulence intensity and scale in AIJ Recommendations for Loads on Buildings
UAV moving from still air to strong lateral flow	Sudden crosswind (equivalent to entry test from area with no wind into area with wind as specified in the Guidelines)		
UAV facing unexpected gust – Momentary change of wind flow	Gusty wind (equivalent to gust test in the Guidelines)		Based on ranks in the Guidelines

The variable wind generator is a rotatable blade row device that fluctuates the wind velocity in the flow direction by opening and closing the flat plates. Since this device was manufactured to simulate natural winds, we used CFD (Computational Fluid Dynamics) to verify in advance whether it could reproduce gusty wind conditions for the evaluation of air mobility vehicles. As shown in **Figure 4**, in the case where the rotatable blade row is placed in the center of the air outlet, the downstream area becomes almost windless when the flat plates are fully closed, and a gusty wind phenomenon in which the wind velocity rises to 10 m/s in about one second can be reproduced when the flat plates are fully opened. In the case where the rotatable blade row is placed at both edges of the wind channel, a steady wind of 10 m/s is reproduced when the flat plates are fully opened, and a gusty wind phenomenon in which the wind velocity increased to 15 m/s in about one second is reproduced when the flat plates are fully closed. This report presents free-flight testing in which a variable wind generator was placed in the center of the air outlet to reproduce a gusty wind from a no-wind condition.

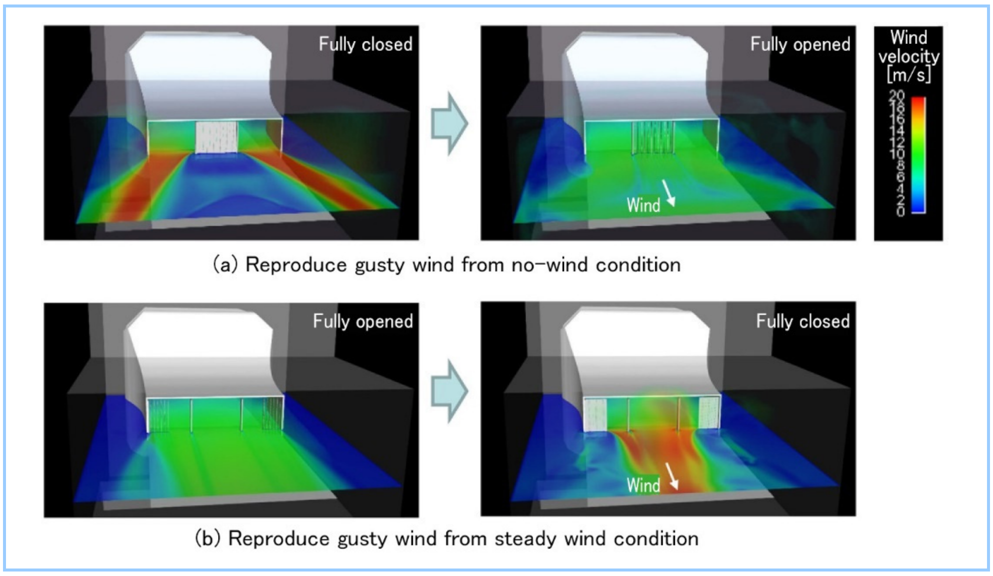


Figure 4 Gusty wind reproduction verification results

4. Case examples of wind resistance evaluation of aerial vehicle

4.1 Performance evaluation

A commercially available photographic drone with a body size of 180 mm x 250 mm x 80 mm and a weight of about 600 g was used as a demonstration vehicle to conduct performance evaluation tests in accordance with the Guidelines.

(1) Time-to-flight performance against payload

As shown in **Figure 5**, flight tests with different payloads and wind tunnel wind velocity (flight speed) with weights in 0.1kg increments mounted on the tether attachment were conducted to evaluate the flight time (aircraft kilometer performed). It is indicated that the larger the payload, the faster the battery consumption rate and the shorter the flight time. Thus, by organizing the relationship between flight speed and payload, it is possible to estimate the range of movement during actual operation in consideration of weather conditions and other factors.

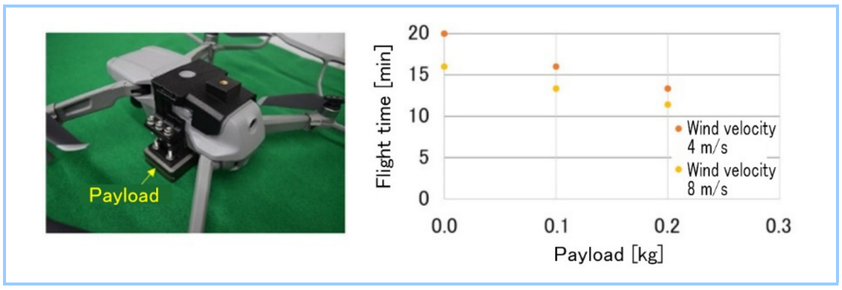


Figure 5 Time-to-flight performance against payload

(2) Wind resistance performance

The evaluation of flight stability when steady or gusty winds act on the aerial vehicle during flight was conducted. **Figure 6** shows the behavior of the drone hovering in a steady headwind and gusty wind conditions. It is indicated that the drone flew stably in steady winds with wind velocity of 5 to 10 m/s. On the other hand, in gusty winds, the amount of movement in the flow direction increased as the wind velocity increased, and it was visually confirmed in a flight case with a 10 m/s gusty wind that the aerial vehicle was swept about one meter, causing the tether to be stretched. In this way, it is possible to evaluate the critical wind velocity at which the aerial vehicle can fly without damaging its body.

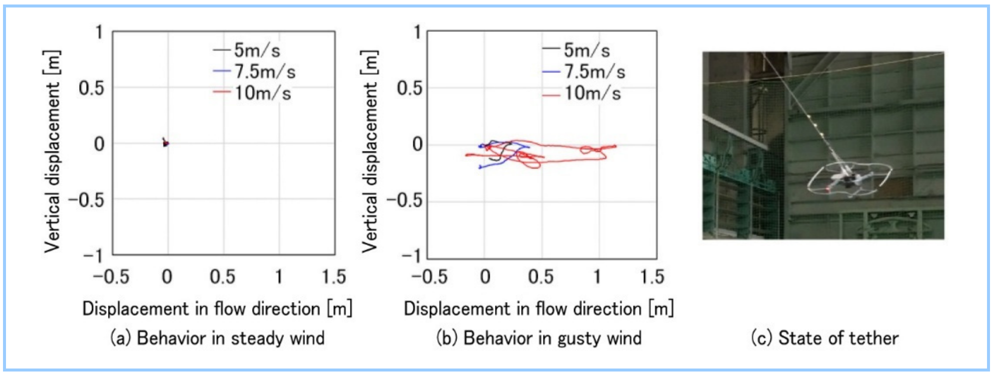


Figure 6　Wind resistance performance

(3)　Takeoff/landing performance

There are two types of takeoff/landing performance in the Guidelines: (i) Basic takeoff/landing performance and (ii) Takeoff/landing performance in a narrow space. In this report, the two types of takeoff/landing performance were evaluated accordingly.

(i)　Basic takeoff/landing performance

The ability of the drone to safely and accurately take off and land in open space even with disturbances was evaluated based on the takeoff and landing radius. **Figure 7** shows an example of drone behavior. Under a certain wind velocity, it was confirmed that the drone could take off and land within a radius of 1.99 m, which is equivalent to rank 5 of the Guidelines' evaluation criteria.

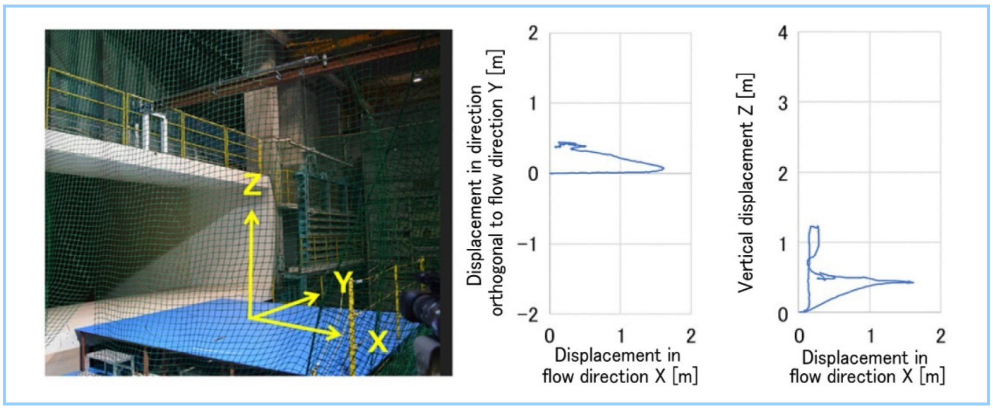


Figure 7　Basic takeoff/landing performance

(ii)　Takeoff/landing performance in narrow space

The ability to take off and land at a takeoff/landing port located in a residential area with walls and ceilings in close proximity was evaluated based on the distance to the walls and ceilings. **Figure 8** shows the drone's behavior in windless conditions when the distance to the wall is 1 m and the ceiling height is 2 m, which are the highest rank 6 of the Guidelines' performance evaluation criteria. It was confirmed that the drone was able to take off and land avoiding the walls and ceilings in close proximity. However, when the drone flew near a wall, it was observed that the aerial vehicle was pulled towards the wall near the corner between the ground and the wall, causing the aerial vehicle to behave unsteadily. This indicated that attention to this needs to be paid during takeoffs and landings in narrow spaces.

As shown in the above evaluation, the examination of operational conditions, e.g., weather and routes, under which the drone can take off and land at each location can be performed.

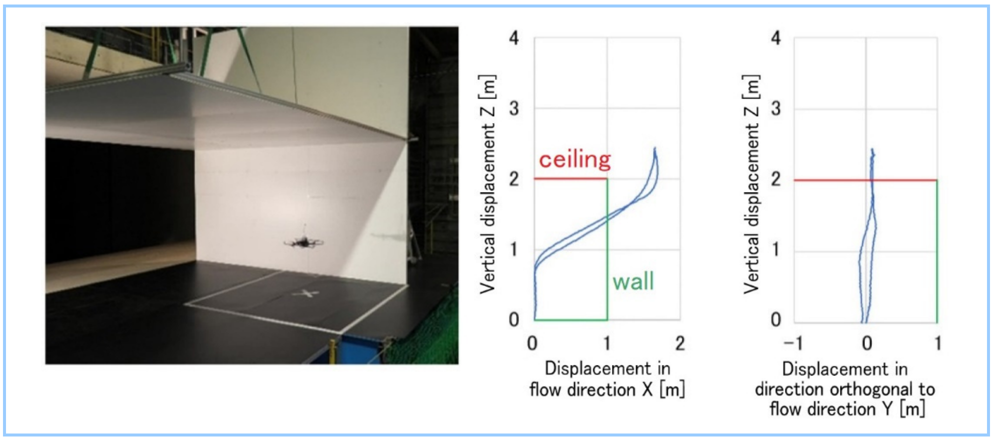


Figure 8 Takeoff/landing performance in narrow space

4.2 Preliminary verification of infrastructure inspection

Assuming a bridge inspection service using a drone, we conducted preliminary verification by setting up a partial model of a bridge girder in the wind channel and simulating 0.2mm cracks, which are required to be identified by the inspection, on the side of the bridge girder. **Figure 9** shows this case example.

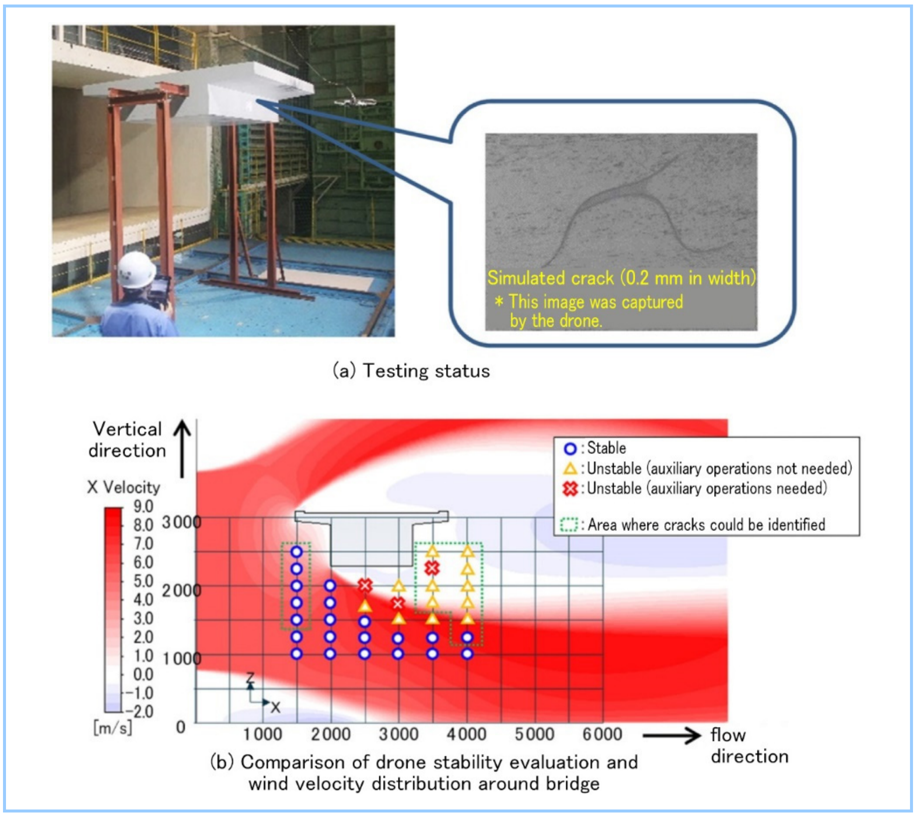


Figure 9 Preliminary verification of infrastructure inspection

The stability of a drone hovering on a grid coordinate with a 500mm pitch in the flow direction and a 250mm pitch in the vertical direction was verified based on the visual observation and the necessity of auxiliary operations. By overlaying the verification result with the CFD-analyzed wind velocity distribution around the bridge, it was indicated that there was no problem in the upstream area even when the drone was brought as close as 250 mm to the bridge girder, but the drone became unstable in the lower and downstream area of the bridge girder in the region (separation shear layer) where the wind velocity changed rapidly due to the flow separation at the upstream lower edge (lower left edge) of the bridge girder and inside that region. In addition, as a result of identifying the areas where cracks can be identified on images captured by a camera mounted on the drone, it was found that it is preferable for the identification of cracks on the downstream side of the bridge girder to be approached outside the separation shear layer from the upstream side. As such, preliminary verification of a drone-based inspection enables verification of the target hovering position with respect to the inspection object as well as the flight route to approach it safely, and training of the pilot.

4.3 Evaluation flow of wind resistance of air mobility vehicles

The establishment of wind resistance evaluation technology for air mobility vehicles through free-flight testing enables us to provide support for CFD-based prediction of the wind environment in the aerial vehicle operation area, reproduction of the actual wind environment and inspection targets in the wind tunnel, as well as evaluation of the aerial vehicle performance, as shown in **Figure 10**.

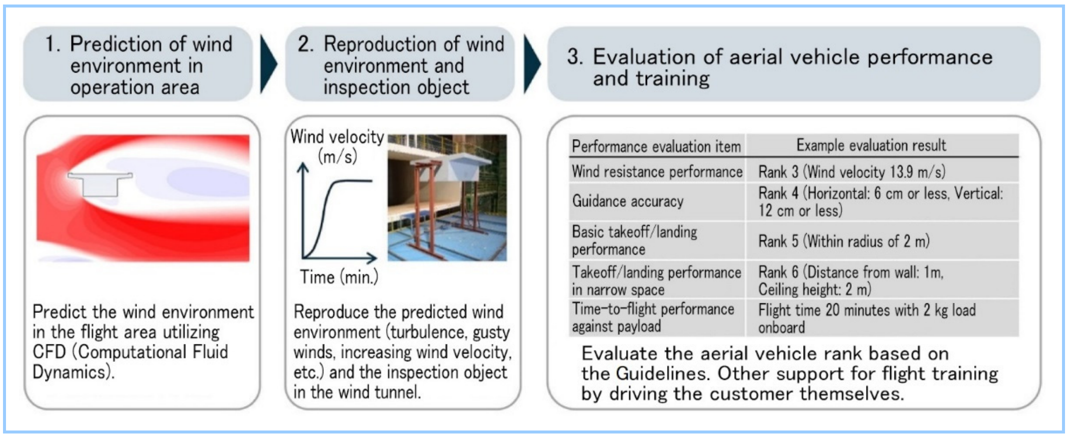


Figure 10 Evaluation flow of wind resistance of air mobility vehicles

5. Conclusion

This report presented the development of technology to realize wind resistance evaluation of air mobility vehicles such as drones, eVTOLs, and unmanned aerial vehicles, case examples of the performance evaluation of aerial vehicles using drones, and a case example of preliminary verification of infrastructure inspection assuming a bridge inspection service. The technology and equipment/devices presented in this report can be utilized for performance evaluation tests to obtain aerial vehicle certification and type certification during the development of aerial vehicles, preliminary verification of service projects, operator training and the determination of operational conditions, etc. The service business utilizing air mobility vehicles is expected to expand into the logistics and security fields, in which such business is in the demonstration and experimental stage, and as the expansion progresses, new requirements and regulations for air mobility vehicles are expected to emerge. We will continue to keep an eye on the trends in the development of aerial vehicles and in the service businesses, and also keep on expanding our wind resistance evaluation technology for air mobility vehicles.

References

(1) Mitsubishi Heavy Industries, Ltd., Press Information, https://www.mhi.com/news/22122202.htm
(2) Mitsubishi Heavy Industries, Ltd., Press Information, https://www.mhi.com/news/23033101.html
(3) Research Report on the Drone Business 2023, Research Impress, https://research.impress.co.jp/report/list/drone/501642
(4) Flight Rules for Unmanned Aircraft (Drones and Model Aircraft, etc.), Ministry of Land, Infrastructure, Transport and Tourism, https://www.mlit.go.jp/en/koku/uas.html
(5) Unmanned Aircraft "Level 4" Flight Web Portal, Ministry of Land, Infrastructure, Transport and Tourism, https://www.mlit.go.jp/koku/level4/en/
(6) Guidelines on Performance Evaluation of Unmanned Aerial Vehicles Developed Ver1.0 (In-Visual and Out-of-Visual Flights Edition), 2020, p.32～37, New Energy and Industrial Technology Development Organization
(7) AIJ Recommendations for Loads on Buildings (2015), Architectural Institute of Japan, Maruzen, p.27