Airship Sling-Load Operations: A Model Flight-Test Approach

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1 Introduction

This section first provides background on the topics being discussed in this paper and continues with the objectives.

1.1 Background

Backgrounds crucial for following the conducted research is given in this section. It starts with technical background on airships, followed by operational backgrounds on aircraft cargo, and concluding with background on the control and operation of airships.

Airships Airships, as a means of transportation, are not a new idea. Historic examples showed that high payloads can be reached with significantly higher transport efficiency compared to airplanes and rotorcraft [1]. Vertical Take-Of and Landing

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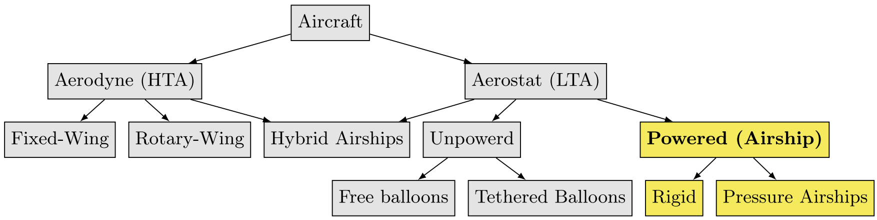

Fig. 1 Overview on categories of aircraft [2]

(VTOL) capabilities are also given with Lighter-Than-Air (LTA) systems. Reducing emissions is a focus of this century, and something airships can help to achieve. Figure 1 shows the taxonomy of aircraft.

Near equilibrium airships There are several classes of LTA vehicles, portrayed in Fig. 1. This research does only consider dirigibles, which means powered, near equilibrium aircraft, called airships. The considered subclass of aircraft is indicated in Fig. 1 by yellow color. Near equilibrium is the capability of achieving zero static heaviness during normal flight operation, meaning that such airships float in the air like fish or submarines in water. An airship heavier than the displaced air sinks to the ground, an airship lighter than air rises until it reaches the height of aerostatic equilibrium.

The inherent safety feature of near equilibrium airships facilitates certification. Even an 'all engines inoperative' incident leaves the airship safe and controllable as a balloon. The consequences of an airship flying in balloon mode are far from the consequences of heavier than air vehicles urgent need for a landing site. Because of this inherent safety feature and the low noise emission, airships could be the preferred air transport system for flights over sensitive areas like areas with a high population density or integrated natural reserves.

Static heaviness A certain degree of deviation from the equilibrium weight is tolerable and can be trimmed using ballast and aerodynamic effects. This tolerable degree is referred to as the static heaviness. Static heaviness for near equilibrium airships has been demonstrated ranging from -5 to $+10\%$ of the airships design equilibrium weight. Static heaviness will be used in this document as a reference to categorize the different types of cargo.

Cargo Cargo is transported goods onboard of vehicles. Different kind of cargo needs to be described in order to understand the transport problem [2]. Due to the nature of LTA technology, the types of cargo can be referred to the static heaviness of an airship. Bottlenecks for transportation are load exchange and maneuverability during the load exchange procedure.

General cargo Pallets, barrels, or bags in larger dimensions, and also standardized container frequently used in aviation, are typical break bulk cargo. Single bits of cargo are usually within the static heaviness of an airship. Single cargo items lighter than the static heaviness can be loaded or re-loaded unit by unit. Each unit dropped needs to be replaced by a corresponding cargo or ballast mass. Loading and unloading of such cargo is common practice in LTA operations.

Passenger One of the ‘cargo’ types that is currently transported commercially successful via airships are passengers. *Zeppelin NT* flies several airships in collaboration with the Commercial Air Transport (CAT) operators *Deutsche Zeppelin- Reederei (DZR)* and *Michelin* in Friedrichshafen.

Passengers are from the loading procedures point of view similar to general cargo. They are usually lighter than the static heaviness of an airship. Passengers can easily be exchanged with other passengers or ballast. Standard procedures exist. Their *‘self-loading capability’* is an advantage against general cargo. There are on the other hand disadvantages like comfort and safety requirements, that have a strong impact on aircraft certification and thus on direct operating costs.

Bulk cargo Cargo that does not come in discrete numbers or packet numbers is referred to as bulk cargo. A continuous process of loading or unloading and ballasting is necessary. Three different types of bulk cargo can be identified.

First, there is gaseous cargo, for which there are no procedures existing today that consider the special requirements coming with handling mostly flammable gaseous cargo. Still, transporting natural gas or hydrogen via airship is an interesting topic and might become important.

The second kind of bulk cargo is so-called dry trade like gravel, ore or agricultural bulk solids like grain.

‘Wet trades’ like oil, agricultural fluids or fuel are probably the most established bulk goods, as refueling is a necessary part of operation. Procedures have been developed both for moored and untethered ‘in-flight’ refueling.

Heavy loads Loads that excessively exceeds static heaviness are defined as heavy loads. In recent airship projects, special interest has often been transportation of heavy loads. Heavy loads are often outsized and strain existing infrastructure due to high punctual forces and larger than usual dimensions. LTA operations could and should be a viable solution for heavy loads, especially in remote areas without or with insufficient infrastructure. Examples of heavy loads are large wind energy converter compounds or surgical wood extraction from forests.

Operation modes Both the aircraft control and the control of load hooks have different states, referred to as ‘flight modes’ and ‘hook modes’.

Flight modes Modern airships often use different flight control modes, ‘cruise mode’ during free flight and ‘hover mode’ during landing and loading operation.

During cruise mode, efficient power usage and stable flight are the most important goals. They are being achieved by properly designed stabilizers and powertrain of the airship.

Hover mode requires the airship to hold a precisely controlled position. Landing or masting and un-masting operations, but also sensor measurement missions and loading operations are driven by position control, which is crucial during those operations.

There are different concepts of how the two flight modes are being implemented, but all modern airships distinguish the two modes. Depending on the deployment scenario of an airship design, emphasis on one of the modes determines an airships propulsion configuration.

Hook modes Helicopter cargo hooks function as 'cargo release units', allowing for remote controlled cargo release. Such systems, mostly of electromagnetic type, are certified for use in Helicopter External Sling-Load Operation (HESLO) [3]. Airship External Sling-Load Operation (AESLO) is going further than HESLO with two exchanged loads instead of one and in consequence two hooks that need to be controlled separately. Introducing two hook modes is important to address certification requirements.

1. Hook mode 1: Load 1 stays
2. Hook mode 2: Load 2 stays.

At some point during loading when both loads are loaded, the Load Master onboard the airship or on ground decides to switch the hook mode. Doing this, free flight condition can always be achieved in a short amount of time.

1.2 Objectives

Objective of this research is focused on how load exchange with near equilibrium airships can be performed. To the knowledge of the authors, proposed solutions aiming at similar targets have not been demonstrated successfully yet, or did not meet certification requirements. We see different viable approaches and want to demonstrate one promising idea on how to do load exchange operations beyond allowed static heaviness viable for airships.

The research should also identify weaknesses and critical points in load exchange procedures.

2 Problem Definition and Formulation

Especially loads excessively beyond static heaviness are of interest to us. Heavy loads introduced in part 1.1 do always require a special load exchange and may at the same time influence the airships' maneuverability negatively. Load exchange procedures have been proposed before, for example in two patents of the company CargoLifter [4, 5], but they potentially fail to correspond certification.

Furthermore, heavy loads often exceed an aircraft storing room dimensions. The solution of external transport may affect maneuverability negatively.

2.1 Load Exchange and Certification

The idea of loading LTA is to keep the Operating Mass (OM) at the same level at all times during operation. In particular, OM should not change beyond allowed static heaviness. When loads exceeding this limit are being dropped or taken, a load with the same mass needs to be exchanged with that load. With heavy loads, the question arises of how this should be achieved. Dropping a very heavy load consequences in a skyrocketing airship which becomes a large threat for pilots, crew and air traffic. Mitigating said risk is aim of this research.

Airship certification does also require to avoid the opposite state, that an airship is bound to the ground by large masses. The original citation of the certification specification is: *'During any cargo exchange [...] the airship must be capable of achieving a safe free flight condition within a time period short enough to recover from a potentially hazardous condition'* [6].

There are two cases, where aborting the loading procedure and achieving free flight condition as a safety measure against hazardous condition seems difficult. The first case is, when the ballast as well as the cargo are loaded onto the airship at the same time. The airship is only able to achieve free flight condition after loosing one of the two, which seems difficult to achieve in a short period of time.

The second case is when neither ballast nor cargo is loaded, and the airship is leashed to the ground like proposed in CargoLifters' patent [5]. Cutting the ropes in a hazardous situation might get the airship safe from the hazard, but achieving free flight while being significantly lighter than air is not possible and poses a great risk and danger as well.

2.2 Maneuverability

Aim of this research is to improve the maneuverability during load exchange operations. Maneuverability reduces risks in ground operations as well as the size and thus cost of the ground crew. Pilot workload is lessened, which is required by certification specifications.

Classical airships like the Zeppelin LZ-120 'Bodensee' required large numbers of ground crew [7], for it is low speed maneuverability was not sufficient to direct the airship towards the wind. Contemporary blimps like the ABC A60, A150, and A170 are smaller, but still need dozens of ground grew. More modern blimps like the Skyship 500 and Skyship 600 feature vectored thrust. This makes them VTOL capable, but still ground crew is needed to direct the airship toward the wind, as low speed rudder efficiency is not sufficient. Due to a stern lateral propeller and vertical propeller, the Zeppelin NT can direct itself toward the wind in low speeds. Dynamic positioning with no speed at all still remains a challenge.

Fig. 2 Onboard Systems' MD500 Dual Cargo Hook kit with Y-rope [8]

3 Methodology

Two steps will demonstrate development of systems and operations of a load exchange procedure for heavy loads with near equilibrium airships. First, a sling load operation is introduced. We then proceed by performing and testing the operational handling. For this purpose a specially developed and built airship model will be used.

3.1 Sling-Load Operation

The well known and often performed procedure Helicopter External Sling-Load Operation (HESLO) is being explained, and its working principal will be transferred to Airship External Sling-Load Operation (AESLO).

HESLO Loads, that cannot be carried inside a helicopter because of their dimension, position on ground or weight, are being carried externally using hooks and sling leashes. Loading and unloading of the load does not require the helicopter to land and thus happens in hover. Outside the rotorcraft, structural elements connect one or two cargo hooks or hoists operated by the pilot [3]. Figure 2 shows an example of such helicopter hooks.

Fig. 3 A Sikorsky Skycrane carrying an accommodation

The lift of a rotorcraft is exclusively aerodynamic lift from the rotor. As long as a load does not exceed the maximum payload of a given vehicle it is capable of carrying it. HESLO is a well established procedure with many applications. Figure 3 shows an eccentric example of using HESLO.

AESLO AESLO is the proposed and favored term of an operation that is oriented on HESLO, but considers the characteristics of airships. Two sling-loads and cargo hooks are what is needed when performing an AESLO. Both, delivery load and return load, are being carried by slings. In advance of an AESLO two loads have to be prepared, one attached to the airship and the other waiting on ground.

The proposed cargo loading and unloading operation consists of the following steps and is visualized in Fig. 4:

1. Airship approaches in cruise mode with two slings, hook 1 holds the delivery cargo. Hook mode 1, described in Sect. 1.1, is active.
2. Airship arrives at the pick-up destination and changes from cruise mode to hover mode.
3. In hover mode, dynamic positioning is used to place the airship precisely over the spot where the delivery load is to be placed. The load is placed on the ground, and the airship moves over the return load.
4. Return cargo is being loaded by the empty sling, held by hook 2.
5. Change hook mode. Hook mode 2 is active.

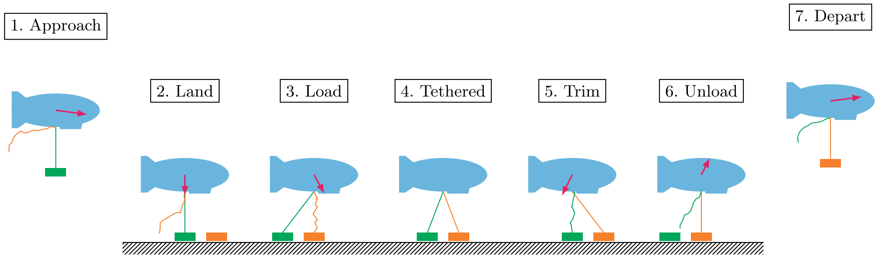

Fig. 4 Step-by-step AESLO operation

6. The delivery cargo is being unloaded and disconnected from the sling.
7. Airship changes from hover mode into cruise mode again, and leaves the loading site.

A critical point in load exchange operation is the certification requirement described in Sect. 2.1. To ensure the safety of the Operation and optimize the time until cruise mode is regained, a Load Master must monitor the load exchange and switch the hook modes.

In case of an event that makes evacuation necessary while both loads are loaded, one of the loads needs to be disconnected from the airship. During load exchange, the 'Load Master', introduced in Sect. 1.1, decides which load to cut in case of emergency. It is also the Load Masters responsibility that one load is connected to the airship at all times.

It is crucial for this operation that either the delivery or the return load is attached at all times. During load exchange, it is the Load Masters responsibility to decide, which load is to cut in case of a hazardous event by controlling the hook modes.

3.2 Model Flight-Test

Model flight tests allow statements about the performance of an aircraft in early design phases. In this section, similarity principles in smaller scale model testing are mentioned. It is continued with the test set-up and preliminary description of the test model to be built. The section concludes by describing the test runs, using the test set-up and airship model.

Similarity Principles Model test, in towing tanks, cavitation tunnels or in this case open environment, require special focus on the similarity principles. Froude's Law [9] gives a good estimation on the different units scaling. When building a model, geometric dimensions scale linear. Other dimensions however, like the time, angular rates, and frictional drag do not scale linearly. The units individual transformation from full size to model size needs to be considered in all model studies.

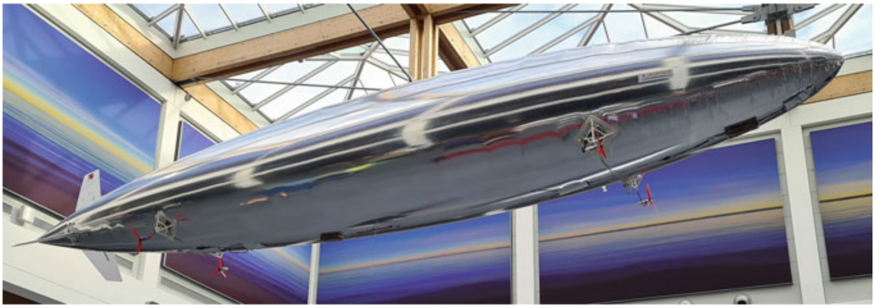

Fig. 5 Airship 'Starocore' at the fair and exhibition *Faszination Modellbau 2021* in Friedrichshafen. First AESLO Trials have been performed with this Airship model

Test set-up For the test procedure, a simpler set-up than described in Sect. 3.1 ensures conducting of the model test with focus on general feasibility. Concepts like the hook mode are named to prove the certification capability of the concept, but are not being investigated in this model flight test. Setting up a test for AESLO requires a model airship capable of precise positioning, carrying two attached cords below the center of buoyancy of the model. Furthermore, two loads of equal mass are required. The loads are attached to cords via manually operated hooks.

Model Main object of the AESLO model flight test is an airship model. The model should have enough buoyancy to carry a payload that exceeds the static heaviness significantly. Further, the model needs to have precise positioning control when in hover mode.

Propulsor configuration Experiences with airship models have shown that a propulsion set-up with four thrusters on pivoted pods can fulfill this requirement [10]. Figure 5 shows the model airship *Starocore* that has been built by this principle. The four pivoting thrusters are clearly visible in the Figure. The model showed good maneuverability in both hover and cruise mode but does not have enough volume to carry additional loads that exceed static heaviness.

Control Performing load operations requires hover control different from cruise control. This mode aims at easy precision hovering instead of stable flight. The different control modes can be implemented in the remote control running openTX. A switch is used to change flight modes. Figure 6 shows the controller layout on an openTX remote control for cruise and hover mode. We want to emphasize that the throttle in hover mode is being set permanently. This is necessary because an AESLO requires permanent thrust during the operation.

Test runs The model flight test follows AESLO from Sect. 3.1, displayed in Fig. 4. The total thrust vector of the four distributed propulsors of the airship is indicated by a red arrow (↗) indicating the estimated direction and magnitude of thrust. The steps from the figure in detail are the following:

1. Payload A is attached to airship via sling A. Airship approaches payload B in cruise mode and changes to hover mode.
2. Payload A is lowered to the ground at loading site of payload B.

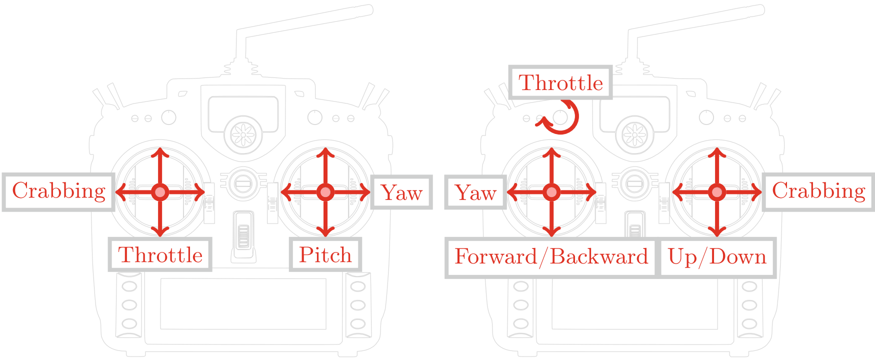

Fig. 6 Control sender configuration in cruise mode (left) and hover mode (right)

3. Airship moves over to payload B. Remote hook B is hooked to payload B.
4. Both slings are tense. Switching hook mode.
5. Airship moves toward payload A. Remote hook A is unhooked from payload A.
6. Airship moves over payload B.
7. Airship lifts off loading site. Flight mode change from hover mode to cruise mode.

Performing several recorded runs using an airship model generates the data necessary for evaluation of the proposed load exchange operation.

4 Results

A model as proposed in Sect. 3.2 has been built and named ‘Hui Hui II’. Initial tests were performed in Berlin during the annual ‘ELRT’ event of the Technical University Berlin (TUB). The airship was built resembling its predecessor ‘Hui Hui’ which flew in Friedrichshafen in 2021 during the FAI CIAM Open International Competition F7B Model Airships. The models’ configuration performed well under competition constraints, both in cruise and hover mode. This track record and the possibility of reusing electronic components lead to the resulting airship model. The Hui Hui II is, however, equipped with a larger envelope, while using the same propulsion system.

4.1 Cruise Mode

Handling qualities in cruise mode were as desired. Stability and controllability were perfectly given. The airship has been flown with a payload of 20% of the overall weight. When decelerating, the airship tended to pitch nose down. This tendency could easily be counteracted by elevator deflection.

Fig. 7 Close-up of the airship model used. The pig-leg configuration of the propulsion system allows dynamic positioning of the airship

4.2 Dynamic Positioning

Dynamic positioning capabilities are crucial for load exchange operations. At the same time, we had the largest difficulties with the airship operating in hover mode. This chapter discusses the controllability by degrees of freedom and proceeds with the operational observations made during the different phases of the flight test.

The two front propulsors provided constant thrust backwards and the rear propulsors provided constant forward thrust during hover mode. This 'pre-tension' provides quicker change in forward-backward direction, as compared to reversing the thrust of all four propulsors (Fig. 7).

Controllability Controllability in all six degrees of freedom has been observed as follows:

Surge (forward/backward) In cruise configuration, the design direction of the propellers has been set to forward thrust at forward speed. In hover configuration, the front propulsors were not swiveled backwards by 180 °C, but operated in reverse RPM. That means the efficiency of the propellers is largely reduced, as the propeller blades operate with reverse camber, and reverse profile sections. As a result, the airship developed more thrust in forward direction than in backward direction, when the propellers were set to equal RPM.

Sway (crabbing, or side wards motion) Crabbing ability has been proven poor, due to the large lateral added mass, and cross flow drag.

Heave (up/down) Heave control was satisfactory, while the asymmetric propeller settings provided additional workload to the pilot.

Roll Roll control in hover mode in this propulsion configuration is not possible, while considered not necessary.

Pitch Pitch control has not been investigated in depths during these tests. However, the airship reacted to pitch-up and pitch down commands.

Yaw (heading) Yaw control was satisfactory, while considerably less agile than with the predecessor airship 'Hui Hui'. This is due to the larger momentum of inertia, and higher yaw-damping due to the larger size.

Sway-yaw coupling When attempting to sway (crab), the airship developed an additional uncommanded yaw motion. This tendency is assumed to result from both, the cross flow drag of the empennage, and from the lateral added mass of the empennage. The two effects provide a forward-backward non-symmetry, leading to said sway-yaw coupling both, in steady- and in accelerated motion.

The human-machine interface, namely the mixer programming of the remote control transmitter, proved to deserve more intuitively operable settings. Several 'modes', as known from model aircraft remote control transmitter settings, are possible. The main challenge in this particular case might be the two very different modes of operations, namely, cruise and hover. Additionally, airships behave considerably different as compared to airplanes and helicopters or multicopters.

Operational observations During the test phases we made the following observations (Fig. 8).

Phase 1., Approach The workload to the pilot was low in cruise. When decelerating, a nose pitch down tendency has been observed. However, without high pilot workload, this tendency could be counteracted. Keeping the airship in position was

Fig. 8 The landing site is indicated by an 'A' for airship and marked with a two by two meter square and a smaller one by one meter square allowing for a rating of maneuverability. Both cargo loads, one attached to the airships sling and one at the loading site, are equal in weight

only possible by high pilot workload. Reason is considered the above-mentioned forward-backward non-symmetry in thrust, as well as poor crabbing ability, and the sway-yaw coupling.

Phase 2., Land When touching the ground too fast, the sling occasionally became slack. This led to bouncing of the payload from the ground. In full scale, this behavior might lead to high slack loads in the sling.

Phase 3., Load When trying to hover over return load 2, it proved difficult to keep load 1 stuck to the ground. Load 1 tended to get dragged along, as it proved tricky to keep the desired sling tension. However, the 'Ground Crew' attached sling hook 2 to return load 2.

Phase 4., Tethered This was the easiest part. In full scale, the pilots' task was to keep the airship aligned against the prevailing wind direction. As in the model test there was no wind indoors, the pilot workload was close to zero.

Phase 5., Trim Same as in Phase 3., Load, the difficulty here was in keeping the desired sling tension. If the tension in sling 2 got too high, Load 2 got dragged along instead of staying in position.

Phase 6., Unload As soon as hook 1 was released, Load 2 tended to bounce.

Phase 7., Depart Comparable to Phase 1., Approach, the pilots' workload was low, as the handling qualities of the airship were uncritical.

5 Discussion and Conclusions

A load exchange procedure for near equilibrium airships has been proposed by the authors. The loads considerably exceed operational static heaviness. The procedure resembles proven HESLO, adapted to near equilibrium airship airworthiness requirements.

Three bottlenecks have been identified for such operations, namely, low speed maneuverability, involved systems, and the operational procedure itself. To comply with low speed maneuverability requirements, a propulsion configuration has been proposed that has proven successful in numerous model flight tests. The proposed load exchange system is an external two-sling configuration, as known from HESLO. We attempted to demonstrate the operational procedure in a model flight test program.

5.1 Discussion

The model flight test program indicated the general feasibility of the proposed approach. However, some challenges have been identified that must be addressed in further research:

Forward-backward non-symmetry of propulsor thrust in hover configuration The non-symmetry in forward-backward thruster configurations proved to increase the pilot workload. This can easily be addressed by, e.g., swiveling the forward thrusters backward for cruise mode. Variable-pitch propellers might also provide a solution.

Sling tension monitoring To prevent bouncing and dragging of the load, the sling tension must be monitored and controlled more closely. Hoists, operated by the load master might be a solution, but add complexity and weight. A spring-balance, visible to pilot and ground crew, might provide a pragmatic solution.

Sway-yaw coupling Yawing due to sway proved to increase pilot workload. However, this issue can be addressed even without an autopilot, by mixing laws for control inputs.

Human machine interface Many different modes are possible for inceptor arrangements. It might be advisable, though, to align with helicopter control input arrangements, as known from manned operations.

5.2 Conclusion

The feasibility of heavy cargo load exchange by near equilibrium airships opens a wide range of air cargo operations, where low speed is permittable. Significant fuel savings can be achieved, meaning drastic cuts in emissions, while increasing range and endurance considerably. In the same time near equilibrium airships can be operated with no downwash, making ground operations much easier and safer, providing enhanced acceptance by authorities and local residents. While challenges became evident during the model test program, pragmatic solutions are in sight, encouraging further investigations in this encouraging approach to future sustainable air transport.

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