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Implementation of Fuel-Saving Relaxed Climb Procedure

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In the previous works, the author investigated an optimal climb trajectory by reducing thrust near the top of climb utilizing vertical speed mode. While the prior study demonstrated the potential for fuel savings through numerical simulations, it only considered a limited flight environment. This paper delves deeper, aiming to implement the proposed climb method in the real world. Specifically, this paper presents three contributions. Firstly, to mitigate the potential concern of flight safety and pilot workload, an enhanced pilot procedure employing maximum cruise thrust setting instead of vertical speed mode is proposed. Secondly, the influence of various flight parameters such as wind, air temperature, and the selection of cruising altitude is investigated to ascertain the applicability of the proposed climb method in the real world. Thirdly, the proposed climb method is evaluated using full flight simulator experiments involving multiple aircraft types, conducted in collaboration with a Japanese aircraft operator. The expected impact of the proposed climb procedure is revealed in terms of fuel saving and pilot workload. According to the findings, the proposed procedure has the potential to yield up to 100 lb fuel per climb, with negligible implications for flight safety and pilot workload.

Nomenclatures

x	=	along track distance [m]
z	=	altitude [m]
v	=	true air speed [m/s]
γ	=	flight path angle [rad]
m	=	aircraft weight [kg]
T	=	thrust [N]
M	=	Mach number
L	=	lift [N]
D	=	drag [N]
$T_{\max}$	=	maximum thrust [N]
$T_{\min}$	=	minimum thrust [N]

I.Introduction

Fuel consumption remains a critical concern in aviation, impacting both economic viability and environmental sustainability. Researchers in the air traffic management research field have continuously explored various aspects of flight including all phases from take-off to landing. The author has been focusing on fuel saving strategies during the

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climb phase. Each flight has a fuel-optimal cruise altitude that depends on various factors, including the aircraft type, weight, and wind condition. Therefore, during the climb, it is advisable to reach the fuel-optimal altitude as soon as feasible. The International Civil Aviation Organization (ICAO) recommends a practice known as continuous climb operation (CCO) to achieve fuel saving[1]. At present, the full thrust climb trajectory [2][3][4][5] is recognized as the optimal climb trajectory and is widely used by the current flight management computer (FMC). However, this full-thrust climb trajectory proves optimal solely under a specific assumption: fuel consumption correlates linearly with the generated thrust. The author questioned this assumption, and previously proposed a new optimal climb trajectory assuming a more realistic fuel-thrust relationship[6]. The actual optimal trajectory deviates from full-thrust climb trajectory, recommending relaxed thrust near top of climb (T/C) to save fuel. For a large jet airliner, the potential fuel saving was estimated to be approximately 50 lb per flight calculated using aircraft performance model, with potential savings varying depending on the aircraft type and aircraft weight.

Nevertheless, the previous study failed to address comprehensively the operational aspect. At present, the FMS lacks the capability to execute the optimal climb trajectory, so the past proposal of utilizing vertical speed (V/S) mode was proposed to achieve a low-thrust climb[6]. The transition to V/S mode requires pilot intervention, yet the resulting workload on the pilot remained unexplored. The pilot workload significantly impacts aircraft safety[7], making it imperative to assess the impact of any additional tasks on the pilot workload[8][9][10]. Besides, the previous study confirmed fuel saving under the limited flight environment only. In reality, an aircraft climbs under various flight conditions, including strong wind or extreme temperatures. Also, an aircraft may not climb to the fuel-optimal altitude due to numerous operational constraints.

Therefore, this paper centers its attention on the practical application of the proposed climb procedure in real-world scenarios. A novel pilot procedure is proposed to facilitate the proposed relaxed climb to alleviate pilot workload. Furthermore, the impact of diverse flight conditions is considered, and it is clarified how often the proposed relaxed climb can be applicable in actual flight operations. Finally, to assess the proposed relaxed climb from a pilot's operational perspective, a full-flight simulator (FFSIM) experiment is conducted. The achieved fuel savings are also compared to those calculated in the author's numerical simulation. This paper is an extended work of Ref. [11].

II.Pilot operation to fly sub-optimal climb trajectory

A. Optimal climb trajectory and sub-optimal climb trajectory using V/S mode

The author previously identified a novel climb optimal trajectory when fuel consumption is not linear to the created thrust. Detailed in Ref. [6], a brief overview is provided here. Fig. 1 shows the comparison between the optimal climb trajectory and the full-thrust climb trajectory via numerical optimization. Throughout the climb, maximum climb thrust (thrust ratio = 1.0) is applied, and the thrust is dropped to the cruise thrust when reaching the cruise altitude. On the other hand, the optimal trajectory gradually reduces thrust around the altitude of 15000 ft, which means the rate of climb is also gradually reduced. The difference of fuel consumption between the full-thrust climb trajectory and the optimal climb trajectory is about 50 lb for a large jet airliner. However, executing the optimal climb trajectory is currently infeasible due to technical limitations. Therefore, a pilot procedure to fly a sub-optimal climb trajectory was proposed using V/S mode, termed "V/S climb" herein. By setting an appropriate constant V/S during the climb, the required thrust is smaller than the full climb thrust, achieving a relaxed thrust climb facilitated by the current FMC. The graphical representation of V/S climb is shown in Fig. 2. In this example, setting V/S to 800 ft/min upon reaching 24000 ft results in about 40 lb of fuel savings. This saving is equivalent of about 2/3 of the fuel saving achieved by optimal climb trajectory. The only action required from the pilot is to set the appropriate V/S at the appropriate altitude (referred to as the transfer altitude).

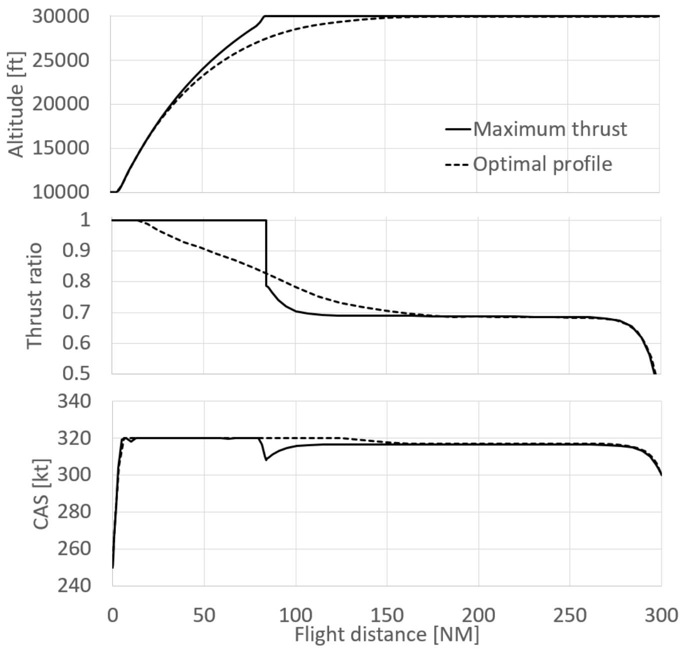

Fig. 1 Optimal climb trajectory. (referred from [6])

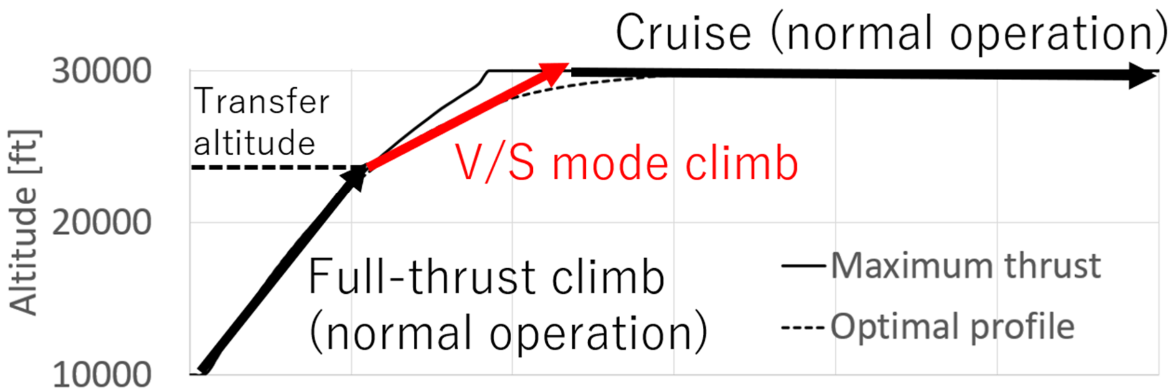

Fig. 2 Graphical representation of V/S climb.

B. Novel pilot procedure to reduce pilot workload

While the proposed V/S climb is a promising method for practical implementation, it also presents several concerns, i.e., 1) flight mode change, 2) lack of speed protection, and 3) selection of the rate of climb and the transfer altitude. Below, each concern is explained in detail.

1) flight mode change

The flight mode provides the guidance to both pilots and autopilots, typically displayed on the flight mode annunciator (FMA) located on the primary flight display (PFD). While the naming of the flight modes differs between Airbus and Boeing, we use the Boeing-specific nomenclature in this research. The proposed procedure, however, can be applied to other manufactures' aircraft as well, as they have similar operational concepts. During the climb, VNAV SPD (vertical navigation – speed) mode is usually engaged. VNAV SPD mode maintains the speed by pitch angle. Transitioning to V/S mode requires the pilot to push the V/S button, and set the desired rate of climb. Upon reaching the cruise altitude, ALT (altitude) mode is engaged after V/S mode, though VNAV PTH (VNAV – path) mode should be engaged afterwards. Therefore, to execute the proposed V/S climb, two distinct pilot actions (VNAV SPD to V/S during climb, ALT to VNAV PTH during cruise) are necessary.

2) lack of speed protection

During the climb, maintaining target speed is critical to prevent the aircraft from stalling. In VNAV SPD operation, speed control is achieved through pitch angle adjustment. If an aircraft encounters very strong tail wind, it may fly level or even descend to keep the target speed. A function known as "speed protection" ensures the target speed maintenance by adjusting the pitch angle. Conversely, in V/S mode operation, the rate of climb is controlled by pitch angle, and the speed is managed by the thrust. If the required thrust exceeds the maximum climb thrust to maintain the target speed, the aircraft cannot maintain the speed. This absence of speed protection in V/S mode raises safety concerns.

3) selection of the rate of climb and the transfer altitude

Achieving significant fuel savings depends on selecting the optimal rate of climb and transfer altitude. However, determining these values effectively is contingent upon numerous flight conditions including aircraft weight and wind conditions. This variability necessitates adjusting the rate of climb and transfer altitude accordingly, which complicates the procedure.

Given the aforementioned problems, implementing the proposed V/S climb in real-world scenarios poses significant difficulty. The so-called full thrust during climb is referred to as "maximum climb thrust (MCL), typically employed during climb. From here, the normal full climb thrust method using MCL is termed "full-thrust climb". In contrast, the maximum cruise thrust (MCR) denotes a configuration where the maximum thrust is capped at a level lower than MCL. MCR is 5-10 % lower than MCL, and MCR is designed for use during cruise. The thrust limitation is automatically set to MCL during cruise, transitioning to MCR as the aircraft levels off. However, this thrust setting can be manually adjusted to either MCL or MCR via control display unit (CDU). This manual configuration to MCR during cruise allows for the reduction of maximum thrust during cruise, leading to fuel savings. This innovative approach is henceforth referred to as "MCR climb".

The first two problems are solved by using the MCR climb. This MCR climb does not change the flight mode, so VNAV SPD mode can be used throughout the climb. Therefore, the MCR climb ensures the speed protection. Upon reaching the cruise altitude, there is no deviation from the conventional full-thrust climb method. Therefore, the sole required action is adjusting to the MCR at a designated transfer altitude, with no further actions needed upon reaching the cruise altitude. Concerning the third problem, while there is no necessity to set the rate of climb is required, the selection of the appropriate transfer altitude remains essential.

Considering the above, the MCR climb emerges as a promising method, likely surpassing the V/S climb from an operational perspective. Therefore, the performance of the MCR climb is evaluated in the following subsection.

C. Performance of MCR climb

In this paper, fuel consumption and flight time are calculated by a simulation model developed by the author. This simulation model incorporates a simplified FMC, enabling the aircraft to follow command inputs such as target speed. Further details can be found in Ref. [12]. The simulation uses the wide-body jet model (referred to large aircraft in this paper), and the performance models derives from BADA model Family 4[13] (referred to BADA4 afterwards). Once the target speed and thrust setting (or its equivalent) are set, the corresponding flight trajectory is obtained. To evaluate the obtained flight trajectory, the following objective function is defined.

$$J = \frac{100}{3600} CI \cdot t_f - 0.453592 \int_0^{t_f} \dot{m}\, dt \quad (1)$$

The objective function consists of both time cost and fuel cost, with its unit expressed in lb. The cost index (CI) serves as a weight factor for the time cost, converting its unit to lb. This time, CI=80 [100 lb/hour] (i.e., CI = 8000 lb/hour) is used, which is a typical CI value for this aircraft model. Table 1 summarizes the initial and terminal conditions of the calculation. The following aircraft trajectory is simulated: 1) The aircraft accelerates to the climb speed (CAS) to 320 kt at 1000 ft/min of rate of climb. 2) After reaching the climb CAS, the aircraft climbs to the cruise altitude of 30000 ft at the climb CAS. 3) The target speed is changed from climb CAS to the climb Mach 0.828 (= cruise Mach) when the aircraft passes the crossover altitude. 4) After reaching the cruise altitude, the aircraft flies level at the cruise Mach. These conditions are established based on the optimal flight altitude considering the given weight and CI. No wind is assumed.

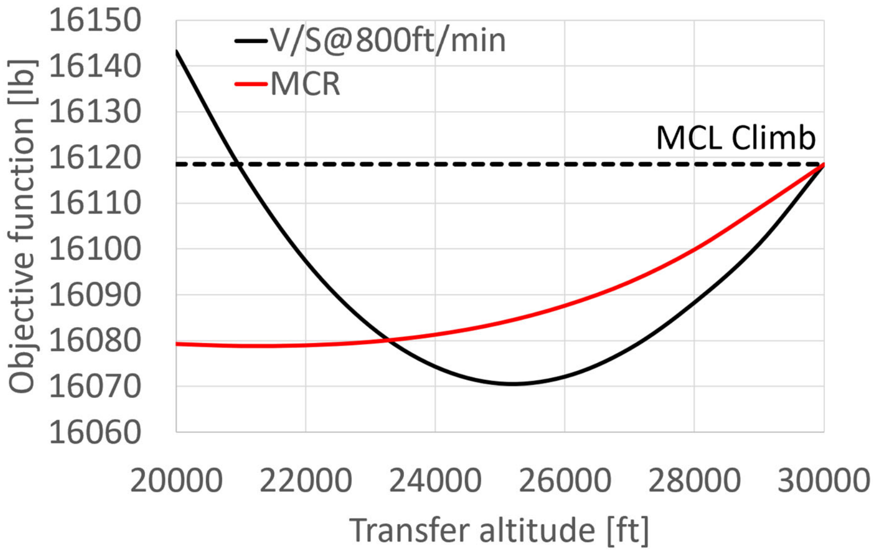

Fig. 3 Performance evaluation of V/S climb and MCR climb across different transfer altitudes.

Table 1 Simulation conditions.

	Initial conditions	Terminal conditions
Along-track distance [NM]	0	200
Speed	250 kt	M0.828
Altitude [ft]	10000	30000
Weight [lb]	700000	-

The calculation of the transfer altitude is essential for conducting the proposed MCR climb. Therefore, Fig. 3 shows the simulation result of the MCR climb using different transfer altitudes. For comparison purposes, the performance of full-thrust climb and V/S climb is also shown. V/S climb requires both the transfer altitude and the specified vertical speed, which is set to 800 ft/min in this scenario. Using the V/S climb method, the optimal transfer altitude is 25000 ft, resulting in a reduction of 48 lb in the objective function. On the other hand, using the MCR climb, the optimal transfer altitude is 21000 ft, resulting in a reduction of 40 lb in the objective function. Based on these findings, the V/S climb demonstrates slightly superior performance compared to the MCR climb. However, the choice of transfer altitude significantly impacts fuel consumption in V/S climb compared to MCR climb. If an inappropriate transfer altitude (e.g., 20000 ft) is chosen for V/S climb, fuel consumption will increase. However, in the case of MCR climb, any transfer altitude between 20000 ft and 29000 ft can effectively reduce fuel consumption. This lower sensitivity in MCR climb is a favorable operational metric, as even minor deviations in the transfer altitude have minimal impact on the fuel consumption.

Table 2 summarizes the difference of fuel consumption among the climb methods. Both MCR climb and V/S climb tend to have slightly longer flight time. This difference in flight time arises from differences in flight trajectories. While IAS remains constant throughout the climb, TAS increases at higher altitude even with constant IAS. The trajectories in MCR climb and V/S climb lie below the one in full-thrust climb, resulting in a smaller TAS compared to full-thrust climb, which contributes the slight difference in flight time. When CI is equal to 80, 1 second flight time corresponds to 2.22 lb in fuel consumption. However, the maximum difference in flight time among the climb methods is only 4 s, which corresponds to less than 10 lb fuel saving. Therefore, it is reasonable to assume that the reduction in the objective function is nearly equivalent to the fuel saving. Since the difference in fuel saving between MCR climb and V/S climb is insignificant, MCR climb emerges as a viable option for fuel saving during the climb.

Table 2 Fuel consumption and flight time under no wind conditions.

Climb methods	Fuel consumption [lb]	Difference from MCL [lb]	Flight time [s]
Full-thrust climb (MCL)	12638.3	-	1566
MCR@21000 ft	12591.6	–46.8	1569
V/S@25000 ft 800 ft/min	12581.6	–56.7	1570

III. Impact of flight conditions to proposed MCR method

While the proposed MCR method shows promise as a fuel saving technique, its effectiveness in real-flight scenarios remains a question. This section evaluates the performance of the MCR method under various flight conditions, specifically examining the influence of wind, air temperature, aircraft weight, and cruise altitude.

A. Impact of winds

Wind significantly impacts aircraft fuel consumption, particularly headwinds and tailwinds. For this evaluation, the author assumes typical headwinds and tailwinds encountered in the jet stream around Japanese airspace based on the discussion with the test pilot. The wind is described as follows:

$$w = \begin{cases} 60\,kt & z < 9000ft \\ 60 + \frac{z-9000}{300}kt & 9000ft \le z \le 30000ft \\ 130kt & 30000ft < z \end{cases} \tag{2}$$

As the wind changes, the optimal cruise speed adjusts accordingly in the simulation. Cruise Mach values shift to M0.837 for headwinds and M0.818 for tailwinds. Similar to Fig. 3, the impact of headwinds and tailwinds on the transfer altitude is summarized in Fig. 4. When the transfer altitude is 26000 ft or higher, the difference in fuel saving among wind conditions is negligible. However, the optimal transfer altitude is 23000 ft for tailwinds, while it is less than 20000 ft for headwinds.

In theory, headwinds effectively mimic additional thrust for the aircraft, necessitating less thrust during climb, thereby leading to a lower transfer altitude. The obtained result aligns with theoretical expectations. However, overall, the wind impact on fuel savings by the MCR climb is limited. Specifically, there is less than a 6 lb difference in fuel savings when the transfer altitude is set at 22000 ft. This means that the proposed MCR climb remains effective under any wind conditions if the transfer altitude is consistently set to 22000 ft, for example.

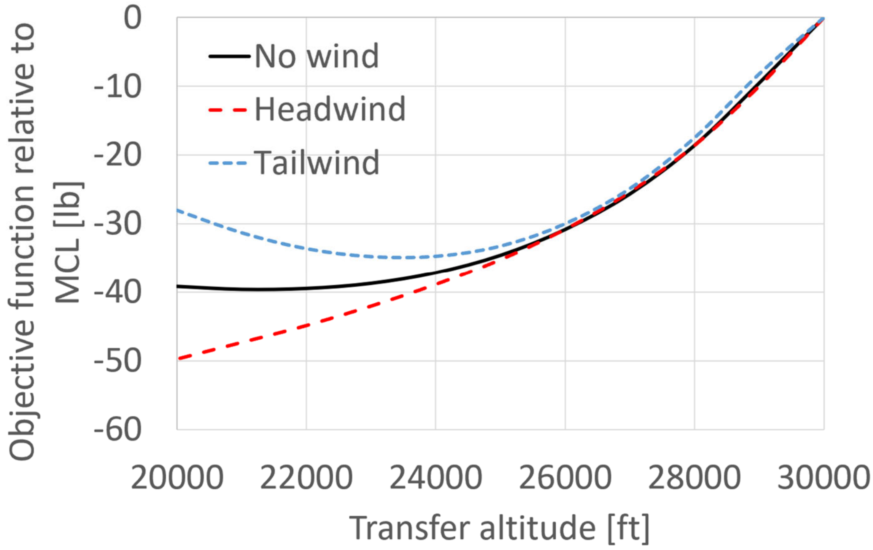

Fig. 4 Performance evaluation of MCR climb across different transfer altitudes under various wind conditions.

B. Impact of air temperatures

Air temperature also significantly impacts aircraft fuel consumption. Since the aircraft operates barometric altitude, the geometric altitude varies with air temperature. Furthermore, the engine performance is directly influenced by air temperature, thereby affecting fuel efficiency. Specifically, high temperatures lead to reduced engine thrust, known as flat-rated thrust[14]. This evaluation examines two conditions of ISA (International Standard Atmosphere)-15 and ISA+15.

Fig. 5 shows the impact of air temperature on transfer altitude. In comparison to ISA conditions, both high and low air temperatures negatively impact fuel savings. Specifically, under high air temperature conditions, potential fuel saving is almost half of that of ISA condition. With reduced engine thrust at high air temperature due to flat-rated thrust, fuel savings are partially achieved. Therefore, the capacity for additional fuel savings using the MCR method is limited, which results in smaller fuel saving in this figure. On the other hand, while low air temperature conditions exhibit a slight reduction in fuel savings compared to ISA conditions, the optimal transfer altitude remains unchanged, mitigating the impact of low temperatures by the MCR method.

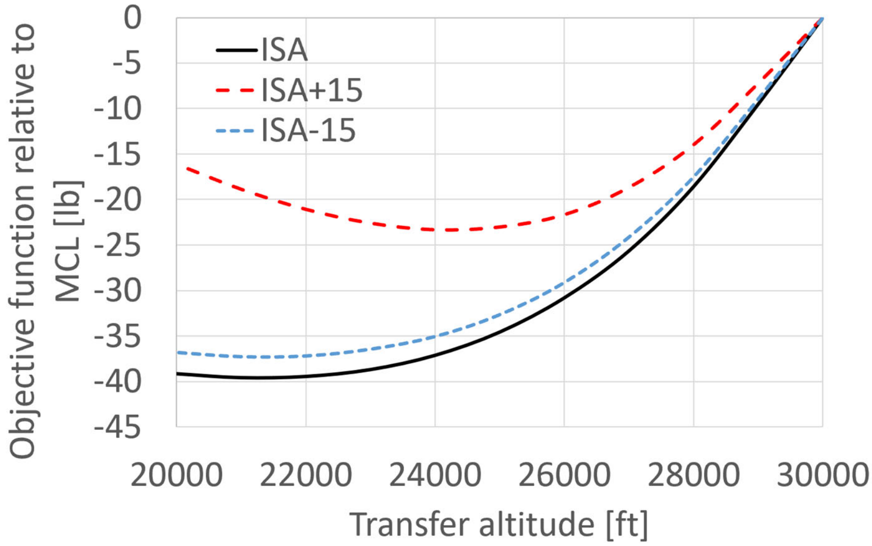

Fig. 5 Performance evaluation of MCR climb across different transfer altitudes under various air temperatures.

C. Impact of aircraft weights

Aircraft weights also affect the potential of fuel savings. The previous research by the author highlighted the variation of fuel savings across aircraft weights and models. This evaluation explorers the impact of transfer altitude among various aircraft weights, including 750,000 lb, 650,000 lb, and 600,000 lb as well as the nominal weight of 700,000 lb. Since the optimal altitude and speed are dependent on aircraft weight, each aircraft is assumed to climb to its optimal altitude at the optimal speed corresponding to its specific weight.

Fig. 6 shows the impact of aircraft weights on transfer altitude. While a slight reduction in fuel savings is observed for the 750,000 lb case, the general trends remain consistent regardless of the weights. Since optimal transfer altitudes typically fall within the range of 8000 to 10000 ft below the cruise altitude, a consistent strategy for selecting transfer altitude is possible.

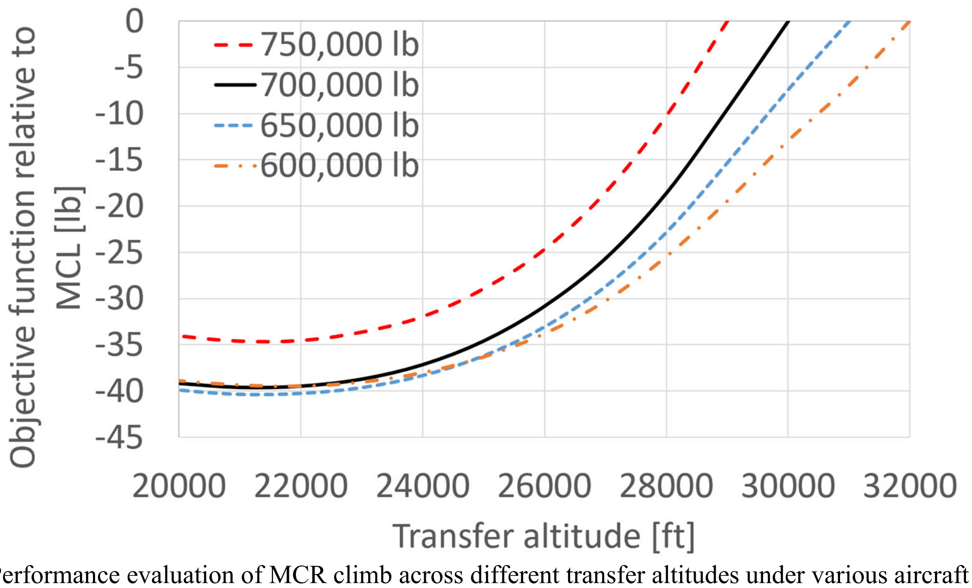

Fig. 6 Performance evaluation of MCR climb across different transfer altitudes under various aircraft weights.

D. Impact of cruise altitudes

All the calculations shown above assume that the aircraft climbs to its optimal altitude. Nonetheless, there exist numerous scenarios where the aircraft is unable to reach its optimal altitude due to various reasons, including heavy traffic, wind turbulence, and ATC instructions. This subsection considers situations where the aircraft climbs to an altitude lower than its optimal altitude. Since the optimal altitude is 30,000 ft for 700,000 lb, the cruise altitude varies between 25,000 ft and 29,000 ft, and its impact on transfer altitude is investigated.

Fig. 7 shows the impact of cruise altitudes on transfer altitude. Despite a decrease in fuel savings as cruise altitudes decrease, fuel savings are still achieved even when cruising below the optimal altitude. It is important to note that the optimal transfer altitude falls between 7000 and 9000 ft below the cruise altitudes (not the optimal altitude). Therefore, if an aircraft climbs to FL250 initially and then climbs to FL300 (optimal altitude), a pilot can transition to MCR at FL180 during the initial climb and use MCR again at FL250 during the second climb, resulting in a fuel saving of 51 lb (greater than the fuel saving of a single climb to FL300).

To be summarized, the proposed MCR climb remains applicable even when an aircraft climbs to an altitude lower than the optimal altitude.

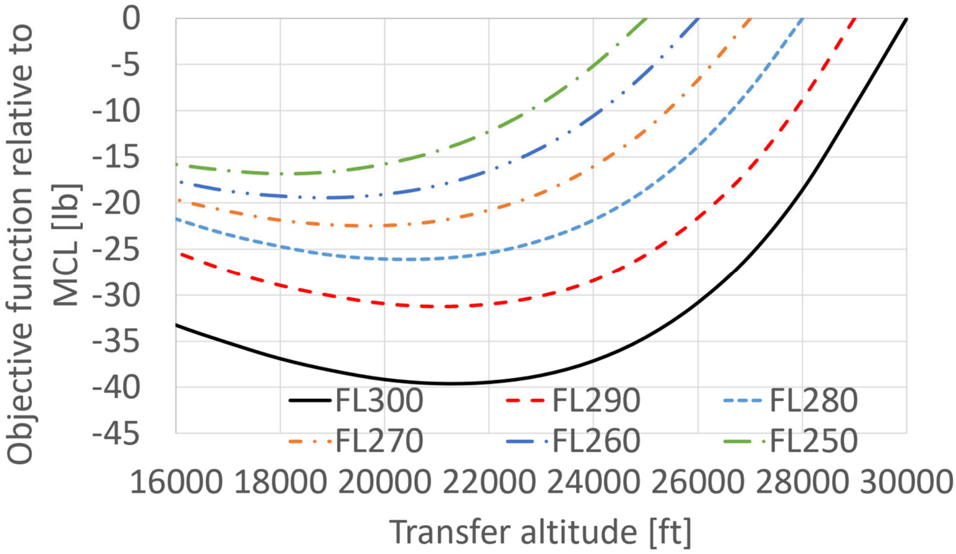

Fig. 7 Performance evaluation of MCR climb across different transfer altitudes under various cruise altitudes.

E. Proposed rule of transfer altitude

According to the results outlined above, the proposed MCR climb remains viable across diverse flight environments. While the optimal transfer altitude may fluctuate with the flight environment, it is imperative to simplify operational procedures to mitigate associated risk. Therefore, the following simplified rule is proposed.

MCR mode is engaged at 8000 ft below the cruise altitude.

While this rule offers simplicity, it may lead to sub-optimal performance across various flight environments. This rule will be employed in the FFSIM experiment detailed in the next section.

IV. Full flight simulator experiments using large aircraft model

A. Experimental conditions

Thanks to the cooperation with All Nippon Airways, the proposed MCR climb is evaluated using the large aircraft FFSIM. The purpose of the experiment is twofold: 1) assessing fuel saving through MCR climb, and 2) evaluating pilot workload during MCR climb. Discrepancies in aircraft performance models between the FFSIM and BADA4 could yield variations in anticipated fuel savings. In the experiment, under precisely identical flight conditions (weight=700,000 lb, CI = 80 [100 lb/hour]), the optimal speed and altitude (i.e., ECON speed and altitude) are calculated. According to the FMS in FFSIM, the optimal altitude is 31,100 ft and the optimal speed is 320kt/M0.833. This result exhibits a slight variance from the calculation result presented in Table 1 due to the difference in aircraft performance models between BADA4 and FFSIM. Additionally, while the recommended transfer altitude is determined by BADA4, it may not be optimal in FFSIM. However, the sensitivity of the transfer altitude in MCR climb, as depicted in Fig. 3, indicates that it is not significantly influential on fuel savings. Therefore, the selection of transfer altitude is unlikely to pose a significant issue. To operate the proposed procedure, a single pilot (captain) was involved in this experiment, with his comments collected afterward.

Three climb methods (full-thrust climb, MCR climb and V/S climb) are conducted in the experiment. The full-thrust climb mirrors standard daily operation. In the case of MCR climb, adhering to the suggested rule, the transfer altitude is designated to be 8000 ft below the cruise altitude. Thus, the simulation commences with level flight at 320 kt with 700000 lb at 18000 ft, which is sufficiently lower than the transfer altitude. The pilot is instructed to change the maximum thrust setting from MCL to MCR at 23000 ft (8000 ft below 31000 ft), and continue the climb. Specifically, this adjustment can be made on the control display unit (CDU) as shown in Fig. 8. First, the pilot navigates to the thrust setting page (THRUST LIM) by pressing "INIT REF" button. Within this page, various thrust settings are available, including MCL (shown in CLB) and MCR (shown in CRZ). The pilot is then asked to select the "CRZ" at the designated transfer altitude. Upon selecting MCR, the throttle lever automatically adjusts downward and the maximum thrust is set to MCR. This process of selecting MCR requires the pilot to press the button twice only.

In the V/S climb, the pilot is asked to switch the pitch mode from VNAV SPD mode to V/S mode with 800 ft/min at 26000 ft.

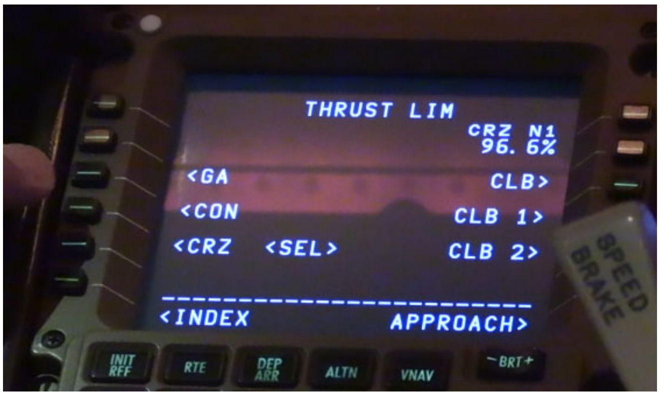

Fig. 8 Maximum thrust setting page in CDU.

B. Experimental result under no wind

First, a no wind case is examined. Analysis commences once the aircraft passes 22000 ft, as the designated transfer altitude is 23000 ft. The obtained flight trajectories are shown in Fig. 9, encompassing full-thrust climb, V/S climb, and MCR climb cases. While the suggested transfer altitude is 8000 ft below the cruise altitude (i.e., 23000 ft), an additional case at 26000 ft transfer altitude is also considered. As expected, the trajectories using MCR and V/S climbs lie below that of the full-thrust climb. T/C points also vary with the methods, but the difference remains within 15 NM, which corresponds to less than 2-minutes gap. During full-thrust and MCR climbs, the rate of climb increases around 30000 ft, which is due to the transition of target speed from 320 kt to M0.833 (i.e., crossover altitude). Maintaining a constant Mach number results in a decrease in both CAS and TAS, facilitating the conversion of speed energy into climb energy.

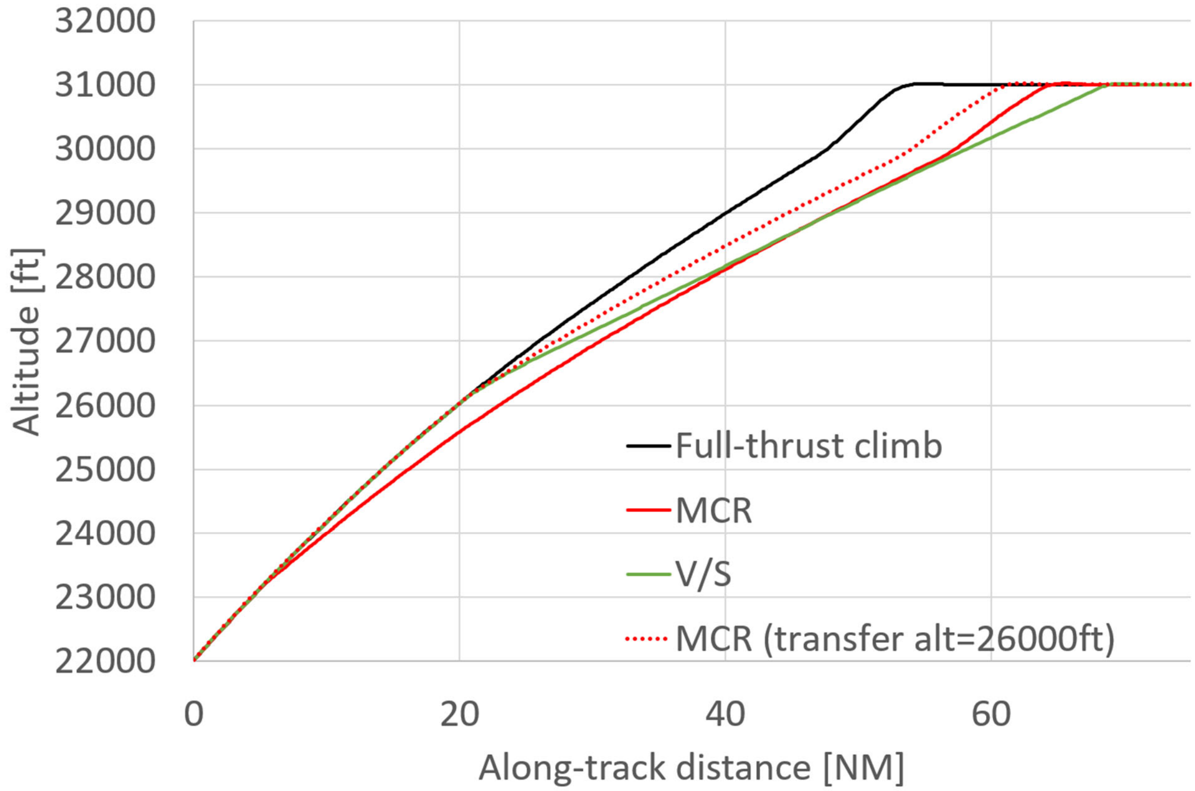

Fig. 9 Obtained flight trajectories by FFSIM experiments under no wind.

Next, fuel consumption and flight time are investigated. As seen in Fig. 9, all four cases reach 31000 ft within 75 NM flight distance. Therefore, fuel consumption and flight time are calculated from 22000 ft altitude to the 75 NM point. The result is summarized in Table 3. Surprisingly, MCR climb exhibits a fuel saving of over 100 lb, while about 50 lb fuel saving was expected from the BADA4 simulation (shown in Table 2). Additionally, BADA4 simulation suggests that V/S climb saves more fuel than MCR climb, the FFSIM experiment reveals the opposite result, i.e., MCR climb is more effective. Regarding the selection of the transfer altitude, the suggested rule (8000 ft below the cruise altitude) outperforms the case where the transfer altitude is set 5000 ft below the cruise altitude.

Concerning flight time, the maximum difference observed is 3 s, which aligns closely with the simulation, so the flight time difference is negligible in this experiment, too.

Table 3 Fuel consumption and flight time to 75 NM flight distance under no wind.

Climb methods	Fuel consumption [lb]	Difference from MCL [lb]	Flight time [s]
Full-thrust climb (MCL)	5017.5	-	570
MCR@23000 ft	4914.5	–103.0	573
V/S@26000 ft 800 ft/min	4925.6	–91.9	571
MCR@26000 ft	4947.1	–70.4	571

C. Experimental result under headwind

The simulation is conducted under headwind, too. Although the headwind profile is the same as the BADA4 simulation (shown in Eq. (2)), it is worth noting that slight discrepancies exist in the aircraft heading angle and wind direction due to limitations within the simulator environment.

Fig. 10 shows the flight trajectory under headwind conditions, excluding V/S climb method from this experiment. The trend of trajectories is similar to the case under no wind. Starting from the transfer altitude (23,000 ft), the trajectory of the MCR climb remains below the that of the full-thrust climb. The difference of T/C point is about 10 NM, which corresponds to roughly a minute. Due to the strong headwind, the ground speed is lower compared to the no wind case, resulting in a T/C point being around 40 NM, in contrast to around 60NM under no wind.

Fig. 10Obtained flight trajectories by FFSIM experiments under headwind.

Table 4 shows the difference of fuel consumption and flight time under headwind. Considering the shift in the T/C point due to wind effects, the analysis focuses on the fuel consumption and the flight time for a 45 NM flight distance. The fuel saving achieved by MCR climb under headwind is 101 lb, mirroring the 103 lb saved under no wind. This outcome aligns with the result in Sec. III A, reinforcing the consistency of the results across various wind conditions.

Table 4 Fuel consumption and flight time to 45 NM flight distance under headwind.

Climb methods	Fuel consumption [lb]	Difference from MCL [lb]	Flight time [s]
Full-thrust climb (MCL)	4188.4	-	456
MCR@23000 ft	4087.4	–101.0	458

D. Experimental result under high temperature

This subsection shows the experimental results under high temperature conditions (ISA+20). According to BADA4 simulation, a decrease in fuel saving was expected, a trend of which is validated. Fig. 11 shows the flight trajectories for both full-thrust climb and MCR climb. The high temperature, results in a further shift of T/C points.

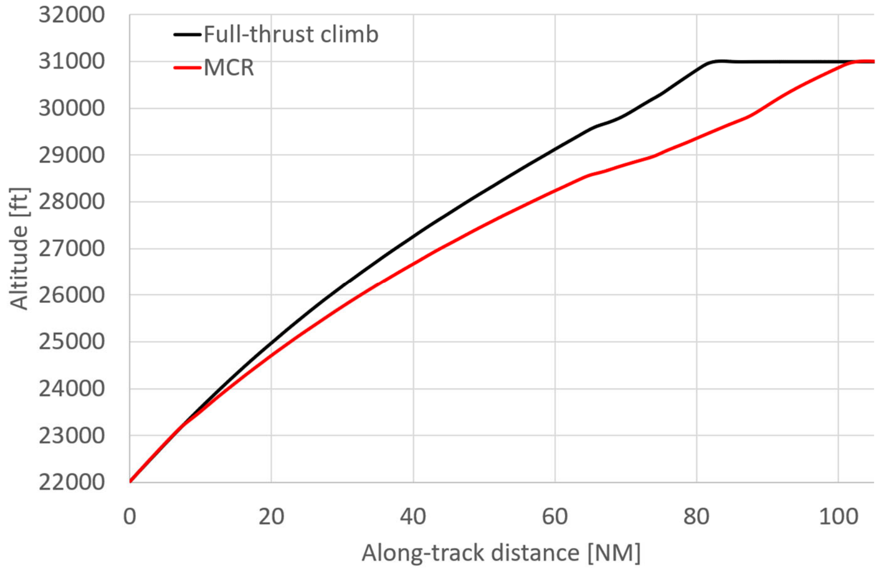

Fig. 11Obtained flight trajectories by FFSIM experiments at high temperature (ISA+20).

Table 5 shows the fuel consumption and flight time under ISA+20. The MCR method achieves a fuel saving of about 60 lb. This saving is smaller than that observed under ISA, aligning with the prediction from the BADA4 simulation in Sec. III B, though the magnitude of fuel saving is different.

Table 5 Fuel consumption and flight time to 105 NM flight distance under high temperature (ISA+20).

Climb methods	Fuel consumption [lb]	Difference from MCL [lb]	Flight time [s]
Full-thrust climb (MCL)	6374.8	-	764
MCR@23000 ft	6315.2	–59.6	767

E. Pilot comments

As demonstrated above, the fuel saving benefit is substantial, i.e., more than 100 lb saving per flight. However, it is equally crucial to reduce pilot workload for practical application. Following the FFSIM experiments, the author queried the pilot regarding the MCR climb, yielding the subsequent comments.

MCR climb is unique and straightforward. If achieving sufficient fuel saving is feasible through MCR climb, I am willing to adopt this approach. The adjustment of cruise thrust settings is executed within the CDU, with no discernible increase in workload. With the maximum thrust reduced, the pilot monitors vertical speed more frequently, which presents a minor concern. Under heavy weight and strong tail wind, it is challenging to attain the sufficient rate of climb. Nonetheless, in such circumstances, cancelling cruise thrust and employing climb thrust resolves the issue. Furthermore, the timing of reaching T/C is slightly delayed by MCR climb, approximately by a minute, which poses no operational difficulties from an ATC standpoint. Conversely, V/S climb requires several pilot interventions, and speed is not protected, mandating vigilant speed monitoring throughout the climb. As such, V/S climb is deemed impractical for real-flight operations.

Overall, the pilot exhibits a strongly positive attitude towards the suggested MCR climb procedure. A fuel saving of 100 lb holds significant value for aircraft operators, serving as a compelling incentive for adopting MCR climb. Regarding pilot workload, the increased monitoring of vertical speed poses only a minor inconvenience. While concerns arise regarding achieving sufficient climb rats in conditions of heavy aircraft and tailwinds, reverting to full-thrust climb proves straightforward, mitigating any potential issues. Although the possible minimum ROC is not uniquely determined by the pilot, a climb rate of 500 ft/min can be applied considering the TCAS (Traffic alert and Collision Avoidance System) display system. The climb/descent status of surrounding traffic is only available when the ROC is greater than 500 ft/min. If the climb rate is less than 500 ft/min, the surrounding traffic may not be aware that the aircraft is climbing, which may be detrimental to situation awareness. However, when using the proposed procedure, the ROC is generally greater than 500 ft/min so the negative impact is limited. Similarly, potential delays in reaching T/C are acknowledged, yet deemed minimally impactful by the pilot. In essence, the proposed MCR climb promises substantial fuel saving exceeding 100 lb, without posing significant challenges to pilot workload.

V.Full flight simulator experiments using middle aircraft

A. Experimental conditions

The previous section highlights the considerable potential of fuel savings through MCR climb using the large aircraft model. This section extends the analysis by conducting additional FFSIM experiment using another aircraft model (referred to as "middle aircraft") which is also a wide-body jet. Regardless of aircraft models, the effectiveness of the proposed MCR climb is expected. However, the selection of transfer altitudes plays an important role in maximizing fuel benefits. This section relies solely on the results of FFSIM experiments to determine the optimal transfer altitude.

During the experiments, the initial weight is set at 380,000 lb, and the optimal altitude and speed calculated by FMS under CI = 20 [100 lb/hour] are FL400 and 301 kt/M.841, respectively. Three transfer altitudes (4000, 7000, and 10000 ft below the cruise altitude) are considered, initiating the simulation at FL280. No wind and ISA conditions are assumed. Another pilot (captain) was involved in the experiment using this middle aircraft. Note that the comments from this pilot were similar to those provided by the pilot in Sec. IV E, which means that multiple pilots have a positive attitude towards the proposed operation.

B. Experimental result under no wind with various transfer altitudes

Fig. 12 shows the trajectories obtained from four flights (full-thrust climb and three MCR climbs). The transfer altitudes for the MCR climbs are designated to 36000 ft, 33000 ft, and 30000 ft. The crossover altitude is located around 33000 ft under the given optimal speeds. No significant differences of trajectories are found between the large aircraft and the middle aircraft; the MCR climbs extend T/C points further by about 10-15 NM.

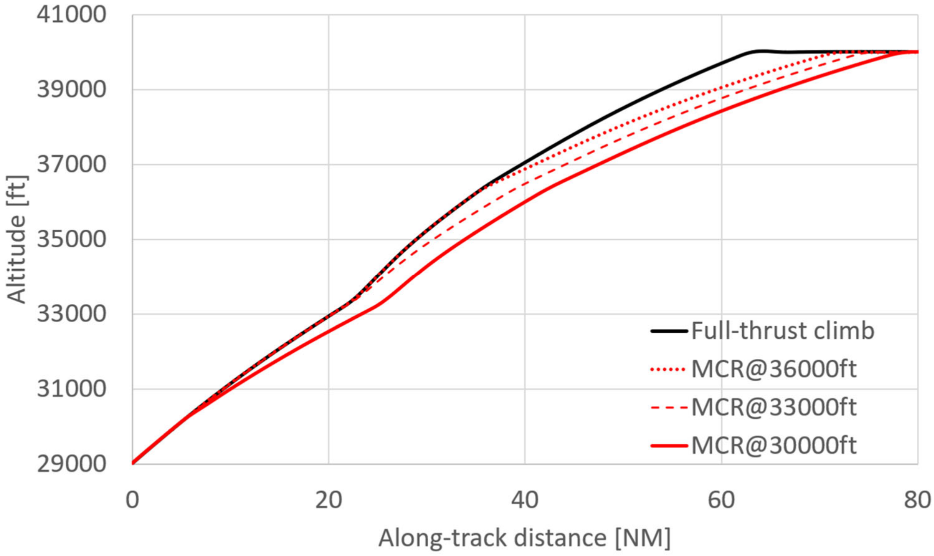

Fig. 12 Obtained flight trajectories by the middle aircraft FFSIM experiments with various transfer altitudes.

Table 6 summarizes fuel consumption and flight time of MCR climbs with various transfer altitudes. Although the magnitude of fuel savings is small compared to the large aircraft model, an approximate fuel saving of 20 lb is achieved. Notably, the optimal transfer altitude among three options is 33000 ft, yielding a fuel saving of 22.2 lb.

Table 6 Fuel consumption and flight time to 80 NM flight distance under no wind using the middle aircraft.

Climb methods	Fuel consumption [lb]	Difference from MCL [lb]	Flight time [s]
Full-thrust climb (MCL)	2701.7	-	598
MCR@36000 ft	2685.1	–16.6	598
MCR@33000 ft	2679.5	–22.2	598
MCR@30000 ft	2681.6	–20.1	599

To align with the rule of transfer altitudes established for the large aircraft model, the following rule is adopted for the middle aircraft.

MCR mode is engaged at 7000 ft below the cruise altitude.

This rule is consistently applied to other flight conditions in subsequent subsections.

C. Experimental result under heavy weight

The additional experiment is conducted under heavy weight, i.e., 520,000 lb. The optimal altitude and speeds are changed accordingly; 34000 ft and 334 kt/M.840. The full-thrust climb and MCR climb are applied in the experiments, and the results are summarized in Table 7. The achieved fuel saving is slightly larger than that of normal weight (380,000 lb). This result infers that the proposed MCR climb works regardless of weights as suggested in Sec. IIIC.

Table 7 Fuel consumption and flight time to 80 NM flight distance under heavy weight.

Climb methods	Fuel consumption [lb]	Difference from MCL [lb]	Flight time [s]
Full-thrust climb (MCL)	3223.5	-	587
MCR@23000 ft	3198.8	–24.7	585

D. Experimental result when climbing to non-optimal altitude

As indicated in Sec. III D, the proposed MCR climb is expected to work even when the cruise altitude differs from the optimal altitude. Therefore, the following scenario is considered; at a normal weight of 380,000 lb, an aircraft climbs to FL300 and maintains level flight. After flying a certain distance, the aircraft climbs to FL400 (the optimal altitude). In this scenario, MCR climb can be applied twice; once to FL300 and again to FL400.

Fig. 13 shows the flight trajectories in this scenario. The analysis begins at FL220. First, the aircraft start the climb to FL300. After passing the 40 NM point, the aircraft starts the climb to FL400 once more. When using the MCR climb, MCR is engaged at FL230 and FL330, 7000 ft below the cruise altitude.

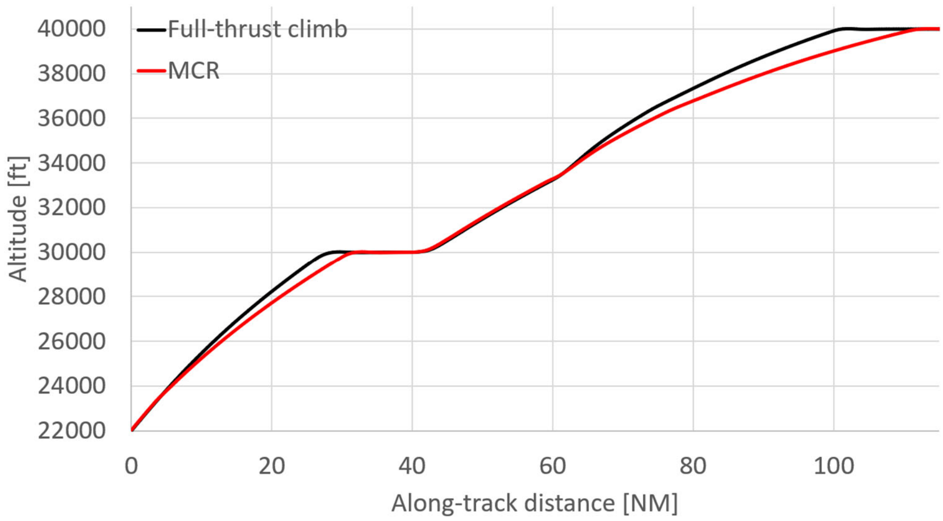

Fig. 13 Obtained flight trajectories by the middle aircraft FFSIM experiments with double climbs.

Table 8 provides a summary of fuel consumption and flight time for this double climb scenario. MCR climb is executed twice, with each case yielding fuel savings. Notably, it is observed that the fuel savings during the initial climb (to a non-optimal altitude) exceed those achieved during the subsequent climb (to the optimal altitude). This finding contrasts with the result provided in Sec. III D; however, it is likely influenced by differences in aircraft type and aircraft performance model. Nevertheless, the MCR climb consistently proves effective in fuel conservation across both cases (climb to non-optimal and optimal altitudes). This means that the proposed MCR climb is applicable to the majority of climb scenarios.

Table 8 Fuel consumption and flight time for double climbs.

Phase	Climb methods	Fuel consumption [lb]	Difference from MCL [lb]	Flight time [s]
0-40 NM	Full-thrust climb (MCL)	1779.5	-	321
	MCR	1733.3	–46.2	321
40-115 NM	Full-thrust climb (MCL)	2490.0	-	560
	MCR	2469.5	–20.5	560

VI. Conclusions

The author previously identified a novel climb optimal trajectory for fuel savings by reducing the thrust near top of climb (T/C). Initially, the use of vertical speed (V/S) was proposed to achieve the fuel saving, but safety concerns arose due to the absence of speed protection. In this study, an alternate method was proposed: adjusting the maximum thrust setting to the maximum cruise thrust (MCR) during climb. The MCR climb effectively addressed the safety issues associated with V/S climb. To simplify the procedure, a universal rule for determining transfer altitude for the large aircraft model was established; MCR is engaged at 8000 ft below the cruise altitude. This rule was demonstrated to be applicable across various wind conditions, air temperatures, aircraft weights, and cruise altitudes. Consequently, the MCR climb can be implemented during climb phase of the majority of flights.

To evaluate the MCR climb in a more realistic setting, full flight simulator (FFSIM) experiments were conducted. The adjustment of the maximum thrust setting, facilitated through the CDU by the pilot, was seamlessly executed without raising any significant concerns. For the large aircraft model, the achieved fuel savings amounted to approximately 100 lb, a substantial incentive to implement the proposed MCR climb. An additional FFSIM experiment was conducted using the middle aircraft model, further demonstrating fuel savings through the MCR climb method in a different aircraft model.

Based on the findings presented in this paper, there is a clear incentive to implement the proposed MCR climb in real-world operations to realize significant fuel savings.

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