Noname manuscript No.
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Supplementary material to 'Steered stratospheric aerosol injection (Part 1): Aircraft and operation design'

Received: date / Accepted: date

This document constitutes the Supplementary Information to 'Steered stratospheric aerosol injection (Part 1): Aircraft and operation design'. In section 1, a detailed description of the coupled aircraft/flight profile optimization framework is provided. Section 2 discusses the design impacts of using alternate propulsion systems and mission altitudes, the economic and environmental impact of these alternate options are covered in part 2 of the paper series and its supplementary material.

1 Coupled Optimization Framework

Both design optimization phases made use of the Stanford University Aerospace Vehicle Environment (SUAVE) conceptual design framework (1; 2; 3). SUAVE can be used to perform multi-disciplinary analyses for aerodynamics, structures, weight estimation, stability and propulsion at multiple levels of fidelity and combine the results to obtain performance estimates for an aircraft over a simulated flight. The SUAVE SciPy wrapper also allows straightforward extension of the program by implementing additional modules. Five such extension modules were implemented for the present study. Their content is summarized below. A more detailed description of their content can be found in chapter 8 of (4).

The first extension module incorporated the variation of payload weight and heating power requirements during the flight. The second incorporated detailed predictions of the wing lift, drag and aerodynamic moment using a vortex lattice code (5) combined with both empirical airfoil data (6; 7; 8) and handbook-based lift and drag prediction methods (9). The third module performed structural weight predictions, based on local optimization using Euler-Bernoulli beam theory and the loads introduced by lift, engine thrust, fuel, payload and engine weight. This model also included the effect of wing struts, which proved to be useful for achieving structural rigidity of the resulting low weight, high aspect ratio configuration.

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The outputs from the second and third modules were fed to a fourth aeroelasticity module, which performed estimates of control reversal, divergence and flutter speeds using lumped-parameter models. These were calibrated and verified using high-fidelity estimates of the same quantities from the NeoCASS simulation package (10). Finally, the required thrust and engine operating conditions were passed to a fifth numerical propulsion module, which estimated the customised engine performance using semi-empirical models. The latter were calibrated and verified using output from the well-known gas turbine simulation program GSP (11). The complete resulting package was validated using alternative analytic and empirical estimates of aircraft performance in comparable conditions (4).

With the added modules in place, SUAVE's SciPy SLSQP-based optimization framework was used to optimize for minimum fuel consumption for a chosen flight range. Fuel consumption was used as the objective for four reasons. First, its impact on aircraft weight directly influences the required lift, drag and thrust in critical operating phases of the flight and is therefore strongly linked to the aircraft's technical feasibility. Second, fuel consumption is directly proportional the annual CO_2 emission, which part 2 of the main paper series will show dominates the environmental impact of the mission. Third, part 2 of the main paper series will also show that fuel costs generally are the largest contribution to the variable operating cost once an operational concept is specified. Finally, fuel consumption estimates from engineering models are relatively precise. If the objective was instead the minimization of economic impact, for example, the optimization would have been subjected to the much higher uncertainties inherent in long-term economic models.

An overview over the resulting coupled aircraft/flight profile design loop is included in figure 1. Each design iteration was started with a fuel optimization step within the original SUAVE design framework, assuming a fixed physical aircraft configuration, payload, delivery range and operating constraints imposed by the aerosol delivery. The resulting flight profile was then passed to the aircraft design and analysis extension modules described above. These modules provided updated information, which was then used to update the SAUVE fight profile optimization in the next iteration. At each stage of this ensuing loop, the design's consistency with several other subdisciplines was manually ascertained and adapted whenever constraints were violated. Such adjustments were followed by a renewed iteration process, until a feasible, fuel-optimised aircraft / flight profile was attained.

2 Consequences of alternate design options

The delivery system presented in the previous sections depends on a number of assumed design options. In this section we consider the consequences resulting from modifications to two of these options, singled out since they strongly influence the configuration and operation of the proposed aircraft. In doing so, we focus on the effects on the performance of the system. The resulting changes to economic and environmental impact are quantified in the supplementary material of part 2 of the main paper series, along with additional impact sensitivities arising from the uncertainties in other design inputs.

In the following analysis, it is assumed that the critical climb segment to the first stratospheric cruise leg remains the constraining flight condition even in the

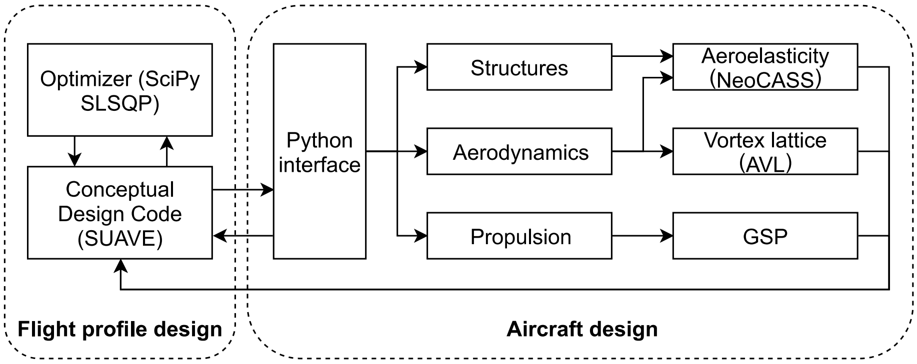

Fig. 1: Iterative loop of the coupled aircraft-flight profile design procedure. Fuel-optimised flight profiles are designed within SUAVE's base framework, which interfaces with the additional aicraft design modules

presence of design perturbations. Hence, less critical flight phases are allowed to change. Modifications are also evaluated at a constant DR. As a result, changes in system performance manifest themselves as changes to the payload-range combinations at which the constraints are encountered.

In order to avoid compounding the uncertainties associated with the achievement of the ***FI*** and ***OFI*** scenarios, the design changes are only presented for the ***CI*** scenario. The general conclusions can be anticipated to be similar for the remaining scenarios, although the specific quantitative effects will differ.

2.1 Choice of propulsion system

The coupled aircraft-flight design procedure of included the design of a custom engine. Although this might be expected to have optimal performance in terms of weight and fuel consumption, it incurs a large development cost. It is therefore worthwhile to review the feasibility and impact of alternative, existing choices of propulsion system, which are thought to be sufficient to power a smaller but similar aircraft to these altitudes (12). For this purpose, two alternatives based on existing engines were considered: F-100-PW-229 low-bypass turbofans (13) or General Electric GE90-115B high-bypass turbofans (14). These options are analyzed by making appropriate adjustments to SUAVE's propulsion networks (1).

The alternative engines have lower thrust and weight than the custom option, hence the weight and therefore T_{crit} of the design will likely change. T_{crit} is therefore allowed to vary in this analysis, provided that the resulting aircraft still completes the segment within the 5 minute margin stipulated. The analysis shows that T_{crit} is higher for both the F100 and GE90 options. As a consequence, more engines are required; 18 engines per aircraft for the F100 option and 6 engines per aircraft for the GE90 option.

The F100 alternative is inferior in the ***CI*** scenario. While a single F100 is considerably lighter than a custom engine, the high engine number only yields moderate savings in the aircraft's operating empty weight (OEW). Futhermore the much higher fuel consumption per unit thrust (specific fuel consumption, or SFC) increases the amount fuel used per flight. This results in a lower payload-range combination, and consequently a higher number of flights and fleet size, as summarised in table 1.

The F100 option would be more attractive at lower delivery ranges, where the relative impact of fuel consumption matters less. However, as the F100's entire $\dot{V}$ is only comparable to the core flow of the proposed custom engine, there is little scope for increasing DR through increased mass flow. Consequently, low delivery ranges can only be reached for H_2SO_4 injection if extremely high increases in diffusivity are achieved. They could, however, be interesting for SO_2 injection scenarios that require neither long delivery ranges nor engine injection.

The GE90 alternative is more challenging to analyse, as no data concerning its fuel consumption rates are publicly available. Therefore, GSP (the gas turbine simulation tool described in section 1) was used to provide an estimate based on inlet diameter, overall pressure ratio, bypass ratio and atmospheric conditions at 20 km altitude.

For the GE90, $\dot{V}$ is comparable to the proposed custom engine value in the ***CI*** scenario, as the GE90's smaller core size is offset by a higher core flow speed. Since 6 GE90s deliver considerably more thrust than 4 custom-design engines, this scenario is not constrained by T_{crit}, but by $C_{L,crit}$ (note that only conventional symmetric engine configurations are considered here).

As shown in table 1, the net result of the GE90 option is an increase in OEW, offsetting fuel savings due to lower SFC and obliging a lower payload-range combination, which in turn leads to increases in the fleet size and number of flights per day. Unlike the F100, the GE90 does allow for bypass injection to increase $\dot{V}$. However, the GE90 option becomes even less attractive than the proposed custom engine at higher DR, at which the fuel efficiency advantage of the former is less important.

From this analysis can thus be concluded that neither of the alternative engine configurations considered here are likely to outperform the proposed custom engine in the ***CI*** scenario from an operational perspective. This was also found to be true for the other H_2SO_4 delivery scenarios. It should be noted that the analysis has some limitations. For instance, the class-II aircraft weight prediction method used was not validated for configurations that feature more than 4 engines. Additionally, the analysis does not account for improvements in engine technology likely to arise within the development period of the aircraft (15).

However, such a custom engine need not differ radically in technology from existing high-thrust engines such as the GE90 when its bypass ratio is high, as the complex jet core remains similar. This stands in contrast to solutions that propose achieving similar thrust levels per engine with low-bypass turbofans, which would require increasing core diameters substantially beyond current technology. Hence, we expect the uncertainties associated with developing the low-bypass option discussed here to be comparatively low.

Therefore, in addition to the relatively large negative consequences of the alternatives considered here, it seems unlikely that a more detailed analysis will to lead to different conclusions concerning the advantages of using custom engines.

Table 1: Changes to mission when choosing the F100 or GE90 engine option at constant dispersion rate.

	F100	%Δ	**GE90**	%Δ
Mission				
Payload/flight [tons]	5.54	-18.5	5.00	-26.5
OEW [tons]	97.4	-4.5	117	+14.7
Delivery range [km]	2697	-20.0	2474	-26.6
Fuel/flight [tons]	46.1	+33.0	25.2	-12.4
Airports	6	+50.0	6	+50.0
Fleet size	2586	+9.58	2636	+11.7
Flights/day	7541	+24.9	8219	+36.1

2.2 Delivery cruise altitude

Higher stratospheric delivery altitudes are beneficial for aerosol residence time and thus radiative effectiveness, although this is partly offset by less effective particles due to increased coagulation (e.g. 16; 17; 18; 19). The main paper outlined the very narrow aerodynamic operating margin at capping thrust requirements at the top of the initial climb, making it difficult to change this mission segment without exceeding critical limits. Thus, higher altitudes can only be achieved with the current aircraft configuration by reducing payload or delivery range, making the aircraft lighter when it negotiates this climb.

Here, the effects of a 0.5 km increase and decrease in the delivery cruise altitude of the ***CI*** scenario are considered. Hence, the delivery range and payload are reduced/increased in proportion until either the T_{crit} or $C_{L,crit}$ constraint are encountered in either the initial climb to cruise or in the intra-cruise climb segment.

Table 2: Changes to mission when increasing and reducing delivery cruise altitude by 0.5 km.

	-0.5 km	%Δ	**+0.5 km**	%Δ
Mission				
Payload/flight [tons]	11.2	+64.2	0.350	-94.8
OEW [tons]	104	+1.57	100	-2.10
Delivery range [km]	4690	+66.0	2350	-94.8
Fuel/flight [tons]	50.0	+61.7	8.34	-73.0
Airports	4	0.00	78	+1950
Fleet size	1980	-16.1	19940	+844
Flights/day	3680	-39.1	117000	+1940

Table 2 indicates a relatively strong influence of altitude on the ***CI*** delivery scenario. Increasing or decreasing the delivery cruise altitude leads to large changes in the capacity of the aircraft. These changes arise due to the rapid local variation of air density as a function of altitude, which affects both the available lift and thrust. Operating 0.5 km above the design delivery altitude (corresponding to an 8% reduction in air density) results such a substantial reduction in capacity, such that the resulting fleet size is impractical. The trend continues up to 21.6 km, the ultimate service ceiling of the aircraft, where it can carry zero payload and cover no delivery range.

Although this analysis was performed for a fixed aircraft configuration, it can be anticipated that alternate designs would not fare better. Higher design delivery altitudes would require an increased wing surface area and engine size, which in turn would increase the OEW and kick off a snowballing weight rise. Developing practical aircraft thus becomes increasingly difficult as the altitude is increased above 20 km. The supplementary material of part 2 of the main paper series will furthermore show that it also becomes extremely expensive in terms of economic and environmental impact.

Reducing the delivery altitude enables larger payloads to be carried over longer delivery ranges. However, if lower altitudes are to be targeted, redesigning the aircraft to have smaller wing area, OEW and less extreme design features and delivery ranges could become beneficial. In particular, retrofitting existing commercial aircraft might then become an increasingly interesting alternative.

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