Coursework 2: Conceptual Design and Mission Analysis – Assignment Specification and Report Template

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Every aircraft design project begins with the design team aiming to understand the competition! What are the key features of competing aircraft, designed for the same mission, and why did their designers make those choices? Large aerospace companies actually have special 'tiger teams' dedicated to the task of unravelling the secrets behind other companies' designs. Here you get to do the same.

This assignment invites you to attempt to reconstruct the conceptual design and mission analysis process that the designers of your chosen aircraft undertook (the same aircraft you picked for Coursework 1). This is your opportunity to use the open literature and constrain analysis methods to unpick the reasons for the most fundamental design decisions that shaped the aircraft of your choice.

You will not be assessed on the accuracy of your estimates – indeed, in most cases there is no public domain information against which we could do that. Rather, the goal is to come up with a *plausible* conceptual design narrative consisting of your best guess of a design brief (based on a typical mission definition), a set of aerodynamic and propulsion performance estimates and a constrain analysis. You may find useful numbers in the open literature (flight test results, mission descriptions, wind tunnel data, etc.) required for parts of this reconstruction work, but if you cannot, that is not a problem – once again, a plausible, self-consistent guess of the journey that may have taken the design team to the design of the aircraft is the main goal.

The main deliverable is a report constructed on the template laid out in this document; indeed, please use this actual document as a form, which, when filled out, will constitute your design analysis report.

For the questions that require an analysis of the open literature, please remember to indicate the sources for every piece of information you supplied. Use reputable sources – Wikipedia, web pages with no clear referencing/fact checking/peer review policy should be treated as an absolute last resort and the numbers should be considered as guesses.

For the questions that require calculations, we recommend using Python in Jupyter notebook (the Aircraft Design Recipes in Python (ADRpy) library contains everything you need), but you may perform calculations by whatever means you prefer (including by hand, on paper, but you need to transcribe it digitally at the end, of course). **Please submit a single file: a pdf version of this document, containing your report.**

Have fun!

Section 1: Describe your chosen aircraft (20 marks)

This section should contain (exclusively*):

- a clear, precise identification of your aircraft: make, model, series, mark, as appropriate
- a photograph and a three-view of your aircraft (do not take up enormous amounts of space with these, but they should be clearly visible); for the three-view make sure you use a credible source, if you're confident in the accuracy of your own CAD model, you can use a three-view of that too
- a clear, precise identification of the propulsion system of the aircraft (make, type, series, mark, etc. of the engine(s) as appropriate), the precise type of engine (e.g., twin-spool turbofan, supercharged V12 piston engine), type of fuel or other energy source (e.g., Jet-A)
- propulsive power or thrust (total or per engine, indicate which, also be specific on whether you're quoting sea level static thrust/max thrust, cruise power/maximum continuous power/take-off power, etc.)
- the wing area (projected, total) of the aircraft (in m^2)
- the maximum take-off weight (MTOW) of the aircraft (in kg)
- the MTOW-based wing loading of the aircraft in Pa (show calculation)
- concise description of the airframe (e.g., 'low wing, tricycle undercarriage, T-tail')

*Do not include any other information.

Indicative marks grid:

Minimal or mostly incorrect information, wrong image/three-view, untidy, the reader has to hunt on the page for the required information amongst irrelevant/not required material, wrong units in multiple places.	0 - 5
Required information mostly present, but imprecise in places (e.g., aircraft only identified as 'Airbus A340', or engine type identified, but not the manufacturer, or not clear on exact model/series, thrust rating given as a range for the whole family or the wrong member of the family/wrong numbers, etc.); presentation reasonably clear, but not professional report quality	6 - 14
Clear, tidy and complete or very nearly complete, presented as one might expect from a professional quality technical report with figure captions and numbers, easily readable, yet not taking up more space than necessary, sources of information clearly referenced.	15 - 20

Mitsubishi A6M3 model 32 (Zeke 32)

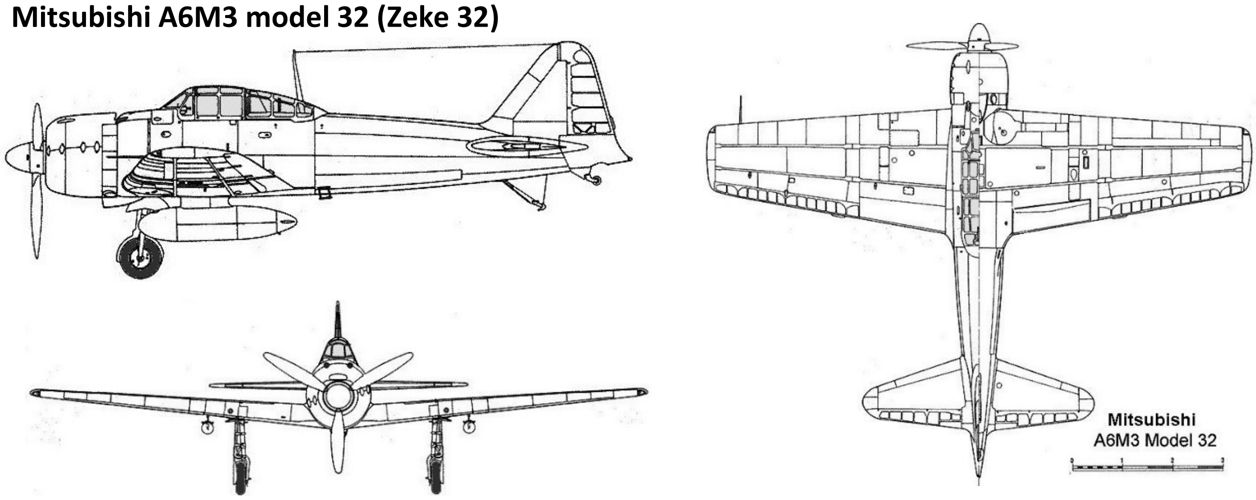


Figure 1. A6M3 Zeke 32 plan views

Engine: Nakajima Sakae 21. 14-cylinder two row radial. Two-speed supercharger, air-cooled. 1130 hp (843kW) in total. 3-blade 3,1m diameter propeller.

Power:
1115hp at takeoff, maximum emergency power at 2600RPM

- 371km/h cruise speed
- 545km/h max speed at 6000m

turning a 10 ft. 3-in, diameter constant speed triple propeller
For WWII fighters with piston engines, the Thrust can be calculated by:

$$T = \frac{P}{v} \times \mu_{prop}$$

Where P is the power in Watts, v is the airspeed and μ_{prop} is the propeller efficiency, usually 0.85 for lightly loaded propellers (Kampf, 2016). This equation is dynamic, only works for given airspeed.
For maximum speed at 6000m at 965hp (Archives of M. Williams, 1944). The maximum Thrust of the engine is:

$$\frac{719600.4\ Watts}{151{,}389\ ms^{-1}} * 0.85 = \mathbf{4050N}$$

Total Wing area: 21.53m^2. Projected area remains the same since there is almost 0 degrees of angle of attack.
MTOW: 2871,693 kg
Wing Loading:

$$W_L = \frac{W}{S} = \ 136.71kg/m^2 = 1155N/m^2$$

Where W is the Weight (MTOW), and S is the Projected wing area.
Description: Low wing, tricycle undercarriage, Conventional Tail

Figure 2. A6M3 Mod 32 in service based at Rabaul Bougainville, 1943

Section 2: Conceptual level layout decisions (20 marks)	
Comment on why you think the designers of the aircraft made the choices they did. Use properly cited, credible reports, articles, papers, etc. (technical reports by reputable organisations, peer reviewed journal articles) where available to support your reasoning. Compare your chosen aircraft to its competitors (aircraft designed for the same mission) and comment on the differences. The section should include: - a clear explanation of why you think the aircraft was equipped with its particular type of **propulsion system**; what alternatives are the design team likely have considered (in terms of the type, number and positioning of engines)? - a clear explanation of why you think the aircraft has the **airframe layout** it does; what alternatives are the design team likely have considered? What objective metrics would have driven the choices? - a clear explanation of why you think the aircraft was equipped with its particular type of **undercarriage**; what alternatives are the design team likely have considered? Comment on any unusual features (e.g., semi-levered gear, electrical brakes) and on the reasons for them.	
Indicative marks grid:	
Very little explanation or very vague, generic statements that apply equally to all aircraft of that class/mission (e.g., 'it has turbofan engines because it has to have a long range').	0 - 5
Some depth of thinking demonstrated, beginnings of an analysis of alternatives. Clearly referenced sources included, but of unverifiable credibility (e.g., Wikipedia, web pages with no clear referencing/fact checking/peer review policy).	6 - 14
Clear, tidy and deep analysis of potential alternatives and cogent, engineering reasoning presented for why the various decisions are likely to have been made. The arguments are precise and, wherever possible, numerical. High quality, scholarly references (journal articles, NASA reports, etc.).	15 - 20

The Mitsubishi A6M3 model 32 is one of the evolutions of a large series of fighter aircrafts throughout Japan's aeronautical history in the WWII. The main family name, A6M Zero is Japan's premier carrier-fighter and it drew upon lessons learned from the world's first operational monoplane fighter, the A5M.

In terms of the powerplants, the structure of the aircraft was determined by a single front engine. Motivated by the chief engineer inspirations in European aircraft, it would make no sense to develop a two or more-engine aircraft, since it would have meant an increase of weight and, since the engines must have been symmetrically placed, a loss of wing efficiency will have been noticed, as well as an increase of form drag in the total aircraft. Therefore, they chose the single engine configuration for the engine to be covered in a cowling and streamlined along with the cabin and the rear fuselage.
During the start of the A6M family, only Mitsubishi's engines, less powerful and reliable than the competition's, were permitted to use. As soon as the Nakaijima Powerplant was approved, the instant decision was made to switch to the Nakaijima Sakae 12, producing 940hp.
However, for the evolution of the A6M3, the new Sakae 21, an air-cooled radial 14-cylinder engine producing 1130hp, was introduced, along with a new two speed supercharger for high altitude performance, achieving a maximum speed of 338mph. However, this was a huge disappointment compared to its predecessor's 331mph. Due to the engine being heavier, the centre of gravity had to be compensated by cutting back the engine mountings and the fuel tank was reduced in size. In total, for a 6.0mph gain in total speed, 1000km of range were sacrificed.

There was a discredited myth that the Zero's success was merely a copy of the West creations on their own aircraft, claiming that Japan was incapable of producing such a machine on their own. In fact, the Japanese aviation industry was heavily influenced by foreign engineers and foreign designs. Jiro Horikoshi, chief designer of the A6M prototype, travelled extensively studying aircraft designs, which heavily influenced decision such as the number and position of the engine, as it was the most used configuration by that time, as well as the whole aircraft layout. He was also unexperienced, and it is believed that this was a key factor in such his lack of knowledge would lead to unconventional designs. In contrast to American planes, was built in one peace, resulting in a very strong structure and improved manoeuvrability. According to US sources, the whole zero's airframe was built with flush rivets, making it a ton lighter to the F4F Wildcat, outperforming any Allies plane, even the spitfire, due to its agility and firepower.
As the design constrains implanted by the IJN choked traditional designs, Horikoshi chose an intensive weight reduction plan that was heavily reflected in safety factors. He understood from experience that traditional materials were not the best options for certain parts of the airplane. As soon as Sumitomo Metals of Osaka created Extra Super Duralumin (ESD), Horikoshi opted to use this in the new creation. All these improvements on the other hand did increase both production costs and duration.
Furthermore, it was noted by experts that the pure role of the Zero was to attack, at the expense of pilot's protection, which reduced a lot of the weight and gave the Zero its deadly agile fame. As stated by test flight reports from the AAF, the aircraft is highly manoeuvrable (Flight Test Engineering Branch, 1944).However, it is also noted that it has a very high visibility compared to competition aircrafts. This meant a penalisation in form drag, which was reflected in the lack of maximum speed.
In case of the A6M3 model 32 evolution, the main difference that was noted with its predecessors is the squared off wings. It is known that the best wing efficiency is given by elliptical wings, however, the design team decided to change this in order to acquire better roll rates. This also allowed for better dive speeds, which improved the performance of the main attack procedure of the Zero. The wing sections were also redesigned for higher fuel storage: due to the new more powerful engine, there was a higher fuel consumption and a smaller fuel tank.

In terms of the undercarriage, it was a quite conventional design for the time. The main gear was raised inward parallel to the wing by hydraulics and were fully enclosed into the wheel wells. The inner wheel covers had a distinct curved shape so as not to interfere with the centreline drop tank. The brakes for the main gear were of traditional design and engaged by rocking the rudder pedals forward. The tail wheel, positioned aft of the arrestor hook, also retracted hydraulically, and could be locked or unlocked from the cockpit. The aircraft had no parking brakes and needed to be chocked after coming to a complete stop.
Early predecessors were fitted with servo tabs on the ailerons to improve the pilot's control, as a response to the pilots stating that the controls were very stiff at high speeds. This solution caused them to overstress the wings during vigorous manoeuvres, so it was withdrawn.

Section 3: Structures (10 marks)

Analyse, briefly, the structural philosophy of the aircraft. This section should contain:

- a brief, clear statement of the fundamental structural philosophy of the aircraft (e.g., 'semi-monocoque construction pressurised aluminium fuselage and carbon fibre composite wings')
- your best estimate of what the V-n diagram of the aircraft looks like at MTOW. Use ADRpy to construct it or draw your own, but please state all aerodynamic and other assumptions clearly in either case (e.g., where do the various key speeds come from).

Indicative marks grid:

Very cursory description, V-n diagram absent or completely implausible	0 - 2
Broadly sensible description, V-n diagram has major flaws or assumptions not stated	3 - 6
Nice description, V-n diagram looks largely plausible, marks at the higher end if the numbers behind the V-n diagram are the results of a more in-depth investigation.	7 - 10

The structural philosophy of the aircraft consists of an all-metal extra super duralumin (ESD) semi-monocoque fuselage and wing structure, with the wings covered in fabric. This material was lighter, stronger, and more ductile than other alloys and was prone to corrosive attack. It was a low wing cantilever monoplane layout, with retractable wings and an enclosed cockpit. A single centred piston engine was the main chosen layout for all WWII carrier fighter planes. This is a Japanese WWII military aircraft, and therefore no certification data has been found. A standard normal category CS-23 was employed for the construction of the V-N diagram.

For the graph available in figure 2, all values have been looked at in reports except for the Lift and Drag coefficients, unable to be found even for similar airplanes like the Spitfire. Default values using ADRPy were used for the calculations, but in case of the form drag coefficient, it was taken as a typical value of Cd0 = 0.02 (spitfire example) (Ackroyd, 2016)

As no clear data on the lift coefficient could be obtained, normally wings usually have about 1.6 maximum clean lift coefficient without flaps deployed. (K. Loftin Jr, 1985).

Speeds were taken from flight test reports. (Archives of M. Williams, 1944).

Finally, stall speed in ADRpy matches with reports [70kts.]. (Flight Test Engineering Branch, 1944).

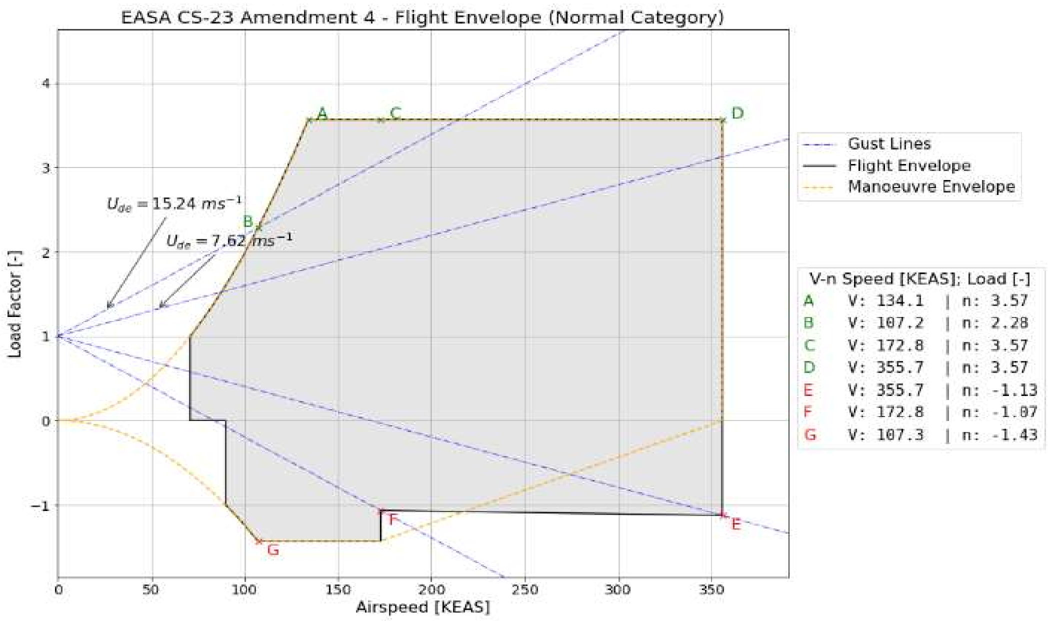


Figure 3. A6M3 flight envelope

Section 4: Mission and constrains (50 marks)	
In Section 1 you identified two key parameters of the aircraft: the propulsive power (or thrust) and the total wing area. Now is the time to work out why the designers of the aircraft will have ended up with those values! This section should contain: - your best estimate of the typical mission profile the aircraft will have been designed for (consisting of representative take-off performance, climb rate, cruising speed, service ceiling, turn rate, stall speed). Note: it may be useful to consider several possible missions, which you believe the aircraft had to be able to satisfy and several points where each constrain would need to be completed (for example several different climb rates at different altitudes) - constrain analysis plot covering ground roll, climb rate, service ceiling, cruise speed, turn rate and stall; in order to understand the origins of the propulsion performance requirement (power or thrust) and wing area requirement, it may be useful to investigate the sensitivities of positions of the constrains with respect to various design and mission parameters - a point on the constrain diagram indicating the location of your aircraft - include references to the sources of any numbers you were able to find in the literature, indicate which numbers you guessed - an explanation (in no more than 500 words) of what you learned by doing the constrain analysis about which constrain(s) are likely to have driven the choices made by the design team (in terms of wing area and powerplant choice) - if you used the constrain analysis tool in ADRpy, include the input dictionaries and the commands used to generate the diagram(s) (a screenshot or a copy-paste from wherever you wrote the code, Jupyter, etc.).	
Indicative marks grid:	
A cursory attempt at a constrain diagram, mission profile not clear, major errors	0 - 10
An attempt with some sensible constrains, but no real depth of analysis. Sources of numbers or the way you arrived at them not clear.	11 - 25
A strong attempt and a complete constrain diagram with broadly sensible numbers. The explanation of why the designers will have chosen the numbers they did, makes sense in general, but it does not clearly reference the process of how you used the constrain analysis to guess the unknown numbers.	26 - 35
Nice, clear, plausible constrain analysis and the explanation makes your reasoning (that is, how the constrain analysis helped you reconstruct the original design rationale) clear. Formal sensitivity analysis evident, showing how you teased out which elements of the design brief and which aerodynamic parameter affected which constrain and an explanation that makes this clear. The whole analysis together tells a nice, compelling story of how the design of your chosen aeroplane turned out the way it did.	36 - 50

A maximum lift coefficient without flaps was assumed to be 1.6 (standard values for the industry by that time) (K. Loftin Jr, 1985)

The Zeke 32 is a carrier fighter aircraft designed for aerial dogfights during WWII. Its mission consisted in many different objectives depending on the scenario, but they can be resumed in Combat Air Patrol standard missions. For this a high manoeuvrability is required, which is translated in high turning speed, high climb speed, and high roll rates.
According to sources, the aircraft needed a climb rate of 2.800fpm, as well as a take-off runway of 230ft with 30mph headwind. Furthermore, with the high manoeuvrability combined with the IJN’s armament being already a massive engineering challenge, the wingspan needed to be short for a standard carrier elevator. (D'Angina, 2016)

Take off constrain:

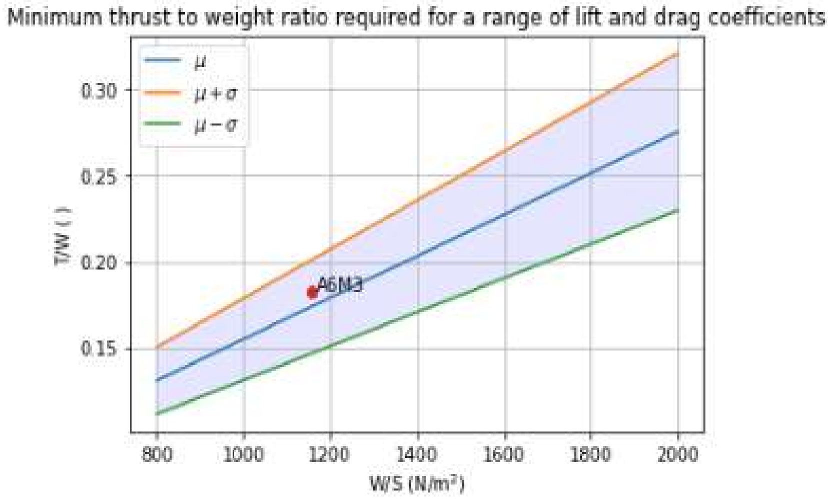


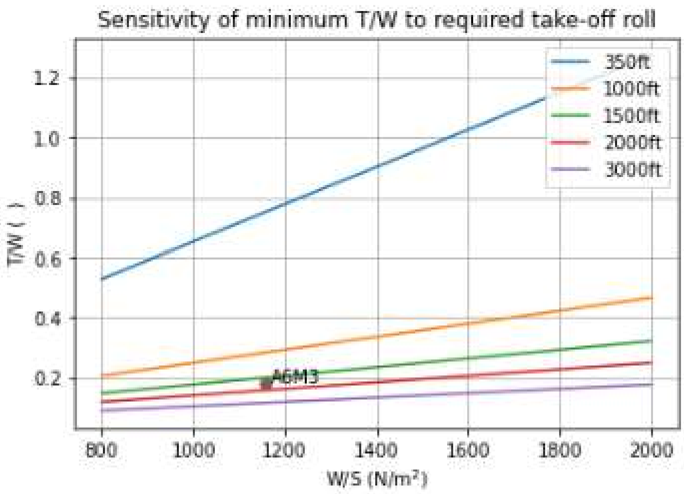
Figure 4. Take off constrain aproximation

The take-off constrain was analysed using the available data from the reports, but as in other parts of the report, no lift/drag coefficients have been found for the specific plane. A reasonable range of points were used to construct a feasible area, shown in figure. A ground roll of 600 meters was used for this analysis.

```
CDTO = np.random.normal(0.04, 0.005)
CLTO = np.random.normal(0.9, 0.1)
CLmaxTO = np.random.normal(1.6, 0.2)
mu_R = np.random.uniform(0.015,0.025)
```

Figure 5. Lift and drag coefficient aproximations

Now the main constrain for this aircraft that will really determine the T/W ratio is the ground roll required for take-off. This is a carrier aircraft and therefore it needs to be able take-off from the carrier (approximately 350 ft. of ground roll). This was, specified in the design requirements as being able to take off in 270ft with a front wind speed of 30fps. (D'Angina, 2016). Using the mean values from the analysis of the lift and drag coefficients, the next plot was produced



Of course, we cannot take this into account, since the procedure for carrier take-off is performed by a hook that accelerates the aircraft to 150kts along the runway. It is suggested that for the original design of the aircraft a normal ground runway length was used, since normally, planes are ‘launched’ with a hook that accelerates them above stall speed.

Figure 6. Take off constrain for different runway rolls

Climb constrain:
The calculations were performed for the data given by the flight reports (climb rate, cruise speed, etc.). Firstly, a specified range of lift and drag coefficients, the one in figure 5, was employed just like in the take-off constrain, as seen in figure 7.

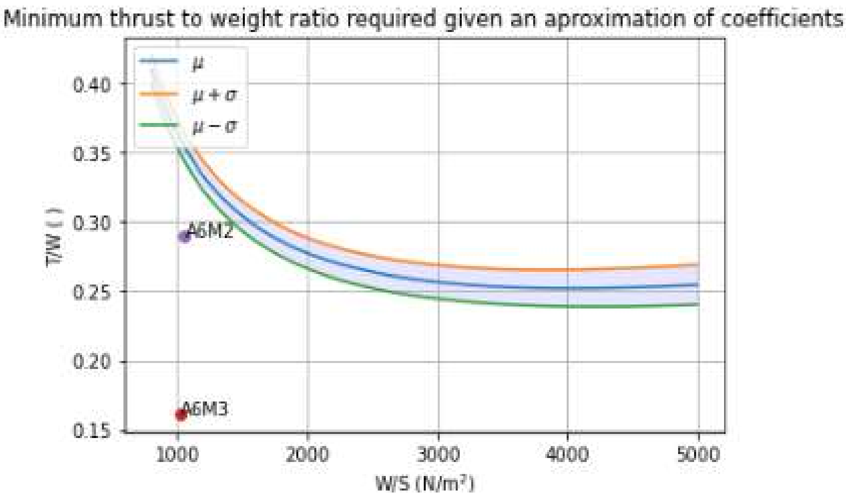


Figure 7. Climb constrain approximation

However, it is clear that they are far from what the original design was.
It was found that for the aircraft's predecessor the A6M2, where more data was found to be available, the curve is slightly closer to what it was expected in the first place.

It is undetermined why this is true or what values may have caused this behaviour. It is suggested that originally, the climb rate was not taken into account, not at least as a Thrust to Weight ratio constrain. As seen in figure 8, the aircraft would not even be able to achieve a climbspeed of 1000fpm at 150kts.

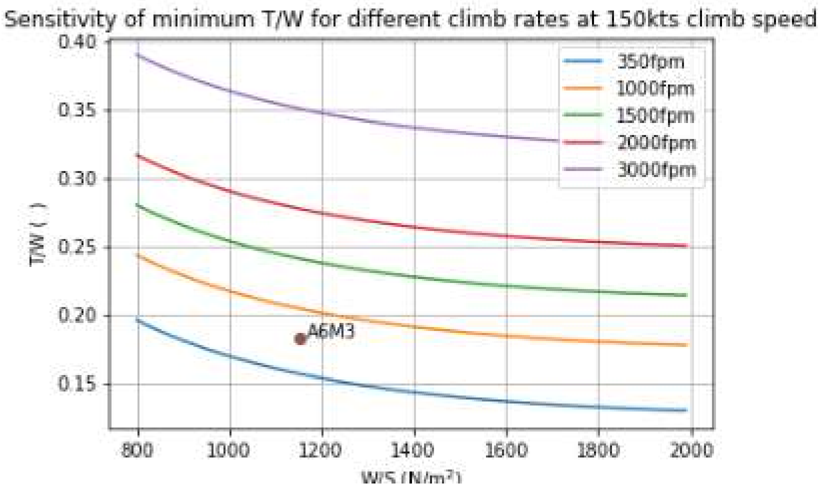


Figure 8. Thrust to Weight sensitivity to climb rate at 150kts. climb speed

Cruise constrain:

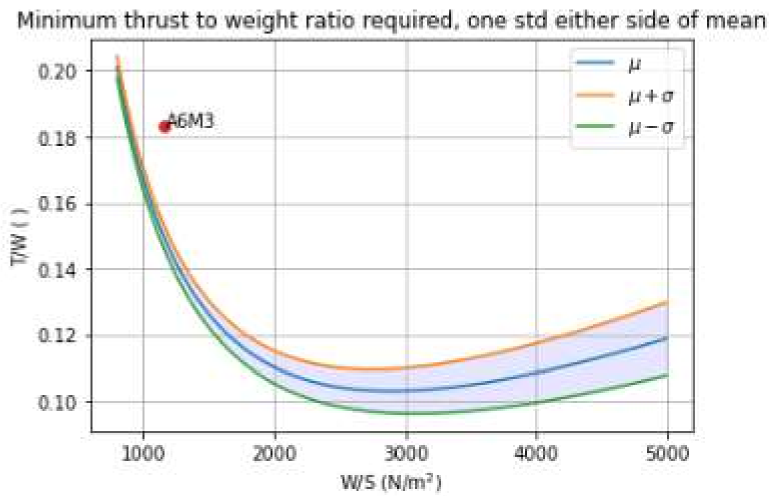


Figure 9. Cruise constrain aproximation

For levelled cruise flight, the same range of lift and drag coefficients were evaluated for given speed parameters obtained from flight reports. It is noted that for this constrain, the aircraft is well within a margin

The main factor that affects this constrain is the cruise speed required for the aircraft.

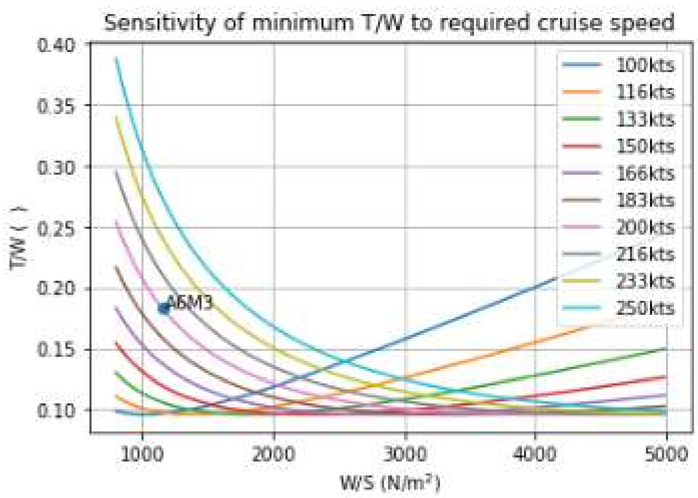


Figure 10. Cruise speed sensitivity

Originally, the aircraft is designed to operate at 175kts of cruise speed. However, given the design parameters it can operate at up to 200kts. This is as mentioned before, a fighter aircraft. High endurance and ranges are not required for this aircraft, since it was not meant to take continental flights.

Turn constrain:

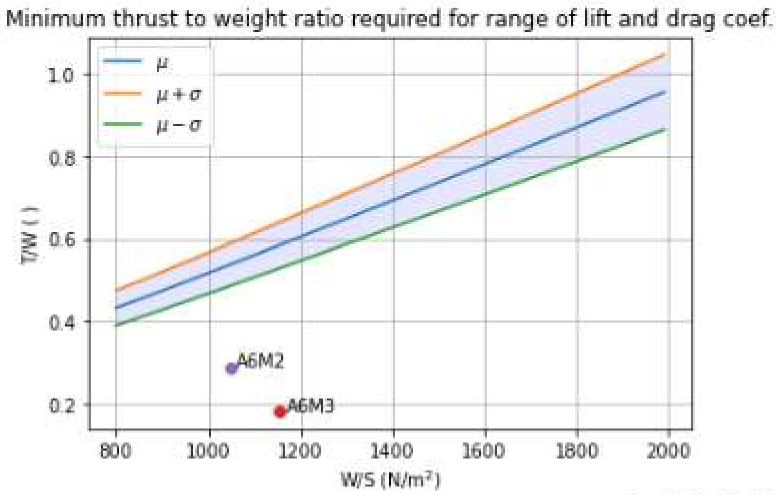


Figure 11. Turn constrain approximation

In the case of the turn constrain, the turn speed and maximum load factor of the aircraft are the main determinants of whether the aircraft will or will perform inside the range. It can be noted that neither the Zeke 32 or its predecessor will be able to sustain any speeds.

The load factor limits the Trust to Weight ratio to be above 0.4 for any turning speed. This means that unless the load factor is reduced for the turning manoeuvre, the aircraft will need to proportionally reduce its speed in order to maintain the turn.

Here are shown different turning speed at 3 different maximum load factors during the turn manoeuvre.

This is however not encountered in the required power graph for the combined constrain analysis.
Seems that, as the aircraft was design during WWII, it satisfies the horsepower constrain but not the wing area and loading constrains.

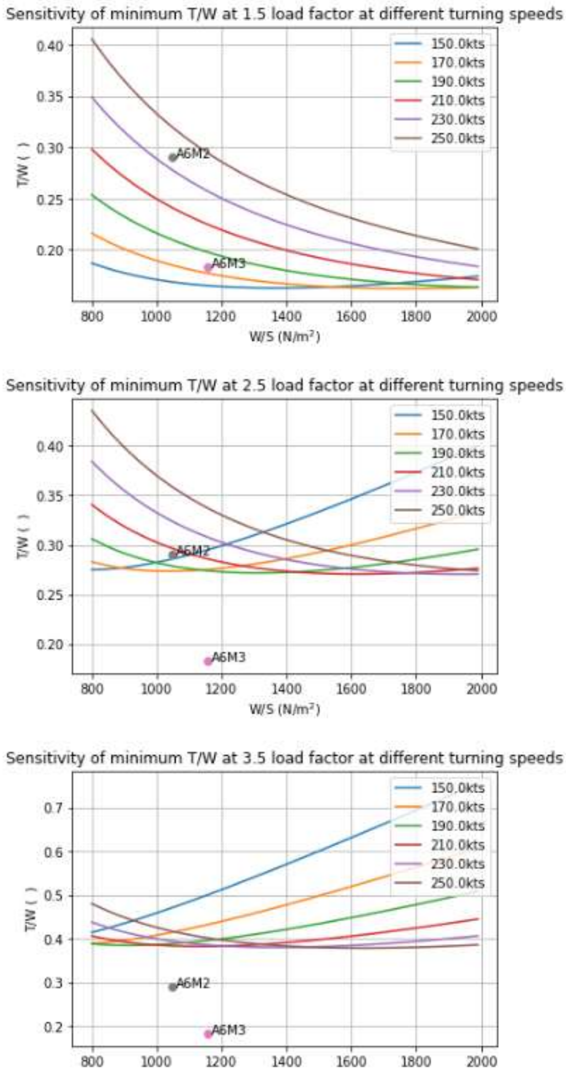


Figure 12. Turning speed sensitivities for different maximum load factors

The combined constrain:
Combining all constrains and using the mean lift and drag coefficients that were indicated, before we can confirm how both the Zeke 32 falls from the A6M2 on power to weight ratio, but overpasses it on horsepower.

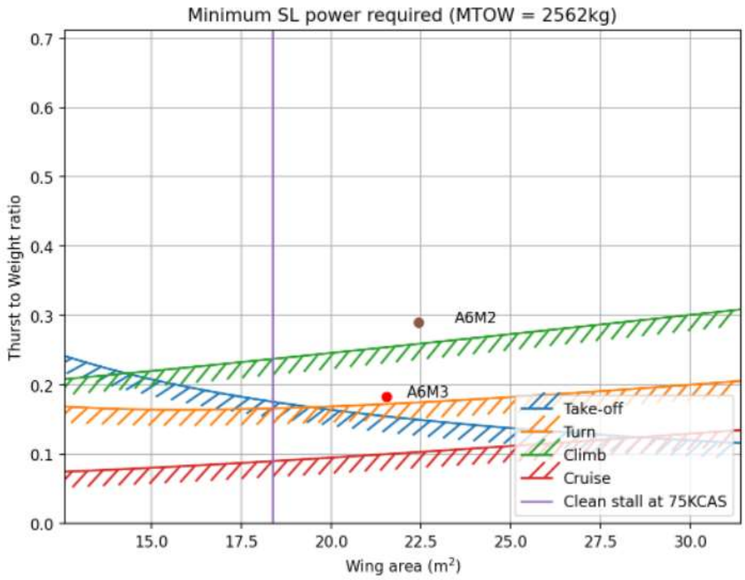


Figure 13. Combined constrain analysis. Thrust to Weight ratio

Looking at the Thrust to Weight ratio, we can appreciate that the lower weight of the A6M2 plays a huge role in obtaining a much higher performance. This confirms why the Zeke 32 only gained 9mph of top speed in comparison, the increase in horsepower also meant an increase of weight, from both the new engine and the fuel needed.

If we now focus on the horsepower analysis, we can see how the A6M3 outperforms its predecessor due highly to the new engine. However, this does not mean that it was a better aerial tool.
In fact, the Zeke 32 was very unsuccessful, and only a bit more than 300 units were produced. Reports say it felt much sturdier and although it did achieve better roll rates, it lacked from many other characteristics like the turning rate.
With no doubt, the evolution of the A6M3 was unsuccessful, and it has been shown in this report how horsepower is not always a solution to being fast and deadly when talking about WWII dogfighters.
It can be appreciated that the constrain that choked the design of the aircraft the most is the Climb. The high climb rate imposed during design stages was the most important factor. This constrain was combined with the limits in wingspan, as well as aspect ratio. The aspect ratio can be increased at the expense of drag, which was also not welcomed given an also very high take off constrain of 280ft of runway.

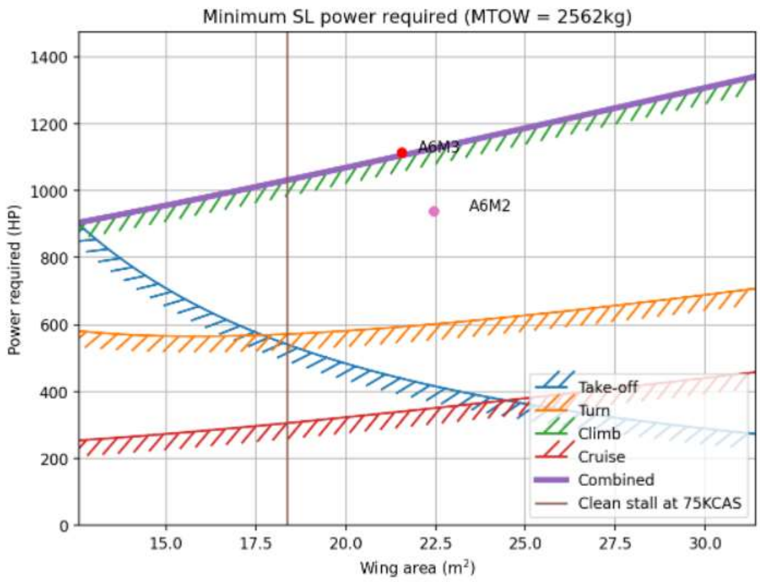


Figure 14. Combined constrain analysis. Required horsepower

Overall, it was a massive engineering challenge that was overcome by unconventional methods and weight reductions that sacrificed the integrity of both the aircraft and the pilot themselves, as well as the production of the aircraft, which was heavily influenced by the airframe and increased the production time by a lot.
The dictionaries used for ADRpy are shown here:

In [231]:
```
TOW_kg = 2562 #normal load
designbrief = {'climbalt_m': 1000, 'climbspeed_kias': 200, 'climbrate_fpm': 2960,
               'cruisealt_m': co.feet2m(1500), 'cruisespeed_ktas': 175,
               'groundrun_m':600,'rwyelevation_m':0,\
               'stloadfactor': 2.5, 'turnalt_m': co.feet2m(5000), 'turnspeed_ktas': 200,
               'servceil_m': co.feet2m(39000), 'secclimbspd_kias': 93.04,
               'vstallclean_kcas': 75}
```

In [232]:
```
wfract = {'turn': 0.85, 'climb': 0.750, 'cruise':0.9, 'servceil': 0.85}
```

In [233]:
```
designdefinition = {'aspectratio':5.5, 'sweep_le_deg':2.5, 'sweep_mt_deg':0, 'bpr':-1,
                    'tr':1, 'weightfractions':wfract,'weight_n': co.kg2n(TOW_kg)}
designperformance = {'CDTO':0.04, 'CLTO':0.9, 'CLmaxTO':1.6, 'mu_R':0.02, 'CDminclean':0.02,
                     'CLmaxclean': 1.5}

designatm = at.Atmosphere()
concept = ca.AircraftConcept(designbrief, designdefinition, designperformance, designatm, "piston"
```

Figure 15. ADRpy dictionaries

The constrain analysis in this case was so strict that the engineers had to come up with new solutions in weight reduction. The evolutions of the A6M up to the Zeke 32 demanded more power to overcome higher maximum speeds and diving speeds. This was the reason of the new engine and the new powerplant, the Nakaijima Sakae 21. The new squared off wingtips also increased the diving speeds, but as the aircraft was also constrain by the carrier elevator, the whole resulted in a drawback scenario for the A6M. The constrain analysis felt like a series of requirements that were impossible to meet at first, rather than a given possible requirements that can help reduce costs, unnecessary material and production. This has been caused by the aircraft of choice being a military fighter of WWII era, which did not require any global certification and therefore felt like a “free-for-all” dogfight plane competition with no standardized rules other than it must fly and be able to kill other planes.

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