A calculation method for parametric design studies of V/STOL aircraft

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ABSTRACT

This paper provides a method that helps the aircraft designer to develop a performance constraint chart (PCC) for vertical/short take-off and landing (V/STOL) aircraft that produce hybrid lift (static lift in combination with aerodynamic lift). The PPC provides a first estimation for the thrust-to-weight ratio (T_0/MTOW) and wing loading (MTOW/S). The method is applicable to concepts, where static lift and main-engine thrust are coupled (e.g. the F-35B system, turbojet and lift-fan, coupled by a shaft) and to concepts, where static lift is produced by separate devices (e.g. lift-engines or other concepts for static lift). It includes thrust vectoring of the main engine.

The method includes the evaluation of certain flight stages, or segments, as short take-off and landing (STOL), vertical landing (VL), one engine inoperative (OEI) climb (for civil aircraft concept applications) and cruise, all these have to be considered. For each of these five segments, standard flight mechanics equations are extended by a static lift component, an augmentation ratio (a factor that describes the dependency of the thrust and the static lift, if coupled) and the thrust vectoring angle. Hence these equations are modified in a way that the aircraft designer can directly calculate T_0/MTOW and MTOW/S for the performance requirements of each segment. Thus, an optimum design point can be selected. Inputs are aerodynamic coefficients, maximum lift coefficient of the wing, mass fraction from take-off to landing, additional static lift during take-off and landing, number of engines, augmentation ratio of the propulsion system and required take-off and landing field length.

A performance constraint chart for a JSF F-35B type aircraft is modelled to show the application of the method. As an application to civil aircraft a PCC and a parameter optimisation for the civil regional jet 'HyLiner' is presented.

NOMENCLATURE

A	aspect ratio
AR	augmentation ratio
C_D	aircraft drag coefficient
C_{D0}	aircraft zero drag coefficient
C_L	aircraft lift coefficient
D	drag
e	oswald efficiency factor
F	safety factor for stall speed
F_S	safety factor for vertical landing
k	k-factor
L	lift
LW	landing weight
L_{ST}	static lift
m	mass
MF	mass fraction
MTOW	maximum take-off weight
N	number of engines
NF	normal force on ground

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S	wing reference area
T	thrust
T_0	static thrust
TOP	take-off parameter
v	airspeed
W	weight
x	field length (ground roll)
α	aircraft angle-of-attack
γ	climb angle
δ	angle of static lift vector
μ	friction co-efficient
ρ	air density
σ	density ratio
φ	angle of main engine thrust vector
Ḣ	climb speed
H/v	climb rate

Subscripts

AC	aircraft
D	(aero)dynamic
Dec	deceleration
L	landing
max	maximum
OEI	one engine inoperative
st	stall
TO	take-off
0	at sea level

1.0 INTRODUCTION

For civil and military applications, V/STOL aircraft are getting more and more important: In the civil sector hub-airport congestion and the growing passenger numbers are the main drivers[1,2,3,4]. For military applications the main driver is flexibility during mission operations.

Bauhaus Luftfahrt launched a project for V/STOL regional transport systems, named 'HyLiner' (hybrid airliner). Three aircraft types are investigated:

- a hybrid airship that produces static and aerodynamic lift[5]
- an intermodal VTOL tilt-wing turbo-prop concept with a removable and railway compatible passenger unit[2]
- the HyLiner ESTOL regional jet, where one of the concepts is a fan-in-wing concept[6]

This paper points out the approach developed to calculate the main aircraft design parameters, T_0/MTOW and MTOW/S for aircraft with additional lift and thrust vectoring during take-off and landing. This approach is driven by the performance requirements of the different mission segments. The method was developed for the calculation of the HyLiner concepts with static lift based on the study of military aircraft concepts with lift-fans and lift-engines.

First a short overview of performance analysis methods for conventional aircraft is given. Subsequently, the origin of these methods is analysed and then the methods are extended to include V/STOL specific parameters. Hence formulas for T_0/MTOW as functions of MTOW/S are derived for the relevant mission segments. These formulas are verified by application to the F-35B. Furthermore performance constraint charts for the ESTOL regional jet 'HyLiner' are shown as a civil aircraft application.

2.0 CONVENTIONAL PERFORMANCE ANALYSIS

The aircraft designer has to ensure, that the aircraft meets the performance requirements for each mission segment. Typical segments for civil transport aircraft are take-off, climb with one engine inoperative, cruise and landing. Therefore T_0/MTOW is plotted as a function of MTOW/S for each mission segment in one chart. This allows visualisation of all the parameters combinations that meet the performance requirements. Subsequently a suitable design point - a combination of T_0/MTOW and MTOW/S which fulfils all requirements – can be selected. To establish an initial appreciation of these parameters, this approach is first shown for conventional fixed-wing aircraft. For a first estimation of these constraints literature refers to the following simplified methods.

2.1 Take-off

Raymer[7] provides a method for the calculation of T_0/MTOW to fulfil the take-off field length requirements:

$$\frac{T_0}{MTOW} = \frac{1{\cdot}44}{TOP \cdot \sigma \cdot C_{LmaxTO}} \cdot \frac{MTOW}{S} \qquad ...(1)$$

where σ is the density ratio (1 for sea level). *TOP* is the so called 'take-off parameter'. It is derived from statistical data based on the required field length and number of engines. The resulting constraint for T_0/MTOW increases arithmetically (Figure 1). With increasing wing loading, the thrust-to-weight ratio has to be increased to meet the required take-off field length.

2.2 Climb one engine inoperative (OEI)

The thrust-to-weight ratio required to fulfil a certain climb gradient is taken from Raymer[7]. This ratio is factored by the term N/(N-1) which accounts for the number of operating engines left to meet the climb performance requirement.

$$\frac{T_0}{MTOW} = \frac{N}{N-1} \cdot \left(\frac{D}{L} + \frac{\dot{H}}{v}\right) \qquad ...(2)$$

For OEI conditions the required climb rate is defined in Federal Aviation Regulations (FAR)[8] of the Federal Aviation Administration (FAA), part 25. The lift over drag is not a function of wing loading. Thus the climb constraint is a horizontal line in the PCC (Fig. 1).

2.3 Cruise

The thrust-to-weight ratio that satisfies cruise requirements is derived from the equilibrium of lift and weight as well as drag and thrust:

$$\frac{T_0}{MTOW} = \left(0.5 \cdot \rho \cdot v^2 \cdot C_{D0} \cdot \frac{S}{MTOW} + \frac{2 \cdot k}{\rho \cdot v^2} \cdot \frac{MTOW}{S}\right) \cdot \frac{\rho_0}{\rho} \qquad ...(3)$$

with

$$k = \frac{1}{\Pi \cdot A \cdot e} \qquad ...(4)$$

2.4 Landing

The landing field length x_L is not a function of T_0/MTOW, as it only depends on MTOW/S, maximum lift coefficient and a statistical factor for conventional aircraft[7]:

$$x_L = 80 \cdot \frac{MF_L \cdot MTOW}{S} \cdot \left(\frac{1}{\sigma \cdot C_{LmaxL}}\right) \qquad ...(5)$$

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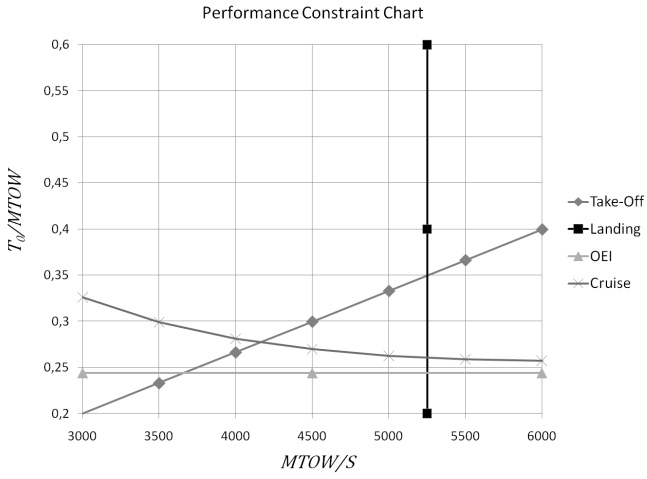


Figure 1. Typical PCC for a regional jet.

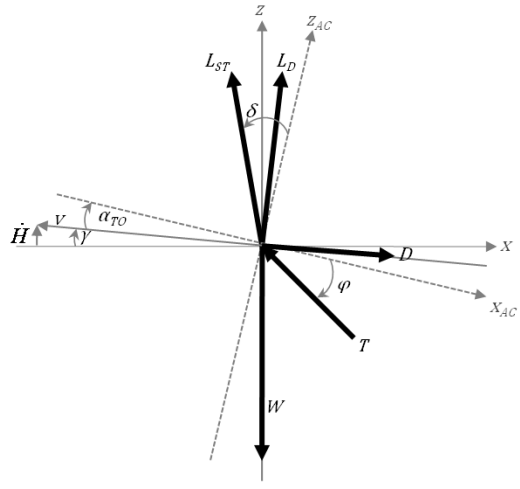


Figure 2. Forces acting on a V/STOL aircraft including thrust vectoring and static lift

Raymer adds an additional distance for obstacle-clearance to the ground roll of 305m for a 3-deg glide path and 137m for STOL 7-deg glide path. With Equation (5) the wing loading constraint can be calculated for a required landing field length:

$$\frac{MTOW}{S} = \frac{\sigma \cdot C_{LmaxL} \cdot x_L}{80 \cdot MF_L} \quad ...(6)$$

2.5 Typical performance constraint chart

A typical PCC for a regional jet is given in Fig. 1, including take-off, climb OEI, cruise and landing.

3.0 V/STOL PERFORMANCE ANALYSIS

The methods shown in chapter 2 are valid for aircraft, that are producing the complete lift with conventional wings (aerodynamic lift), and for which a maximum lift co-efficient can be estimated. Hence they can also be applied to ESTOL aircraft with e.g. upper surface blown flaps or externally blown flaps. They are not applicable to aircraft using static lift devices. Static lift may refer to thrust producing devices, such as lift-fans and lift-engines, or buoyancy devices that make use of gases such as helium. Thus, for aircraft that are producing static lift, new methods to determine the parametric constraint chart have to be developed. Figure 2 shows the forces acting on the aircraft: The aerodynamic lift L_D of the aircraft's wing is acting perpendicular to the flight direction. The aerodynamic drag D is acting contrarily to the flight direction. W is the aircraft's weight, and T represents the main engine thrust that in conventional aircraft acts in or close to flight direction. However, in order to include thrust vectoring, the vectoring angle φ of the main engine thrust is introduced. L_{ST} is the static lift component and δ denotes the vectorisation of the static lift in the aircraft's coordinate system (e.g. thrust vectoring of the lift-engines or the lift-fans). Here it has to be mentioned that induced effects of the static lift devices are not considered for this initial vehicle sizing. These effects have to be taken into account for detailed analysis. Additional angles are the angle-of-attack α of the aircraft at current fight condition and the climb angle γ.

The approach for the development of these new methods is to convert the force related balance equations to a function of T_0/MTOW over MTOW/S for each flight segment to be evaluated.

3.1 Stall speed

The calculation of the stall speed is required for the performance calculation of the take-off, climb and landing segments. It results from the balance of forces in z-direction:

$$W = T \cdot \mathrm{Sin}(\varphi + \gamma + \alpha) + L_{ST} \cdot \mathrm{Cos}(\delta - \alpha - \gamma) + L_D \cdot \mathrm{Cos}\,\gamma - D \cdot \mathbf{Sin}\,\gamma \quad ...(7)$$

The aerodynamic lift at stall condition is:

$$L_D = \frac{\rho}{2} \cdot v_{st}^2 \cdot S \cdot C_{Lmax} \quad ...(8)$$

For the calculation of stall speed usually γ =0 is assumed, therefore Cosγ = 1 and Sinγ = 0. Equation (7) with L_D from Equation (8) is solved for v_{st}^2 :

$$v_{st}^2 = \frac{2 \cdot [W - T \cdot \mathrm{Sin}(\varphi + \alpha) - L_{ST} \cdot \mathrm{Cos}(\delta - \alpha)]}{\rho \cdot S \cdot C_{Lmax}} \quad ...(9)$$

3.2 Segment speed calculation

As safety margins for flight speeds are defined by the Federal Aviation Administration (FAA) in the Federal Aviation Regulations (FAR), the speed for any segment i is higher than the stall speed:

$$v_i = F_i \cdot v_{st} \quad ...(10)$$

Table 1 shows the minimum factors F for the different segments as defined in FAR part 25:

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Table 1
Safety factors for the relevant flight segments

Take-Off	F_{TO}	1·2
Climb OEI (2nd segment)	F_{OEI}	1·2
Landing	F_L	1·3

Hence Equation (9) becomes:

$$v_i^2 = \frac{2 \cdot F_i^2 \cdot [W - T \cdot \mathrm{Sin}(\varphi + \alpha) - L_{ST} \cdot \mathrm{Cos}(\delta - \alpha)]}{\rho \cdot S \cdot C_{Lmax}} \quad \ldots(11)$$

3.3 Definition of the augmentation ratio

The goal of this method is to calculate the ratio of static thrust-to-weight (T_0/MTOW). T is the available thrust during flight. T equals T_0, if the installed static high lift devices are powered by separate energy sources. In the case where static high lift devices are powered by the aircraft's main engines, T represents the main engines' residual thrust. For this case a correlation of T_0 and T has to be found. The augmentation ratio describes the ratio between generated static lift L_{ST} and thrust loss of the main engine due to power-offtake for the static lift device. For low speed segments the thrust loss equals the static thrust minus the available thrust of the main engines.

$$AR = \frac{L_{st}}{T_0 - T} \quad \ldots(12)$$

Consequently the augmentation ratio describes the correlation between the available main engine thrust and static thrust:

$$T = T_0 - \frac{L_{st}}{AR} \quad \ldots(13)$$

For example for the F-35B the AR as defined here is 2·56, calculated with data from JSF.mil[9]. The GE-Ryan had an AR of 3, calculated with data from the International V/STOL Historical Society[10]. For a system, where the static lift is produced by separate devices, the augmentation ratio is ∞. Since the static lift does not affect the main engine's thrust, T is then equal to T_0.

3.4 Take-off

The distance x required to accelerate a mass m with a thrust-force T to a certain speed v (drag and friction is neglected) is taken from Brandt[11]:

$$x = \frac{m \cdot v^2}{2 \cdot T} \quad \ldots(14)$$

For the take-off segment T is derived from Equation (13) and equals the stall speed from Equation (9) multiplied with F_{TO}. Thus the take-off distance (ground roll) is:

$$x_{TO} = \frac{F_{TO}^2 \cdot MTOW \cdot \left[MTOW - \left(T_0 - \frac{L_{st}}{AR}\right) \cdot \mathrm{Sin}(\varphi + \alpha) - L_{ST} \cdot \mathrm{Cos}(\delta - \alpha)\right]}{g \cdot \rho \cdot S \cdot C_{LmaxTO} \cdot \left(T_0 - \frac{L_{st}}{AR}\right)} \quad \ldots(15)$$

This equation can be used to calculate the take-off performance of a given aircraft. To calculate the constraint for the PPC the take-off field length is given and the thrust-to-weight ratio has to be calculated. Thus Equation (15) has to be solved for T_0/MTOW as a function of MTOW/S:

$$\frac{T_0}{MTOW} = \frac{1}{\frac{x_{TO} \cdot g \cdot \rho \cdot C_{LmaxTO}}{1.44 \cdot \frac{MTOW}{S}} + \mathrm{Sin}(\varphi + \alpha)} \cdot \quad \ldots(16)$$

$$\left[1 + \mathrm{Sin}(\varphi + \alpha) \cdot \frac{L_{st}}{MTOW} \cdot \frac{1}{AR} - \frac{L_{st}}{MTOW} \cdot \mathrm{Cos}(\delta - \alpha) + \frac{L_{st}}{MTOW} \cdot \frac{1}{AR} \cdot \frac{x_{TO} \cdot g \cdot \rho \cdot C_{LmaxTO}}{1.44 \cdot \frac{MTOW}{S}}\right]$$

For a conventional take-off Equation (16) simplifies to (all angles zero, L_{ST}/MTOW zero):

$$\frac{T_0}{MTOW} = \frac{1.44}{x_{TO} \cdot g \cdot \rho \cdot C_{LmaxTO}} \cdot \frac{MTOW}{S} \quad \ldots(17)$$

This equation corresponds to the equation given in Brandt[11].

3.5 Climb OEI

The climb rate is the ratio of climb speed $\dot{H}$ to airspeed v and equals Sinγ (see Figure 2). Sinγ is calculated from the sum of the forces in flight-direction. Hence, the climb rate is:

$$\mathrm{Sin}\,\gamma = \frac{\dot{H}}{v} = \frac{T \cdot \mathrm{Cos}(\alpha + \varphi)}{MTOW} + \frac{L_{ST} \cdot \mathrm{Sin}(\delta - \alpha)}{MTOW} - \frac{D}{MTOW} \quad \ldots(18)$$

The drag force D for this segment is:

$$D = \frac{\rho}{2} \cdot F_{OEI}^2 \cdot v_{st}^2 \cdot S \cdot \left[C_{D0} + k \cdot \left(\frac{C_{LmaxTO}}{F_{OEI}^2}\right)^2\right] \quad \ldots(19)$$

With Equations (11) and (13) Equation (19) becomes:

$$D = \left[MTOW - \left(T_0 - \frac{L_{st}}{AR}\right) \cdot \mathrm{Sin}(\varphi + \alpha) - L_{ST} \cdot \mathrm{Cos}(\delta - \alpha)\right] \cdot \frac{F_{OEI}^2}{CL_{maxTO}} \cdot \left[C_{D0} + k \cdot \left(\frac{CL_{maxTO}}{F_{OEI}^2}\right)^2\right] \quad \ldots(20)$$

For a better clearness $C1$ is introduced:

$$C1 = \frac{F_{OEI}^2}{CL_{maxTO}} \cdot \left[C_{D0} + k \cdot \left(\frac{CL_{maxTO}}{F_{OEI}^2}\right)^2\right] \quad \ldots(21)$$

Equations (13) and (20) are inserted into Equation (18). Now, the thrust-to-weight ratio can be expressed as a function of the required climb rate. Similar to Equation (2), this ratio is factored by the term $N/(N–1)$ to account for one engine inoperative condition.

$$\frac{T_0}{MTOW} = \frac{N}{N-1} \cdot \left\{\frac{C1 + \frac{L_{st}}{MTOW} \cdot \left[\frac{\cos(\alpha + \varphi)}{AR} - \mathrm{Sin}(\delta - \alpha) + C1 \cdot \left(\frac{\mathrm{Sin}(\alpha + \varphi)}{AR} - \mathrm{Cos}(\delta - \alpha)\right)\right] + \frac{\dot{H}}{v}}{\mathrm{Cos}(\alpha + \varphi) + C1 \cdot \mathrm{Sin}(\alpha + \varphi)}\right\} \quad \ldots(22)$$

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3.6 Cruise

The thrust-to-weight ratio for cruise can be calculated according to Equation (3) as the lift-fans are not operating during this segment.

3.7 Short landing

Similar to take-off, the distance x to decelerate a mass m from a certain speed v to zero is given in Equation (23). According to Brandt[11] the acting forces have to be evaluated at 0·7 times this speed.

$$x = \frac{m \cdot v^2}{2 \cdot (D + \mu \cdot NF)_{@0.7 \cdot v}} \quad ...(23)$$

For landing, v^2 equals v_L^2, while μ is the friction coefficient due to brakes. The force normal to the ground NF equals landing weight LW minus the static lift. The landing weight LW is calculated with the mass fraction from take-off to landing (MF_L):

$$LW = MTOW \cdot MF_L \quad ...(24)$$

The aerodynamic drag D at 0·7 times landing speed is:

$$D_{@0.7 \cdot v_L} = \frac{\rho}{2} \cdot 0.7^2 \cdot v_L^2 \cdot S \cdot C_{D0Dec} \quad ...(25)$$

Landing speed v_L^2 can be derived from Equation (11).

$$v_L^2 = \frac{2 \cdot F_L^2 \cdot \left(MTOW \cdot MF_L - T \cdot \mathrm{Sin}(\varphi + \alpha) - L_{ST} \cdot \mathrm{Cos}\,(\delta - \alpha)\right)}{\rho \cdot S \cdot C_{LmaxL}} \quad ...(26)$$

By using Equations (23), (24), (25) and (26) the landing field length (ground roll) is given by:

$$x_L = \frac{MTOW \cdot MF_L \cdot F_L^2 \cdot \left(MTOW \cdot MF_L - T \cdot \mathrm{Sin}(\varphi + \alpha) - L_{ST} \cdot \mathrm{Cos}(\delta - \alpha)\right)}{g \cdot \rho \cdot S \cdot C_{LmaxL} \cdot \left(\frac{\rho}{2} \cdot 0.7^2 \cdot v_L^2 \cdot S \cdot C_{D0Dec} + \mu \cdot (MTOW \cdot MF_L - L_{ST})\right)} \quad ...(27)$$

Applying Equations (13) and (26) to Equation (27) the thrust-to-weight ratio that is needed to achieve a required landing field length is:

$$\frac{T_0}{MTOW} = \frac{\frac{L_{st}}{MTOW} \cdot \left\{[\mathrm{Cos}(\delta - \alpha) \cdot (1 - C2 \cdot C3) - C2 \cdot \mu] + \frac{\mathrm{Sin}(\gamma + \varphi + \alpha)}{AR} \cdot (C2 \cdot C3 - 1)\right\} + MF_L \cdot [C2 \cdot (C3 + \mu) - 1]}{\mathrm{Sin}(\varphi + \alpha) \cdot (C2 \cdot C3 - 1)} \quad ...(28)$$

Where C2 and C3 are introduced for a better clearness:

$$C2 = \frac{x_L \cdot g \cdot \rho \cdot C_{LmaxL}}{1.69 \cdot MF_L \cdot \frac{MTOW}{S}} \quad ...(29)$$

$$C3 = 0.7^2 \cdot 1.69 \cdot \frac{C_{D0Dec}}{C_{LmaxL}} \quad ...(30)$$

3.8 Vertical landing

For vertical landing the total thrust must be greater than the weight by a safety factor F_S (typical value is 1·2). The flight speed is zero, the thrust of the engine is assumed to be vectored totally downwards. Therefore, the balance of all forces in z-direction is:

$$F_S \cdot MTOW \cdot MF_L = L_{ST} + T \quad ...(31)$$

Taking T from Equation (13), Equation (31) can be solved for T_0/MTOW:

$$\frac{T_0}{MTOW} = F_S \cdot MF_L - \frac{L_{ST}}{MTOW} \cdot \left(1 - \frac{1}{AR}\right) \quad ...(32)$$

This formula applies to vertical take-off, if MF_L is 1.

4.0 APPLICATION

As this developed method is an analytical method, it can be applied in two ways (Fig. 3):

Design Point Estimation: The main aircraft's parameters, T_0/MTOW and MTOW/S, are calculated based on the specified requirements for take-off and landing field length and climb rate, e.g. for take-off with Equation (16).

Performance Estimation: The performance (take-off and landing field length and climb rate) of an aircraft with specified T_0/MTOW and MTOW/S is calculated, e.g. take-off field length with Equation (15).

The application of the method is demonstrated on the basis of the calculation of two examples: The first one is a JSF F-35B type aircraft with a shaft driven lift-fan (hybrid propulsion system) and thrust vectoring of the main engine. The second example is a fan-in-wing ESTOL regional jet 'HyLiner' with a hybrid propulsion system that is investigated at Bauhaus Luftfahrt.

The data for the two reference aircraft are given in Table 2, the calculation of them is documented in the following chapters.

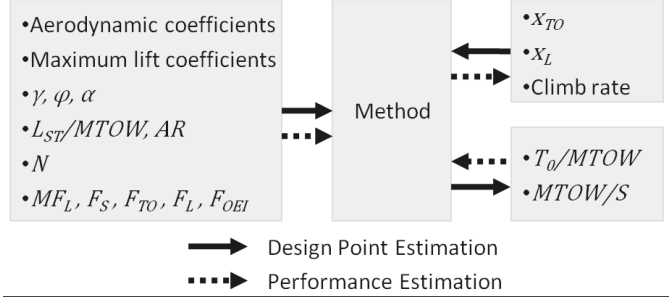


Figure 3. Different ways to apply the developed method.

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Table 2
Input data for two aircraft types

		JSF F-35B	HyLiner
L_{ST}/MTOW	[-]	0·4	0·4
AR	[-]	2·56	2·56
φ	[°]	55	65
δ	[°]	0	5
ρ_0	[kg/m³]	1·225	1·225
x_{TO}	[m]	550	550
CL_{maxTO}	[-]	1·6	1·8
F_{TO}	[-]	1·1	1·2
x_L	[m]	vertical	500
CL_{maxL}	[-]	-	2
F_L	[-]	-	1·3
MF_L	[-]	0·55	0·9
μ_L	[-]	-	0·3
$F_{ThrustVL}$	[-]	1·2	-
C_{D0Dec}	[-]	-	0·08
$C_{D0Clean}$	[-]	-	0·02
C_{D0OEI}	[-]	0·052	0·06
k	[-]	0·15	0·04
$\frac{\dot{H}}{v}$	[-]	0·05	0·03
N	[-]	1	3

4.1 JSF F-35B

For the F-35B type aircraft, results of 'design point' and 'performance' estimation are presented. For the 'design point' estimation three mission segments are investigated: short take-off, climb and vertical landing. As the F-35B has one engine, OEI is not considered. For the 'performance' use case, take-off field length is analysed. Table 3 shows the basic data of the F-35B taken from JSF.mil[9].

4.1.1 Design point estimation

As detailed data is not available for the F-35B several assumptions had to be made: The available thrust during short take-off is assumed to be equal to the lift of the engine during hover. The thrust vector angle φ of the main engine is assumed to be 55° during short take-off based on the available video material. For the required take-off field length at MTOW a value of 550m was selected. For the mass fraction from take-off to landing a value of 0·55 was chosen, C_{LmaxTO} is estimated to be 1·6. The lift of the roll posts and the lift-fan are summed up to the static lift L_{ST} that is 105,422N. Thus the ratio L_{ST}/MTOW is 0·4. The augmentation ratio is 2·56 calculated with Equation (12). The aerodynamic coefficients are calculated with methods of Roskam[12], giving CD_{0TO} = 0·052 and k = 0·15. The following performance constraint chart (Fig. 4) results from the original F-35B data (Table 2). The chart includes the take-off constraint calculated with Equation (16), the climb segment constraint calculated with Equation (22) (modified for one installed engine and a climb rate of 5%) and the vertical landing constraint derived from Equation (32).

Table 3
F-35B basic data[9]

		JSF F-35B
b	[m]	10.60
S	[m²]	42.70
MTOW	[kg]	27,216
T_0	[N]	111,000
Lift-fan „on" mode		
LMainEngine = T	[N]	69,837
LRollPost	[N]	16,458
LFan	[N]	88,964

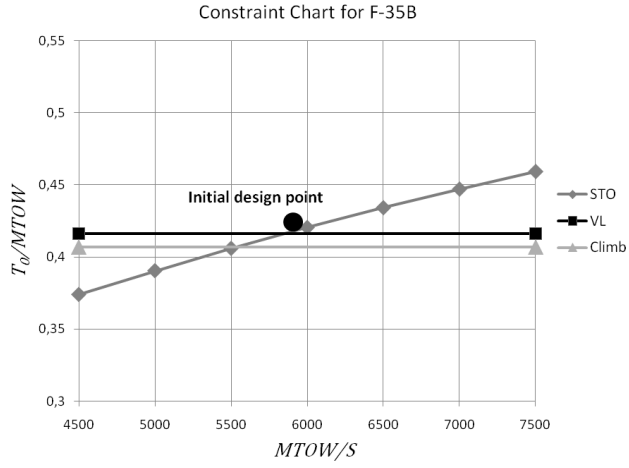


Figure 4. Performance constraint chart for F-35B.

With these results an initial design point would be T_0/MTOW = 0·42 and MTOW/S = 5,900N/m². The actual design point of the F-35B is T_0/MTOW = 0·42 and MTOW/S = 6,253N/m². The exact match of T_0/MTOW results from the dominating VL requirement which is calculated from real data except for MF_L. This means that the chosen value of 0·55 for the assumed mass fraction MF_L is close to reality.

The take-off constraint can be modified towards higher MTOW/S by increasing φ for example to 65° (Fig. 5). The climb segment constraint moves up to a value of 0·46 for T_0/MTOW as less forward thrust is available for climb at the main engine. This constraint gets significantly lower if δ is increased from 0° to 5° (Fig. 6) due to the forward component of the lift-fan. A modified (better) design point with MTOW/S of 6,250N/m² results with these parameter changes.

As a conclusion one can say that increasing φ reduces the take-off field length, while it also reduces the climb rate. This climb rate reduction can be compensated by increasing δ without having a penalty in take-off field length.

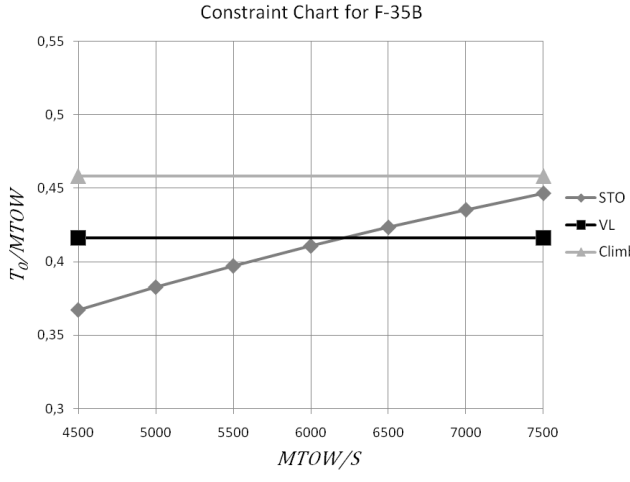


Figure 5. Variation of thrust vector angle, φ = 65°.

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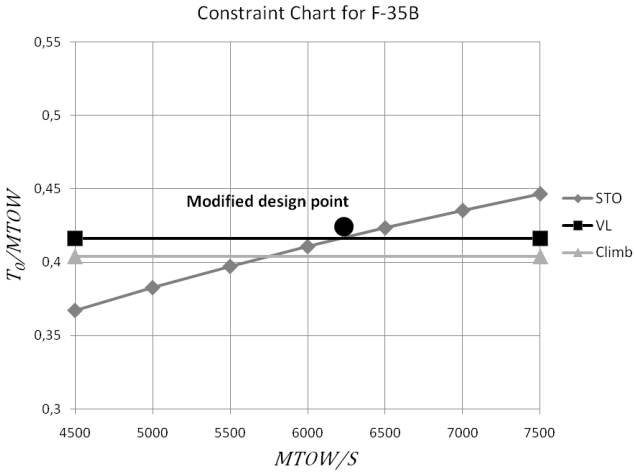


Figure 6. Variation of static lift thrust vector angle, δ = 5°.

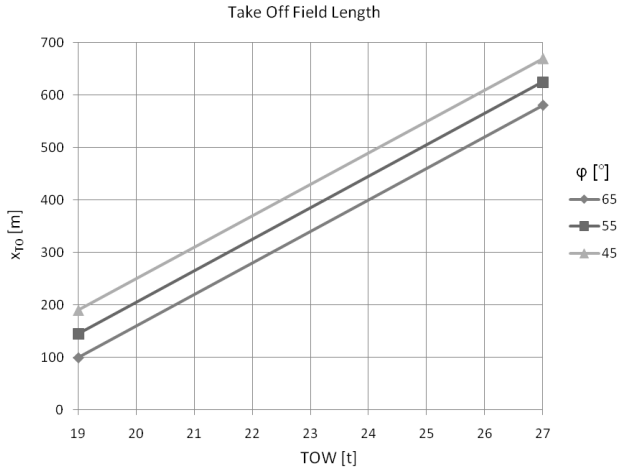


Figure 8. Trade study for x_{TO} over TO-mass and φ.

4.1.2 Performance estimation

As a performance use case the take-off field length was analysed with the available data. Figure 7 and Fig. 8 show trade studies for the take-off field length x_{TO} against take-off mass. As C_{LmaxTO} and φ are estimated, their influence on the take-off field length is evaluated. With increasing take-off mass the influence of C_{LmaxTO} on take-off field length increases as the ratio of aerodynamic lift to static lift is getting higher. At a take-off mass of 19,000kg the difference between C_{LmaxTO} 1·4 and 1·6 is about 20m. At a take-off mass of 27,000kg it is about 90m. The influence of the thrust vector angle φ is constant over take-off mass. For φ = 45° and φ = 65° the difference in take-off field length is about 80m. Higher φ results in lower stall speed and thus in lower take-off field length.

4.2 HyLiner regional jet

The values for L_{st}/MTOW and *AR* that were achieved for the F-35B were used as a baseline for the design of the civil regional jet 'HyLiner'. The developed methods for the short take-off segment (Equation (16)), for the climb OEI segment (Equation (22)), for cruise (Equation (3)) (M = 0·78) and for the short landing segment (Equation (28)) were implemented in an EXCEL tool to create the PCC. In this tool a change of the input parameters has a direct influence on the PCC and thus allows parameter optimisations.

The aerodynamic coefficients were calculated based on methods of Roskam[12] for the category 'transport jets'. Figure 9 shows the PCC of a reference configuration with the initial input values from Table 2. The main difference to the conventional PCC is the landing constraint. In the conventional chart this constraint is a vertical line, since the landing field length depends on the stall speed, and the stall speed is a function of wing loading. For the HyLiner regional jet the stall speed, and so the constraint for short landing is a function of thrust-to-weight ratio and wing loading, due to the thrust vectoring at the main engine. For this parameter setting the optimum design point is a thrust-to-weight ratio of 0·35 and a wing loading of 4,000N/m^2.

Figure 10 shows the effect on the constraints in the PCC when L_{st}/MTOW is increased to 0·6. The OEI segment almost does not change. The curves for the take-off and landing segments are getting flatter. This shows that the wing area is getting less important for the take-off and landing segment with increasing static lift. However, a ratio of 60% of static lift to aerodynamic lift may be high for a civil regional jet.

Figure 11 shows the PCC for a configuration with a lower thrust vector angle (φ =30°). Compared to the reference configuration in Fig. 9, the constraint for STO moves up, the constraint for short landing is changing towards a vertical line, as the thrust influence on stall speed decreases. The OEI constraint is moving down, because more thrust is available in *x*-direction during climb. MTOW/*S* would be reduced to 3200N/m^2 which is too low for a regional jet.

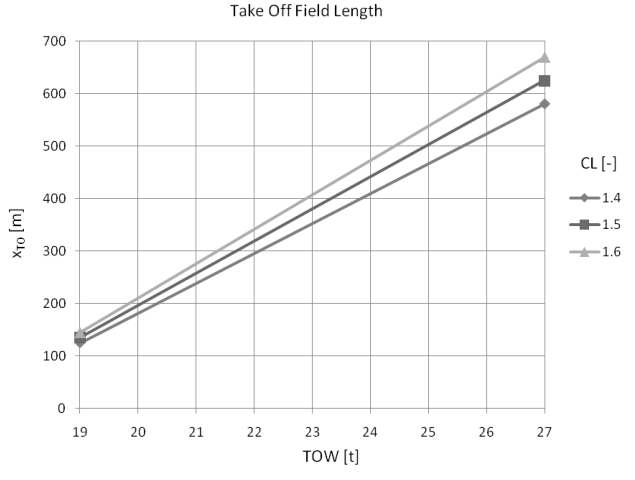


Figure 7. Trade study for x_{TO} over TO-mass and C_{LmaxTO}.

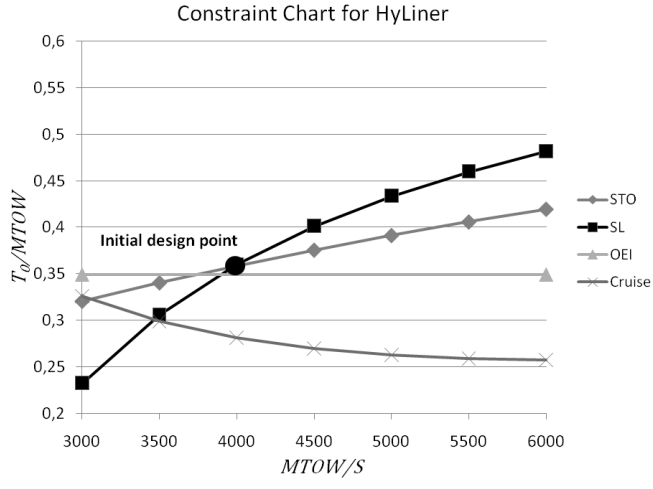


Figure 9. PCC for reference configuration.

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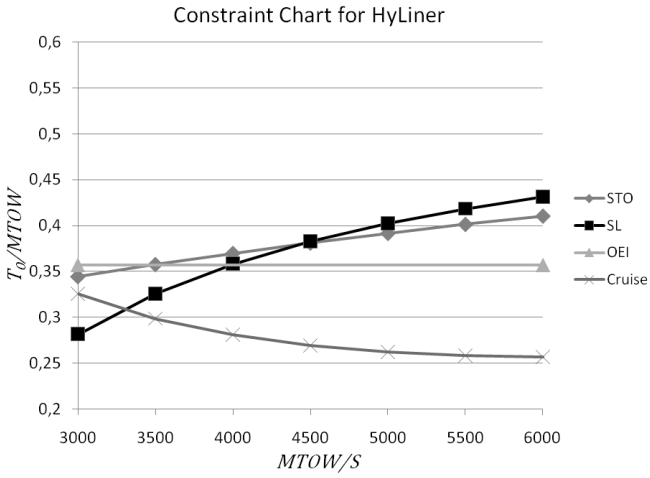


Figure 10. PCC for L_{ST}/MTOW = 0·6.

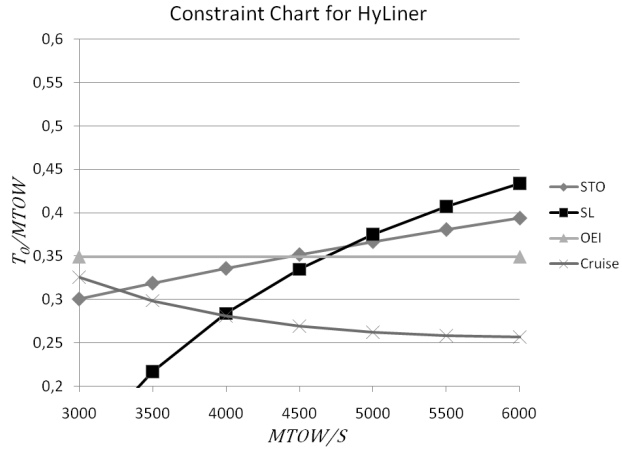


Figure 12. PCC of configuration with increased field length by 100m.

Figure 12 shows the effects of increasing the take-off and landing field length by 100m. The take-off and landing constraints are moving down. A higher MTOW/S (4,600N/m^2) would be possible.

As concluded in 4.1.1 the design point can be optimised by modifying φ and δ. A good design point was found for φ = 75° and δ = 7°. Figure 13 shows the PCC of the optimised configuration. Compared to the reference configuration (Fig. 9), T_0/MTOW is slightly higher (0·36) and MTOW/S is improved to 4,200N/m^2 which means less drag and thus a better efficiency.

Figure 14 shows the HyLiner fan-in-wing concept that was designed based on these studies. It has four lift-fans integrated into the wing, two on each side, with a diameter of 2m. The main engines have thrust vectoring (for additional control and lift during low speed flight) and are partly integrated into the aft-fuselage to allow low pressure spool power offtake.

5.0 CONCLUSION

A method for the calculation of a performance constraint chart for V/STOL aircraft was developed. This was achieved by extending standard flight mechanic equations to include representation of V/STOL specific parameters, namely a static lift component, an augmentation ratio and the thrust vectoring angles of the main and the lift engines. Evaluated mission segments included are short take-off and landing (STOL), vertical landing (VL), one engine inoperative (OEI) conditions during climb and cruise conditions.

The derived equations are also applicable to concepts with hybrid lift as to concepts with separate lift devices. In addition to the estimation of the design point the method can be used for the performance estimation of existing V/STOL aircraft.

A performance constraint chart for the JSF F-35B was modelled and take-off field length was calculated for different take-off masses. The design point calculated with the method was T_0/MTOW = 0·42 and MTOW/S = 5,900N/m^2 which is close to the real value of T_0/MTOW = 0·42 and MTOW/S = 6,253N/m^2. The influence of the thrust vector angle of the static lift device and the main engine on the constraints was studied showing the optimisation potential of these parameters. With modification of these parameters the real design point could be reproduced.

Subsequently a tool for the calculation of a performance constraint chart for the ESTOL regional jet 'HyLiner' with a hybrid propulsion system was implemented based on the developed methods. Starting with an initial design point the thrust vector angles were optimised to maximise the wing loading of the aircraft.

The method could be extended by including the thrust vector angle of the static lift device during acceleration and by the consideration of induced effects based on the wind tunnel experiments and CFD simulations that were conducted at the Institute of Aerodynamics of the Technical University of Munich.

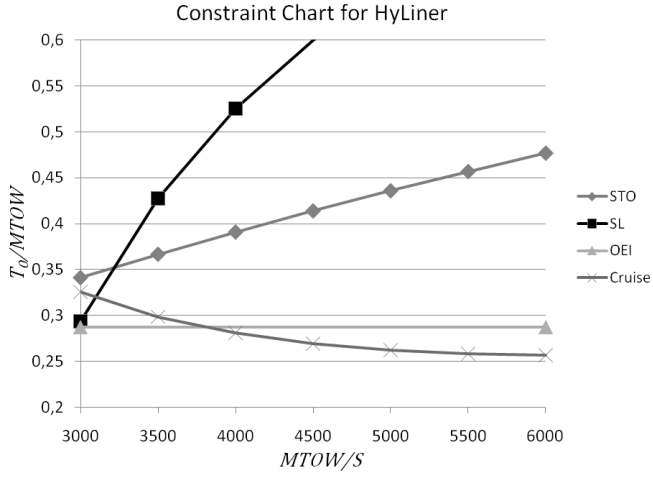


Figure 11. PCC of configuration with lower thrust vector angle (φ = 30°).

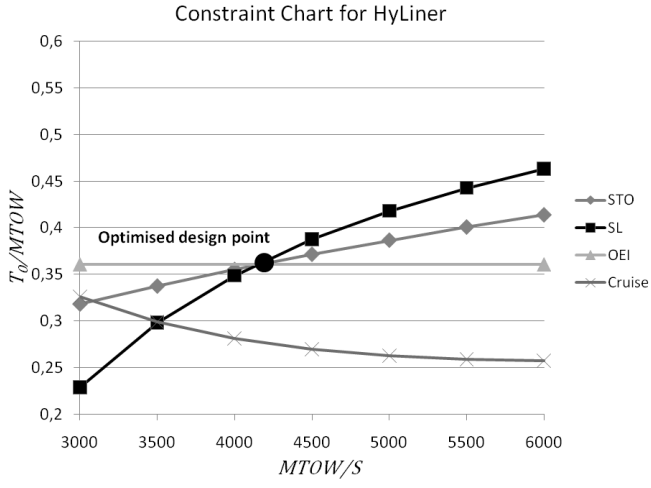


Figure 13. PCC of reference configuration (left) compared to optimised configuration.

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Figure 14. HyLiner fan-in-wing concept.

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