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Aircraft Design Considerations to Meet One Engine Inoperative (OEI) Safety Requirements

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NOMENCLATURE

A	area, sq ft
ABC	Advancing Blade Concept
AGL	above ground level
AI	autorotative index
av	available
CAA	Civil Aviation Authority
CDP	critical decision point, ft AGL
DL	disk loading, psf (GW/A_{rotor})
FAA	Federal Aviation Administration
fe	equivalent flat plate area, sq ft
fpm	feet per minute
fps	feet per second
ft	feet
GW	gross weight, lb
HLR	heavy lift rotorcraft
hp	horsepower
I_{rotor}	total rotor inertia, slug-ft ²
ISA	International Standard Atmosphere
K	thousand
kts	knots
L/D	aircraft overall lift-to-drag ratio
N_{eng}	number of engines
OEI	one engine inoperative
PDR	power deficiency ratio, ($OEI_{\text{hp av}}/HP_{\text{req hover}}$)
ROC	rate of climb, fpm
RPM	revolutions per minute
sq ft	square feet
TOWG	takeoff gross weight
TRP	takeoff rated power, hp
V_{broc}	best rate of climb speed
VDTR	variable-diameter tiltrotor
V_{toss}	takeoff safety speed, kts
Ω	rotor rotational speed, rad/sec

AIRCRAFT DESIGN CONSIDERATIONS TO MEET ONE ENGINE INOPERATIVE (OEI) SAFETY REQUIREMENTS

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Commercial airlines are obligated to operate such that an aircraft can suffer an engine failure at any point in its mission and terminate the flight without an accident. Only minimal aircraft damage is allowable, such as brake replacement due to very heavy application, or an engine inspection and/or possible removal due to use of an emergency rating. Such performance criteria are often called zero exposure, referring to zero accident exposure to an engine failure. The critical mission segment for meeting one engine inoperative (OEI) criteria is takeoff. For a given weight, wind, and ambient condition, fixed-wing aircraft require a balanced field length. This is the distance to takeoff if an engine fails at a predetermined critical point in the takeoff profile, or the distance to reject the takeoff and brake to a stop, whichever is longer. Rotorcraft have requirements for horizontal takeoff procedures that are equivalent to balanced field length requirements for fixed-wing aircraft. Rotorcraft also perform vertical procedures where no runway or heliport distance is available. These were developed primarily for elevated heliports as found on oil rigs or rooftops. They are also used for ground-level operations as might be found at heliports at the end of piers or other confined areas.

Figure 1 shows a vertical takeoff profile for an elevated platform. The takeoff procedure starts with a vertical climb at takeoff rated power. There is a critical decision point (CDP), which is typically at about a 30-foot wheel height. If an engine failure occurs before this point, the aircraft lands back at its takeoff point. If an engine failure occurs after CDP, the takeoff is continued by dropping the nose and accelerating to takeoff safety speed, (V_{toss}). At V_{toss} the aircraft must be capable of a 100- fpm rate of climb (ROC). The aircraft initiates this ROC upon attaining V_{toss} and continues to 1,000 feet above ground level (AGL). The aircraft must remain 35 feet AGL or higher throughout the continued takeoff procedure. At 1,000 feet AGL, the aircraft accelerates to best rate of climb speed (V_{broc}) where ROC must be 150 fpm or higher. These values are Federal Aviation Administration (FAA) requirements. The Civil Aviation Authority (CAA) has slightly different ROC and clearance requirements, but the takeoff method is the same. The drop down exchanges potential energy for the kinetic energy required to reach V_{toss} . The larger the drop down, the less engine OEI power required. Elevated heliports have the advantage of more potential energy available for exchange than ground-level heliports. The continued takeoff profile for a ground-level heliport is the same as shown in figure 1. However, the CDP could be less than the 35-foot clearance, and an aircraft may actually have to climb slightly as it accelerates to V_{toss} .

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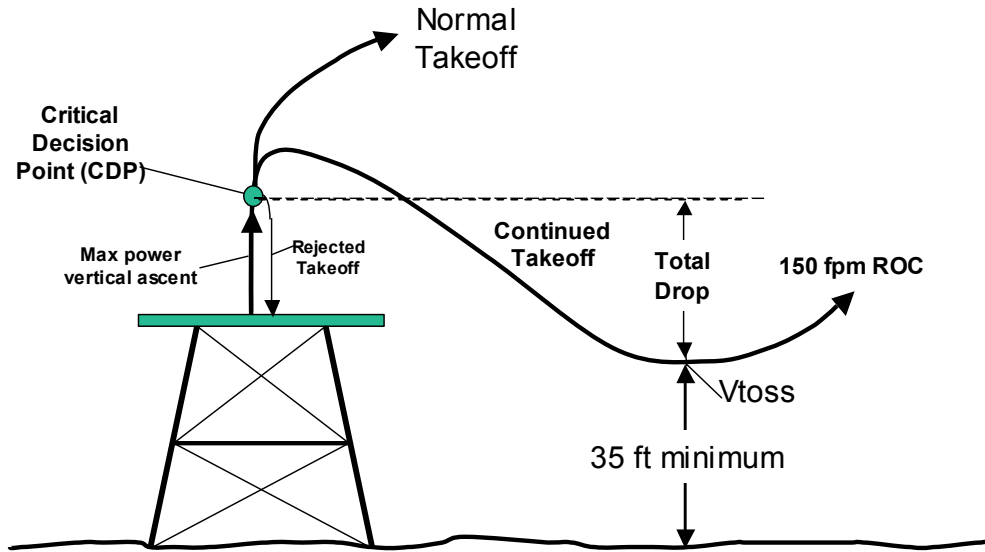


Figure 1. Helicopter vertical takeoff profile.

Figure 2 shows a parametric trend developed to estimate the total drop down from CDP for helicopters as a function of aircraft OEI power available to power required to hover ratio. This is called a Power Deficiency Ratio (PDR). Conversely this ratio can be found for a given total drop-down requirement. There have been several papers that trend drop-down distance by the same or similar ratio. The points shown are for a variety of helicopters at different gross weights. Results of some limited analyses of 50-passenger-class civil tiltrotors as part of past civil tiltrotor and variable-diameter tiltrotor (VDTR) work are shown as well.

The commercial heavy lift rotorcraft (HLR) focus of this study dictates vertical ground-level procedures. Selection of CDP is a function of rotor inertia, engine spool-up time, engine control delays, pilot reaction time, pilot visibility, and landing gear sink rate capability. For this analysis a 50-foot CDP was chosen assuming favorable gains in the above parameters and, in particular, high-sink-rate landing gear. A 50-foot CDP and a 35-foot clearance requirement allow only a 15-foot total drop down. Based on figure 2, a conventional rotorcraft and a tiltrotor require a PDR of 0.80 and 0.93, respectively. Tiltrotors require a higher PDR due to lower relative stored rotational energy in the rotor system and a higher V_{toss} . When a helicopter loses an engine abruptly, there is a finite amount of time for the second engine to reach full emergency OEI power. During this time rotor RPM decays. A helicopter rotor has a high amount of rotational energy relative to the kinetic energy required to accelerate to V_{toss} . This energy helps keep the rotor close to 100 percent RPM and allows more ballooning and forward speed gain just after CDP. A tiltrotor, with its lighter and smaller diameter rotors, does not have nearly as much rotational energy, therefore descent starts very shortly after CDP. The larger contributor to higher OEI power requirements is the higher V_{toss} speed associated with higher disk loadings. The physics of induced power dictates the speed for minimum power required increases with higher disk loading. A tiltrotor, with its higher disk loading, has to accelerate to a higher V_{toss} , which requires more energy, and therefore more drop down or engine power than a helicopter (figure 3).

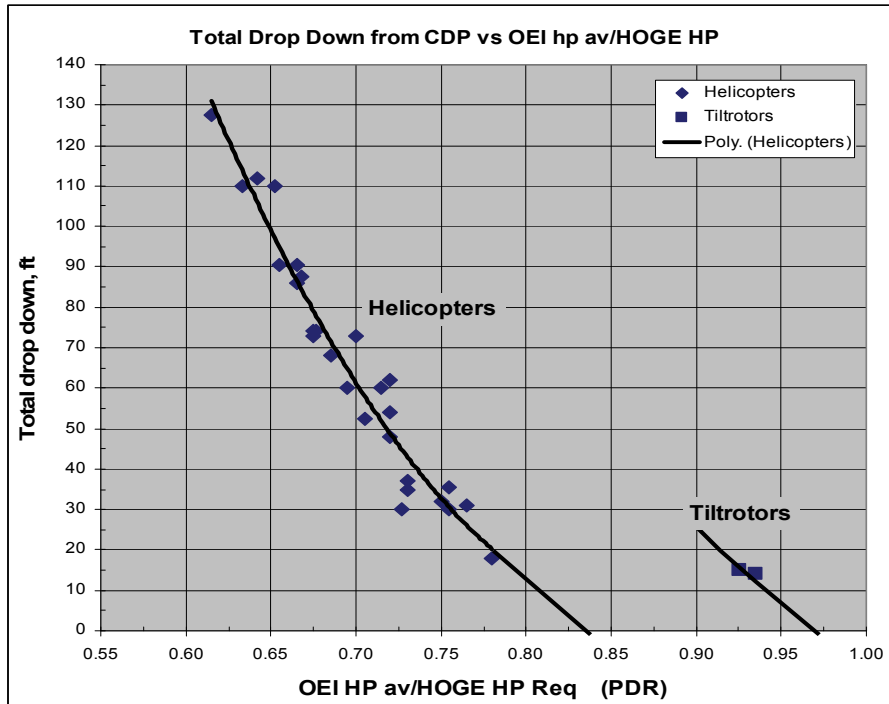


Figure 2. Vertical procedure total drop down from CDP vs. PDR.

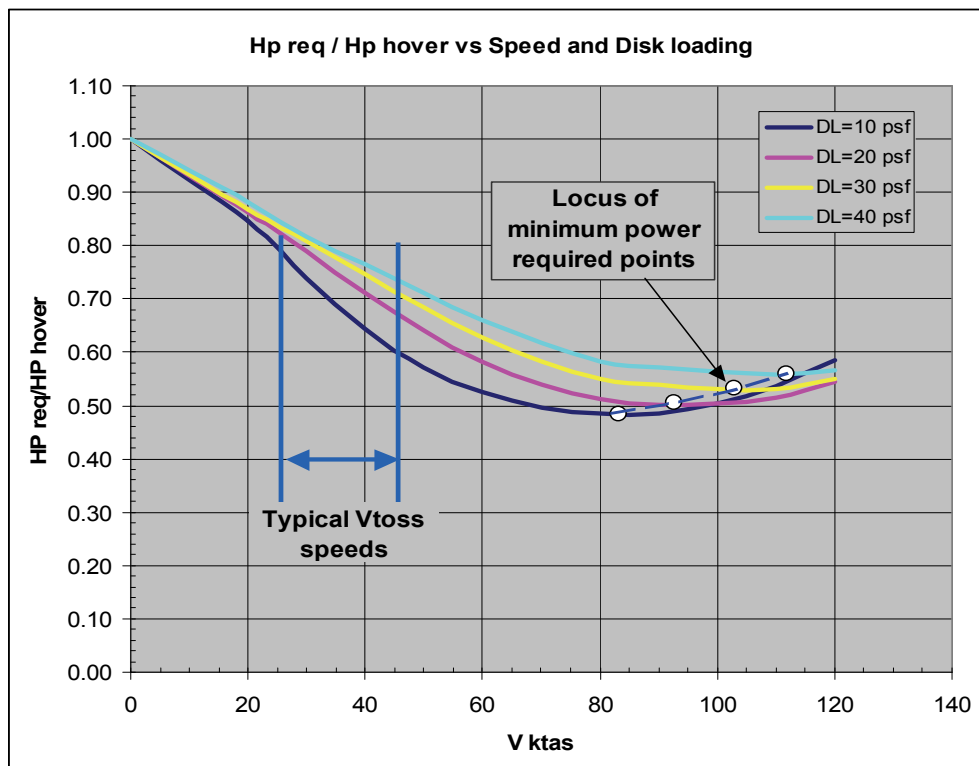


Figure 3. Horsepower required ratio vs. speed and disk loading.

The effect of rotational energy and disk loading is captured in a nondimensional term called Autorotative Index (AI) (eq. 1). This parameter relates the rotational kinetic energy stored in the rotor to aircraft weight and rotor aerodynamic efficiency. AI is a nondimensional value that is used as an index. Pilot-rated flying qualities for autorotation improve with increased AI. The same is true for OEI takeoff procedures for a constant PDR. Figure 4 shows how PDR trends with AI at a 15-foot-total drop down. Preliminary sizing of a twin rotor tiltrotor meeting mission requirements is in the 120K lb takeoff gross weight (TOGW) class. Disk loadings in the range of 30 to 50 psf are expected. The AI index was calculated for a 30- and 50-psf tiltrotor and are plotted in figure 4.

$$AI = I_{rotor} * \Omega^2 / DL / GW \tag{1}$$

There is a size effect on AI. Generally, as aircraft size increases, AI is reduced. Therefore, AI values for a 120K lb tiltrotor are expected to be lower than the 50K lb tiltrotor points. Figure 4 indicates a PDR of 0.945 at an average DL of 40 psf. Knowing that lower disk loadings are sought and some advanced flight controls may bring benefits, a PDR value of 0.93 was selected for an HLR tiltrotor. An Advancing Blade Concept (ABC) aircraft in the 120K lb class at 17.5-psf disk loading has an AI around 12.5. Therefore for a 15-foot drop height, the ABC requires a PDR of about 0.88.

With the PDR requirements determined, the question is what engine OEI/takeoff rated power (TRP) ratio is required? This ratio is a function of how oversized the engines are in hover, and how many engines are on the aircraft. Equation 2 relates these three parameters to engine OEI/TRP ratio required. The first term in equation 2 is PDR, the second is the hover power margin.

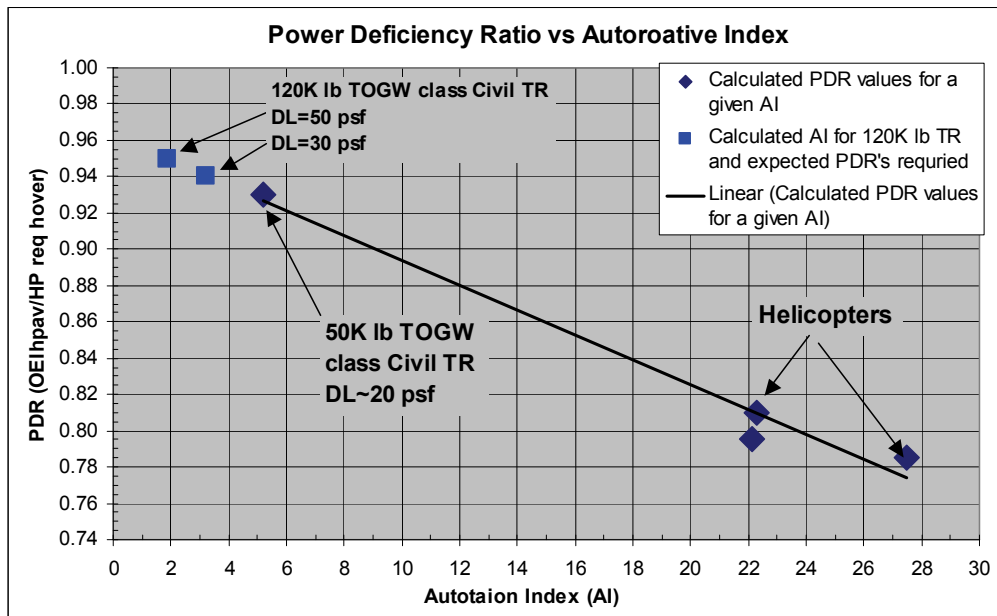


Figure 4. PDR vs. AI at 15-foot-total drop down.

Plots of required engine OEI/TRP as a function of hover power margin and engine number are shown in figure 5 for the selected tiltrotor PDR of 0.93. The most demanding case is where a two-engine aircraft hovers at 100 percent TRP. In an OEI condition, where the remaining engine must provide 93 percent of the power required to hover, the engine OEI/TRP ratio must be 1.86. If the engines were oversized such that only 75 percent of the available TRP were required to hover, the OEI/TRP ratio would be 1.4. A four-engine aircraft hovering at 80 percent TRP does not need an elevated OEI engine power rating.

$$(OEI_{hp\ av} / TRP) = (Hp_{av\ OEI} / Hp_{req\ over}) * (Hp_{req\ hover} / TRP_{av}) * (N_{eng} / (N_{eng}-1)) \quad (2)$$

Usually determination of hover power margin is a function of engine OEI/TRP. For the HLR study engine ratings ratios are not set, so the benefit of increased OEI/TRP in terms of disk loading increase, and weight reduction can be quantified. Figure 6 shows the results of sizing runs for various aircraft L/D ratios and disk loadings. A low L/D aircraft requires more installed power to cruise. At a low disk loading there is more than enough power to hover. Such an aircraft is said to be sized by cruise. Conversely, a high L/D aircraft (which requires less installed power for cruise) with a high disk loading may not have enough power to hover. Therefore, more installed power is required, and the aircraft is said to be sized by hover. As an example, a tiltrotor with an L/D of 10 and a 30-psf disk loading only requires 66 percent of installed TRP to hover. If this aircraft had two engines, extrapolation of the top line in figure 5 shows an OEI/TRP requirement of 1.2.

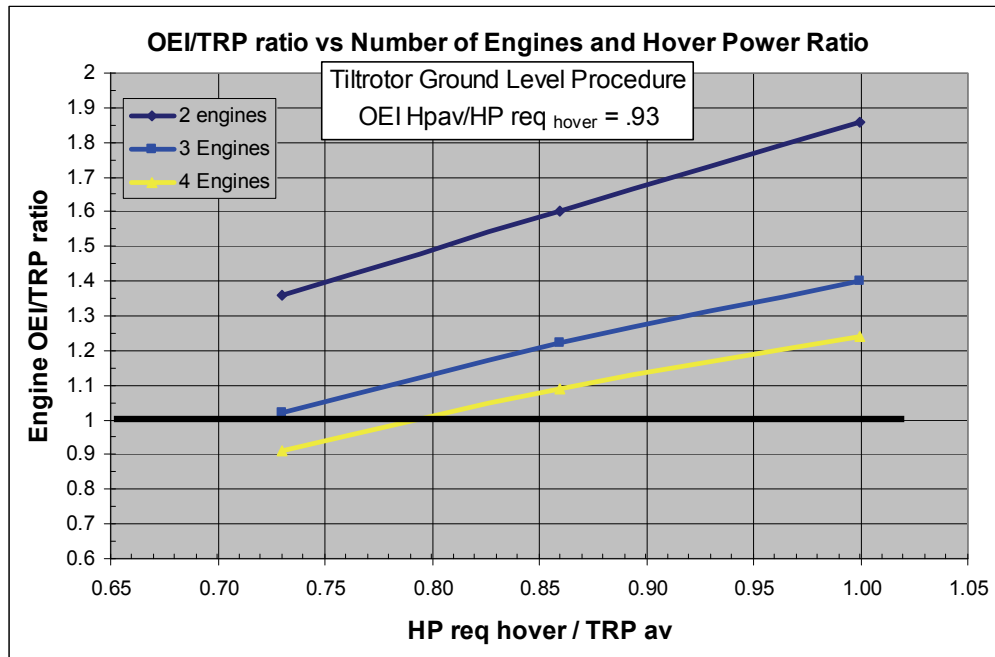


Figure 5. OEI/TRP vs. engine number and hover power ratio.

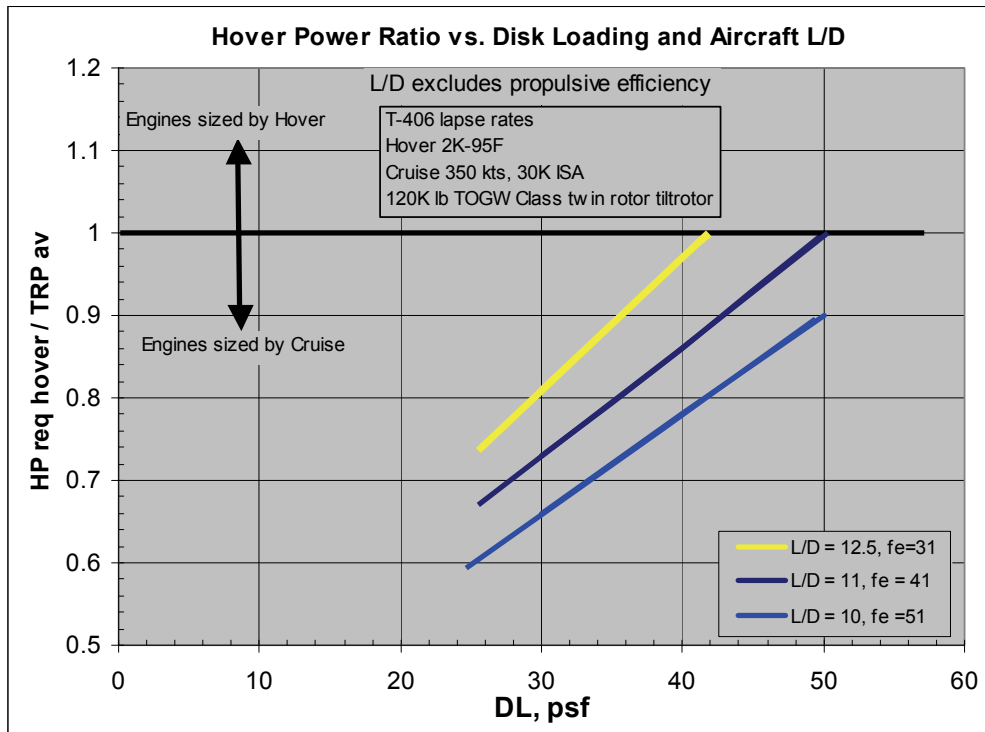


Figure 6. Hover power ratio vs. disk loading and L/D.

Figure 5 is independent of mission profile and engine lapse rates. Figure 6 was created with hover and cruise ambients of 2K-95F and 30K ISA, 350 kts respectively. The engine lapse rates were based on a T-406 engine variant. The selected rotor hover FM was 0.81 and vertical drag was 10 percent of GW for a DL of 25 psf, linearly increasing to 16.3 percent of GW at DL = 50 psf. For a given cruise condition, hover ambients and engine lapse rates change the results. For example, higher hover density altitude demands more installed power and shifts the curves in figure 6 up. Similarly, if the engine were able to retain more power with density altitude the curves would move up as well. Figures 5 and 6 indicate that at L/Ds around 12, a four-engine aircraft does not need an OEI/TRP ratio greater than one.

Figures 2 and 5 can be used as part of an aircraft trade study. For a matrix of design disk loadings and engine number, PDR values can be found for a given drop down. Then OEI/TRP ratios, the associated propulsion system weight and cost, and ultimately the overall aircraft weight, cost, and productivity can be found. Similarly, aircraft productivity impact as a function of drop down can be quantified. For a CDP of 35 feet and zero total drop down, a tiltrotor will require a PDR close to 0.97.

Based on the results shown, historical trends, and past experience, a drag level of 36 sq ft and a disk loading of 30 psf are expected for a 120K lb aerodynamically clean civil tiltrotor. Based on figure 6, an $HP_{req\ hover} / TRP_{av}$ ratio of 0.77 is required. Figure 5 shows an engine OEI/TRP ratio of 1.43 for a two-engine aircraft. This is a high rating by today's standards, but most likely achievable given

improving engine technology. A two-engine aircraft is also much more attractive from a cost, complexity, and weight standpoint.

Based on extrapolation in figures 5 and 6, an ABC aircraft with an L/De^2 of 11 and a disk loading of 17.5 psf requires only 55 percent of installed TRP to hover. Even at the more stringent tiltrotor PDR of 0.93, a two-engine ABC would only require a modest OEI/TRP ratio. Therefore, the OEI performance of an ABC should be exceptionally good up to high-density altitudes.

² L/De includes rotor induced drag, H force, and profile power converted to a drag.