Chapter 11
Power plant and Transmission

Introduction

A WIG is a flying machine that takes off and lands on water, in a similar manner to a flying boat. The craft structure has to follow much of the experience and concepts developed in aviation in order to achieve successful flight performance. Power plants also need to comply with aviation criteria of acceptability – reliability, lightest possible weight and highest practical fuel economy.

An important additional criterion to take into consideration for power plant selection is the total weight combining the engine, transmission and propulsor system.

The WIG performance envelope will also have a strong influence on power plant selection. High-speed WIG, with cruise speed above 300 kph, demands jet engine propulsion, preferably high bypass turbofan(s).

Modern lightweight internal combustion engines are useful candidates for medium to small WIG application, so long as the electronic systems have been uprated for marine service. Automotive engine technology has significantly improved durability and power-to-weight ratio over the last two decades. A turbo charger can be effective in increasing the power output of an engine and achieve higher power-to-weight ratio design.

Although diesel engines have been successfully used in modern hovercraft, the highest power-to-weight ratio engines are only available at power ratings suitable for cars. Small WIG craft may be able to use these engines, but larger WIG have to base engine selection on aviation power plants, whether reciprocating, or gas turbines. A recent NASA supported development programme as well as other recently commercialised lightweight aviation diesel engines has nevertheless introduced a possible new engine source for small-size WIG once such power plants become available commercially.

Gas turbine engines in the past have been complex and expensive with relatively poor specific fuel consumption. New technology development in the last 15 years has revolutionised modern turbine engines. New generation engines have been developed with 40% better specific fuel consumption while some of the smaller turbine engines have 70% lower part count than before. Very high bypass turbofans and

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high efficiency turboshaft engines paired with ducted fans hold promise for various size WIG applications.

ACV and SES have utilised industrial power units successfully as an alternative to heavier marine engines with steel crankcase and cylinder heads, for example air-cooled diesel engines. ACV face the same challenge as WIG related to engine-cooling systems, in that direct one path through salt water cooling, as used on most high-speed marine craft, is not possible. Water-cooled engines therefore have to be designed with a closed-cooling system incorporating a heat exchanger (radiator). This system adds weight, which is not so critical for an ACV, but may become so for WIG craft. An air-cooled engine is attractive for the simplicity and light weight, but water-cooled system (with radiator and cooling fan) has its advantage in terms of better cooling and control especially at low operating speed.

Whether an automotive, marine or aerospace derivative power plant is selected, the WIG designer has to be aware that engines are available in specific power ranges. There are a limited number of products available, and powering of a WIG has to be based on selection of an existing power plant, as development of a new engine specifically for the WIG project would be prohibitive in both time and cost. The WIG craft sizing and mission potential will have to be adjusted so as to obtain the maximum from the available power plant!

In this chapter, we will discuss selection criteria for WIG and design issues for incorporation of power plant and their associated systems (control, cooling, fuel, etc.) into the overall craft design.

WIG Power Plant Type Selection

The basic requirements of WIG power plant are linked to the operating environment of the WIG, including similar conditions to fast marine craft for the take-off and landing runs, and aviation conditions of high-speed during cruising. Key elements for success are

- High power-to-weight ratio
- Ruggedness of engine *and* support systems for multi-environment operation
- Low acquisition cost
- Low operating and maintenance cost
- Adaptability to the proposed transmission and connected propulsion/lift system

Various engine types are suitable for WIG application, as discussed above, depending on the size of the vehicle, the operating envelope and the basic vehicle configuration, particularly the lift and propulsion system arrangements.

Selection of engine type has often been driven by the power requirement in the different operating modes. For a design that requires significantly more power for take-off than cruise mode, an automotive engine may be readily adaptable for the application, while turbine engines are often designed to operate continuously at near maximum power so are more suitable for high-speed craft. A comparison of characteristics for different engine types in aviation use is shown in Fig. 11.1.

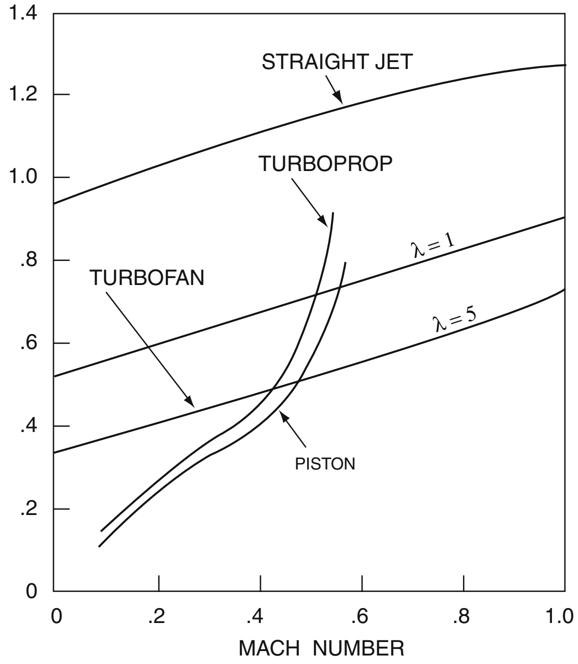


Fig. 11.1 Fuel consumption/drag versus mach number

Internal Combustion Engines

For small WIG vehicles, the internal combustion engine is a very good choice due to its low acquisition cost, minimum or no special maintenance equipment or training required, and reasonable power-to-weight ratio.

The advancement in two- and four-cycle gasoline engines today offers high fuel efficiency, low environmental emissions and low weight. Modern automotive engines use aluminium for both the crankcase block and the head. A good example is the lightweight Northstar all aluminum 300 hp 4.6 L V8 IC engine shown in Fig. 11.2, the same engine is now available in marinised form that can be directly adapted for small WIG craft application.

Generally the automotive power rating of an engine is not intended for continuous operation at the rated horsepower. The rating is for maximum power for a short period of continuous output mostly during acceleration, cars generally operate at speeds where an engine is at 50% maximum power or less. For automotive applications, a more important parameter than power is torque for acceleration but this is less critical for WIG applications especially with variable pitch propeller or fan system.

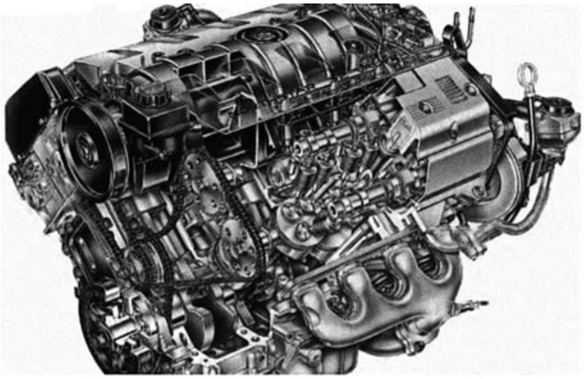


Fig. 11.2 Northstar all aluminum 300 hp 4.6 L V8 IC engine

Aircraft engines normally have a continuous rating between 70 and 85% of maximum power. The maximum rating is valid for transitions such as take-off and landing. Aircraft cruise speed is then set, so the engine is running below 85% power rating. The cooling system is arranged so that engine temperature can be maintained optimal at cruise speed, and maintain CHT within limits during take-off and climb flight segments especially for hot day operations.

A marine engine is rated with a maximum power suitable for short burst operations up of 10–15 min and a continuous rating at 80–85% of maximum power. Torque is only important at the matching speed of the propulsor it is connected to. If the propulsor is a variable pitch device, there will be two design conditions to consider, maximum thrust while in still water at zero speed and maximum thrust while passing through hump speed or take-off to planing, which ever is the most demanding.

For WIG applications, the requirements for power plant are quite similar to marine power plant, while needing a lower engine weight.

For small personal WIG craft or experimental trials craft, two-cycle petrol engines developed for snow-mobiles, jet-ski water craft and hovercraft applications offer high power-to-weight ratio. Although not the most fuel-efficient power plant for short-range small WIG craft that do not require years of daily operations, the light weight and low acquisition cost of two-cycle petrol engines can easily offset the shortcomings. Figure 11.3 shows a typical installation as installed in a small hovercraft. This type of engine was also used for the MARIC 750 manned test craft, two-ducted engine and fan units as bow thrusters, and a further two-ducted fan and engine units for propulsion, see Fig. 3.7. Modern developments of this type of engine have been adapted to the flight requirements of microlight aircraft with uprated ignition and fuel systems for reliability. These models are particularly suitable for smaller WIG craft.

The small two stroke motors have been developed for micro-light aircraft applications, including dual ignition systems. These reliability based upgrades are important for WIG craft. In the same way, larger automotive derivative engines need

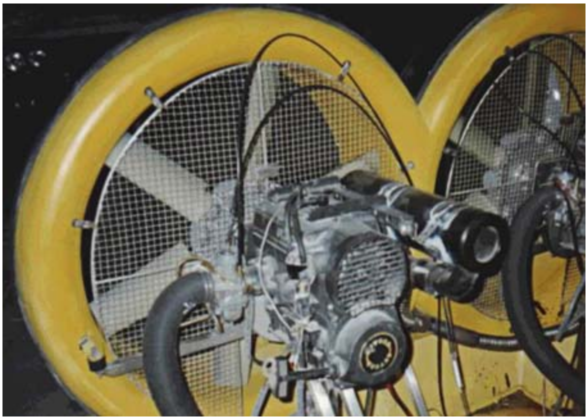


Fig. 11.3 ACV engine plus fan duct

to be modified both for marine use, and to incorporate the system redundancy of aircraft specifications. An appreciation of the systems specifications required can be gained from [1].

Turbofan/Turboshaft/Turboprop Engines

The aircraft turbine engine has long been the choice for high-performance vehicles that require high power output. The fuel efficiency of turbine engines has improved at least 30% over the last 10 years. Modern turbine engines offer the very high power-to-weight ratio and fuel efficiency needed for medium- to large-size WIG. The fuel efficiency improvement is vitally important for medium- to long-range WIG craft as it can reduce the fuel fraction of total vehicle weight, reducing the maximum take-off weight of the resulting design and improving the overall performance.

Of course, there is nothing in the world that is perfect. Turbine engines are still expensive – not only the acquisition cost but also maintenance. Also not every turbine engine type is available in a marinised version, which limits the choices.

Among turbine engines, turbofan, turboprop and turboshaft versions are all applicable for WIG craft. Figure 11.4 shows the Rolls Royce RB 580 turbofan engine as an example. The choice depends on the vehicle configuration and specifically whether a power augmented lift system is planned, whether engines are to be imbedded in fuselage and whether direct drive or shaft transmission is intended.

Interestingly, the small turbine engine development in the last 10 years has been even more dramatic than the big engines. The current generation small turbofan engine may be represented, for example, by the Williams International FJ44 engine family. Figure 11.5 shows the FJ44-3 3,000 lb Thrust Fanjet Engine. This offers

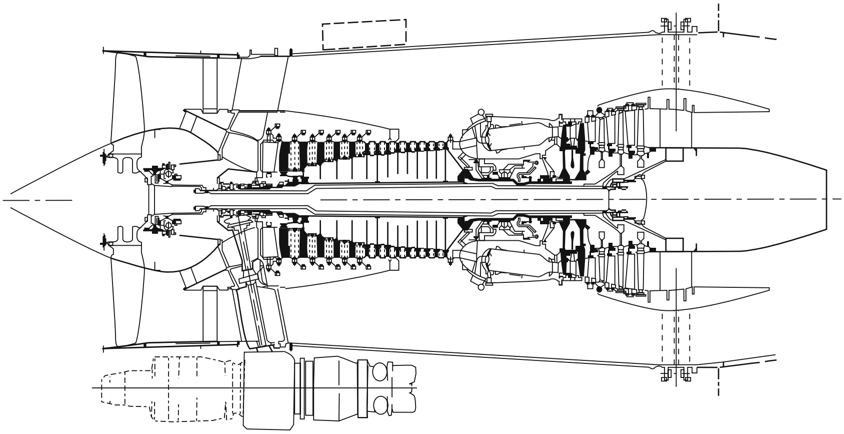


Fig. 11.4 Rolls Royce RB 580 turbofan engine

Fig. 11.5 FJ44-2C 2,300 lb thrust fanjet engine

the fuel efficiency of its much larger counter parts, light weight, simple installation and only one third of the component parts of older generation engines. This translates to lower manufacturing cost as well as simpler and lower maintenance requirements.

It should be noted that most aerospace turbofan engines are designed and optimised for high-speed and high-altitude operations. Marine versions will generally configure as a turboshaft unit, in a fairly large and heavy modular enclosure. The air intake for a marine turbine is separate to the engine itself and incorporates filter banks to remove water droplets. Unless a WIG gas turbine is located inside the hull with air intakes on the upper side, such as arranged for Orlyonok (see Fig. 11.6), air filters are difficult to configure. The banks of gas turbines at the bow of KM and Spasatel created a large amount of heavy salt spray during take-off and landing (see Fig. 11.7) and so the engines required careful washing after each mission. The figure shows how powerful the action of the high-speed jet efflux is in creating spray at slow speeds over water. While the bow thrusters are out of the spray, the tail is completely enveloped, including the cruising engine.

Fig. 11.6 Orlynok showing bow intakes

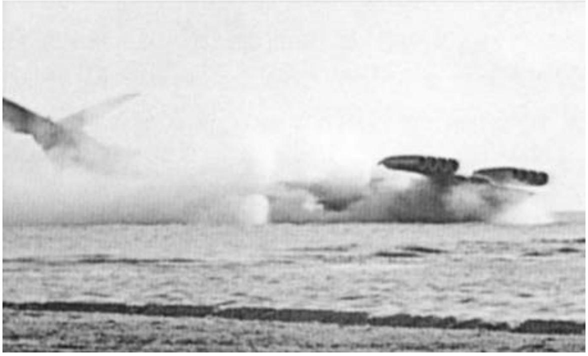


Fig. 11.7 KM launching

The Orlyonok thrusters do not create quite such a cloud of spray, as shown in Fig. 11.8, though the main wings are clearly enveloped, and rough water accentuates the problem. Placing the main propulsion engine at the top of the fin is at least a partial solution to the spray problem and is most convenient for close coupled turboprop installations. Figure 11.9 shows an allison turboprop engine installation with six-blade propeller on a regional airline aircraft, this engine and propeller system would suit a medium-sized WIG installation very well. An alternative arrangement for turbofan engines would be the over-wing location towards the back of a WIG main wing in an arrangement similar to Fig. 11.10. While being a little more sensitive to spray, this arrangement has a lower pitching moment than fin top installations.

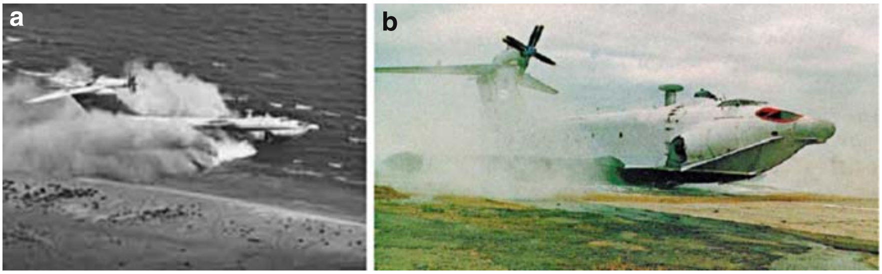


Fig. 11.8 Orlynok launching: (**a**) crossing beach edge and (**b**) accelerating over waves

Fig. 11.9 Allison turboprop engine installation with six-blade propeller

Fig. 11.10 A-40 flying boat with over-wing mounted turbofan propulsion

Such a position may also be better favoured for the classic WIG configuration since there will be less spray without a bow-thruster installation.

Classic WIG designs such as the Flightship series in Australia and the AFD Hoverwing series from Germany have adopted this configuration, see Fig. 2.51 for example. These craft are powered by engines installed in the rear cabin space.

WIG Application Special Requirements

Marinisation

WIG normally operate at or near the water surface, so it is important to ensure that the power plant selected can handle the water spray of the worst operating condition envisioned. The inlet location and its relationship to the bow are a very critical configuration design choice.

Operating in a high water content environment requires additional corrosion protection for the engines; this is particularly critical if the WIG is designed for salt-water operations. Aluminium engine components are vulnerable to salt-water corrosion and so special coating is required for proper protection. Watertight sealed wiring and connectors are a necessary practice for marinised engines.

All engine controls and linkages require stainless steel or non-metallic parts. For the turbine engines, the housing requires special treatment for protection, and the compressor and turbine blades may also require either coating or material changes. Figure 11.11 shows the allied signal TF40 marine gas-turbine engine that includes all these reliability upgrades for marine application. The TF40 is used in US Navy LCAC assault hovercraft and so has been designed with both heavy salt and sand particle ingestion in mind, and makes it a useful candidate for medium-size WIG.

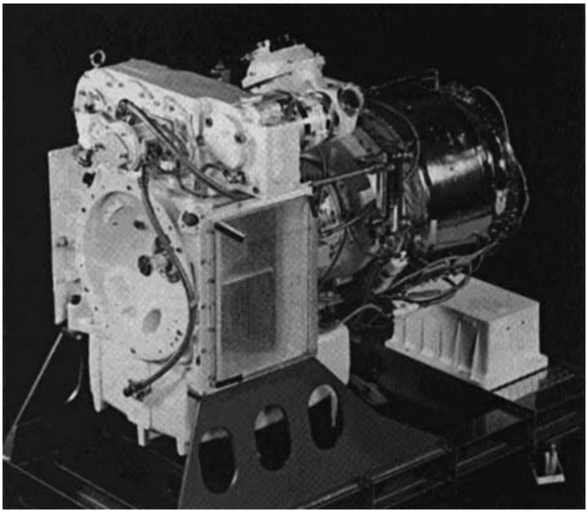


Fig. 11.11 Allied signal TF40 marine gas-turbine engine

Altitude Operations

Since WIG generally operate at low altitude compared to typical aircraft, the engine can be optimised for sea level operation. In the case of turbofan engines, a higher by pass ratio engine will be preferred since these have higher static and low-speed thrust and fuel efficiency.

Internal combustion engines can also be optimised for sea level operation, rather than aircraft engines that are set up for cruise altitude. The only challenge comes if a WIG is to operate on a high-altitude lake, where a different set up of turbo charging may be required and an intercooler might be needed. To maximise the power available for a specific engine under consideration, an intercooler installed between the turbocharger and engine induction air intake can be effective in cooling down induction air and thus improve engine power rating compared to turbo charging only.

Some turbo-charged/intercooled engine designs can provide sea level power up to 2500 m. If high elevation operation is an important design parameter, the WIG designer should also consider aircraft engines for this application. Some aircraft engines are already designed to have matched and tuned turbocharger and intercooler, but more helpfully there is test data available for high elevation operation allowing much easier and effective power plant/vehicle design matching and optimisation. Of course, aircraft engines come with a high price tag and still require proper marinisation to be done for WIG-operating environment. Figure 11.12 shows a Teledyne Continental Motors turbocharged combustion engine performance chart as an example.

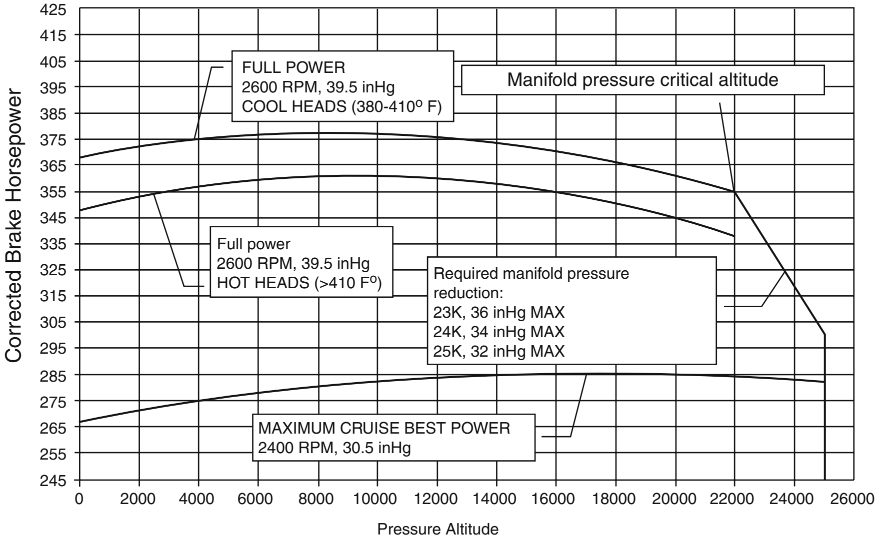


Fig. 11.12 AVCO Lycoming IC aircraft engine performance diagram

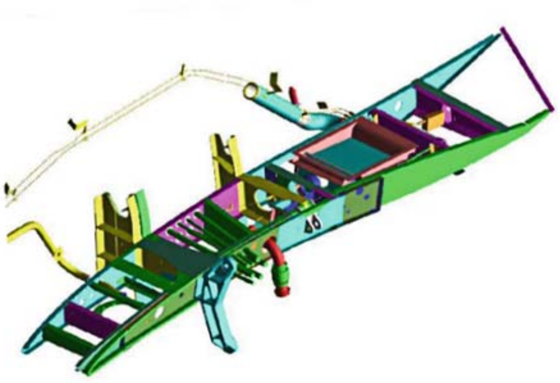
Power Plant Installation Design

Pylon/Nacelle Installation

For turbofan, turboprop and aircraft IC engines that are designed to provide direct mounted propulsor or lift system, the pylon/nacelle combination provides an efficient configuration. The suitability depends on the vehicle/power plant configuration. The pylon can be vertically or horizontally arranged with the engine axis parallel to the vehicle. Horizontal mounting would be designed similar to an aircraft aft fuselage turbofan engine installation. Vertical pylon mount for WIG application would be a mirror image of the under-wing engine installation for most large-passenger aircraft like the Boeing 737 airliner design.

Key design considerations include pylon structural stiffness, effective load path through into the fuselage or wing/tail main structures, pylon aerodynamics, firewall protection and engine yoke fireproofing. The engine controls and engine electronic data link will all have to go through the pylon, therefore adequate system penetrations should be provided in the design. Figure 11.13 shows a typical jet engine pod pylon structure and systems configuration.

Fig. 11.13 Pylon structural and system configuration



The pylon-mounted turbofan and turboprop engine installation provides a simple configuration and easy maintenance accessibility by using large nacelle panels. A turboprop engine pylon mounting requires special attention to structural dynamics, to ensure avoidance of structural tuning to the engine natural vibration frequencies.

Turboprop installations require the engine to be cantilevered further away from fuselage or wing to clear the large diameter propeller. The propeller disk also acts as a lifting surface such that when a vertical gust is encountered in forward flight for instance, there is a tangential force vector generated on the propeller disk. The gust load, engine mass under various g-loads and propeller thrust all act on the cantilevered pylon structure. These loads can be significant and will have to be properly analysed to verify adequate structural design.

Flexible shock mounting is used in many engine installations to reduce engine vibration transmission into the fuselage structure and cabin to improve structural fatigue and provide improved passenger comfort. Shock mounting adds additional springs into the structural system and this must be taken into account during the structural analysis of the propulsion system assembly.

A turbofan engine installation has similar design challenges, though with a smaller "disk" diameter, shorter distance from engine to the mounting fuselage or wing, the problem is somewhat less than the equivalent turboprop installation design. Figure 11.10 shows the A-40 flying boat with over-wing mounted turbofan engines. Figure 11.14 shows pylon-mounted turboprop propulsion engines for a proposed large twin fuselage WIG.

Fig. 11.14 Pylon-mounted turboprop propulsion engine arrangement for large WIG

Engine and System Cooling

Internal Systems Installation

For designs that install the basic power plant internally, there are some different design issues to deal with. The obvious one is that there are requirements for a transmission system that transfer the power from the internally mounted engine to the external lift or propulsion units.

The weight and cost of the additional transmission system should be taken into consideration when conducting the overall vehicle design optimisation. The internal engine installation does provide some benefits and one is the design and engine selection flexibility. The engine envelope, size and profile are less restricted compared to external mounted engines. The engine frontal area does not cause excessive drag. The cooling system, especially with remote-located radiators, can be arranged to give a flexible hull internal layout.

Internally installed turbine engines do require provision for effective inlet and exhaust systems that can handle the large airflow required. The inlet can be a scoop or pitot type or it can be flush like the NACA inlet design.

The pitot-type inlet generally provides better inlet pressure recovery and thus offers better engine performance, but inlet de-icing is required. The NACA flush inlet does not offer as high-pressure recovery as the pitot-type inlet, but the vortex formation in the curved lip profile eliminates the ice protection requirement.

Fuselage-mounted side inlet designs are sensitive to vehicle sideslip angle, and similarly the top-mounted inlets are sensitive to the angle of attack. Care must be taken to design an inlet configuration that can handle various flight conditions within the design flight envelope.

In many cases, an inlet is designed offset from the fuselage therefore offering a boundary layer bypass effect to provide more uniform inlet flow velocity and recovery effectiveness. The benefit of top or near top-mounted engine inlet designs is to locate the inlet such that the water spray ingestion issues are minimised.

Water Spray

Water spray is always a major design consideration for engine location for a WIG vehicle. Most turbine engines are designed to be able to handle a moderate amount of water to be swallowed by the engine, but a WIG has to be designed to be able to operate on water at various wave conditions.

The locations of externally mounted engines are critically important in order to minimise the possible water spray ingestion. Designers normally mount the engine as high above the waterline as possible, but that also creates a problem as the high thrust line creates a significant pitching moment. Taking advantage of wing, canard or fuselage to shield the engine inlet from water spray is common design practice for WIG as it is also for seaplane design.

Engine and System Cooling

Turbine engines have airflow pass through the engine core continuously and require no additional engine-cooling provision in most designs. The cooling requirements are in the systems such as the generator and the ECU (engine control unit).

For internal combustion engines, the installation considerations are similar to turbine engines but the system functions and cooling design are different. Internal combustion engines require a separate cooling system. For designs that incorporate propulsor direct mounting to the engine output shaft flange, a nacelle that provides a streamlined engine housing and also incorporates an engine-cooling inlet and exhaust passage are required.

The aircraft-type air-cooled IC engines are normally designed to have cylinders with cooling fins arranged such that the cooling airflow either comes from the top then flows through cylinder fins downward or the other way around. It is important to divide the nacelle into two chambers, the upper (relative to inlet-connected chamber) chamber and the lower chamber should be separated by the engine cylinders.

The higher pressure of the upper chamber is to be generated by ram air through the inlet and pressure recovery generated by the diffuser (if any). The low pressure of the lower chamber can be just ambient pressure at the exit or further lowered by an aft-facing exit ramp that generates negative pressure.

The pressure differential between the two chambers forces the airflow through the engine-cooling fins that maintain CHT to be within design spec throughout the operating envelop. The cooling flow rate can be adjusted by opening up the exit ramp angle to generate more negative pressure as necessary. Propeller slip stream can be helpful in engine cooling especially at low forward speed operations (low dynamic pressure from free air stream generated by the vehicle speed)

Some designs provide a tighter seal around the upper chamber by adding a “dog house” on to the engine so that the inlet flows directly into the dog house to maximise cooling effectiveness. It is very important to understand that internal drag is as bad as external drag. A well-optimised cooling system for an IC installation can reduce the cooling drag from an average 12% down to 5% of total engine power compared to a brute force low-tech design.

Additional provisions for an oil cooler, air-conditioning condenser unit and intercooler system if applicable require special attention, as if any of these systems over-heat the result will be operating limitations for the vehicle. Figure 11.15 shows a Teledyne Continental Motor FADEC internal combustion engine installation in a light aircraft.

Fig. 11.15 Avco Lycoming light aircraft engine installation showing air-cooling arrangement

Automotive and marine engines are mostly designed to work with a radiator for engine cooling (water-cooled) as well as some aircraft engines. This arrangement allows remote installation of the radiators that offers some flexibility in configuration design. The cooling air system for a radiator is no different than a direct air-cooled engine-cooling system design. The inlet, the diffuser, the exhaust duct, etc. all have to be designed to maximise the ram air dynamic pressure recovery, avoid any flow separation in the ducting and the diffuser, and that the exit chamber and exit flow dynamic pressure recovery are maximised for minimum cooling drag. Variable speed electrical cooling fan for the radiator can be a useful device for adjusting the amount of cooling provided to the engine under different operating speed and conditions.

Ice Protection

The WIG vehicle's low operating altitude exposes these vehicles to the worst possible icing envelope. All lifting surfaces and engine inlets are required to be anti-iced or with de-ice capabilities in order to operate safely in icing conditions.

Engine bleed air from the high- or low-pressure compressor stages of the turbine engines is commonly used to provide anti-ice heating for the engine inlet. This is to prevent large ice block build-up on the inlet and that would cause engine damage if sucked into the engine after breakage.

The inlet anti-icing can be accomplished by routing a fraction of the available engine bleed air through the ducted inlet lip. The high bleed air temperature will prevent ice from forming on the inlet. Additional bleed air can be routed to the wing and tail leading edge to provide ice protection. The power plant installation design should include all these system connections, routing and control unit installations.

Transmission Systems

Drive Shaft

For WIG designed with an engine installed separate from the fan or propeller for either a lift system or propulsion requires a gearbox and/or drive shaft as part of the transmission. One of the important parameters to take into consideration in drive system design is the system dynamics.

It is very important to design a drive system that will not create vibration at the structure natural frequencies. This can be accomplished by designing the fuselage and transmission support structures to have natural frequencies away from the drive system or adjusting the propulsion system to operate at rpm offset from the structural natural frequencies.

If the natural frequency of the drive shaft coincides with the first several harmonics of the basic vehicle structure or flight control system natural frequencies, sympathetic vibration can result and induce fatigue failure quickly. Depending on the drive shaft length and diameter ratio, a long slender drive shaft can have a low natural frequency that is more likely to fall in the range of the structural natural frequencies. Modern graphite composite drive shafts can be designed to provide a lightweight, rigid drive system with high natural frequency thus avoiding many of the system dynamics problems. Figure 11.16 shows a WIG drive shaft arrangement. Figure 11.17 shows a composite drive shaft design.

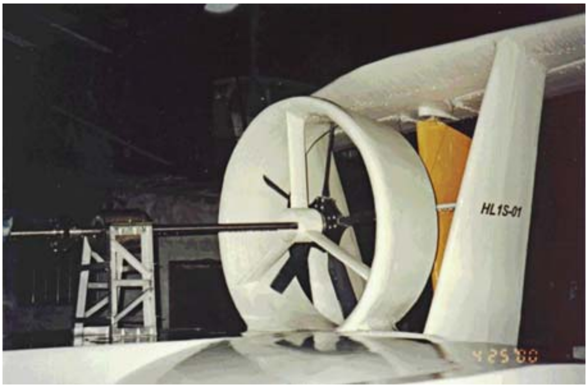


Fig. 11.16 WIG-ducted fan installation

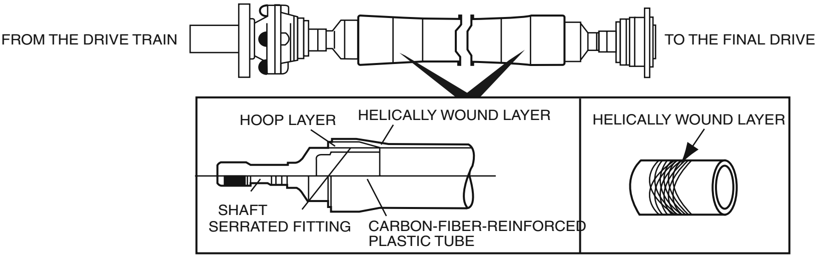


Fig. 11.17 Carbon fibre transmission shaft

Transmission

For some engines, the engine rpm can be significantly higher than the propulsor or lift fan requirement. To match the rpm and torque to the “driven device”, a reduction drive is required. There are many possible designs including gearboxes, belt drive and a fluid drive system. The requirement for transmission can come from the need for the offset of drive shaft centreline to the engine output shaft. In many cases, the transmission design would provide the combined solution. Figure 11.18 shows a belt drive reduction system with centreline offset.

A planetary gear reduction system is sometimes installed on turbine engines where the core operates at 40,000 rpm or higher. Turboprop engines sometimes

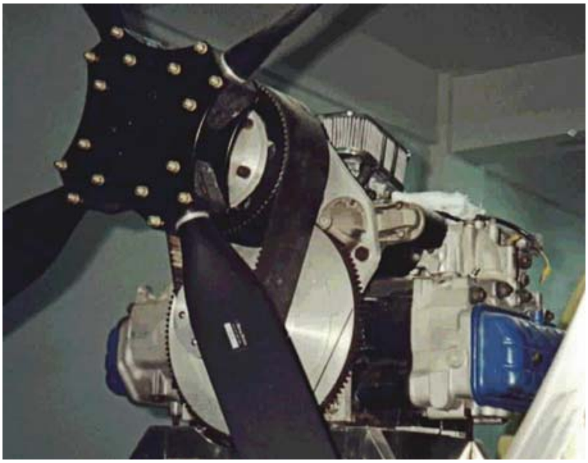


Fig. 11.18 Belt drive reduction to propeller transmission

incorporate an additional external-mounted gear reduction unit attached to the core engine to match with the required propeller speed. These engines are often designed as a package to interface with a propeller directly and are equipped with hydraulic lines through the shaft to provide hydraulic propeller pitch control. Figure 11.19 shows the Honeywell TPE 331 turboprop engine with direct mounted reduction gearbox

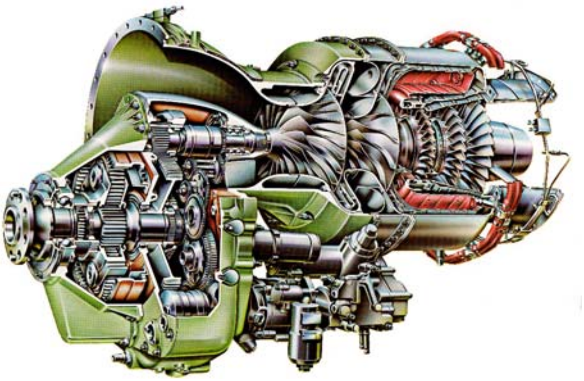


Fig. 11.19 Garrett TPE 331 turboprop engine with direct mounted reduction gearbox

For internal engine installation, a turboshaft engine would commonly incorporate an integrated gear reduction drive to reduce the output shaft to 3,000 rpm range. For turboshaft applications, an additional drive system to interface the engine output to the propulsor or lift system is required.