Helicopter Turboshafts

Luke Stuyvenberg
University of Colorado at Boulder
Department of Aerospace Engineering

The application of gas turbine engines in helicopters is discussed. The workings of turboshafts and the history of their use in helicopters is briefly described. Ideal cycle analyses of the Boeing 502-14 and of the General Electric T64 turboshaft engine are performed.

I. Introduction to Turboshafts

Turboshafts are an adaptation of gas turbine technology in which the principle output is shaft power from the expansion of hot gas through the turbine, rather than thrust from the exhaust of these gases. They have found a wide variety of applications ranging from air compression to auxiliary power generation to racing boat propulsion and more. This paper, however, will focus primarily on the application of turboshaft technology to providing main power for helicopters, to achieve extended vertical flight.

II. Relationship to Turbojets

As a variation of the gas turbine, turboshafts are very similar to turbojets. The operating principle is identical: atmospheric gases are ingested at the inlet, compressed, mixed with fuel and combusted, then expanded through a turbine which powers the compressor. There are two key diferences which separate turboshafts from turbojets, however.

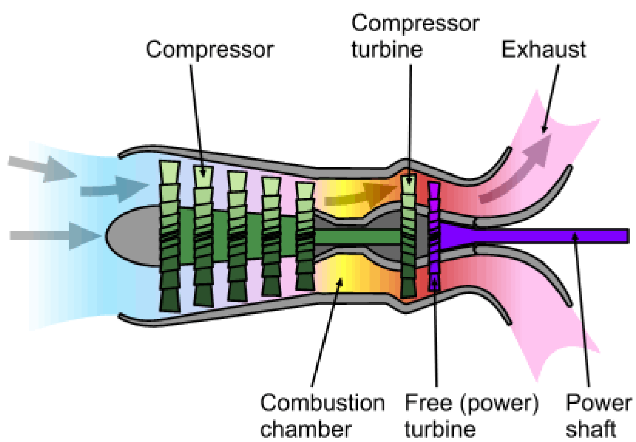

Figure 1. Basic Turboshaft Operation

Note the absence of a mechanical connection between the HPT and LPT. An ideal turboshaft extracts with the HPT only the power necessary to turn the compressor, and with the LPT all remaining power from the expansion process.

A. Emphasis on Shaft Power

Unlike turbojets, the primary purpose of which is to produce thrust from the expanded gases, turboshafts are intended to extract shaft horsepower (shp). This emphasis, in fact, leads to a desire in a maximally-efficient turboshaft engine to minimize what becomes known as 'residual thrust'. In a turboshaft engine, the turbine is usually split into two sections. The first, the high pressure turbine (HPT), is used to drive the compressor, closing the thermodynamic 'loop'. The second, low-pressure section of the turbine (low pressure turbine (LPT)) is usually mechanically disconnected from the first, and is thus referred to as a 'free power turbine'. Just as the HPT provides shaft power to the compressor, it is this section that provides the *output* shaft power.

B. Gear Reduction

As a direct result of the shaft power focus, turboshaft engines are very often required to use a transmission gearbox to exchange the shaft's rotational velocity for torque. For instance, while the free power turbine (FPT) might rotate at over 3,000 RPM, helicopter blades tend to rotate at speeds between 300 and 400 RPM. This reduction, possibly as high as or higher than a ratio of 10:1, unavoidably requires a heavy transmission. However, unlike their turboprop cousins, turboshaft transmissions can often be connected to the structure, rather than requiring the engine itself to bear the load of a propeller.

Recent helicopter designs have included electromagnetic transmissions,[1] which can greatly reduce the mechanical wear, and perhaps failure rate,[2] of previously mechanical transmissions.

III. Turboshaft Applications

Although this paper will focus on the application of turboshafts to vertical flight, turboshafts have found a wide variety of applications worth briefly mentioning.

A. Aircraft

Besides their use powering helicopters, turboshafts are also employed on most airliners as auxiliary power units (APUs), where they power electrical generators to ensure the aircraft can continue to function when the main engines have been damaged.

B. Ground Vehicles

Turboshaft engines have also been used to drive ground vehicles, ranging from the MTT Turbine Superbike (powered by the Rolls-Royce 250-C18: 320 shp at 52,000 RPM) to the American M1 Abrams main battle tank (powered by the Honeywell AGT1500: 1,500 shp at 2865 RPM).[3]

C. Marine

Some high-performance racing boats use turboshaft engines for power. Often these are adapted from military surplus; the General Electric T53, T55, and T58[a] are especially popular. (These produce anywhere from 1250 shp to 1870 shp.)[4]

[a]Interestingly, the GE T58 was among the first turbines certified for use in civilian helicopters. Now retired from that use, surplus units find a home in hobbyists' racing boats.

D. Other

Some other applications of turboshaft engines beyond powering transportation include generating electrical power (as in aircraft APUs), and as high-performance fluid pumps (often used by petroleum companies in a process known as hydraulic fracturing).[5]

IV. Helicopter History

Most sources suggest the idea for vertical flight stems from the synthesis of a Chinese toy – a two-bladed propeller extending from a shaft, spun between the hands and released – and Leonardo da Vinci's sketch of a 'flying screw'. Da Vinci provided the idea: vertical flight carrying individuals; while the toy provided the feasible rotor.[6] Arguably the next most important step was taken by Mikhail Lomonosov, who produced a spring-powered coaxial model with counter-rotating blades, solving the torque-balancing issue.

However, inventors pursuing these early designs quickly found that propulsion was a significant issue. The external-combustion steam engine technology of the mid- to late-1700's could not be made both light enough and powerful enough to lift a significant payload. Attemps of the mid-1800's were focused on reducing the helicopter's weight – Gustave de Ponton d'Amécourt produced a prototype in 1861 made of aluminium, but was unable to lift off.

Seventeen years later, in 1878, Italian inventor Enriko Forlanini produced a steam-powered unmanned model which successfully lifted off. This was followed by numerous models from other inventors – Thomas Edison's failed attempt at using an internal combustion engine in 1885, Gustave Trouvé's tethered electric model in 1887, and Ján Bahýl"s successful internal combustion model in 1905.

From then on, development proceeded more rapidly: French brothers Jacques and Lois Breguet succeeded in manned (but tethered) flight in 1907; Paul Cornu succeeded in untethered piloted flight later that same year; Jacob Ellehammer built a prototype with coaxial counter-rotating discs in 1912. Between 1920 and 1930, records were slowly established using internal combustion model helicopters, increasing maximum payload and flight duration steadily, improving controls. In 1942, the Sikorsky R-4 became the first helicopter model to enter full production.

Finally, in 1951, Charles Kaman retrofitted a K-225 Synchrocopter with a Boeing 502 turboshaft engine, becoming the first turbine-powered helicopter. In 1954, a Navy HTK-1 was fitted with two turbines to provide additional power and engine redundancy. In 1955, the French company Sud Aviation developed the Aérospatiale Alouette II, the first helicopter designed with a turboshaft engine in mind – the Turbomeca Artouste IIC6 turboshaft. This marked the beginning of a new age of helicopter design, making use of the light, high-power gas turbine engines to power the drive shaft for the main roter – a turboshaft.

Figure 2. K-225 w/ Boeing 502 Turboshaft

Windsor Locks, CT; piloted by William Murray. 10 December 1951. Image via Flickr under CC-BY-SA.

V. Helicopter Applications

Since their inception, helicopters have found uses wherever landing space is in short supply. Standing military forces of nations around the world often employ helicopters where an airstrip can't be located, where terrain might prohibit the take-off or landing of fixed-wing aircraft. These helicopters might serve cargo operations, carrying both supplies and personnel between locations; or they may be armed, acting as aerial support for forces on the ground, providing cover in tight locations that fixed-wing aircraft would be unable to reach.

The private sector, too, has need of the vertical take-off and landing capabilities of helicopters: some hospitals, for example, use helicopters as ambulances, ferrying the sick or injured from locations difficult to reach by ground. Oil companies invested in offshore drilling usually use helicopters to transport workers to the drilling platforms. Construction companies often use helicopters as 'aerial cranes,' lifting heavy equipment into otherwise-inaccessible locations. Some law enforcement agencies use helicopters to pursue fleeing criminals.

VI. Engine Analyses

A. Boeing 502-14

The Boeing 502, as noted earlier, was the first turbine installed in a helicopter – the Kaman K-225 Synchroncopter. First developed in 1947, the 502 consists of a single-stage centrifugal compressor, followed by two can combustors, a single-stage HPT which powers the compressor, and a single-stage LPT which provides up to 330 shp at a specific fuel consumption of 0.532 kilograms per kilowatt-hour.

According to Jane's "All the World's Aircraft," the 502-14 had a overall pressure ratio (OPR) of 4.35:1, a turbine entry temperature (TET) of (approximately) 889 Kelvins, and a mass flow rate of 1.9 kilograms per second.[7] The achieved power-to-weight ratio is 2.523 kilowatts per kilogram.

Ideal Cycle Analysis We'd like to perform an ideal cycle analysis on this engine. We start with a few constants (these will be the same in later analyses):

$$\begin{aligned} \gamma &= 1.4 \\ c_p &= 1004 \text{ J kg}^{-1} \text{ K}^{-1} \\ h_{pr} &= 42.8 \text{ MJ kg}^{-1} \\ R = c_p \frac{\gamma - 1}{\gamma} &= 286.86 \text{ J kg}^{-1} \text{ K}^{-1} \end{aligned}$$

Now some parameters for the 502. We'll suppose a low intake mach number – the K-522's top speed was 117 kilometers per hour, with a well-understood piston engine. We'll also assume near-sea-level operation, and a 50% conversion efficiency.

$$\begin{aligned} \eta_c &= 0.5 \\ T_0 &= 288 \text{ K} \\ M_0 &= 0.1 \\ a_0 = \sqrt{\gamma R T_0} &= 340.09 \text{ m s}^{-1} \end{aligned}$$

We first calculate relevant temperature ratios:

$$\begin{aligned} \tau_\lambda = \frac{\text{TET}}{T_0} &= 3.0868 \\ \tau_r = 1 + \frac{\gamma - 1}{2} M_0^2 &= 1.0020 \\ \tau_c = \pi_c^{\frac{\gamma-1}{\gamma}} &= 1.5220 \end{aligned}$$

We can use this to write an expression for the ratio of the exit flow speed (which we'd like to minimize) to the ambient sound speed:

$$\frac{u_9}{a_0} = \left[\frac{2}{\gamma - 1} \left(\frac{\tau_\lambda}{\tau_r \tau_c} \right) (\tau_r \tau_c \tau_t - 1) \right]^{1/2}$$

Since the ideal power-specific fuel consumption occurs when $u_9 = u_0/\eta_c$, where η_c represents the output power conversion efficiency, we can solve the above equation for the overall turbine temperature ratio:

$$\frac{u_0}{\eta_c a_0} = \left[\frac{2}{\gamma-1}\left(\frac{\tau_\lambda}{\tau_r\tau_c}\right)(\tau_r\tau_c\tau_t - 1)\right]^{1/2}$$

$$\frac{M_0^2}{\eta_c^2}\frac{\gamma-1}{2}\frac{\tau_r\tau_c}{\tau_\lambda} = \tau_r\tau_c\tau_t - 1$$

$$\tau_t = \frac{1}{\tau_r\tau_c} + \frac{(\gamma-1)M_0^2}{2\tau_\lambda\eta_c^2} = 0.65829$$

$$\frac{u_9}{a_0} = 0.2$$

Knowing that the power across the HPT must equal the power required to drive the compressor,

$$\tau_{tH} = 1 - \frac{\tau_r}{\tau_\lambda}(\tau_c - 1) = 0.83054$$

we can calculate the LPT temperature ratio

$$\tau_{tL} = \frac{\tau_t}{\tau_{tH}} = 0.79261$$

Returning to the exit flow velocity ratio, we can calculate the core stream specific thrust:

$$\frac{F_c}{\dot{m}_0} = a_0\left(\frac{u_9}{a_0} - M_0\right) = a_0\left(\left[\frac{2}{\gamma-1}\left(\frac{\tau_\lambda}{\tau_r\tau_c}\right)(\tau_r\tau_c\tau_t - 1)\right]^{1/2} - M_0\right) = 34.009 \text{ m s}^{-1}$$

We then write the specific power as

$$S_P = \frac{F_c u_0}{\dot{m}_c} + \frac{\eta_c P}{\dot{m}_c} = \frac{F_c a_0 M_0}{\dot{m}_c} + c_p T_0 \tau_\lambda \tau_{tH}(1 - \tau_{tL})\eta_c = 78.027 \text{ kW (kg s}^{-1})^{-1}$$

which gives a total shaft power

$$P = S_P \times \dot{m}_0 = 148 \text{ kW}$$

Since the enthalpy balance over the combustor is unchanged from a turbojet,

$$f = \frac{c_p T_0}{h_{pr}}(\tau_\lambda - \tau_r\tau_c) = 0.010551$$

and so we can write the power-specific fuel consumption

$$S_{Pfc} = \frac{f}{S_P} = 135.2 \text{ mg s}^{-1} \text{ kW}^{-1}$$

As expected for ideal cycle analysis, the estimated power-specific fuel consumption is considerably lower than the rated value, even at 'cruise' conditions. Likewise the predicted power output is much lower than the stated value.

B. General Electric T64

The General Electric T64 Turboshaft was originally produced in 1964. This engine has a 14-stage axial high pressure compressor (HPC) to pressurize the incoming gas, uses annular combustors to impart energy to the stream, then expands these gases through a 2-stage axial HPT to power the turbine, followed by a 2-stage axial LPT to drive the output gearbox.[8]

Numerous helicopters have used the GE T64 as their power plant. The Sikorsky CH-53E Super Stallion uses three such engines to provide power and redundancy for continuous flight, with a maximum take-off weight (MTOW) of 33,300 kilograms, a cruise speed of 278 kilometers per hour, and a service ceiling of 5,640 meters. The T64 was also used to power the Lockheed AH-56 Cheyenne, one of the U.S. Army's first attack helicopters, with a MTOW of 11,740 kilograms, a cruise speed of 362 kilometers per hour, and a service ceiling of 6,100 meters. The T64 has also, as a turboprop, powered numerous fixed-wing aircraft, both military and civilian.

According to GE, the engine produces a maximum of 4330 shp (T64-100) with a specific fuel consumption of 0.292 kg kW^{-1} hr^{-1}. The OPR is 14.9:1; the TET is 911.15 K.[9] Its design power-to-weight ratio is 9.887 kW kg^{-1}.

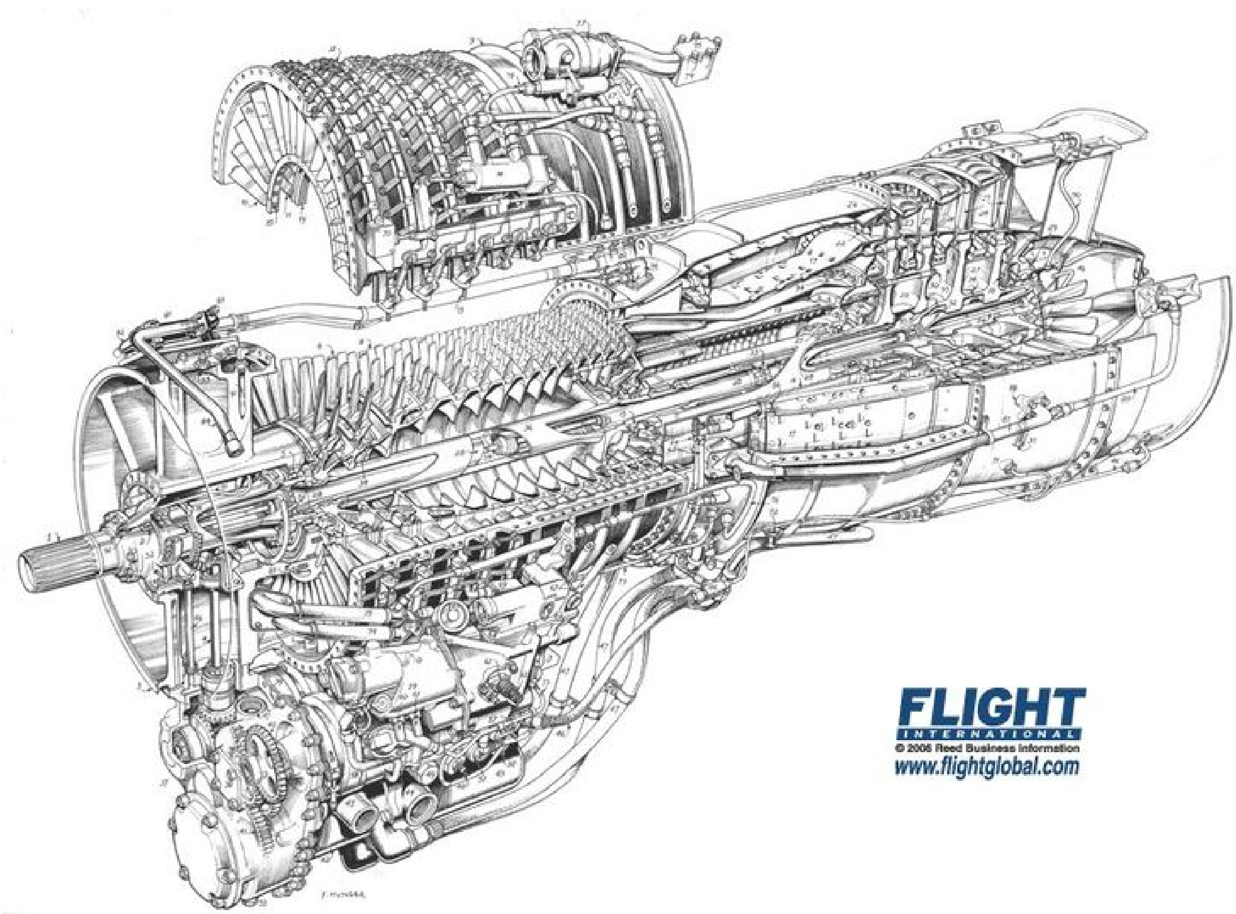

Figure 3. GE T64 Cutaway View

Note the 14-stage compressor and 2- and 2-stage turbines. Image via www.flightglobal.com.

Ideal Cycle Analysis

We'll also perform an ideal cycle analysis on the T64, first at cruise conditions for a Sikorsky Super Stallion. Keeping the constants from above, but with different conditions, we calculate,

$$T_0 = 252 \text{ K}$$
$$M_0 = 0.22$$
$$a_0 = \sqrt{\gamma R T_0} = 318.13 \text{ m s}^{-1}$$

We first calculate relevant temperature ratios:

$$\tau_\lambda = \frac{\text{TET}}{T_0} = 3.6157$$
$$\tau_r = 1 + \frac{\gamma-1}{2}M_0^2 = 1.0097$$
$$\tau_c = \pi_c^{\frac{\gamma-1}{\gamma}} = 2.1637$$

As before, we assume an ideal power-specific fuel consumption and solve the above equation for the overall turbine temperature ratio:

$$\tau_t = \frac{1}{\tau_r\tau_c} + \frac{(\gamma-1)M_0^2}{2\tau_\lambda\eta_c^2} = 0.46193$$

$$\frac{u_9}{a_0} = 0.275$$

We then calculate the turbine temperature ratios:

$$\tau_{tH} = 1 - \frac{\tau_r}{\tau_\lambda}(\tau_c - 1) = 0.67504$$
$$\tau_{tL} = \frac{\tau_t}{\tau_{tH}} = 0.68430$$

Which, along with the core stream thrust

$$\frac{F_c}{\dot{m}_0} = a_0\left(\frac{u_9}{a_0} - M_0\right) = a_0\left(\left[\frac{2}{\gamma-1}\left(\frac{\tau_\lambda}{\tau_r\tau_c}\right)(\tau_r\tau_c\tau_t - 1)\right]^{1/2} - M_0\right) = 17.4968 \text{ m s}^{-1}$$

gives the specific power

$$S_P = \frac{F_c u_0}{\dot{m}_c} + \frac{\eta_c P}{\dot{m}_c} = \frac{F_c a_0 M_0}{\dot{m}_c} + c_p T_0 \tau_\lambda \tau_{tH}(1 - \tau_{tL})\eta_c = 157.2 \text{ kW (kg s}^{-1})^{-1}$$

$$f = \frac{c_p T_0}{h_{pr}}(\tau_\lambda - \tau_r\tau_c) = 0.0084594$$

which yields the power-specific fuel consumption

$$S_{Pfc} = \frac{f}{S_P} = 0.194 \text{ kg kW}^{-1} \text{ hr}^{-1}$$

As before, ideal cycle analysis drastically underestimates the power-specific fuel consumption. Unfortunately, without knowing the mass flow rate, we can't validate the engine's power production according to the ideal analysis.

Repeating the analysis at sea-level static conditions:

$$\begin{aligned}
T_0 &= 288 \text{ K} \\
M_0 &\approx 0 \\
a_0 &= 340 \text{ m s}^{-1} \\
\tau_t &= 0.46217 \\
\tau_{tH} &= 0.63217 \\
\tau_{tL} &= 0.73108 \\
u_9/a_0 &\approx 0 \\
F_c/\dot{m}_0 &\approx 0 \text{ m s}^{-1} \\
f &= 0.0067560 \\
S_P &= 124.4 \text{ kW (kg s}^{-1})^{-1} \\
S_{Pfc} &= 54.303 \text{ mg s}^{-1} \text{ kW}^{-1}
\end{aligned}$$

Obviously, the engine itself is not ideal; most likely, losses in the FPT leading to a non-optimum exhaust velocity (and thus a non-negligible residual thrust) lead to a higher power-specific fuel consumption; as well, excessive power extraction in the HPT might reduce the power available to the FPT.

VII. Other Notable Engines

A. Lotarev D-136

The Lotarev D-136 is a product of Ukranian company Ivchenko Progress. Two of these engines are used to power the Soviet Mil Mi-26 heavy transport helicopter, used both for civilian and military cargo operations. According to Ivchenko Progress' product page, the D-136 produces 11,400 shp and has a specific fuel consumption of 0.198 kg hp^{-1} hr^{-1} at sea level static (SLS) conditions.

B. Pratt & Whitney F135-PW-600

Although technically a turbofan engine, the P&W F135-PW-600 bears mentioning here due to its unique ability to operate in a partial-turboshaft mode when powering the Rolls-Royce LiftSystem in the F-35 Joint Strike Fighter. When operating in this mode, it is quoted as producing 30,000 shp to drive the body-centered LiftFan which produces the bulk of the 182 kilonewtons of lift required for STOVL operation.

VIII. Conclusion

The technology behind helicopters was developed primarily over a stretch of one hundred years, from the late 1800's to the modern day. During that time, internal combustion engines became lighter and more efficient, leading up to the Bell 47, one of the most popular helicopter models of the pre-turbine age, with a maximum speed of 169 kilometers per hour, a range of 395 kilometers, and a MTOW of 1340 kilograms. Then came the era of the turbine-powered helicopter. The Aérospatiale Alouette II, the first helicopter designed with a gas turbine engine in mind, had a maximum speed of 185 kilometers per hour, a range of 565 kilometers, and a MTOW of 1600 kilograms.

Certainly, other advancements in materials and engineering during this ten year design gap may have contributed to this dramatic performance increase, but nevertheless, turboshaft engines have proliferated in the years since, and presently only the lightest of manned helicopters are still powered by internal combustion engines.

References

[1]Andrew, A. F. et al., "Helicopter flight control system," March 30 1965, US Patent 3,175,786.

[2]"Annual Safety Review," 2011.

[3]Colucci, F., "Heavy duty: overhaul underway for Abrams tank engine," 2006.

[4]Walsh, P. P. and Fletcher, P., *Gas turbine performance*, John Wiley & Sons, 2004.

[5]Crom, E., "Pump system for high pressure applications," May 22 2014, WO Patent App. PCT/US2013/069,463.

[6]Johnson, W., *Helicopter Theory*, Dover Books on Aeronautical Engineering, Dover Publications, 2012.

[7]Taylor, J. W. R. and Jane, F. T., *Jane's All the World's Aircraft, 1965-66*, McGraw-Hill Book Company, 1965.

[8]Aviation Week, *Aerospace Source Book 2009*, Aviation Week & Space Technology, 2009.

[9]Leyes, R. and Fleming, W., *The History of North American Small Gas Turbine Aircraft Engines*, Library of Flight, AIAA, 1999.

Glossary

APU auxiliary power unit.

FPT free power turbine.

HPC high pressure compressor.

HPT high pressure turbine.

LPT low pressure turbine.

MTOW maximum take-off weight.

OPR overall pressure ratio.

shp shaft horsepower.

SLS sea level static.

TET turbine entry temperature.