Comparison of Helicopter Turboshaft Engines

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Although they garnish less attention than their flashy jet cousins, turboshaft engines hold a specialized niche in the aviation industry. Built to be compact, efficient, and powerful, turboshafts have made modern helicopters and the feats they accomplish possible. First implemented in the 1950s, turboshaft geometry has gone largely unchanged, but advances in materials and axial flow technology have continued to drive higher power and efficiency from today's turboshafts. Similarly to the turbojet and fan industry, there are only a handful of big players in the market. The usual suspects - Pratt & Whitney, General Electric, and Rolls-Royce - have taken over most of the industry, but lesser known companies like Lycoming and Turbomeca still hold a footing in the Turboshaft world.

Nomenclature

shp = Shaft Horsepower
SFC = Specific Fuel Consumption
FPT = Free Power Turbine
HPT = High Power Turbine

Introduction & Background

Turboshaft engines are very similar to a turboprop engine; in fact many turboshaft engines were created by modifying existing turboprop engines to fit the needs of the rotorcraft they propel. The most common use of turboshaft engines is in scenarios where high power and reliability are required within a small envelope of requirements for size and weight. Most helicopter, marine, and auxiliary power units applications take advantage of turboshaft configurations. In fact, the turboshaft plays a workhorse role in the aviation industry as much as it is does for industrial power generation.

While conventional turbine jet propulsion is achieved through thrust generated by a hot and fast exhaust stream, turboshaft engines creates shaft power that drives one or more rotors on the vehicle. Figure 1 shows a view of the internals of a typical turboshaft engine. Air comes into the engine through an inlet and is sent through a compressor. The compressor can be a combination of one to many stages of both centrifugal and axial compressors depending on the engine size, manufacturer, and power output. The compressed air is then sent through the combustor raising the temperature of the air.

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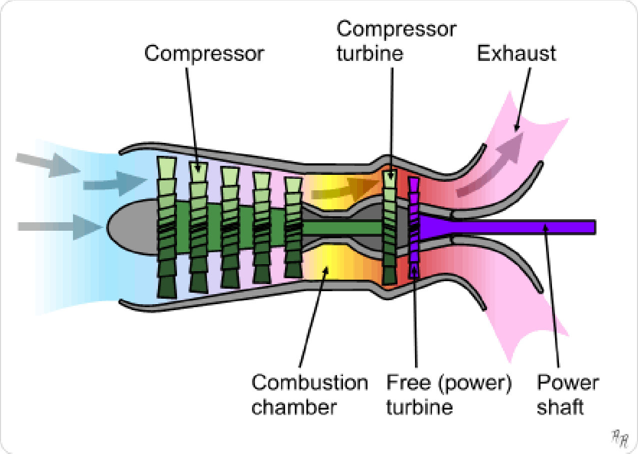

Figure 1: Inside of a typical turboshaft engine

Upon exiting the combustor the air goes through the compressor turbine(s). Here the necessary power is extracted to operate the compressor. Again the compressor turbine can be a single stage or many stages depending on the power requirements of the compressor. Finally the gas reaches the Free Power Turbine (FPT) and exhausted. This is the main difference between turboshaft and turboprop engines. As mentioned previously, the purpose of a turboshaft engine is to drive a rotor of the helicopter. The exhaust of the engine is not intended to provide much if any thrust to the vehicle. The job of the FPT is to extract as much power from the gas and turn that into shaft power. In turn the power shaft (shown in purple in Figure 1) connects to a gearbox and is then translated to the rotor itself. Note that the exhaust of the engine does not exit axially out the back of the turboshaft engine in all cases. Although Figure 1 shows one implementation of a turboshaft, it is not consistent throughout the field. Many times the power shaft traverses through the entire engine to the front of the engine, and commonly the air inlets are at the rear of the engine. One other big difference between turboprops and turboshafts is that the stress of the rotor is not placed on the engine in a turboshaft. The engine power shaft connects to a transmission/gearbox which is attached to the frame of the aircraft. The frame then takes the load and not the engine.

Development of the gas turbines and turboshafts especially really picked up in the 1950s era. One of the first was the Turbomeca Artouste which was originally designed as an APU later becoming the Turmo engine. However, the first engine to power a helicopter was the Boeing T50 turboshaft, which flew on the Karam K225 Synchropter in 1951. Today there are a few companies that lead the way, controlling the turboshaft market. These being: Pratt and Whitney Canada, Rolls-Royce, Turbomeca, Lycoming, and GE.

Pratt and Whitney Canada

PWC is a division of the Pratt and Whitney company, however it performs its own research and development. It is based out of Canada and focuses on the design, development, and manufacturing of smaller aircraft engines, in particular turboprops and turboshafts. PWC started developing the PT6 turboprop in the 1950's and launched in the early '60s becoming its flagship product. Almost all of their turboshaft engines were derived from turboprops as they are very similar in nature. Many variants, like the PT6B/C and PT6T Twin-Pac, found in Table 1, all came from the PT6A, falling in the 1000-2000 shp category.. The Twin-Pac is made up of two of these PT6A engines that meet at a combining gearbox. Figures 2 and 3 show the PT6T engine. The first gives a side profile, including the internal mechanics. It also shows the use of a reverse flow combustor. Figure 3 on the right shows an iso-view with the combining gearbox on the front.

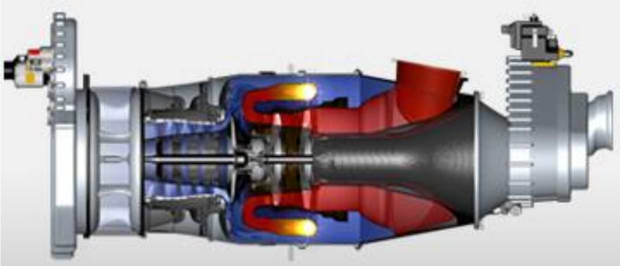

Figure 2:Inside of a PT6T engine

Figure 3:PT6T engine with showing combining gearbox in front

Table 1: PWC Turboshaft Engine Comparison

Engine	PT6B	PT6C	PT6T	PW200
Notable applications	AW119 Koala	UH-1 Global Eagle	Bell 212/412 CH-146, AH1J SeaCobra	EC135, Bell 429
Power (shp)	1000	1600-2000	1800-2200	500-700
Weight (lbs)	385	418	660	237
Pressure Ratio	7.1	Unknown	6.3	8
Turbine inlet Temp (K)	Unknown	Unknown	Unknown	Unknown
SFC	0.594	~0.59	0.596	0.548
Compressor configuration	3 axial, 1 centrifugal	4 axial, 1 centrifugal	3 axial, 1 centrifugal	1 centrifugal
Turbine configuration	2 HPT, 2 FPT	2 HPT, 2 FPT	2 HPT, 1 FPT each	1 HPT, 1 FPT
P/m (shp/lb)	2.6	3.8-4.8	2.7-3.3	2.1-3.0

Rolls-Royce

Rolls-Royce is known as being one of the largest producers of power systems for air, land, and sea[**]. They develop and manufacture all different kinds of engines for both commercial and defense for airplanes, marine vessels, and helicopters. The main turboshaft engines produced by RR are shown in Table 2. The M250 series is the bread and butter of their turboshaft sector. The M250 shown in Figure 4, was first developed by the Allison Engine Company in the 1960s, and has been in production ever since. Allison Engine Company was later purchased by Rolls-Royce in the '90s, becoming a subsidiary company. Today there have been over 31000 engines produced with about half of them still in operation. The engine was designed to have the compressed air exiting the compressor is sent to the rear of the engine around the turbine system and turns 180 degrees to enter the combustor. The exhaust air then leaves at the middle of the engine, shown by the two large openings in Figure 4.

The engine has been applied to many different systems with over 40 variants. Of these, two of the most interesting applications are the RQ-8A unmanned helicopter produced by Northrop Grumman (Figure 5), and the MTT Turbine Superbike (Figure 6).

Figure 4: RR M250 turboshaft. Notice the color of paint indicating the temperature of the gases in that section

Figure 5: Northrop Grumman RQ-8A Fire Scout

Figure 6: The MTT Superbike uses an M250 turboshaft engine

With the success of the M250 series, RR developed a new slightly smaller engine, the RR300, based off the M250 containing modern improvements to materials and manufacturing. The RR300 contains only a single centrifugal compressor and with the traditional 4-stage turbine and puts out around 300 shp. At the current time, its major application is to the Robinson R66 helicopter.

Table 2: RR Turboshaft Engine Comparison

Engine	**M250 Series**	**RR300**	**CTS800**	**GEM**
Notable applications	RQ-8A, Fire Scout, Bell 206	Robinson R66	AW Lynx	AW Lynx
Power (shp)	450-715	240-300	1300-1600	1000
Weight (lbs)	161-274	176	375	414
Pressure Ratio	6.2-9.2	6.2	14	12
Turbine inlet Temp (K)	1250	Unknown	Unknown	Unknown
Specific fuel consumption (lb/lf-hr)	0.468	Unknown	Unknown	Unknown
Compressor configuration	4-6 axial, 1 centrifugal	1 centrifugal	2 centrifugal	4 axial 1 centrifugal
Turbine configuration	2 HPT, 2 FPT	2 HPT, 2 FPT	2 HPT, 2 FPT	2 HPT, 2 FPT
P/m (shp/lb)	2.6-2.8	1.7	3.5-4.3	2.4

One of the newer engines is the CTS800. This engine has been created by a joint venture between RR and Honeywell, called Light Helicopter Turbine Engine Company or LHTEC. The CTS800 produces a high pressure ratio of 14 using only two centrifugal compressors.

Safran Turbomeca

Turbomeca is a French manufacturer specializing in the design and production of small to medium sized helicopter engines ranging from 500 to 3000 shp. Currently about one of every three turboshaft engines employed on helicopters are made by Turbomeca, with over 18,000 in operation *. By far, Turbomeca's most popular engine is the Arriel with almost 12,000 produced to date with over 30 certified variants. The engine falls in the 590-990 shp category weighing in at 245 lbs. Like the majority of Turbomeca's engines it has a combined compressor consisting of centrifugal and axial stages. The only exception is the Ardiden engine, which has a two stage centrifugal compressor.

Table 3: Turbomeca Turboshaft Engine Comparison

Engine	Arrius	Arriel	TM333	Ardiden	Makila	RM322
Notable applications	Bell 505	A109, S-76C	HAL Cheetah/Dhruv/Chetak	Russian Ka-62	Eurocopter AS532 Cougar	AW AH-64D Apache
Power (shp)	450-750	590-990	900-1100	1400-2000	1800-2200	2100-2600
Weight (lbs)	223	245	367	452	615	503
Pressure Ratio	Unknown	9	10	Unknown	14	14.2
Turbine inlet Temp (K)	1140	1100	1500	Unknown	Unknown	Unknown
SFC	Unknown	0.573	0.529	Unknown	0.481	0.45
Compressor configuration	1 centrifugal	1 axial, 1 centrifugal	2 axial, 1 centrifugal	2 centrifugal	3 axial, 1 centrifugal	3axial, 1 centrifual
Turbine configuration	1 HPT, 2 FPT	2 HPT, 1 FPT	1 HPT, 1 FPT	1 HPT, 2 FPT	2 HPT, 2 FPT	2 HPT, 2 FPT
P/m (shp/lb)	2.0-3.4	2.4-4.0	2.6	3.0-4.4	2.9-3.5	4.2-5.2

One of the newest engines at Turbomeca is the Arrano. It fills a gap in the preceding table with a shaft power of 1100 to 1300. The Arrano was designed to be more fuel efficient, claiming a 10-15% increase in the specific fuel consumption of the engine. To do this many innovations were introduced to the design. These include a new thermodynamic core, with a dual-stage centrifugal compressor with variable-pitch inlet guide blades. It also used additive manufacturing to create the injectors for the combustion chamber. This engine has been selected as the sole source for the new twin-engined H160 from Airbus entering into service in 2018.

Textron (Avco) Lycoming

Paving the way for turboshaft propulsion aboard modern helicopters, the Bell UH-1 "Huey" was powered by the Lyocoming T53 turboshaft. In production since the early 1950s, the T53 was originally designed by Anselm Franz - the man behind the famous Jumo 004 World War II turbojet. The T53 and the Huey it propelled would go on to secure a definitive place for turboshaft driven military helicopters following its role in the Vietnam War. Today, Lycoming is a part of the Textron umbrella corporation, and produces turboshaft engines for aviation as well as other marine and military applications. The original Lycoming T53 that powered the UH-1 Huey (Figure 7) was a 600 shp 688 lb engine in 1959. Today the T55 has replaced the T53, generating 4867 shp and weighing in at 831 lbs.

From the original T53 variant, the T55 produces more than eight times the thrust with only a 20% increase in weight. The more powerful T55 powers the twin rotor heavy-lifting Chinook helicopters (Figure 8).

Figure 7: The UH-1 Huey helicopter is powered by a Lycoming T53.

Figure 8: The popular transport helicopter, CH-47 Chinook

Table 4: Lycoming Turboshaft Engine Comparison

Lyco Engine	**T53**	**T55**	**LTS**
Notable applications	Bell UH-1 Helicopter	CH-47 Chinook	HH-65 Coastguard SAR Helicopter
Power (shp)	600	4867	675
Weight (lbs)	688	831	241
Pressure Ratio	7.3	9.32	8.4
Turbine inlet Temp (K)	Unknown	1088	Unknown
SFC (kg/kW/hr)	Unknown	Unknown	0.57
Compressor configuration	5 axial, 1 centrifugal	7 axial, 1 centrifugal	1 axial, 1 centrifugal
Turbine configuration	1 HPT, 1 FPT	2 HPT, 2 FPT	1 HPT, 1 FPT
P/m (shp/lb)	0.87	5.6	2.8

In addition to their role in the aviation turboshaft industry, Lycoming is responsible for turboshaft engines powering US Army M1 Abrams tanks, turbine class locomotives, and the US Navy LCAC hovercraft. Outside of turbine engines, Lycoming has made a name in general aviation, producing internal combustion engines that power over half of the world's general aviation aircraft.

Allison Engines (Rolls-Royce Allison)

Allison Engines broke into the aircraft engine industry with the V-1710 V12 internal combustion engine. Over 70,000 were produced for World War II fighters such as the P-39, P-40 and P-51. After the war, Allison used their production capabilities to begin derivations of the General Electric Whittle engine. By 1953 Allison had begun on axial flow engine designs, notably a “twinned” turboprop engine, the T40. Ultimately, Allison’s post-war engine design culminated in the creation of the T406 turboshaft, designed to power the unique V-22 Osprey

Table 5: Allison Engine Turboshaft Engine Comparison

Allison Engine	**T406**	**AE2100 (turboprop)**	**250**
Notable applications	V-22 Osprey	Lockheed C-130J Hercules	HH-65 Coastguard SAR Helicopter
Power (shp)	6150	4637	250
Weight (lbs)	971	1727	136
Pressure Ratio	16.7	16.6	6.2
Turbine inlet Temp (K)	Unknown	Unknown	1258
SFC (kg/kW/hr)	Unknown	Unknown	0.77
Compressor configuration	14 axial stages	14 axial stages	6 axial stages, 1 centrifugal
Turbine configuration	2 HPT, 2 FPT	2 HPT, 2 FPT	2 HPT, 2 FPT
P/m (shp/lb)	6.3	2.7	1.8

Figure 9: V-22 Osprey uses two T406 turboshafts

Despite being shrouded by complexity and controversy, the Osprey is undoubtedly one of the most unique and innovative rotorcraft ever put into consistent production. Due to the power needed to both lift the aircraft as well as propel it to 20,000 ft, an extremely powerful turboshaft is needed. The Allison/RR T406 engine is one of the most powerful turboshafts in production, and the most powerful examined by this paper. The shaft power out exceeds 6000 shp.

Beyond their involvement in turbomachinery, Allison was also one of the first engine manufactures to begin experimenting with ceramic materials. In partnership with General Motors in the 1970s, they were successful incorporating ceramics in automotive truck engines. Work continued on ceramic turbine components into the 1990s, however nothing significant ever came from the venture.

General Electric

General Electric (GE) is one of the giants in the aviation engine world. Known worldwide for their turbofan engines, they also produce many turboshaft engines. GE joined the aviation industry when they first began developing the turbosupercharger for the U.S. government in 1917. It was designed to increase the power of a piston engine at high altitude by using the exhaust gases to run an air compressor. From here GE's influence in the field only grew. They entered the turboshaft industry with the development of the T58 in the 1950s. Originally developed for 800 shp, today it puts out more than 1200 shp. The T58 is the engine that drives Marine One, a Sikorsky Sea King helicopter that carries the President of the United States.

Table 6: General Electric Turboshaft Comparison

Engine	**T58**	**T64**	**T700/CT7**	**GE38**
Notable applications	Sikorsky Sea king, Marine One	CH/MH-53E	AH-64 Apache Sikorsky S-92	Sikorsky CH-53K Super Stallion
Power (shp)	1250-1870	3925-4750	1900-2600	7500
Weight (lbs)	391	720	450	1105
Pressure Ratio	8.3	14.9	18	18.6
Turbine inlet Temp (K)	Unknown	900-1050	Unknown	Unknown
SFC (kg/kW/hr)	.389	0.466-0.48	0.46	~.39*
Compressor configuration	10 axial	14 axial	5 axial 1 centrifugal	5 axial 1 centrifugal
Turbine configuration	2 HPT, 1 FPT	2 HPT, 2 FPT	2 HPT, 2 FPT	2 HPT, 3 FPT
P/m (shp/lb)	3.2-4.8	5.4-6.7	4.2-5.7	6.8

Another popular helicopter ran by a GE engine the T700, is Boeing's AH-64 Apache shown in Figure 10. Two of these engines, shown on the left of Figure 10, put out about 1900 shp each to power this aircraft.

Figure 10: GE's T700 turboshaft (left) which powers the AH-64 Apache (Right)

The newest GE turboshaft is the GE38. It delivers an extreme amount of power, giving off 7500 shp. With this kind of power it is targeted at larger applications for heavy lifting. The engine is built to outperform its predecessor the T64, providing 57% more power and an estimated 63% fewer parts. No specific value for its sfc was found, but it claims to be 18% more efficient than the T64. The GE38 fills a missing gap in the turboshaft industry, falling between Europrops TP400-D6 (10,000 shp) and RR AE2100 (6000 shp). It has also been considered to replace the engines aboard the V-22 Osprey, pictured in Figure 9.

Russian Turboshaft Engines

Often overlooked due to their age and lack of presence in the modern turboshaft industry, Soviet era turboshafts were some of the most powerful produced, and can be found on dozens of helicopter models in service around the developing world. The major manufacturers are the Soleviev, Ivchenko-Lotarev, and Klimov Design Bureaus. Lotarev (Ukraine) was responsible for the powerful engines that made the largest aircraft in the world possible, Figure 11. Klimov built the infamous TV3-117, which powered over 95% of Russian helicopters, like the Mi-24 pictures in Figure 12

Figure 12: Russian Mi-24 helicopter powered by the TV3-117

Figure 11: Russian Mi-26 Helicopter.

Table 7: Russian Turboshaft Engine Comparison

Engine	**Klimov TV3-117**	**Klimov VK-2500**	**Soloviev D-25**	**Lotarev D-136**
Country of Origin	**Soviet Russia**	**Soviet Russia**	**Soviet Russia**	**Soviet Ukraine**
Notable applications	Various Kamov and Mil Mi Helicopters	Kamov Ka-50, Mil Mi-28	Mil Mi-10	Mil Mi-26
Power (shp)	2200	2700	3925-4750	11400
Weight (lbs)	648	661	1325	1077
Pressure Ratio	9.4	Unknown	Unknown	Unknown
Turbine inlet Temp (K)	1263	Unknown	Unknown	Unknown
SFC (kg/kW/hr)	.308	0.22	Unknown	0.23
Compressor configuration	Unknown	Unknown	9 axial	5 axial 1 centrifugal
Turbine configuration	Unknown	Unknown	1 HPT, 2 FPT	2 HPT, 3 FPT
P/m (shp/lb)	3.4	4.1	3.0-3.6	10.58

Comparisons & Conclusion

Due to their use in helicopters, turboshaft engines are generally small in size, often utilizing at least one centrifugal compressor, sometimes in parallel with two or more axial stages. Because helicopters become significantly more inefficient as their size increase, extremely powerful turboshafts are not necessary; even the largest helicopters can utilize 2 or in some cases 4 turboshaft engines linked by a gearbox. Two soviet era Lotarev D-136 power the largest Helicopter ever produced, the Mil Mi-26, and produce 11400 shaft horsepower (a power/mass ratio over 10!). Typically engines in the 1000 shp and lower have power/mass ratios in the range of two to three. Engines from 2000 to 3000 shp have ratios usually between three and four.

Almost all of the turboshaft engines use 2 spool design. One to two high power turbines run the compressor and the rest of the power extraction is performed by usually 2 free power turbines. The larger engines like the D-136 and GE38 use 3 FPTs. Earlier versions like GE's T58 and T68 used a completely axial turbine, almost every turboshaft now uses a combination of at least one centrifugal. In fact some engines like Turbomecas Ardiden and RR CST800 use only a dual centrifugal compressor, and still achieve pressure ratios around 14. The highest found for this report was 18.6 from the GE38 engine, (a combination of 5 axial and 1 centrifugal). Older turboshaft engines have a specific fuel consumption in the 0.5-0.6 kg/kW/hr range while newer engines have improved close to 0.39 (GE38).

The aerospace industry is constantly changing, and turboshafts are not an exception to this. Driven by the constant pressure of competitors along with new technologies and manufacturing techniques, companies have to do everything in their power to maintain or increase their footprint in the field. This paper has given some insight into the many available engines on the turboshaft market and the companies behind them. Of course not all of the companies are listed here, but the major game players in the industry were.

Acknowledgments

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Matlab Code

```
clear all; close all; clc
%% Givens
gamma = 1.4;
gam_c = 1.4;            % for temps through compressor,combustor
gam_t = 1.33;           % for temps after the combuster -> turbine

c = 1005;       % specific heat
cpc = 1004;             % for temps in the compressor,combustor
cpt = 1156;             % for temps in the turbine

hp2W = 0.7457*1000; % conversion from hp to W
lb2kg = 0.453592; % conversion from lb to kg
%T5=T9 == T0 (should be ambient for maximum)
%p5=p9=p0
%M = 0

% Ambient Values
M0 = 0;        % Mach
[T0,a0,P0,rho0] = atmosisa(0); % Standard Atmospher [K,m/s,kg/m3,Pa]

mdot = 26*lb2kg;    % Air mass flow rate [kg/s]
hpr = 42.8e6;    % Fuel Heating value [J]
Tt4 = 1100+273.15;      % Turbine Entry Temperatureb[K]
P = 4230*hp2W;           % Power extracted to turboshaft
Pi_c =12;

%-------------------Efficiencies----------------------------------------
ec = .92;               % Polytropic Efficiency of Compressor
et = .92;               % Polytropic Efficiency of Turbine
Eta_b = .96;            % Efficiency of burner (combustor)
eta_c = .85; %power conversion losses, 1 = no loss
%%

tau_r = 1+.5*(gamma-1)*M0^2;    % Tt0/T0 : stagnation to static Temp Ratio
tau_c = Pi_c^((gamma-1)/gamma); % Tt3/T2 : compressor
tau_lam = Tt4/T0;               % ht4/ht0 = cpt*Tt4/cpc*T0



tau_tH = 1-(tau_r/tau_lam)*(tau_c-1);

%tau_tL, tau_t for a turboshaft
tau_tL = 1-(1/(tau_lam*tau_tH))*(P/(mdot*c*T0));
tau_t = tau_tH*tau_tL;

%tau_tL, tau_t for a turboprop
%{
tau_t = 1/(tau_r*tau_c)+(gamma-1)*M0^2/(2*tau_lam*eta_c^2);
tau_tL = tau_t/tau_tH;
%}

Sp = (a0*M0)^2*(1/eta_c-1) ...
```

```
    +cpc*T0*tau_lam*tau_tH*(1-tau_tL)*eta_c;

f = cpc*T0*(tau_lam-tau_r*tau_c)/hpr;

Spfc = f/Sp *3600*1000

eta_0 = Sp/(c*T0*(tau_lam-tau_r*tau_c));
eta_th = 1-(1/(tau_r*tau_c))
eta_P = eta_0/eta_th;

%% real cycle
tau_r = 1+.5*(gam_c-1)*M0^2;     % Tt0/T0 : stagnation to static Temp Ratio
tau_c = Pi_c^((gam_c-1)/(ec*gam_c)); % Tt3/T2 : compressor
tau_lam = cpt*Tt4/(cpc*T0);



tau_tH = 1-tau_r/tau_lam*(tau_c-1);

%tau_tL, tau_t for a turboshaft
tau_tL = 1-(1/(tau_lam*tau_tH))*(P/(mdot*cpt*T0));
tau_t = tau_tH*tau_tL;

%tau_tL, tau_t for a turboprop
%{
tau_t = 1/(tau_r*tau_c)+(gamma-1)*M0^2/(2*tau_lam*eta_c^2);
tau_tL = tau_t/tau_tH;
%}

Sp = (a0*M0)^2*(1/eta_c-1) ...
    +cpc*T0*tau_lam*tau_tH*(1-tau_tL)*eta_c;

f = cpc*T0/(Eta_b*hpr)*(tau_lam-tau_r*tau_c);

Spfc_real = f/Sp *3600*1000

eta_0 = Sp/(gam_c*T0*(tau_lam-tau_r*tau_c));
eta_th = 1-(1/(tau_r*tau_c))
eta_P = eta_0/eta_th;
```