AVIATION THEORY

# Aircraft Propulsion

## Pistons, Turbines, Propellers & Thrust

Aviation Theory Centre

David Robson

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David Robson

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***Aircraft Propulsion***
by David Robson



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# Author & Editor-in-Chief – David Robson


David Robson is a career aviator having been nurtured on balsa wood, dope (the legal kind) and tissue paper. He made his first parachute jump at Fairoaks and his first glider flight at White Waltham, just after his sixteenth birthday. At the age of seventeen, he won a Flying Scholarship with the Air Training Corps and made his first solo flight in a de Havilland Chipmunk from the Surrey and Kent Flying Club at a famous Battle of Britain aerodrome – Biggin Hill (*Biggin on the Bump*).

His first job was as a junior draughtsman (they weren't persons in those days) at the Commonwealth Aircraft Corporation in Melbourne. At that time he continued learning to fly in Chipmunks with the Royal Victorian Aero Club.

He joined the Royal Australian Air Force in 1965 and served for twenty-one years as a fighter pilot and test pilot. He flew over 1,000 hours on Mirages and 500 on Sabres. He completed the Empire Test Pilots' course at Boscombe Down in 1972, flying everything from sailplanes to Lightnings and Argosies. In 1969-70 he completed a tour in Vietnam as a Forward Air Controller flying the O-2A and conducting operations in support of the First Australian Task Force. He was a member of the Mirage formation aerobatic team, the *Deltas*, which celebrated the RAAF's 50th anniversary in 1971.

After retiring from the Air Force he became a civilian instructor and lecturer and spent over ten years as the Business Development Manager of the Australian Aviation College - an airline cadet training college which trained over 1,000 pilots in a ten year period for the foremost international airlines. During 1986-88 he was the editor of the Aviation Safety Digest (the *crash comic*) which won the Flight Safety Foundation's international award. He has completed the KLM Human Factors (KHUFAC) introductory course. He has recently completed the GAPAN TEM Implementation course. At the same time, he has enjoyed exploring the world of recreational aircraft and also flies the restored O-2A at the wonderful Temora Aviation Museum.

He has been honoured to receive the Australian Aviation Safety Foundation's Certificate of Air Safety.

January 2012 marked a career milestone of 50 years since his first solo flight - which he still remembers in detail.

# *WINGS*

by David Robson, 1996

*How Proudly*
*they stood*
*uniformed and winged*
*young – yet not so*
*confident, ready*
*and eager to go*
*forward and upward*
*higher and faster*
*than we would ever know*
*but we knew*
*that they went*
*with the knowledge and skill*
*of all that we,*
*who went before,*
*could instill*
*and so,*
*in our hearts and souls,*
*we, in our way,*
*could also go,*
*and therefore stay,*
*with them –*
*forever*

# Introduction

*Aircraft Propulsion* introduces all aspects of aircraft propulsion from the principles of power and thrust to the technical details of engines - including four-stroke piston engines, radial engines, superchargers, turbochargers and propellers.

Gas turbine (jet) engines are introduced in their various configurations of:

- turbojet;
- turbofan;
- turboprop; and
- turboshaft.

Engine-related controls and displays are discussed - as are the fuels and lubricants used by aircraft engines.

This volume comprises five parts:

# Table of Contents

## Part Three – Gas Turbine Engines

## Part Four – Propellers



## Part Five – Aviation Fuels & Lubricants

# Abbreviations

**A/B** afterburner (reheat)

**ACU** acceleration control unit

**AFM** aircraft flight manual

**ANM** air nautical miles

**APU** auxiliary power unit

**ATM** aerodynamic twisting moment

**AVCAT** aviation turbine fuel for aircraft carrier operations

**AVGAS** aviation gasoline

**AVTUR** aviation turbine fuel (kerosene)

**BDC** bottom dead centre

**BFTS** basic flying training school

**BHP** brake horsepower

**CCM** chemically correct mixture

**CHT** cylinder head temperature

**CTM** centrifugal twisting moment

**EGT** exhaust gas temperature

**EPR** engine pressure ratio

**ESHP** equivalent shaft horsepower

**F** thrust

**FADEC** full authority digital engine control

**FEG** force element group

**$F_N$** nett thrust

**FHP** friction horsepower

**FOD** foreign object damage

**FTH** full throttle height

**HP** horsepower

**HP** high pressure

**IGV** inlet guide vanes

**ITT** inter-turbine temperature

**JP4** A ‘wide-cut’ turbine fuel drawn from gasoline and kerosene distillates (equivalent to AVTAG). NATO designation F-40.

**JP5** A ‘high flash point’ turbine fuel (equivalent to AVCAT). NATO designation F-44.

**JP8** turbine fuel with icing inhibitor (equivalent to AVTUR/JET A1). NATO designation F-34

**JP8+100** turbine fuel with high temperature thermal stability additive. NATO designation F-37

**JPT** jet pipe temperature

**LP** low pressure

**MAP** manifold air pressure

**MCP** maximum continuous power

**MILSPEC** military specification

**MTBH** mean time between overhaul – an indication of demonstrated reliability

**N** rpm

**NGV** nozzle guide vanes

**NTS** negative torque sensing

**P** pressure

**PCL** power control lever

**RAT** ram air turbine

**RATO** rocket assisted take off

**RCS** reaction control system

**rpm** revolutions per minute

**SAE** society of automotive engineers (US)

**SAR** specific air range (air nautical miles per pound of fuel)

**SFC** specific fuel consumption

**SG** specific gravity

**SHP** shaft horsepower

| | |
|---|---|
| **T** | temperature |
| **TDC** | top dead centre |
| **THP** | thrust horsepower |
| **TIT** | turbine inlet temperature |
| **TRD** | total rotor drag |
| **TRT** | total rotor thrust |
| **VG** | vortex generator |

# Glossary

### Accessory Drive Gearbox
An auxiliary drive shaft and unit to power generators, fuel pumps and hydraulic services.

### Afterburner/ing
The addition of fuel to the hot exhaust to take advantage of the unused oxygen to increase thrust.

### Ambient
The conditions that exist in the local environment – temperature, pressure and density.

### Annular
The circular chamber that forms a concentric cylinder around the axis of the engine. *See* Cannular.

### Athodyd
Aerothermodynamic duct – another name for a ramjet.

### Auto-Feather
Automatic feathering of a propeller when pre-determined parameters are sensed.

### Axial
In the direction of the engine axis (straight-through).

### Beta Range
Propeller blade angles that produces zero or reverse thrust.

### Blade Angle
The angle of the propeller blade relative to the plane of rotation (measured at a point 75% of the blade length from the hub).

### Blade Creep
The increased length of a turbine blade due to heat stress. This often determines the temperature limits of the engine.

### Bleed Air
Air that is extracted from the compressor to provide pressurisation or auxiliary drive.

### Bore
The diameter of a cylinder of a piston engine.

### Cannular
The annular arrangement of individual combustion chambers around the circumference of the engine.

### Centrifugal
Flowing outwards from the centre e.g. centrifugal compressor which propels air outwards and centrifugal force due to acceleration during turns.

### Compressor Stall/Surge
Interruption of airflow to the compressor resulting in a loss of thrust and possible reverse flow from the turbine to the rear of the compressor.

### Continuous Ignition
A manual selection where the igniters are firing continuously to counter possible flame out due to bird or water ingestion.

### Critical Altitude
The maximum altitude at which the engine can maintain sea level maximum power is the *maximum power critical altitude* for the engine. Similarly there is a *maximum continuous power critical altitude*. Note that power relates to critical altitude and MAP relates to *full throttle height*.

### Dry Thrust
Thrust without afterburning.

### Engine Core
The gas generator or power producing core of the engine which then drives the fan or propeller shaft.

### Engine Pressure Ratio (EPR)
The ratio of the gas turbine engine total output pressure to compressor inlet pressure (P7/P1).

### Fir Tree
A means of attaching turbine blades to the turbine wheel.

### Flame-Out
Extinction of the combustion flame.

### Flash Point
The lowest temperature, corrected to a barometric pressure of 1013.2 kPa, at which application of a test flame causes the vapour of the test portion to ignite under the specific conditions of test.

### Four-Stroke Cycle (Otto Cycle)
The cycle of the piston engine – intake, compression, power and exhaust.

### Fuel Control Unit

The mechanism that controls the rate of increase of fuel flow to the engine to achieve optimum acceleration (spool-up).

### Full Throttle Height

Full throttle height is the maximum altitude at which a supercharged or turbocharged engine is able to maintain a specified MAP. Note that power relates to critical altitude and MAP relates to full throttle height.

### Gross Fuel Consumption (GFC)

The total fuel used per unit of time. At any moment GFC equates to fuel flow. *See* Specific Fuel Consumption.

### Helix Angle

The angle formed between the resultant of the blade motion and the plane of rotation.

### Hung Start

A start where engine acceleration deviates from the normal schedule such that fuel may be excessive and the resulting heat may rise beyond limits. Generally the rpm hangs below self-sustaining speed.

### Idle rpm

The rpm which the engine maintains at minimum power – a small margin above minimum self sustaining rpm.

### Inlet Guide Vanes (IGV)

Guide vanes that direct airflow to the first stage of the compressor.

### Intake Buzz

Vibration and airflow disturbance due to the oscillation of the shock wave into and out of the intake.

### Intake Ramps

Devices used to control shock waves in the engine intake.

### Inter Turbine Temperature (ITT)

The temperature between the turbine stages (T5).

### Jet Pipe Temperature (JPT)

The absolute temperature in the jet pipe before the afterburner.

### Mach Number

The ratio of TAS to the local speed of sound – expressed as a decimal e.g. M = 0.8 or 0.8 IMN

### Mach One

The local speed of sound (which varies with ambient temperature).

### Manifold Air Pressure

The total pressure in the inlet manifold of a piston engine.

### Modified Otto Cycle

The modified four-stroke cycle which changes valve timing and ignition timing to increase power and efficiency.

### Nozzle Guide Vanes (NGV)

The fixed or variable guide vanes which direct airflow at the optimum angle to the first stage of the compressor.

### Octane Rating

Grades of AVGAS with ratings up to 100 are identified by their nominal minimum lean-mixture anti-knock rating (resistance to detonation) relative to a blend of pure iso-octane which is designated with a value of 100 and n-heptane which is designated as zero. Grade 80 fuel has the detonation resistance *equivalent* to a blend of 80% iso-octane and 20% n-heptane. Grade 91 fuel (car petrol) has a detonation resistance equivalent to 91% iso-octane and 9% n-heptane.

### Over-Boost

Exceedance of allowable manifold air pressure.

### Over-Temp

Exceedance of temperature limits.

### Over-Torque

Exceedance of torque limits.

### Performance Rating (Fuel)

Grades of AVGAS with ratings of 100 or more are identified by their nominal minimum lean-mixture anti-knock rating (resistance to detonation) relative to a blend of pure iso-octane which is designated with a value of 100, and the quantity of an anti-knock additive tetra-ethyl lead require to achieve the level of detonation resistance. Grade 100 fuel has the detonation resistance equivalent to 100% iso-octane. This quality is achieved by blending a fuel with a quantity of tetre-ethyl lead. Grade 100 fuel and Grade 100 LL (low lead) have same detonation resistance but Grade 100 LL has half the lead content of Grade 100. Grade 100 LL is manufactured from a higher grade base fuel needing less additive to achieve the same detonation.

### Pitch

The linear dimension of the blade angle – measured at a point 75% of the blade length from the hub.

### Radial

Radiating from the centre e.g. radial engine cylinders.

### Ramjet

A fuel burning engine which has no moving parts.

### Rated Thrust/Rated Power

Any specified thrust/power condition for which the engine is rated (guaranteed) e.g. rated take-off thrust, rated maximum continuous power.

### Red Line

Limiting speed, power, torque, rpm or temperature.

### Reheat

*See* Afterburner.

### Relight

Active (spark) re-ignition of combustion in a gas turbine engine.

### Reverse Pitch

Negative propeller blade angle generating thrust opposite to the direction of aircraft monitor.

### Reverse Thrust

Jet or fan efflux partly or wholly opposite to the direction of aircraft motion.

### Rotor (Helicopter)

Rotating aerodynamic surfaces that convert engine torque to lift and thrust.

### Rotor (Piston Engine)

The distributor has a rotor which directs electrical current to each spark plug at the optimum time.

### Rotor (Turbine Engine)

The rotating assembly consisting of a central wheel and blades – in both the compressor and turbine.

### Scavenge Pump

A pump that acts to return oil to the oil reservoir/tank.

### Shock Cones

Shaped devices which form part of an air intake and whose purpose is to move the shock wave out of the intake.

### Shock Wave

Pressure wave that forms when a volume of supersonic flow decelerates.

### Slam Acceleration

Rapid application of full power. The ACU accelerates the engine at its maximum rate.

### Specific Fuel Consumption (SFC)

The ratio of gross fuel consumption to power or thrust.

### Specific Gravity (SG)

The mass of fuel per unit volume in comparison to that of water at a given temperature; also *relative density.* The SG of AVTUR is deemed to be 0.8 at +20° Celsius – therefore one litre of AVTUR at 20° C, will have a mass of 0.8 kg.

### Spool-Up

The delay in engine acceleration due to the FCU.

### Static Thrust

The maximum force generated by the jet efflux, fan and propeller when the aircraft is stationary.

### Stators

Fixed aerofoils between the rotating assemblies in an axial compressor to optimise the angle of attack of succeeding rotors.

### Stroke

The distance the piston travels between BDC and TDC.

### Supercharger

An engine-driven compressor which provides a higher MAP to a piston engine.

### Thrust Augmentation

Boosted thrust due to water injection or afterburning.

### Top Dead Centre

The point at which the piston reaches the top of its travel on the compression stroke.

**Turbine Inlet Temperature (TIT)**

The absolute temperature at the face of the turbine's first stage (T4).

**Turbocharger**

An exhaust-driven compressor which provides a higher MAP to a piston engine.

**Turbofan**

A turbine engine where not all of the compressor/ fan output passes through the engine core.

**Turbojet**

A turbine engine where all of the compressor output passes through the engine core.

**Turboprop**

A turbine engine whose primary output is torque used to turn a propeller.

**Turboshaft**

A turbine engine which drives an output shaft (which in a helicopter drive a transmission/rotor assembly).

**Variable Nozzle**

Variable exhaust nozzle which changes cross-sectional area in response to afterburner selection.

**Vectored Thrust**

Deflection of the jet exhaust nozzle for vertical lift or increased manoeuvre capability.

**Volumetric Efficiency**

The ratio of the actual mass of fuel and air drawn into the cylinder of a piston engine to the maximum possible mass of fuel and air at standard temperature and pressure that could be drawn into the cylinder.

**Wastegate**

The manual or automatic valve which varies the area of the exhaust and therefore changes turbocharger output. If the wastegate is closed the most exhaust charge is directed to drive the turbocharger.

**Windmilling**

A state where the propeller is driven by the airflow.

# Part One – Principles of Propulsion

# 1 – Thrust

# Introduction

**1.1** Thrust is the force that propels an aircraft sustaining its flight path and speed. Thrust also permits an aircraft to climb by using thrust in excess of that required for a particular speed to gain height or to descend by using less thrust than that required for a particular speed to lose height. The theoretical basis of thrust is found in Newton's third law of motion-to every action there is an opposite and equal reaction. By accelerating a mass of air through a propeller or jet engine and expelling the mass of air rearward thrust is generated, which propels the aircraft forward. Similarly, a mass of air could be accelerated through a propeller or jet engine and expelled forward to propel the aircraft rearward as is used in thrust reverser systems. In either case, the greater the mass of air and the greater the acceleration of the air mass through the propeller or jet engine, the greater the reaction and the greater the thrust.

**1.2** In the case of a helicopter, the mass of air is accelerated downward through a rotor directly producing lift and it is the 'rotor thrust' that must be vectored to generate a motive force. As a basic concept, the thrust produced by a helicopter rotor is similar to that of a propeller and is not discussed in any detail in ***Aircraft Propulsion***. Further discussion about the complexities of helicopter thrust is contained in another ATC volume, titled ***Helicopter Flight Dynamics***.

**1.3** Propellers and jet engines generate thrust in different ways:

- A propeller generates thrust by converting the rotation force from the engine to thrust by accelerating a relatively large mass of air through the propeller and expelling it at relatively low velocity.
- The jet engine generates pure thrust by accelerating a relatively small mass of air through the engine and expelling it through the exhaust at high velocity.

# Principles of Propeller Thrust

**1.4** The blade of a propeller functions on the same aerodynamic principles as the aerofoil of an aircraft; air accelerates over the curved forward face of the propeller blade causing a reduced pressure, while there is an increased pressure on the flat aft face of the propeller blade. This leads to a net pressure force over the propeller (where pressure differential times the blade area equals the pressure force). The same as an aerofoil, the total force will have two components, one parallel to the direction of propeller rotation called propeller drag and the other parallel to the axis of rotation called thrust (Figure 1–1).

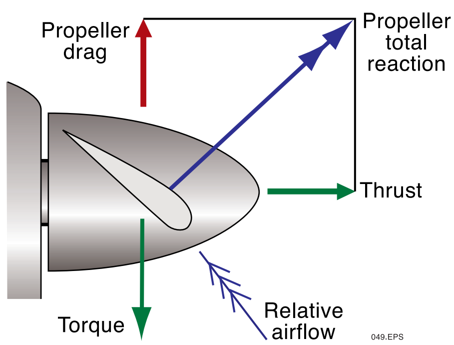



**Figure 1–1** Thrust and propeller drag.

1.5 As a result of the pressure differential around the propeller, air will flow and be accelerated through the disc scribed by the propeller blades. The thrust force will be a product of the mass of the air processed and the rate of acceleration of the air through the propeller. Stated another way, the thrust is the product of the mass flow rate (mass of air per unit of time) and the change in velocity (Figure 1–2):

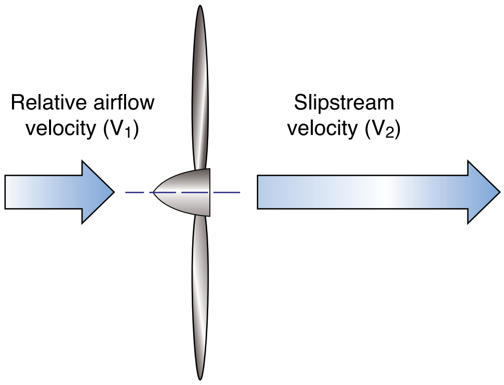



**Figure 1–2** Propulsion.

$$\begin{aligned} thrust &= mass \times acceleration \\ &= mass\ flow\ rate \times change\ velocity \\ &= M \times (V_2 - V_1) \end{aligned}$$

*Where:*

$$\begin{aligned} M &= mass\ flow\ rate \\ V_1 &= velocity\ of\ relative\ airflow \\ V_2 &= velocity\ of\ slipstream \end{aligned}$$

1.6 The same thrust may be generated by causing a small change in momentum to a large mass of air (as occurs with a propeller) or a large change of momentum to a small mass of air. The latter is the underlying principle of jet propulsion.

## Principles of Jet Thrust

1.7 Jet thrust is the reaction generated by accelerating the mass of air through the engine and hence a jet engine is sometimes referred to as a reaction engine. The acceleration of a mass of air produces the jet thrust (force) and the thrust will be the product of the mass flow rate of air through the engine and the change in velocity, just as it was for a propeller. However, in a jet engine a relatively small mass flow of air is accelerated through the engine such that the exhaust velocity is much greater than the intake velocity (Figure 1–3).

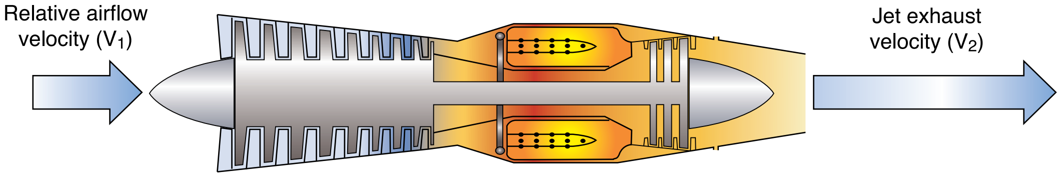
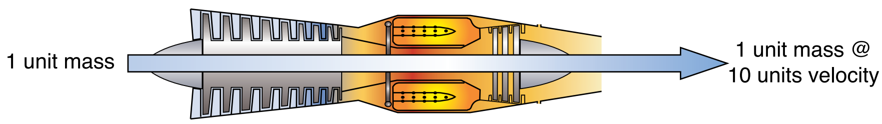



**Figure 1–3** Jet propulsion.

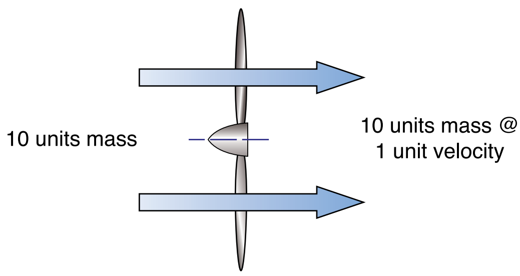
## Propulsive Efficiency

1.8 Although a jet engine through accelerating a small mass of air to high velocity can produce the same thrust as a propeller accelerating a large mass of air to moderate velocity, the energy expended by a jet engine is considerably more than that of a propeller for the same thrust. The change in energy of the air mass (change in kinetic energy) is a function of the square of the change in velocity. For a jet engine a mass of 1 unit accelerated by 10 units of velocity to produce 10 units of thrust requires 50 units of energy. However, 10 units of mass accelerated by 1 unit of velocity by a propeller to produce 10 units of thrust only requires 5 units of energy (Figure 1–4).




$$\begin{aligned} thrust &= 1 \times 10\,units \\ &= 10\,units \end{aligned}$$

$$\begin{aligned} energy &= \frac{1}{2} \times 1 \times 10^2\,units \\ &= 50\,units \end{aligned}$$




$$\begin{aligned} thrust &= 1 \times 10\,units \\ &= 10\,units \end{aligned}$$

$$\begin{aligned} energy &= \frac{1}{2} \times 10 \times 1^2\,units \\ &= 5\,units \end{aligned}$$

**Figure 1–4** Relative efficiency of jet and propeller propulsion.

1.9 The energy to accelerate the air mass flow is generated by burning the fuel in the engine and, in the simple analysis here, it is apparent that a propeller is much more efficient in producing thrust than a jet engine. However, the effect of airspeed, which significantly modifies the relative efficiency of the two methods of generating thrust, needs to be considered.

# Effect of Airspeed on Thrust

## *Thrust Required*

**1.10** The thrust required in flight is a function of the total drag on the aircraft, the higher the drag the more thrust required. A fixed-wing aircraft has high drag at the minimum flight speed due to the drag associated with the strong vortex flow generated in flight at high lift coefficient (lift-dependent drag). As airspeed increases vortex drag reduces, but the drag associated with the air-resistance on the aircraft (zero-lift drag) increases. Consequently the drag and hence thrust required decreases from its value at the minimum flight speed until reaching a point where the drag on the aircraft becomes significant at which point the drag and thrust required increases with increasing airspeed (Figure 1–5).

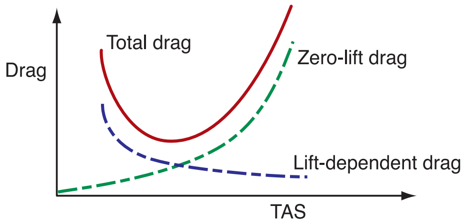



**Figure 1–5** Effect of airspeed on drag (thrust required).

## *Propeller Thrust Available*

**1.11** As airspeed changes, the combined effect of the forward velocity and the rotational velocity will change the propeller angle of attack and hence affect the thrust and the propeller drag. The maximum angle of attack for both fixed pitch and constant speed propellers will be at zero forward velocity. As airspeed increases the angle of attack reduces and the thrust will decrease. Hence the maximum thrust from a propeller occurs when it is stationary and as forward velocity increases thrust reduces until, at a speed where the propeller is at its *zero thrust angle of attack*, the thrust reduces to zero (Figure 1–6).

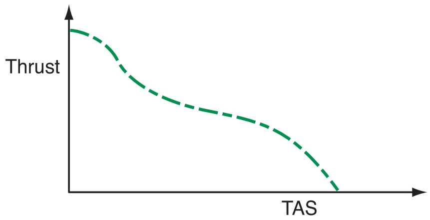



**Figure 1–6** Loss of propeller thrust with airspeed

**1.12** At high TAS, the effects of compressibility become significant and limit the maximum airspeeds at which a propeller can produce thrust. As a propeller has both rotational and forward velocity, the propeller tips will reach the speed of sound when the flight velocity reaches about 0.7 times the speed of sound (M0.7). As low-speed propellers have blades of considerable thickness and chord, shockwave effects and associated propeller drag and thrust penalties will occur from flight velocities around M0.6. A conventional propeller capable of producing thrust when operated near these speeds will experience a marked reduction in thrust (Figure 1–7).

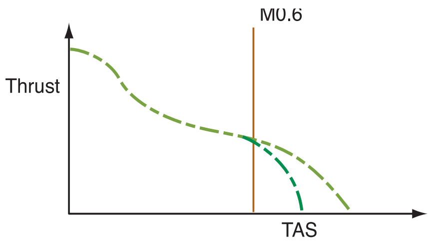



**Figure 1–7** Loss of propeller thrust at high Mach number.

### Jet Thrust Available

1.13 As the velocity of a jet engine increases from zero the difference between the relative airflow velocity and the jet exhaust velocity reduces leading to reducing thrust (less acceleration of the air mass flow). However, while the overall acceleration of the air mass flow is decreasing, compression of the relative airflow at the engine intake increases the mass flow rate through the engine. The net result is a slow decrease in the thrust to a certain speed before recovering due to the proportionally larger increase in air mass flow. For practical purposes, the thrust of the engine in essentially constant as airspeed increases (Figure 1–8).

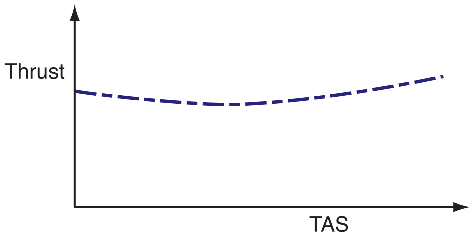



**Figure 1–8** Thrust of a jet engine.

## Summary

1.14 Propeller thrust decreases as airspeed increases, with a rapid reduction occurring at flight speeds where shockwaves form on the propeller, while jet thrust is nearly constant with airspeed. Aircraft drag and hence the thrust required initially decreases to a minimum value as airspeed increases; as airspeed increases beyond the 'minimum drag speed', the thrust required increases. This relationship is shown in Figure 1–9.

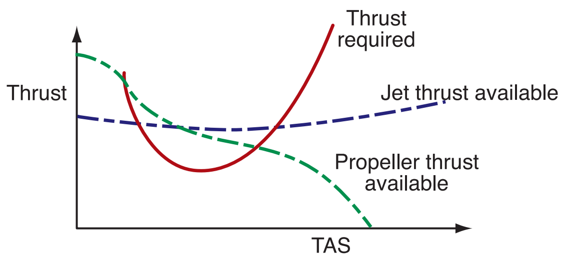



**Figure 1–9** Relationship of thrust required to thrust available.

1.15 The following points can be derived from the relationship of thrust required and thrust available shown in Figure 1–9:

- The minimum speed for a propeller aircraft is slightly less than that of a jet aircraft.
- The speed of maximum excess thrust (distance between the thrust required curve and thrust available curve) is higher for a jet aircraft than a propeller aircraft.
- The maximum speed is higher for a jet aircraft than a propeller aircraft.

1.16 The aerodynamic aspects of propeller thrust, propeller efficiency including the effect of Mach number, jet thrust and the relationship of thrust available to thrust required for both propeller and jet propulsion to aircraft performance are very complex and are further explained in ***Aircraft Flight Dynamics***.

## Review 1

1. Explain the principle of physics that allows a propeller or jet engine to produce thrust. (Para 1.1)
2. How does this principle apply to a helicopter? (Para 1.2)
3. Briefly compare how propellers and jet engines produce thrust. (Para 1.3)
4. Sketch a diagram showing the section through a rotating propeller blade in flight. Show the relative airflow, the total propeller reaction (at that station) and the division of the force into thrust and torque. (Para 1.4)
5. List the two basic factors that determine the thrust produced by a propeller. Does this relationship also apply to a jet engine? (Para 1.5)
6. Which system of thrust production is inherently more efficient – the propeller or the jet engine? Explain. (Para 1.8)
7. What happens to the total drag of an aircraft in level flight as airspeed increases from just above the stall to maximum cruising speed? (Para 1.10)
8. How does propeller thrust vary as airspeed increases? As Mach number increases? Explain. (Para 1.11)
9. How does the thrust of a jet engine vary with increasing airspeed? Explain. (Para 1.13)
10. Briefly discuss the choice of a thrust-producing system to match the design flight performance of an aircraft. (Para 1.15)