



# THE TURBINE PILOT'S FLIGHT MANUAL

Gregory N. Brown | Mark J. Holt

FIFTH EDITION



Includes all ATP-CTP topics



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AVIATION SUPPLIES & ACADEMICS, INC.  
NEWCASTLE, WASHINGTON

*The Turbine Pilot's Flight Manual*

Fifth Edition

by Gregory N. Brown and Mark J. Holt

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First edition published 1995. Fifth edition published 2024 by Aviation Supplies & Academics, Inc.

See the ASA website at [asa2fly.com/tpfm](https://asa2fly.com/tpfm) for reader and instructor resources and additional information and updates relating to this book.

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**ASA-TURB-PLT5**

ISBN 978-1-64425-392-2

Additional formats available:

eBook EPUB ISBN 978-1-64425-393-9

eBook PDF ISBN 978-1-64425-394-6

Printed in the United States of America

2028 2027 2026 2025 2024 9 8 7 6 5 4 3 2 1

Figures: Illustrations for the Airline, Regional, and Business Aircraft Spotter's Guide and several other figures by AvShop's Civil Aviation Clip Art CD-ROM and ©Onno van Braam, the-blueprints.com. All other illustrations by Gregory N. Brown and Mark J. Holt, except where noted.

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*Library of Congress Cataloging-in-Publication Data*

Names: Brown, Gregory N. (Gregory Neal), 1953- author. | Holt, Mark J., author.

Title: The turbine pilot's flight manual / Gregory N. Brown, Mark J. Holt.

Description: Fifth edition. | Newcastle, Washington : Aviation Supplies & Academics, Inc., 2024. | "ASA-TURB-PLT5"—Title page verso. | Includes bibliographical references and index.

Identifiers: LCCN 2024013304 (print) | ISBN 9781644253922 (trade paperback) | ISBN 9781644253939 (epub) | ISBN 9781644253946 (pdf)

Subjects: LCSH: Aircraft gas-turbines—Handbooks, manuals, etc. | Jet planes—Piloting—Handbooks, manuals, etc. | LCGFT: Handbooks and manuals.

Classification: LCC TL709.5.T87 B76 2024 (print) | LCC TL709.5.T87 (ebook) | DDC 629.132/5—dc23/eng/20240415

LC record available at <https://lcn.loc.gov/2024013304>

LC ebook record available at <https://lcn.loc.gov/2024013305>

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# Preface

THIS MANUAL GREW from the need to summarize in one place the information a pilot is expected to know when moving up to high-performance turbine aircraft. Flying professionally in today's competitive environment demands good basic knowledge of aircraft systems and procedures. This knowledge pays off at job interviews, at ground school, and of course, in flight operations.

Most initial pilot training programs cover only those areas of "aeronautical knowledge" required to pass FAA knowledge and practical tests up through commercial and CFI certificates. By nature, such training emphasizes low-altitude piston airplane systems and operations. This book is designed to be a ready, readable source for pilots to learn and prepare for that first step up into turbine equipment and operations and for the subsequent transition into more advanced types. Such preparation is important for several reasons.

Interviewers for turbine flight positions expect a certain basic level of knowledge among applicants. This book is designed to capsule that knowledge in one place for purposes of interview preparation.

Initial training ground schools for turbine operators are relatively similar. They anticipate basic knowledge from participants and dive right into the detailed specifics of their own aircraft. We wanted to provide the basics in a form that would allow new-hire pilots to prepare for first-time turbine ground schools.

Review for recurrent training is equally important. When the annual checkride rolls around the first few times in a pilot's career and at upgrade time to the captain's seat, many of the basics have been forgotten.

This is the place to refresh understanding of the basic principles of aircraft systems.

Each step of a pilot's flying career takes him or her into more advanced aircraft—from piston aircraft to turboprops, then to corporate and regional jets, and for many pilots, on to transport category aircraft. This book is designed to make every one of those transitions easier.

Finally, this manual is also for pilots and other aviation enthusiasts who simply enjoy the opportunity to learn about more advanced aircraft, even if they don't anticipate flying them anytime soon.

New and returning readers alike will appreciate the many enhancements made in this fifth edition of *The Turbine Pilot's Flight Manual*. Along with dozens of technology and terminology updates throughout the book, we have incorporated new material addressing the many recent electronic flight bag (EFB) developments applicable to professional piloting.

This edition contains all required academic subject matter for completion of an Airline Transport Pilot Certification Training Program (ATP-CTP). The ATP-CTP is required under 14 CFR §61.156 for applicants for an ATP Certificate with Airplane category Multiengine class rating or type rating and is designed to bridge the "knowledge gap" for pilots moving up from flying piston-powered aircraft under Commercial Pilot Certificates to operating turbine-powered aircraft. This requires training in essential subject areas listed in Advisory Circular 61-138, *Airline Transport Pilot Certification Training Program*, covering the baseline knowledge and experience to prepare

them for the duties, responsibilities, and challenges of corporate aviation and air carrier environments. Newly added or expanded ATP-CTP aeronautical knowledge areas include:

- Aerodynamics
- Automation
- Adverse weather conditions
- Air carrier operations
- Transport airplane performance
- Professionalism and leadership development

Our ongoing goal with *The Turbine Pilot's Flight Manual* has been to ease and accelerate pilot transition into each level of turbine aircraft, from small

turboprops and very light jets to the largest commercial jetliners. Over nearly three decades since this book was first published, it has become a popular university and professional flight school text and required reading for many corporate and regional airline new-hire pilots in preparation for ground school.

With the inclusion of required ATP-CTP subject matter, along with new material addressing the many recent electronic flight bag (EFB) developments applicable to professional piloting, we hope to better prepare pilots advancing to turbine-powered aircraft. We have pulled out all the stops in this book to make the next step in your flying career smoother and more exciting than ever.

# Acknowledgments

AMONG THE GREAT DIFFICULTIES of assembling a complex, comprehensive book such as *The Turbine Pilot's Flight Manual* is gathering and checking all of the information. Aircraft systems vary by manufacturer, type, and model. Procedures for flying any one aircraft type also vary tremendously from one operator to the next. Our objective is to cover turbine flying in a general way, but with enough detail to provide all of the basics. No one person can be knowledgeable in all these things.

Many individuals and companies have helped us greatly over all editions to date by sharing their expertise. We'd like to thank, first and foremost, the individuals who spent their valuable time reviewing our manuscript and sharing suggestions and information.

Among major-airline pilots who have generously shared their expertise via this and past editions are Keith Lamb, Andrew Hoban, Dave Holt, Brian Rouse, Pat O'Donnell, Don Cronk, Dick Ionata, Ray Holt, Bill

Niederer, Dan Moshiri, John Trimbach, and Shane LoSasso. Engines consultant Vick Viquesney, aeronautical engineers Bruce Haeffele, Richard W. Thomas, and Paul S. Sellers, and Professor Tom Carney of the Purdue University Aviation Technology Department also contributed valuable expertise. We are grateful to them all.

We also wish to thank the many fine companies and their people who answered our technical questions and provided supporting information. While it is impossible to name them all here, among them are Allied-Signal Garrett Engine and AiResearch Los Angeles Divisions, United Technologies Pratt & Whitney, Honeywell Business and Commuter Aviation Systems, and Aerospace Systems and Technologies.

Finally, thanks to Mike Collins and the Aircraft Owners and Pilots Association for Greg's author photo on the back cover.

# About the Authors



GREG BROWN'S love for flying is obvious to anyone who follows his popular *Flying Carpet* podcast or who has read his other books, *The Savvy Flight Instructor*, *Flying Carpet: The Soul of an Airplane*, *Job Hunting for Pilots*, and *You Can Fly!* or his long-running "Flying

Carpet" column in AOPA *Flight Training* magazine. An active pilot since 1971 and flight instructor since 1979, Greg's credentials include 2000 Industry/FAA National Flight Instructor of the Year, the 1999 NATA Excellence in Pilot Training Award, and the first ever Master Flight Instructor. He was recently inducted into the Flight Instructor Hall of Fame and earned the FAA's Wright Brothers Master Pilot Award. Mr. Brown holds an ATP Certificate with Boeing 737 type rating and Flight Instructor Certificate with all fixed-wing aircraft ratings. He has flown professionally in both scheduled and corporate aviation. Visit Greg Brown's website at [gregbrownflyingcarpet.com](http://gregbrownflyingcarpet.com).



MARK J. HOLT, a captain for a major airline, soloed at age sixteen and has logged more than 23,000 hours in over 40 years of flying. He holds an Airline Transport Pilot (ATP) Certificate with Boeing 757/767, Airbus 319/320/321, and BAE

Jetstream 41 type ratings and a Flight Engineer (Turbojet) Certificate. His professional aviation career includes extensive flight and ground school instructing experience and service as a check airman for a large regional airline. Mark is also co-author of another popular aviation book, *Air Carrier Operations*.



# Chapter 1

## Introduction

### HOW TO USE THIS MANUAL

This manual is designed for both comprehensive reading and quick reference. We recognize that some readers will want to familiarize themselves with turbine operations and will read it from beginning to end. At the same time, we feel that the manual should be in a form that allows easy access to information in order to answer a question or review a system.

Pilots will immediately notice the familiar sections of an aircraft *Pilot's Operating Handbook* or *Pilot's Information Manual*, so they should find it easy to access reference information. While most sections of the book correspond to those found in aircraft manuals, we have rearranged the order of the sections in order to make logical reading for straight-through readers.

We have tried our best to minimize specific references to Federal Aviation Regulations (FARs) due to their constant state of change. (Holding speeds changed at least twice during the writing of this manual.)

In general, procedures discussed in this book are based on commercial operations conducted under 14 CFR Parts 135 and 121. This is because the largest percentage of turbine aircraft and pilots operate commercially. Many corporate flight departments also elect to operate under more conservative commercial rules, and in any case most of our readers are already familiar with less-stringent Part 91 operations.

One of the most exciting aspects of a flying career is the continuing personal growth that comes from mastering new knowledge. We've tried our best to

convey turbine aircraft information in a manner that's as enjoyable and interesting for you as it is for us. We hope you'll agree.

### TRANSITIONING PISTON PILOTS

You've earned your Commercial Pilot Certificate, perhaps your CFI, and even an ATP. You're over the hump and off to a good start on your professional aviation career.

Now is a good time to reflect upon the knowledge and experience you've gained to date. You're an expert on piston aircraft operations and systems, sectional charts, basic aerodynamics, pilot certification requirements, low-altitude weather, and the basics of instrument flying. But there's a lot more to learn as you transition to ever more sophisticated aircraft. The hours you've invested in learning the system probably have been spent flying at slow airspeeds at altitudes below 12,000 feet. Chances are that you'll soon be operating faster equipment at higher altitudes. Looking up the career ladder you probably won't be flying those piston aircraft you've mastered for long. Turbine engines power the airplanes at the next levels. Their mechanical and electrical systems vary considerably from the aircraft you've trained in. You'll be dealing with big-time hydraulic systems, additional flight controls, and computerized flight management systems. Some interesting new aerodynamic issues also arise with the move into turbine aircraft—when did you last worry about the sound barrier? The terminology is also different. There is no  $V_{NE}$  in turbine-powered

aircraft. Maximum operating speeds are instead defined in terms of  $V_{MO}$  and  $M_{MO}$ . Approaches are conducted relative to  $V_{REF}$ .

Even your psyche as a pilot must change. As part of a two- or three-pilot crew, you'll have to master careful and precise team coordination.

Why should you care? Employers will expect at least rudimentary knowledge of turbine systems and operations at your interviews. Your first turbine ground schools will be a heck of a challenge, and plenty of pilots are waiting to fill the shoes of any washouts. You'll want to prepare as much as possible ahead of time. Finally, knowledge will help get you hired. How can you network with a friendly corporate or airline captain if you don't know what kind of jet he or she is flying?

Where does a pilot learn about these things? Most entry-level turbine jobs require a Commercial Pilot Certificate with Multi-Engine and Instrument Ratings. The FAA doesn't require any turbine aircraft knowledge or experience to earn any of those ratings. And many private flight schools don't even address turbine topics since graduates are still 1,000 hours away from their ATPs. Graduates of university flight programs are sometimes introduced to turbine operations and systems, but years may pass before the knowledge is applied.

"I want a turbine job, but I don't know anything about it. Somewhere there must be a straightforward book that explains this stuff in general terms!" This book is designed to do just that: introduce you to the basic concepts and terminology of multipilot turbine aircraft.

We recommend that you read the book from front to back, with an eye toward picking up the principles and the terminology. If you have a ground school scheduled, follow up by seriously reviewing topics that directly relate to your upcoming job. Then go back to the training section in Chapter 2. You'll be able to prepare a specific study program for yourself by following the suggestions there.

Obviously, we can't cover every aspect of every turbine aircraft in one book. Our goal, rather, is to familiarize the upgrading pilot with turbine aircraft in a broad introductory manner. You won't be ready to fly a turboprop or jet after reading this book, but you will know what they're talking about in ground school.

## TRANSITIONING MILITARY AVIATORS

Among our target readers are current or ex-military pilots interested in pursuing civilian flying careers. Military fliers have always been rated among the best candidates for civilian jobs. However, some aspects of civilian flying are markedly different from what military pilots may be used to. Military pilots, while having received excellent training, often lack exposure to certain topics that civilian employers expect them to know. Throughout the book, we have made a thorough effort to point out issues of special interest to you, the military pilot. Based on the comments of military pilots who've already transitioned to civilian aviation, we especially encourage you to concentrate on certain topics as you proceed through this book. Even minimal understanding of the following areas should pay off at interview time, in ground school, and on the flight line.

### Crew Resource Management

If there is a single, most important topic impacting your success in today's civilian aviation market, it is "CRM": "crew resource management" (also known as "cockpit resource management"). This term refers to the latest procedures for interaction and coordination of multipilot crews. At interviews, on your simulator checkride, during flight training, and on line you can expect constant evaluation of your performance in this context.

Crew resource management skills become virtually a state of mind among multipilot crews. Your career may be heavily impacted based on whether employers perceive you as part of the CRM process or as a lone-wolf pilot. (See "Crew Resource Management" in Chapter 8.)

If you've been flying single-pilot operations, pay particular attention to CRM issues in your reading. It would also be well worth your time to take one of the excellent CRM workshops offered around the country.

A related topic is checklist procedures. These vary significantly between civilian and some military operations, especially if you've been flying single-pilot aircraft. We recommend covering that section (Chapter 8, also) in some depth and perhaps practicing checklist procedures with friends who've already made the civilian transition.

## Training by Civilian Employers

Once hired by a civilian employer, you'll probably enjoy your training. While often challenging and intensive, civilian ground and flight training is generally based on the concept of "train to proficiency." The intent is to train all hired pilots until they're sharp, rather than wash people out. Standard training procedures and preparation suggestions are covered in Chapter 2.

If there's anything to be careful of in civilian training, it's to avoid coasting, due to the relaxed and supportive nature of classes. Pilots do flunk out of training. Participants need to be self-motivated because there are plenty of other applicants waiting if anyone drops out. (It's not uncommon for outside pilots to show up uninvited at smaller operations on the first day of ground school, with hopes of filling any unexpected slots.)

## Civilian Aircraft and Civilian Aviation Terminology

As a military pilot, you probably haven't spent much time around regional or corporate aircraft or the latest airline equipment. You may be familiar with the Boeing 747s and the Airbus A-320s operated by the majors. But can you tell the difference between an Airbus A-330 and a Boeing 767? How about the forty or so most common commuter and corporate aircraft?

You may lump civilian aircraft identification skills into the "nice to know but not really important" file. However, it takes only one detailed taxi clearance at a major airport to prove that civilian aircraft identification skills are a necessity (for example, "American 71, wait for the A-330, then taxi via the inner, hold short of K, wait for the Embraer RJ145, then transition to the outer behind, and follow the Falcon Jet to 25R").

Review the Airline, Regional, and Corporate Aircraft Spotter's Guide (see Appendix 2) to improve your civilian aircraft identification skills. Spend some time at the airport checking out these aircraft. The knowledge will pay off for you on the line. Aircraft familiarity is also important when deciding where to apply for a flight position. Your life on the job will vary tremendously depending on whether or not the aircraft you fly are pressurized, carry flight attendants and refreshments, and are equipped with lavatories or autopilots.

A civilian airline and corporate terminology section has also been included in this book, with you in mind. (See the Glossary.) Like the military, civilian aviation has its own lingo. The more familiar you are with the system, the more comfortable your transition to civilian aviation will be.

Once you've gotten through the book, we strongly encourage you to subscribe immediately to some of the excellent civilian aviation magazines currently available. Join online aviation forums (Google "aviation forums"), read active posts, and ask questions. You'll learn more about the airplanes, lingo, and issues facing the industry. Go hang around the airport, too. Pilots everywhere love to show off their airplanes. Besides, some may turn into job contacts.

## Aircraft Systems

Depending upon what types of aircraft you've been flying, there are probably significant differences in aircraft systems that you'll need to learn. We recommend skimming all of the systems chapters (Chapters 3–6) for minor differences and then returning in more depth to those systems unfamiliar to you.

One system, in particular, is brand new and challenging for many transitioning military pilots: propellers. We have included a special supplement on propeller basics for those who may not be going straight into jets. (Review "Propeller Supplement for Transitioning Military Jet Pilots" and then "Turboprop Propeller Systems" in Chapter 3.)

## Contemporary Issues in the Aviation Industry

While brief, "Contemporary Issues in the Aviation Industry" in Chapter 2 is very important to you. Social and union issues have become extremely sensitive in today's civilian aviation industry. It's important to maintain the proper mind-set if you want to get hired and to keep and enjoy your job.

## About Your Civilian Counterparts

Finally, a few words are in order regarding your civilian counterparts. Many military pilots wonder about the credentials of the civilian pilots they'll be flying with. Most civilian pilots earn their ratings through university flight programs, at private flight

schools, or with private flight instructors. Civilian flight training varies tremendously in quality. While some pilots graduate from top-notch programs comparable in quality with military training, others collect their training from many different sources, a la carte. (The predictable nature of military training is one of your competitive points as a job candidate.)

To gain flight hours and professional experience, the typical newly graduated civilian pilot works first as a flight instructor (CFI) for a year or so, then moves on to cargo, air-tour, or air-taxi operations. ("Air-taxi" refers to commercial, on-demand charter operators.) From there, he or she moves to a regional (commuter) airline or corporate flight department. (The luckier ones may skip a level or two on their way

up the ladder.) To be sure, by the time civilian pilots make it to the higher professional levels, they're pretty sharp. In particular, many have excellent all-weather flying experience in commercial operations. Like your military peers, most civilian pilots aspire to corporate or airline jet captains' positions.

In the course of flying you'll probably hear about some interesting "time-building" jobs held by your civilian counterparts during their careers. Bush flying, island cargo hopping, emergency medical flying, water bombing, mercenary and missionary flying make some of their stories almost as good as yours! Most pilots would agree that a combination of military and civilian backgrounds makes for a great flight department.

# Chapter 15

## Operational Information

### AERODYNAMICS OF HIGH-SPEED/HIGH-ALTITUDE AIRCRAFT

This section introduces some basic concepts relating to high-speed aerodynamics. Even if you won't be flying high-speed jet aircraft any time soon, it's important to be familiar with some of the basic aerodynamic principles of aircraft you'll be sharing airspace with.

First, what do we mean when we say "high altitude?" According to Federal Aviation Regulations Part 61, the high-altitude environment begins at FL250. Pilots who fly at or above FL250 in pressurized aircraft must receive training regarding safe flight in high altitude operations. Required topics include:

- Criteria defining maximum operating altitude and service ceilings.
- Required high altitude training and endorsement.
- Flight crew and passenger use of oxygen systems.
- Airspace issues (e.g., reduced vertical separation minimum [RVSM]).

### High-Speed Flight and the Sound Barrier

For our purposes, we'll define high-speed flight as cruise flight at near, but less than, the speed of sound. The speed of sound varies with air temperature. At standard temperature, sound travels in air through a

range from about 740 mph at sea level to 660 mph or so up at 40,000 to 50,000 feet. Since the few supersonic jobs available to civilian pilots disappeared with the retirement of the Concorde fleet, there's no need for us to delve too deeply into supersonic flight. At the same time, it's important to understand what happens to an airplane as it approaches supersonic speeds, speeds at which it encounters some of the major aerodynamic limitations of high-speed flight.

### Indicated Airspeed, True Airspeed, Mach Number and Changeover Altitudes

Before addressing the aerodynamics of high-speed/high-altitude flight, let's review some basic terms we will be using in this chapter's discussion.

#### Indicated Airspeed (IAS)

**Indicated airspeed (IAS)** is simply the speed shown on the airspeed indicator. This speed is calculated by comparing ram or dynamic air pressure from the pitot tube(s) with static air pressure sensed at the static ports. The greater the difference between ram air pressure and static air pressure, the greater the indicated airspeed. Because that proportion remains similar regardless of air density, it reflects the aircraft's maneuvering flight performance without regard to density altitude. As you know, IAS does not accurately reflect the aircraft's actual velocity through an air mass except under standard conditions at sea level. Rather, IAS is important because, since it's proportional, indicated airspeeds do not vary with altitude or temperature.



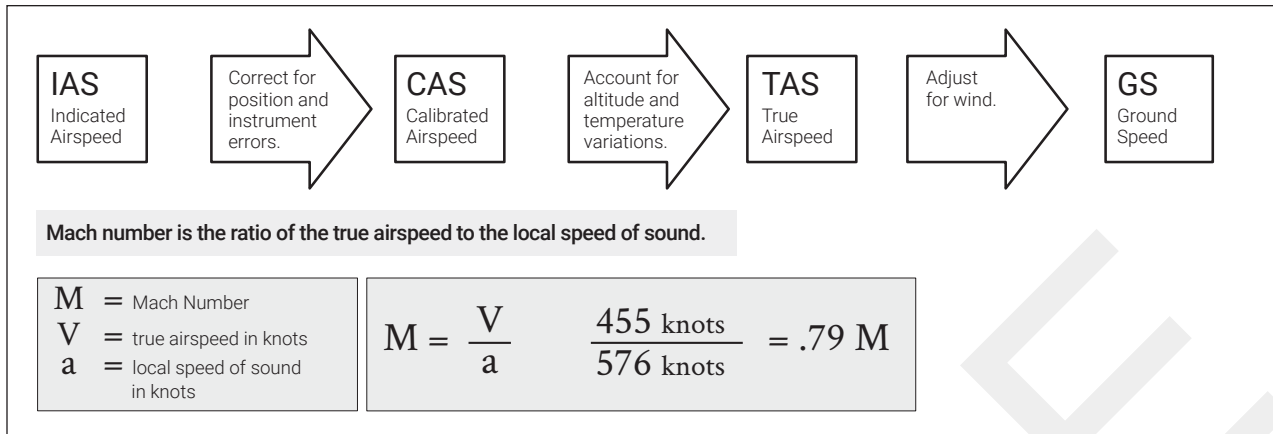


FIGURE 15.1 | Aviation speeds review.

Therefore, manufacturers use IAS as the basis for determining and defining airplane performance in maneuvering regimes. Takeoff, climb, landing, and stall speeds listed in the aircraft flight manual (AFM) are indicated airspeeds precisely because they provide constant control and maneuvering reference regardless of altitude or temperature. Finally, at lower altitudes, air traffic controllers issue speed restrictions based on IAS.

### True Airspeed (TAS)

**True airspeed (TAS)** is the aircraft's indicated airspeed corrected for altitude and nonstandard temperature. In other words, TAS is the actual speed of an aircraft relative to the air mass through which it is flying, and in a no-wind condition TAS equals the aircraft's ground speed. Since air density decreases with altitude, an airplane must be flown faster at higher altitudes to generate the same pressure difference between pitot ram air pressure and static air pressure. Therefore, for a given indicated airspeed, true airspeed increases with altitude and decreases with decreasing altitude. (See Figure 15.2.)

### Calibrated Airspeed (CAS)

**Calibrated airspeed (CAS)** is simply indicated airspeed, corrected for instrument and installation error. Calibrated airspeed is equal to true airspeed (TAS) in a standard atmosphere at sea level (15°C, 29.92 inHg/1013 hPa). While CAS is important to understand for testing purposes, it has little application to daily flight operations. First, position and instrument errors are usually pretty small, so for our purposes we can assume CAS is equal to IAS. Second (and probably most important to a pilot), as previously mentioned, placarded and AFM airspeed limits are given in IAS

and Mach number. Therefore, in this chapter we will focus mainly on the use of IAS and Mach number.

### Ground Speed (GS)

**Ground speed (GS)** is the actual speed of an aircraft over the ground. It is true airspeed adjusted for wind. Ground speed decreases with a headwind and increases with a tailwind.

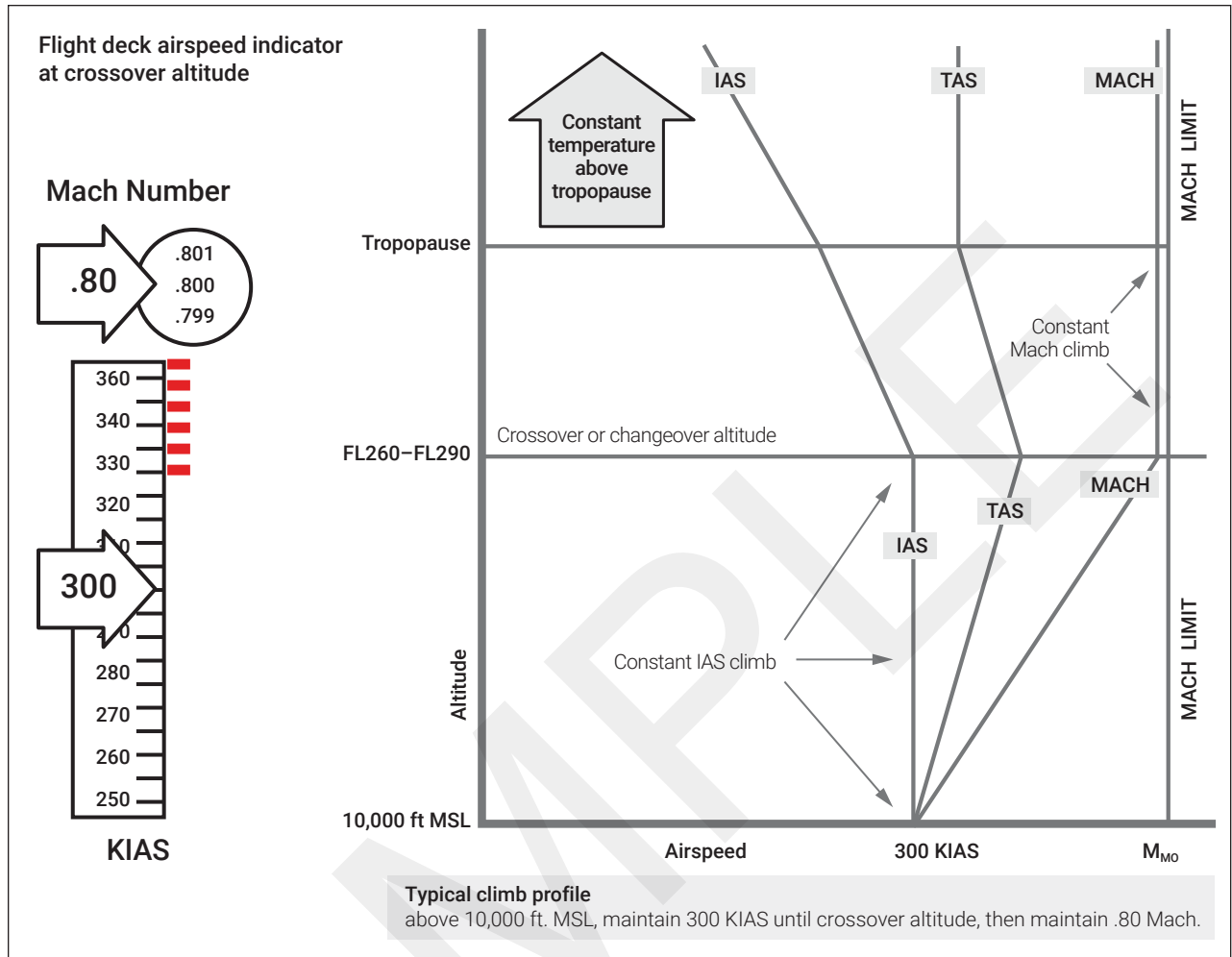
### Mach Number

Airspeeds of high-speed aircraft are measured relative to the speed of sound using an index known as **Mach number**. Mach number is the ratio of an aircraft's airspeed to the speed sound travels under the same atmospheric conditions. If an airplane is flying at the speed of sound, it is said to be traveling at Mach 1. At 0.8 Mach, the aircraft is traveling at 80 percent of the speed of sound. An aircraft at 1.2 Mach is traveling at 120 percent of the speed of sound.

Three categories or regions of flight, based on the speed of sound, are commonly used to describe high-speed flight. Flight is grouped into one of the following categories, not by the speed of the aircraft per se but by the speed of the airflow over the aircraft's surface.

**Subsonic flight** includes Mach 0 up to approximately 0.75 Mach. The upper limit of subsonic flight for a given aircraft is the maximum airspeed at which none of the airflow over its surfaces reaches the speed of sound.

**Transonic flight** is generally considered to be between 0.75 Mach and Mach 1.2. (Again, the parameters of this region vary with the design of the aircraft.) In transonic flight airflow over aircraft surfaces is



**FIGURE 15.2** | Constant IAS climb to crossover altitude, then constant Mach Climb.

mixed between airflow below the speed of sound and airflow above the speed of sound.

In **supersonic flight** all airflow traveling over the surfaces of the aircraft is above the speed of sound. This is generally considered to be aircraft speeds above Mach 1.2.

### Indicated Airspeed to Mach Speed Crossover Altitude

Pilots flying turbine-powered aircraft typically begin the climb to cruise altitude at the mandated constant IAS of 250 knots until above 10,000 feet MSL. (We'll discuss exceptions later.) Above 10,000 feet MSL, pilots fly a constant airspeed either chosen by the onboard flight management computer (see Chapter 13), based on pilot preference, or assigned by air traffic controllers. Typically, turbine-powered passenger aircraft climb in a range of 250 to 340 KIAS. Remember,

however, that a few things happen as an aircraft climbs at a constant IAS. (See Figure 15.2.)

- When climbing at a constant IAS, the aircraft's TAS increases (i.e., it takes a higher TAS to provide the same impact air pressure through the pitot tube to maintain a constant IAS) (see Figures 15.2 and 15.3).
- The speed of sound varies directly with temperature (i.e., the speed of sound increases with increasing temperature, and decreases with decreasing temperature). Climbing at a constant Mach number, the TAS for a given Mach number decreases.
- Crossover Altitude (sometimes informally called "changeover altitude") is the altitude at which IAS and Mach value coincide at the same TAS. Above crossover or changeover altitude, pilots climb using Mach number.

Altitude	IAS	TAS	Mach	$M_{MO}/V_{MO}$
FL390	242	485	.79	.86/265
FL350	270	470	.79	.86/294
IAS to Mach crossover altitude				
FL300	300	460	.785	.84/300
FL250	300	446	.73	.82/325
FL200	300	415	.68	.75/350

**FIGURE 15.3** | 300 KIAS/.79 Mach climb schedule (Boeing 757-200).

Crossover altitude is necessary because since true airspeed increases with altitude at a given IAS, eventually TAS approaches the speed of sound. If we were to fly a constant 300 KIAS climb, for example (approximately Mach 0.54 at 10,000 feet MSL), we would approach Mach 1.0 at 41,000 feet, exceeding the aircraft's **maximum operating speed** or  $M_{MO}$ . (See Figures 15.2 and 15.5.)

To prevent this from happening, the aircraft's FMC or autopilot automatically switches at crossover altitude from climbing at a constant IAS to climbing at a constant Mach number. During descent, it switches from Mach number back to IAS at the changeover altitude. On a given aircraft, crossover altitude may be calculated where IAS and target Mach number actually coincide, or approximated at a specific pressure altitude (e.g., FL260). Regardless of how crossover altitude is computed, there is only one crossover altitude for a particular aircraft.

Above crossover altitude, ATC issues speed assignments by Mach number (e.g., "American 71, for traffic maintain .80 Mach or greater"). When issuing speed assignments for transitions to or from higher flight levels, controllers do so in an appropriate combination of Mach number and IAS (e.g., "American 71, start your descent to 15,000 feet; maintain .78 Mach in the descent and 290 KIAS in the transition to IAS.").

Notice from Figure 15.2 that above the tropopause, the outside air temperature (OAT) remains constant up to around FL600. Therefore, the aircraft climbs at a constant *temperature-dependent* Mach number, meaning the TAS remains constant as well. However, the *air pressure-dependent* IAS will continue to decrease with decreasing air density. Of course, the inverse is true as we descend. These concepts are important to jet pilots because they spend a good deal of time cruising the

lower stratosphere, just above the tropopause. (The average height of the tropopause over the United States is 36,000 feet.) Most large airliners cruise at altitudes from FL310 to FL410, while some higher-performing business jets can cruise as high as FL510.

## Compressibility

Except for military pilot readers, chances are that during primary training your studies in aerodynamics concentrated on aircraft with relatively slow airspeeds. Because airflow at slow airspeeds undergoes only small density changes, it was simplest to treat air as incompressible, making airflow appear analogous to the flow of water.

Air is compressible, however, and at high airspeeds above around 260 KIAS, large air density changes do occur. Therefore, high-speed aircraft must be designed to compensate for these compressibility effects. The concept of **compressibility** is relatively simple. When an aircraft flies at slow airspeeds, the surrounding air molecules have time to "get out of the aircraft's way." As the vehicle's speed increases, air molecules begin to "pile up" ahead of the aircraft, increasing air pressure, density, and temperature in that region. As the aircraft enters transonic speeds, the air going over parts of the wing becomes supersonic, resulting in sudden tremendous increase in air density as air piles up in front of the vehicle.

Think of it this way. The maximum speed of a pressure wave through air is the speed of sound. As long as an airplane is traveling below that speed, the waves caused by its movement through the air radiate out in front of the vehicle. However, once the speed of sound is reached, the vehicle travels faster than the air can "get out of the way." A powerful compression wave, or **shock wave**, forms at the boundary between the disturbed air and undisturbed air around the now transonic aircraft (Figure 15.4).

High-speed aircraft are designed to accommodate compressibility effects. Since air behaves differently at high airspeeds, aircraft that fly at transonic speeds must have differently shaped wings and control surfaces than slower flying aircraft. In fact, the transonic flight regime is challenging for design engineers because while parts of the wing experience supersonic airflow, other parts of the wing are subsonic. Additionally, with increasing speed, a wing's center of pressure moves aft. The center of pressure in a typical subsonic aircraft is normally about 25 percent behind the leading edge. As aircraft speed increases, the

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Gregory N. Brown | Mark J. Holt

FIFTH EDITION



Greg Brown's love of flying is obvious to all who follow his popular *Flying Carpet* podcast or long-running *Flying Carpet* column in *AOPA Flight Training* magazine. The

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