#### JOSEPH R. BADICK BRIAN A. JOHNSON

# FLIGHT THEORY AND AERODYNAMICS A PRACTICAL GUIDE FOR OPERATIONAL SAFETY

# FOURTH EDITION

### **Table of Contents**

Cover Title Page Copyright Page Preface About the Authors About the Companion Website <u>1 Introduction to the Flight Environment</u> **INTRODUCTION BASIC QUANTITIES** FORCES MASS SCALAR AND VECTOR QUANTITIES **MOMENTS** EQUILIBRIUM CONDITIONS **NEWTON'S LAWS OF MOTION LINEAR MOTION ROTATIONAL MOTION ENERGY AND WORK** POWER **FRICTION SYMBOLS KEY TERMS PROBLEMS** 2 Atmosphere, Altitude, and Airspeed Measurement **PROPERTIES OF THE ATMOSPHERE** 

ICAO STANDARD ATMOSPHERE ALTITUDE MEASUREMENT **CONTINUITY EQUATION BERNOULLI'S EQUATION** AIRSPEED MEASUREMENT **SYMBOLS KEY TERMS** PROBLEMS 3 Structures, Airfoils, and Aerodynamic Forces AIRCRAFT STRUCTURES AIRFOILS **DEVELOPMENT OF FORCES ON AIRFOILS AERODYNAMIC FORCE AERODYNAMIC PITCHING MOMENTS AERODYNAMIC CENTER ACCIDENT BRIEF: AIR MIDWEST FLIGHT 5481** SYMBOLS **KEY TERMS PROBLEMS** 4 Lift INTRODUCTION TO LIFT ANGLE OF ATTACK

**BOUNDARY LAYER THEORY** 

**REYNOLDS NUMBER** 

ADVERSE PRESSURE GRADIENT

**AIRFLOW SEPARATION** 

STALL

AERODYNAMIC FORCE EQUATIONS

LIFT EQUATION

AIRFOIL LIFT CHARACTERISTICS

HIGH COEFFICIENT OF LIFT DEVICES

EFFECT OF ICE AND FROST

LIFT DURING FLIGHT MANEUVERS

<u>SYMBOLS</u>

KEY TERMS

**PROBLEMS** 

5 Drag

**INDUCED DRAG** 

**GROUND EFFECT** 

LAMINAR FLOW AIRFOILS

PARASITE DRAG

**DRAG EQUATION** 

TOTAL DRAG

LIFT-TO-DRAG RATIO

DRAG REDUCTION

<u>SYMBOLS</u>

KEY TERMS

PROBLEMS

<u>6 Jet Aircraft Performance</u>

THRUST-PRODUCING AIRCRAFT

THRUST-REQUIRED CURVE

PRINCIPLES OF PROPULSION

THRUST-AVAILABLE TURBOJET AIRCRAFT

SPECIFIC FUEL CONSUMPTION

FUEL FLOW

THRUST-AVAILABLE/THRUST-REQUIRED **CURVES** ITEMS OF AIRCRAFT PERFORMANCE VARIATIONS IN THE THRUST-REOUIRED CURVE <u>SYMBOLS</u> **KEY TERMS** PROBLEMS 7 Propeller Aircraft Performance POWER AVAILABLE PRINCIPLES OF PROPULSION POWER-REOUIRED CURVES ITEMS OF AIRCRAFT PERFORMANCE VARIATIONS IN THE POWER-REQUIRED CURVE **SYMBOLS KEY TERMS PROBLEMS** 8 Takeoff Performance NORMAL TAKEOFF **IMPROPER LIFTOFF REJECTED TAKEOFFS INITIAL CLIMB** LINEAR MOTION FACTORS AFFECTING TAKEOFF PERFORMANCE **SYMBOLS KEY TERMS PROBLEMS** 9 Landing Performance PRELANDING PERFORMANCE

NORMAL LANDING **IMPROPER LANDING PERFORMANCE** HAZARDS OF HYDROPLANING LANDING DECELERATION, VELOCITY, AND DISTANCE LANDING EQUATIONS **SYMBOLS KEY TERMS PROBLEMS 10 Slow-Speed Flight REGION OF REVERSED COMMAND** STALLS **SPINS** HAZARDS DURING SLOW-SPEED FLIGHT - LOW-LEVEL WIND SHEAR AIRCRAFT PERFORMANCE IN LOW-LEVEL WIND SHEAR HAZARDS DURING SLOW-SPEED FLIGHT - WAKE **TURBULENCE KEY TERMS PROBLEMS 11 Maneuvering Performance** GENERAL TURNING PERFORMANCE LOAD FACTOR THE *V-G* DIAGRAM (FLIGHT ENVELOPE) LOAD FACTOR AND FLIGHT MANEUVERS **SYMBOLS KEY TERMS PROBLEMS** 

**12 Longitudinal Stability and Control DEFINITIONS OSCILLATORY MOTION** WEIGHT AND BALANCE AIRPLANE REFERENCE AXES STATIC LONGITUDINAL STABILITY DYNAMIC LONGITUDINAL STABILITY PITCHING TENDENCIES IN A STALL LONGITUDINAL CONTROL **SYMBOLS KEY TERMS** PROBLEMS **13** Directional and Lateral Stability STATIC DIRECTIONAL STABILITY DIRECTIONAL CONTROL MULTI-ENGINE FLIGHT PRINCIPLES LATERAL STABILITY AND CONTROL STATIC LATERAL STABILITY LATERAL CONTROL DYNAMIC DIRECTIONAL AND LATERAL **COUPLED EFFECTS SYMBOLS KEY TERMS PROBLEMS** 14 High-Speed Flight THE SPEED OF SOUND HIGH-SUBSONIC FLIGHT DESIGN FEATURES FOR HIGH-SUBSONIC FLIGHT

**TRANSONIC FLIGHT** SUPERSONIC FLIGHT **SYMBOLS KEY TERMS PROBLEMS** <u>15 Rotary-Wing Flight Theory</u> MOMENTUM THEORY OF LIFT **AIRFOIL SELECTION** FORCES ON ROTOR SYSTEM THRUST DEVELOPMENT HOVERING FLIGHT **GROUND EFFECT** ROTOR SYSTEMS DISSYMMETRY OF LIFT IN FORWARD FLIGHT HIGH FORWARD SPEED PROBLEMS HELICOPTER CONTROL HELICOPTER POWER-REQUIRED CURVES POWER SETTLING, SETTLING WITH POWER, AND VORTEX RING STATE **AUTOROTATION** DYNAMIC ROLLOVER PROBLEMS Answers to Problems CHAPTER 1 CHAPTER 2 CHAPTER 3 CHAPTER 4 **CHAPTER 5** 

CHAPTER 6 CHAPTER 7 CHAPTER 8 CHAPTER 9 CHAPTER 10 CHAPTER 11 CHAPTER 12 CHAPTER 13 CHAPTER 13 CHAPTER 14 CHAPTER 15 Bibliography GOVERNMENT PUBLICATIONS PERIODICALS PERSONAL INTERVIEW Index

End User License Agreement

# List of Tables

Chapter 2

Table 2.1 Standard atmosphere table

Chapter 11

Table 11.1 Load factors at various bank angles

## List of Illustrations

Chapter 1

Figure 1.1 Forces on an airplane in steady flight.

<u>Figure 1.2 Resolved forces on an airplane in steady</u> <u>flight.</u>

Figure 1.3 Vector of an eastbound aircraft.

Figure 1.4 Vector of a north wind.

Figure 1.5 Vector addition.

Figure 1.6 Vector of an aircraft in a climb.

Figure 1.7 Vectors of groundspeed and rate of <u>climb.</u>

Figure 1.8 Balance Lever.

<u>Figure 1.9 Coefficients of friction for airplane tires</u> <u>on a runway.</u>

Chapter 2

Figure 2.1 Standard pressure.

Figure 2.2 Properties of a standard atmosphere.

Figure 2.3 Field elevation versus pressure altitude.

<u>Figure 2.4 Pressure altitude conversion and density</u> <u>altitude chart.</u>

<u>Figure 2.5 Flow of air through a pipe.</u>

Figure 2.6 Pressure change in a venturi tube.

<u>Figure 2.7 Velocities and pressures on an airfoil</u> <u>superimposed on a venturi ...</u>

Figure 2.8 Flow around a symmetrical object.

<u>Figure 2.9 Schematic of a pitot-static airspeed</u> <u>indicator.</u>

Figure 2.10 Air data computer and pitot-static sensing.

Figure 2.11 Blocked pitot tube and drain hole.

Figure 2.12 Compressibility correction chart.

Figure 2.13 Altitude and EAS to TAS correction chart.

Figure 2.14 IAS, CAS, and TAS comparison.

Chapter 3

<u>Figure 3.1 Modern transport category control</u> <u>surfaces.</u>

Figure 3.2 Helicopter flight controls.

Figure 3.3 Differential ailerons.

Figure 3.4 Frise-type ailerons.

Figure 3.5 Elevator movement.

Figure 3.6 Adjustable horizontal stabilizer.

Figure 3.7 Rudder movement.

Figure 3.8 Common flap designs.

Figure 3.9 Ground spoilers deployed.

Figure 3.10 Trim tabs.

Figure 3.11 Antiservo Tab.

<u>Figure 3.12 Secondary control surfaces and their</u> <u>location.</u>

Figure 3.13 Airfoil section.

Figure 3.14 Airfoil terminology.

Figure 3.15 Cambered versus symmetrical airfoil.

Figure 3.16 Examples of airfoil design.

Figure 3.17 NACA airfoils (NACA data).

<u>Figure 3.18 Effect of pressure disturbances on</u> <u>airflow around an airfoil.</u> Figure 3.19 Velocity changes around an airfoil.

Figure 3.20 Static pressure on an airfoil (a) at zero AOA, and (b) at a posi...

Figure 3.21 Components of aerodynamic force.

<u>Figure 3.22 Pressure forces on (a) nonrotating</u> <u>cylinder and (b) rotating cyl...</u>

<u>Figure 3.23 Pitching moments on a symmetrical</u> <u>airfoil (a) at zero AOA and (b...</u>

<u>Figure 3.24 Pitching moments on a cambered</u> <u>airfoil: (a) zero lift, (b) devel...</u>

Figure 3.25 Flaps extended pitching moments.

Figure 3.26 Beech 1900D pitch control system.

Chapter 4

Figure 4.1 Pressure distribution on an airfoil with AOA.

Figure 4.2 Critical angle of attack, stall, and angle of attack indications....

Figure 4.3 Boundary layer composition.

Figure 4.4 Laminar boundary layer.

Figure 4.5 Turbulent boundary layer.

Figure 4.6 Laminar and turbulent velocity profiles.

<u>Figure 4.7 Reynolds number effect on airflow on a</u> <u>smooth flat plate.</u>

Figure 4.8 Adverse pressure gradient.

Figure 4.9 Airflow separation velocity profiles.

<u>Figure 4.10 Sphere wake drag: (a) smooth sphere,</u> (b) rough sphere.

Figure 4.11 Critical angle of attack and stall.

Figure 4.12 C<sub>L</sub> vs. AOA for a symmetrical airfoil.

Figure 4.13 C<sub>L</sub> vs. AOA for a cambered airfoil.

Figure 4.14 Thickness effect.

Figure 4.15 Camber effect.

Figure 4.16 High-*C*<sub>L</sub> devices.

<u>Figure 4.17 Common leading edge high-*C*<sub>L</sub> devices.</u>

Figure 4.18 Effect of a camber changer on the  $C_{L}-\alpha$  curve.

Figure 4.19 Micro-vortex generators.

Figure 4.20 Fixed slot at (a) low AOA and (b) high AOA.

Figure 4.21 Effect of an energy adder on the  $C_{\underline{L}}-\alpha$  curve.

Figure 4.22 Effect of ice and frost on wings.

Figure 4.23 Forces in a banked turn.

Figure 4.24 Force vectors during a stabilized climb.

Chapter 5

Figure 5.1 Wing planform examples.

Figure 5.2 Wing planform terminology.

Figure 5.3 Aspect ratio.

Figure 5.4 Wingtip vortices.

Figure 5.5 Airflow about an infinite wing.

<u>Figure 5.6 Vertical velocity vectors of an infinite</u> <u>wing.</u>

Figure 5.7 Vertical velocity vectors of a finite wing.

Figure 5.8 Airflow about a finite wing.

<u>Figure 5.9 Relative wind and force vectors on a finite wing.</u>

Figure 5.10 Induced drag versus velocity.

<u>Figure 5.11 Wingtip vortex at altitude versus near</u> <u>the ground.</u>

Figure 5.12 Downwash at altitude versus near the ground.

<u>Figure 5.13  $T_r$  and  $C_L$  curves in ground effect.</u>

Figure 5.14 Ground effect.

<u>Figure 5.15 Comparison of drag characteristics of</u> <u>conventional and laminar f...</u>

Figure 5.16 Microscopic surface of a wing.

Figure 5.17 Form drag.

Figure 5.18 Interference drag at the wing root.

Figure 5.19 Parasite drag-airspeed curve.

Figure 5.20 C<sub>L</sub> vs. AOA and C<sub>D</sub> vs. AOA.

Figure 5.21 Drag vector diagram.

Figure 5.22 Total drag curve.

Figure 5.23 L/D<sub>Max</sub>.

Figure 5.24 Typical lift-to-drag ratios.

Figure 5.25 Wingtip vortex reduction methods.

Figure 5.26 Winglets.

Chapter 6

Figure 6.1 Aircraft in equilibrium flight.

Figure 6.2 Turbojet engine.

Figure 6.3 Turbofan engine.

Figure 6.4 Dual-spool axial-flow compressor.

Figure 6.5 Jet engine compressor stall.

Figure 6.6 T-38 drag curve.

Figure 6.7 T-38 thrust required.

Figure 6.8 Engine thrust schematic.

Figure 6.9 Propulsion efficiency.

Figure 6.10 Variation of thrust with rpm.

Figure 6.11 Typical jet acceleration times.

Figure 6.12 T-38 installed thrust.

Figure 6.13 T-38 thrust variation with altitude.

<u>Figure 6.14 T-38 *c*t-rpm.</u>

Figure 6.15 T-38 c<sub>t</sub>-altitude.

Figure 6.16 T-38 fuel flow–altitude.

Figure 6.17 T-38 thrust available-thrust required.

Figure 6.18 Forces acting on a climbing aircraft.

Figure 6.19 Velocity for maximum climb angle.

Figure 6.20 Wind effect on climb angle to the ground.

Figure 6.21 Obstacle clearance for jet takeoff.

Figure 6.22 Climb angle and rate of climb.

Figure 6.23 Rate of climb velocity vector.

Figure 6.24 Velocity for maximum rate of climb.

Figure 6.25 Finding maximum endurance velocity.

<u>Figure 6.26 Finding the maximum specific range</u> <u>velocity.</u>

Figure 6.27 Wind effect on specific range.

Figure 6.28 Total range calculation.

<u>Figure 6.29 Effect of weight change on induced</u> <u>drag.</u>

Figure 6.30 Effect of weight change on the  $T_{r}$  curve.

<u>Figure 6.31 Effect of weight change on specific</u> <u>range.</u>

<u>Figure 6.32 Effect of configuration on parasite</u> <u>drag.</u>

<u>Figure 6.33 Effect of configuration on the  $T_r$  curve.</u>

<u>Figure 6.34 Effect of altitude on  $T_r$  and  $T_a$ , curves.</u>

<u>Figure 6.35 Range improvement using cruise-</u> <u>climb.</u>

Chapter 7

Figure 7.1 Airfoil sections of a propeller blade.

Figure 7.2 Propeller tip speed versus propeller hub.

Figure 7.3 Propeller blade angle.

Figure 7.4 Geometric pitch versus effective pitch.

<u>Figure 7.5 Blade angle in flight.</u>

Figure 7.6 Various blade angle ranges.

Figure 7.7 Thrust from a propeller.

Figure 7.8 Propeller pitch angle configurations.

Figure 7.9 Propeller range positions.

<u>Figure 7.10 (a) Thrust-required and (b) power-</u> required curves.

Figure 7.11 Power required.

Figure 7.12 Power available curve.

Figure 7.13 Power required and power available.

Figure 7.14 Fixed-shaft turboprop engine.

<u>Figure 7.15 Split shaft/free turbine engine.</u>

Figure 7.16 Turbocharged engine.

Figure 7.17 Forces on a climbing aircraft.

Figure 7.18 Thrust versus climb angle.

Figure 7.19 Climb angle versus velocity.

<u>Figure 7.20 Comparison of maximum AOC between</u> <u>jet and propeller airplanes....</u>

Figure 7.21 Rate of climb velocity vector.

<u>Figure 7.22 Comparison of maximum ROC between</u> <u>jet and propeller airplanes....</u>

Figure 7.23 Finding the maximum rate of climb.

Figure 7.24 Finding the maximum endurance and range.

Figure 7.25 Effect of wind on range.

<u>Figure 7.26 Effect of weight change on a  $P_{\rm r}$  curve.</u>

<u>Figure 7.27 Effect of weight change on specific</u> <u>range.</u>

<u>Figure 7.28 Effect of configuration on the  $P_{\rm r}$  curve.</u>

<u>Figure 7.29 Effect of altitude on a  $P_{\rm r}$  curve.</u>

<u>Figure 7.30  $V_{\rm X}$  versus  $V_{\rm Y}$  with altitude.</u>

Figure 7.31 Effect of altitude on specific range.

Chapter 8

Figure 8.1 Takeoff distance graph.

Figure 8.2 Normal takeoff and climb.

Figure 8.3 Crosswind takeoff.

Figure 8.4 Short-field takeoff.

Figure 8.5 Soft-field takeoff.

<u>Figure 8.6 Water drag and propeller thrust on</u> <u>takeoff.</u>

<u>Figure 8.7 Hydrodynamic lift while on the step.</u>

Figure 8.8 Premature takeoff.

<u>Figure 8.9 Accelerate-stop distance, accelerate-go</u> <u>distance, and climb gradi...</u>

Figure 8.10 Balanced field length.

<u>Figure 8.11 Single-engine velocity-distance</u> <u>profiles.</u>

Figure 8.12 Multi-engine velocity-distance profiles.

Figure 8.13 FAR takeoff field length.

Figure 8.14 RTO and tire failure.

Figure 8.15 Performance chart examples.

Figure 8.16 Jet takeoff and departure profile.

Figure 8.17 Segmented one-engine climb graph.

Figure 8.18 Forces on an airplane during takeoff.

Figure 8.19 Effect of wind on takeoff.

<u>Figure 8.20 Takeoff distance chart with runway</u> <u>surface adjustment.</u>

Figure 8.21 U.S. Chart Supplement information.

Chapter 9

Figure 9.1 Landing distance graph.

Figure 9.2 Forces in equilibrium.

Figure 9.3 Forces acting in a power-off glide.

Figure 9.4 Glide ratio vector diagram.

Figure 9.5 Jet approach and landing profile.

Figure 9.6 FAR landing field length required.

Figure 9.7 Stabilized approach for a jet aircraft.

Figure 9.8 Approach glide paths.

<u>Figure 9.9 Approach glide path views from the flight deck.</u>

<u>Figure 9.10 Lift from (a) propellers and (b)</u> <u>turbojets.</u>

<u>Figure 9.11 Coefficient of lift comparison for flap</u> <u>extended and retracted p...</u>

Figure 9.12 Effect of flaps on final approach.

<u>Figure 9.13 Changing angle of attack during</u> <u>landing.</u>

Figure 9.14 Improper drift correction.

Figure 9.15 Sideslip during crosswind.

<u>Figure 9.16 Short-field approach and landing over</u> <u>an obstacle.</u>

Figure 9.17 Soft/rough-field approach and landing.

Figure 9.18 High round out.

Figure 9.19 Bouncing during touchdown.

Figure 9.20 Porpoising during round out.

Figure 9.21 Go-around procedure.

<u>Figure 9.22 Forces on tire: (a) static condition, (b)</u> <u>rolling tire.</u> <u>Figure 9.23 Hydroplaning forces on tire: (a) low</u> <u>speed, (b) medium speed, (c...</u>

<u>Figure 9.24 Forces acting on an airplane during</u> <u>landing.</u>

Figure 9.25 Aerodynamic braking and wheel braking.

Figure 9.26 Normal and friction forces.

<u>Figure 9.27 Coefficient of friction versus wheel</u> <u>slippage.</u>

<u>Figure 9.28 Effect of runway condition on</u> <u>coefficient of friction.</u>

Figure 9.29 Thrust reversers.

Figure 9.30 Effect of wind on landing.

<u>Figure 9.31 Effect of headwind during landing</u> <u>approach.</u>

Chapter 10

<u>Figure 10.1 Effect of sweepback on  $C_{\rm L}$ - $\alpha$  curves.</u>

Figure 10.2 Regions of normal and reversed command.

Figure 10.3 Constant airspeed climb. Stick or throttle?

<u>Figure 10.4 Region of reversed command for a</u> power producer.

Figure 10.5 Spanwise lift distribution.

Figure 10.6 Wing spanwise lift distribution.

Figure 10.7 Stall patterns.

Figure 10.8 Stall recovery template.

Figure 10.9 Power-off stall and recovery.

<u>Figure 10.10 Secondary stall due to improper stall</u> <u>recovery.</u>

Figure 10.11 Stall speed chart.

Figure 10.12 Spin entry and recovery.

Figure 10.13 Stall hitting the horizontal tail.

Figure 10.14 Swept wings stall at tips first.

Figure 10.15 Aerodynamics of spin for straightwing aircraft.

<u>Figure 10.16 Aerodynamics of spin for swept-wing</u> <u>aircraft.</u>

Figure 10.17 Wind shear caused by a downdraft.

Figure 10.18 "Bursts" caused by a thunderstorm.

Figure 10.19 Thunderstorm gust front.

Figure 10.20 Temperature inversion LLWS.

<u>Figure 10.21 Tailwind wind shear encountered on</u> <u>takeoff: (a) flight path, (b...</u>

<u>Figure 10.22 Tailwind shear encountered in landing</u> <u>approach: (a) flight path...</u>

Figure 10.23 Wingtip vortices behind an aircraft.

Figure 10.24 Helicopter vortices.

Figure 10.25 Wake turbulence avoidance.

<u>Figure 10.26 Wake turbulence avoidance</u> <u>procedures</u>

Chapter 11

Figure 11.1 Overbanking tendency.

<u>Figure 11.2 Forces on an aircraft in a coordinated</u> <u>level turn.</u> Figure 11.3 Load factors at various bank angles.

Figure 11.4 Forces on an aircraft during a 90° roll.

Figure 11.5 Increase in stall speed with load factor.

Figure 11.6 Load factor and stall speed.

<u>Figure 11.7 First-stage construction of a *V*-*G* <u>diagram.</u></u>

<u>Figure 11.8 Second-stage construction of V-G</u> <u>diagram.</u>

Figure 11.9 Antisymmetrical loading.

Figure 11.10 Maneuver speed.

Figure 11.11 Ultimate load factors.

<u>Figure 11.12 Stall speed and turn radius with</u> varying angle of bank.

Figure 11.13 Rate and radius of a turn.

Figure 11.14 Constant altitude turn performance.

Figure 11.15 Forces on the complete aircraft.

Figure 11.16 Thrust-limited turn radius.

Figure 11.17 Perfect and normal loop.

Figure 11.18 Centripetal force in a vertical loop.

Figure 11.19 Loading on an example aircraft.

Chapter 12

Figure 12.1 Types of static stability.

Figure 12.2 Dynamic stability.

Figure 12.3 Positive static and negative dynamic stability.

<u>Figure 12.4 Positive static and neutral dynamic</u> <u>stability.</u> <u>Figure 12.5 Positive static and positive dynamic</u> <u>stability.</u>

<u>Figure 12.6 Key weight and balance locations on an aircraft.</u>

<u>Figure 12.7 Weight and balance diagram and</u> <u>computational method calculation....</u>

Figure 12.8 Effect of load distribution on balance.

Figure 12.9 Airplane reference axes.

<u>Figure 12.10 Establishing positive moment</u> <u>direction.</u>

Figure 12.11 Airplane axes and moment directions.

<u>Figure 12.12 Movement of the longitudinal axis in pitch.</u>

Figure 12.13 Positive static longitudinal stability.

Figure 12.14 Types of static longitudinal stability.

Figure 12.15 Degrees of positive static stability.

Figure 12.16 Aircraft static longitudinal stability.

<u>Figure 12.17 Effect of CG and AC location on static</u> <u>longitudinal stability....</u>

<u>Figure 12.18 Static longitudinally stable flying wing</u> <u>in equilibrium.</u>

<u>Figure 12.19 Airplane with static longitudinal</u> <u>stability.</u>

Figure 12.20 Pressure distribution about a body of revolution.

Figure 12.21 Thrust line and longitudinal stability.

<u>Figure 12.22 Power changes and longitudinal</u> <u>stability.</u> <u>Figure 12.23 Engine nacelle location contribution</u> <u>to pitch stability.</u>

<u>Figure 12.24 Lift of horizontal stabilizer produces a</u> <u>stabilizing moment.</u>

Figure 12.25 Effect of speed on tail-down force.

<u>Figure 12.26 Typical buildup of aircraft</u> <u>components.</u>

<u>Figure 12.27 Effect of CG location on static</u> <u>longitudinal stability.</u>

Figure 12.28 Stick free-stick fixed stability.

Figure 12.29 Phugoid longitudinal dynamic mode.

Figure 12.30 Short period dynamic mode.

Figure 12.31 Forces on a pitching plane.

<u>Figure 12.32 Wing wake influences on a low-tail</u> <u>aircraft.</u>

<u>Figure 12.33 Wing wake influences on a sweptwing</u> <u>T-tail aircraft.</u>

<u>Figure 12.34 Change in pressure distribution at</u> <u>stall.</u>

Figure 12.35 Sweptwing stall characteristics.

<u>Figure 12.36 Forces producing moments during</u> <u>takeoff.</u>

Chapter 13

<u>Figure 13.1 (a) Negative yawing moment, (b)</u> <u>positive yawing moment.</u>

Figure 13.2 (a) Unstable, (b) stable in yaw.

Figure 13.3 Static directional stability.

<u>Figure 13.4 Static directional stability at high</u> <u>sideslip angles.</u>

<u>Figure 13.5 Effect of wing sweepback on</u> <u>directional stability.</u>

Figure 13.6 Directional instability of fuselage.

Figure 13.7 Vertical tail is stabilizing in yaw.

<u>Figure 13.8 Dorsal fin decreases drag and</u> <u>increases stability.</u>

<u>Figure 13.9 Typical buildup of component effects</u> <u>on static directional stabi...</u>

<u>Figure 13.10 Rudder-fixed-rudder-free yaw</u> <u>stability.</u>

<u>Figure 13.11 Loss of directional stability at high</u> <u>AOA.</u>

Figure 13.12 Slipstream rotation causes yaw.

Figure 13.13 Asymmetrical loading.

<u>Figure 13.14 Yawing moment due to asymmetrical</u> <u>thrust.</u>

Figure 13.15 Yawing moment due to critical engine.

Figure 13.16 Comparison of forward slip to sideslip.

Figure 13.17 Propeller drag contribution.

Figure 13.18 Effect of rearward CG on yaw.

Figure 13.19 Relationship of  $V_{\rm MC}$  to  $V_{\rm S}$ .

Figure 13.20 Rolling moment caused by sideslip.

<u>Figure 13.21 (a) Stable, (b) neutral, and (c)</u> <u>unstable static lateral stabil...</u>

Figure 13.22 Static lateral stability.

Figure 13.23 Dihedral angle.

<u>Figure 13.24 Dihedral producing static lateral</u> <u>stability.</u>

Figure 13.25 Dihedral effect of sweepback.

Figure 13.26 NASA X-29 aerodynamic features.

Figure 13.27 Vertical tail effect on lateral stability.

Figure 13.28 Adverse yaw.

<u>Figure 13.29 High AOA: (a) upgoing wing: (b)</u> <u>downgoing wing.</u>

Figure 13.30 Coupled ailerons and rudder.

<u>Figure 13.31 Yaw damper impact on Dutch roll</u> <u>characteristics.</u>

<u>Figure 13.32 Flight paths due to coupled dynamic</u> <u>effects: (a) spiral diverge...</u>

Chapter 14

Figure 14.1 (a) Subsonic flow, (b) supersonic flow.

Figure 14.2 Airflow over a wing section.

Figure 14.3 Comparison of supercritical and laminar flow airfoils at Mach 0....

<u>Figure 14.4 Effect of wing sweep on a  $C_{\rm L}$  –  $\alpha$  curve.</u>

Figure 14.5 Vortex generators.

<u>Figure 14.6 High-speed subsonic flight control</u> <u>surfaces.</u>

Figure 14.7 Force divergence effect on  $C_{\rm D}$ .

Figure 14.8 Force divergence effect on C<sub>L</sub>.

Figure 14.9 Normal shock wave on bottom of wing.

Figure 14.10 Aerodynamic center location shift.

Figure 14.11 Stick forces versus Mach number.

Figure 14.12 Normal shock waves move to trailing edge.

<u>Figure 14.13 Unattached bow wave at transonic</u> <u>speed.</u>

Figure 14.14 Formation of an oblique shock wave.

Figure 14.15 Formation of an expansion wave.

<u>Figure 14.16 Summary of supersonic wave characteristics.</u>

<u>Figure 14.17 Double-wedge airfoil in supersonic</u> <u>airflow: (a) wave pattern, (...</u>

<u>Figure 14.18 Double-wedge airfoil developing lift:</u> (a) wave pattern, (b) pre...

<u>Figure 14.19 Circular arc airfoil in supersonic flow:</u> (a) wave pattern, (b) ...

Figure 14.20 Effect of wing sweep on *C*<sub>D</sub>.

Figure 14.21 Mach cone.

Figure 14.22 Swept wing in supersonic flight.

<u>Figure 14.23 The area rule. (a) Cigar shaped</u> <u>fuselage (b) Waisted fuselage....</u>

Figure 14.24 Subsonic control surface.

Figure 14.25 Supersonic control surface.

Figure 14.26 Normal shock engine inlet.

Figure 14.27 "Spike" oblique shock engine inlets.

Figure 14.28 Stagnation temperatures.

<u>Figure 14.29 Effect of temperature on tensile</u> <u>strength of metals after half-...</u> Chapter 15

<u>Figure 15.1 Momentum theory airflow: (a)</u> <u>schematic, (b) pressure and velocit...</u>

Figure 15.2 NACA 0012 airfoil.

Figure 15.3 Location of critical forces on an airfoil.

<u>Figure 15.4 Centrifugal force straightens rotor</u> <u>blade.</u>

Figure 15.5 Lift force and centrifugal force.

Figure 15.6 Resultant of lift and centrifugal forces.

Figure 15.7 Forces acting on a lifting blade.

Figure 15.8 Entire lifting rotor system.

Figure 15.9 Hovering helicopter at light weight.

Figure 15.10 Hovering helicopter at heavy weight.

Figure 15.11 Forward flight forces.

Figure 15.12 Lift component of 10 000-lb total thrust at 15°.

Figure 15.13 Rotor velocity distribution in hover.

<u>Figure 15.14 Lift distribution on a</u> <u>twisted/untwisted blade.</u>

Figure 15.15 Hovering out of ground effect.

Figure 15.16 Hovering in ground effect.

Figure 15.17 Antitorque rotor.

Figure 15.18 Correction for antitorque rotor drift.

Figure 15.19 Rigid rotor system.

Figure 15.20 Semirigid rotor system.

Figure 15.21 Articulated rotor system.

Figure 15.22 Rotor tip velocities in a hover.

Figure 15.23 Blade-tip velocity in forward flight.

<u>Figure 15.24 Rigid rotor rolling moment in forward</u> <u>flight.</u>

<u>Figure 15.25 Angle of attack and flight path</u> <u>changes: (a) advancing blade, (...</u>

<u>Figure 15.26 CG radius change with flapping</u> <u>motion.</u>

<u>Figure 15.27 Hunting motion of a fully articulated</u> <u>blade.</u>

<u>Figure 15.28 AOA distribution during a retreating</u> <u>blade stall.</u>

Figure 15.29 Gyroscopic precession.

Figure 15.30 Swash plate schematic.

<u>Figure 15.31 Rotor flapping caused by cyclic stick</u> <u>movement.</u>

Figure 15.32 Tail rotor dissymmetry of lift.

<u>Figure 15.33 Helicopter power available and power</u> <u>required.</u>

Figure 15.34 Running/rolling takeoff.

Figure 15.35 Vortex ring state.

Figure 15.36 Height/velocity diagram.

Figure 15.37 Induced flow velocity in a hover.

Figure 15.38 Airflow and force vectors in forward flight.

<u>Figure 15.39 Airflow and forces in steady-state</u> <u>descent.</u> <u>Figure 15.40 Airflow and forces during autorotative flare.</u>