



AEROSPACE RECOMMENDED PRACTICE

ARP5770™

REV. A

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Superseding ARP5770

(R) Design Guidelines for Aircraft Mechanical Control Systems and Components

RATIONALE

This document has been revised, following a Five-Year Review process, for the following reasons:

- To introduce additional design topics,
- To clarify or improve the contents as required, and
- To correct editorial errors found in the original issue.

FOREWORD

Mechanical control systems have been used since the advent of aviation to manually operate primary and secondary control surfaces as well as to actuate utility systems, such as engine control, steering, and wheel brakes. The design and fabrication methods for mechanical control systems are now well established. When powered control actuation was introduced for larger and faster aircraft, mechanical control systems continued to play a major role to transmit the pilot commands to the hydraulic servoactuators that drive control surfaces or other systems. Although those conventional mechanical control systems are being replaced by recent fly-by-wire and control-by-wire technologies, the systems will still need to consist of various mechanical sub-systems, such as cockpit controls, surface driving mechanisms, and mechanical backup systems. In addition, mechanical control systems remain a practical option for most general aviation aircraft, as they provide simple, reliable, and economical way of controlling the aircraft systems and can significantly reduce the type certification effort.

This SAE Aerospace Recommended Practice (ARP) is intended to provide useful guidelines for control system engineers and designers on recommended practices for the design of mechanical control systems with desirable system characteristics and reliability. This is intended to allow the aircraft to meet its handling quality, flutter, and operational requirements. The main topics discussed in this document are: design requirements, system design and installation guidelines, mechanical devices for improving aircraft handling qualities, artificial feel systems, control disconnect/breakout mechanisms, cable loop design and required rigging tension, pushrods and bellcranks, chain and sprocket systems, and mechanical hardware selections. The information provided in this ARP has been accumulated from the inputs of various aircraft and system manufacturers as well as the personal experiences of several control system engineers and designers.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) provides design guidelines for aircraft mechanical control systems and components. Topics contained in this document include design requirements, system design and installation guidelines, and component design practices for primary flight controls, secondary flight controls, and utility controls.

NOTE: Although the information in this document is based on mechanical flight control systems on fixed-wing aircraft, these design philosophies and methods are applicable to similar flight control systems on other aircraft categories and for utility systems.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of a conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org

AS21150	Bearing, Ball, Rod End, Double Row, Precision, Solid Shank, Self-Aligning, Airframe, Type I, -65 to 300 °F
AS21151	Bearing, Ball, Rod End, Double Row, Precision, External Thread, Self-Aligning, Airframe, Type II, -65 to 300 °F
AS21152	Bearing, Ball, Rod End, Double Row, Precision, Hollow Shank, Self-Aligning, Airframe, Type III, -65 to 300 °F
AS21443	Bearing, Ball, Airframe, Anti-Friction, Pulley
AS27640	Bearing, Ball, Airframe, Anti-Friction, Heavy Duty
AS27641	Bearing, Ball, Airframe, Anti-Friction, Intermediate Duty
AS27642	Bearing, Ball, Airframe, Extra Light Duty
AS27647	Bearing, Ball, Airframe, Anti-Friction, Extra Wide, Double Row, Intermediate Duty
AS94900	Vehicle Management Systems - Flight Control Function, Design, Installation and Test of Piloted Military Aircraft, General Specification for

Maeda, T., "The Seven Parameters of Highly Effective Cable Control Systems," *SAE Int. J. Aerosp.* 1(1):701-713, 2009, <https://doi.org/10.4271/2008-01-2264>.

2.1.2 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany, Tel: +49 221 8999 000, www.easa.europa.eu.

CS-23	Certification Specifications for Normal, Utility, Aerobatic and Commuter Aeroplanes
CS-25	Certification Specifications for Large Aeroplanes

2.1.3 European Union Publications

Available from the European Commission, https://ec.europa.eu/info/index_en.

No 965/2012 Commission Regulation (EU) No 965/2012 of 5 October 2012 Laying Down Technical Requirements and Administrative Procedures Related to Air Operations Pursuant to Regulation (EC) No 216/2008 of the European Parliament and of the Council

2.1.4 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR 23 Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes

14 CFR 25 Airworthiness Standards: Transport Category Airplanes

14 CFR 91 General Operating and Flight Rules

14 CFR 121 Operating Requirements: Domestic, Flag, and Supplemental Operations

14 CFR 135 Operating Requirements: Commuter and on Demand Operations and Rules Governing Persons on Board Such Aircraft

AC 20-128 Design Consideration for Minimizing Hazards caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure

AC 23-17 System and Equipment Guide for Certification of Part 23 Airplanes and Airships

AC 23.607-1 Self-Locking Nuts on Bolts subject to Rotation

AC 23.629-1 Means of Compliance with Title 14 CFR, Part 23, §23.629, Flutter

TSO-C21b Aircraft Turnbuckle Assemblies and/or Turnbuckle Safelying Devices

2.1.5 NAS Publications

Available from Aerospace Industries Association, 1000 Wilson Boulevard, Suite 1700, Arlington, VA 22209-3928, Tel: 703-358-1000, www.aia-aerospace.org.

NAS428 Bolt, Machine, Crowned Hexagon Head, Adjusting

NAS509 Nut, Jam, Drilled and Undrilled

NAS513 Washer, Rod End, Locking

NAS537 Bushing, Sleeve, Press Fit, Undersize Inside Diameter

NAS538 Bushing, Flanged, Press Fit, Undersize Inside Diameter

NAS559 Lock, Rod End (Key Type)

NAS623 Screw, Shear, Pan Head, Alloy Steel, Cruciform Recess, Short Thread, 95 ksi Fsu

NAS1149 Washer, Flat

NAS1193 Locking Device, Positive Index

NAS1368	Grommet, Plastic Flip Type
NAS6203 THRU NAS6220	Bolt, Tension, Hex Head, Close Tolerance, Alloy Steel, Short Thread, Reduced Major Threat Dia., Self-Locking and Nonlocking, 160 ksi Ft _u
NASM21042	Nut, Self-Locking, 450 °F, Reduced Hexagon, Reduced Height, Ring Base, Non-Corrosion Resistant Steel
NASM21209	Insert, Screw Thread, Coarse and Fine, Screw Locking, Helical Coil, CRES

2.1.6 Military Guide Specifications

Available from ASC/ENSI, Building 560, 2530 Loop Rd. West, Wright-Patterson AFB, OH 45433-7101, Tel: 937-255-6296.

AFSC DH 1-5	Air Force Systems Command Design Handbook - Environmental Engineering
AFSC DH 2-2	Air Force Systems Command Design Handbook - Crew Station and Passenger Accommodations
JSSG-2006	Joint Service Specification Guide - Aircraft Structures

2.1.7 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

AN665	Terminal - Threaded Clevis Type Tie Rod
MIL-A-8870	Airplane Strength and Rigidity - Vibration, Flutter, and Divergence
MIL-B-8584	Brake Systems, Wheel, Aircraft Design of
MIL-DTL-5541	Detail Specification, Chemical Conversion Coatings on Aluminum and Aluminum Alloys
MIL-DTL-5688	Detail Specification, Wire Rope Assemblies; Aircraft, Proof Testing and Prestretching of
MIL-DTL-6117	Detail Specification, Wire Rope Assemblies, Aviation, Swaged Type
MIL-DTL-83420	Detail Specification, Wire Rope, Flexible, for Aircraft Control, General Specification for
MIL-DTL-87218	Detail Specification, Cable, Lockclad, for Aircraft Control
MIL-F-8785	Flying Qualities of Piloted Airplanes
MIL-PRF-7958	Military Performance Specification, Push-Pull Controls, Flexible and Rigid
MIL-PRF-16173	Military Performance Specification, Corrosion Preventive Compound, Solvent Cutback, Cold-Application
MIL-PRF-23827	Military Performance Specification, Grease, Aircraft and Instrument, Gear and Actuator Screw
MIL-STD-203	Aircrew Station Controls and Displays: Location, Arrangement and Actuation of, for Fixed Wing Aircraft
MIL-STD-461	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
MIL-STD-464	Electromagnetic Environmental Effects Requirements for Systems
MIL-STD-1472	Design Criteria Standard - Human Engineering

MS21251	Turnbuckle Body, Clip Locking
MS21256	Clip, Locking, Turnbuckle
MS21259	Terminal, Wire Rope, Swaging, Stud, Long Thread

2.1.8 AGARD Publications

Copies of these documents are available online at www.sto.nato.int.

AGARD-AG-332 Stick and Feel System Design

2.1.9 ASME Publications

Available from ASME, P.O. Box 2900, 22 Law Drive, Fairfield, NJ 07007-2900, Tel: 800-843-2763 (U.S./Canada), 001-800-843-2763 (Mexico), 973-882-1170 (outside North America), www.asme.org.

ASME B29.1 Precision Power Transmission Roller Chains, Attachments, and Sprockets

ASME B29.2M Inverted Tooth (Silent) Chains and Sprockets

2.1.10 Commercial Publications

Perkins, C.D. and Hage, R.E., Airplane Performance Stability and Control, 1949 (New York: John Wiley and Sons, Inc.), ISBN: 9780471680468

Macwhyte Wire Rope Company, Catalog of Tables, Data, and Helpful Information G-17, 1962 (Kenosha, WI: Macwhyte Wire Rope Company)

2.2 Abbreviations, Acronyms, Symbols

14 CFR	Title 14 of the Codes of Federal Regulations
AC	Advisory Circular
ABMA	American Bearing Manufacturers Association
AFCF	Automatic Flight Control Functions
AFSC DH	Air Force Systems Command Design Handbook
AGARD	Advisory Group for Aerospace Research & Development
ARI	Aileron-Rudder Interconnect
ARP	Aerospace Recommended Practice
ASME	American Society of Mechanical Engineers
b	Wing Span
C	Celsius
CBW	Control-by-Wire
CCW	Counterclockwise
c.g.	Center of Gravity

C _h	Control Surface Hinge Moment Coefficient
C _L	Lift Coefficient
C _I	Rolling Moment Coefficient
C/L	Centerline
C _m	Pitch Moment Coefficient
cm	Centimeters
C _n	Yawing Moment Coefficient
CRES	Corrosion-Resistant Steel
CS	Certification Specifications
CTR	Cable Tension Regulator
CW	Clockwise
D, d, dia	Diameter
D/d	Pulley Root Diameter to Cable Diameter Ratio
E	Young's Modulus
EA	Primary Modulus of Cable, Tensile Rigidity
ea	Each
EASA	European Aviation Safety Agency
EMF	Electro-Magnetic Forming
F	Cable Friction, Fahrenheit
FAA	Federal Aviation Administration
FBW	Fly-by-Wire
FCS	Flight Control System
FDR	Flight Data Recorder
FMECA	Failure Mode, Effect, and Criticality Analysis
F/T	Cable Friction to Tension Ratio
ft	Feet
FTA	Fault Tree Analysis
ft-lb, ft-lbs	Foot Pounds (Torque)
G	Gearing Ratio
g	Gravitational Acceleration, Pulley Groove Diameter

HM	Control Surface Hinge Moment
in	Inches
in-lb	Inch-Pound (Torque)
in-oz	Inch-Ounce (Torque)
JSSG	Joint Service Specification Guide
K, k	Stiffness, Kilo
kg	Kilogram Force, Kilogram Mass
km/h	Kilometers per Hour
kts	Knots
L	Rolling Moment, Cable Length
lb, lbs	Pounds
lb/g, lbs/g	Pound Stick-Force-per-g
LH	Left Hand
LRU	Line Replaceable Unit
M	Moment, Mega
m	Meters
Max, max	Maximum
MBS	Minimum Breaking Strength
MIL	Military
Min, min	Minimum
mm	Millimeters
m/s	Meters per Second
MUTS	Minimum Ultimate Tensile Strength
N	Newtons, Yawing Moment, Number of Turnbuckles
n	Load Factor, Number of Sprocket Teeth
NAS	National Aerospace Standard
N/g	Newton Stick Force per g
N·m	Newton Meters (Torque)
OD	Outside Diameter
OS	Operational State

P	Pressure
Pa	Pascals (Pressure, Stress)
PE	Pilot Effort
PFCS	Primary Flight Control Systems
PR	Pitch Radius
PTFE	Polytetrafluoroethylene
q	Dynamic Pressure
R	Radius
Ra	Roughness Attribute
RH	Right Hand
S	Wing Area
s	Cockpit Control Deflection
Sc	Rod Compression Stress
SFCS	Secondary Flight Control Systems
STD	Standard
T	Cable Tension, Thrust
TED	Trailing Edge Down
TEL	Trailing Edge Left
TER	Trailing Edge Right
TEU	Trailing Edge Up
TSO	Technical Standard Order
TYP	Typical
UCS	Utility Control Systems
V	Velocity
V ₁	Takeoff Decision Speed
V _{MC}	Minimum Control Speed
V _{MCG}	Minimum Control Speed on Ground
β	Sideslip Angle
δ	Control Surface Angle
ε	Strain

μ	Coefficient of Friction
ρ	Air Density
$^{\circ}$	Degrees

3. CONTROL SYSTEM CLASSIFICATIONS

The following are classifications of aircraft control systems and their operational states and criticalities:

3.1 Primary Flight Control Systems

Primary flight control systems (PFCS) are control systems that transmit commands from the pilot, or other sources, to the flight control surfaces to provide direct control of the aircraft's attitude and motion in pitch, roll, and yaw axes. The PFCS typically consist of three individual systems: pitch, roll, and yaw control systems, each corresponding to the respective aircraft control axes. The pilot controls used for commanding the PFCS include a control wheel(s) or stick(s) for pitch and roll control and rudder pedals for yaw control. The typical flight control surfaces driven by the PFCS are elevators (pitch control), ailerons and/or roll spoilers (roll control), and rudder(s) (yaw control).

3.2 Secondary Flight Control Systems

Secondary flight control systems (SFCS) are control systems that control the flight control surfaces that are not included in the PFCS. The SFCS control trim tabs and/or horizontal stabilizer to trim out the pilot control forces, and drive flaps, slats, spoilers, and/or speedbrakes to obtain the desired lift and drag characteristics of the aircraft.

3.3 Utility Control Systems

Utility control systems (UCS) include all control systems of the aircraft other than the PFCS and SFCS. Typical functions of the UCS include engine control, nose wheel steering, door operation, wheel brakes, landing gear actuation, and other similar systems. FAA Airworthiness Standards and EASA Certification Specifications categorize control systems for wheel brakes and landing gear operation as Secondary Control Systems (refer to 14 CFR or CS 23.405 and 25.405).

3.4 Automatic Flight Control Functions

Automatic flight control functions (AFCF) generate and transmit control commands independent of the pilot action through automatic or semi-automatic flight control to provide pilot workload reduction. The AFCF include autopilot, control wheel or stick steering, yaw damper, auto-trim, auto-throttle, and similar control functions.

3.5 Flight Control System Operational State Classifications

The following are military classifications for the flight control system operational state. Refer to AS94900 for the applicable definition.

- Operational State I (Normal Operation),
- Operational State II (Restricted Operation),
- Operational State III (Minimum Safe Operation), and
- Operational State IV (Controllable to an Immediate Emergency Landing).

For the corresponding failure conditions of the flight control systems on civil airplanes, refer to system safety sections of 14 CFR Part 23, CS-23, 14 CFR Part 25, or CS-25.

3.6 Flight Control System Criticality Classifications

The following are military classifications for the flight control system criticality. Refer to AS94900 for the applicable definition.

- Essential,
- Flight phase essential, and
- Non-critical.

For the corresponding criticality of the failure conditions of the flight control systems on civil airplanes, refer to system safety sections of 14 CFR Part 23, CS-23, 14 CFR Part 25, or CS-25.

4. CONTROL SYSTEM OPERATIONAL REQUIREMENTS

4.1 Control System Load Requirements

The control system load requirements for numerous civil aircraft categories are outlined in the following Code of Federal Regulations and European Aviation Safety Agency Certification Specifications:

- 14 CFR Part 23 Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes,
- CS-23 Certification Specifications for Normal, Utility, Aerobatic and Commuter Aeroplanes,
- 14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes, and
- CS-25 Certification Specifications for Large Aeroplanes.

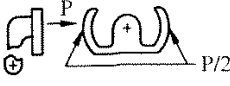
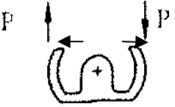
4.1.1 Control System Limit/Ultimate Design Loads

The design loads of control systems are defined as follows:

- Limit loads for primary control systems are the maximum loads to be expected in service.
- Limit loads for secondary and utility control systems are the maximum forces that a pilot is likely to apply to those controls.
- Ultimate loads for control systems are defined as 1.5 times the limit loads for those systems.

The limit design loads of control systems for civil airplanes are shown in Table 1.

Table 1 - 14 CFR Part 23 and 25/EASA CS-23 and -25 control system limit design loads

Aircraft Control	Cockpit Control	Limit Design Load		Load Location and Direction
		14 CFR/CS 23.397 ⁽¹⁾	14 CFR/CS 25.397	
Longitudinal (pitch)	Stick (floor mounted) 	P = 167 pounds (743 N) maximum P = 100 pounds (445 N) minimum	P = 250 pounds (1112 N) maximum P = 100 pounds (445 N) minimum	A longitudinal force at top of the stick and perpendicular to a radial from the stick's pivot.
	Wheel 	P = 200 pounds (890 N) maximum P = 100 pounds (445 N) minimum	P = 300 pounds (1335 N) maximum P = 100 pounds (445 N) minimum	Two forces on the wheel rim, diametrically opposite, acting perpendicular to the wheel plane in the same direction.
Lateral (roll)	Stick (floor mounted) 	P = 67 pounds (298 N) maximum P = 40 pounds (178 N) minimum	P = 100 pounds (445 N) maximum P = 40 pounds (178 N) minimum	A lateral force at top of the stick and perpendicular to a radial from the stick's pivot.
	Wheel 	T = 50 D inch-pounds (222 D N·m) maximum T = 40 D inch-pounds (178 D N·m) minimum	T = 80 D inch-pounds (356 D N·m) maximum T = 40 D inch-pounds (178 D N·m) minimum	Two tangential forces on the wheel rim, diametrically opposite, and acting in the opposite direction. The critical parts of the lateral control system should be designed for a single tangential force with a limit value equal to 1.25 times the couple force determined by the specified requirement.
Directional (yaw) and brake	Pedals 	P = 200 pounds (890 N) maximum P = 150 pounds (667 N) minimum	P = 300 pounds (1335 N) maximum P = 130 pounds (578 N) minimum	Force acting on the line connecting pedal foot contact point and hip joint with pilot's seat in mean landing position.
Flap, tab, stabilizer, spoiler, and landing gear controls	Crank, wheel, or lever operated by push or pull force	14 CFR/CS 23.405: The maximum force that a pilot is likely to apply	14 CFR 25.405: ((1+R)/3) x 50 pounds but not less than 50 pounds nor more than 150 pounds (R = radius in inches) or CS 25.405: ((25.4+R)/76.2) x 222 N but not less than 222 N nor more than 667 N (R = radius in mm)	A force on the circumference of the wheel, or the grip of the wheel, or the lever that acts at any angle within 20 degrees of the plane of the control.
	Small wheel or knob to be twisted		133 inch-pounds or 15 N·m if operated by twisting	
	Small knob to be pushed or pulled		To be chosen by applicant	
Primary controls	Dual control system ⁽²⁾	14 CFR/CS 23.399	14 CFR/CS 25.399	

⁽¹⁾ For an aircraft design weight of more than 5000 pounds (2268 kg or 22240 N), the specified maximum values must be increased linearly with weight to 1.18 times the specified values at a design weight of 12500 pounds (5670 kg or 55600 N), and for commuter category aircraft, the specified values must be increased linearly with weight to 1.35 times the specified values at a design weight of 19000 pounds (8618 kg or 84520 N).

⁽²⁾ Each dual control system must be designed to withstand the force of the pilots operating in opposition, using individual pilot forces not less than the greater of:

- 0.75 times those obtained under 14 CFR 23.395 or 25.395, or CS 23.395 or 25.395.
- The minimum forces specified in 14 CFR 23.397 or 25.397, or CS 23.397 or 25.397.

Each dual control system must be designed for pilot forces applied in the same direction, using individual pilot forces not less than 0.75 times those obtained under 14 CFR 23.395 or 25.395, or CS 23.395 or CS 25.395.

4.1.2 Control System Operational Forces

4.1.2.1 Maximum Operational Forces

Longitudinal, lateral, and directional flight controls have their maximum operational forces specified for each flight condition. For military airplanes, they are specified by MIL-F-8785. For civil airplanes, 14 CFR 23.143 and 25.143, or CS 23.143 and 25.143 specify the maximum forces permitted during aircraft certification testing as shown in Table 2. For 14 CFR Part 23 or EASA CS-23 aircraft with a stick cockpit control, the maximum operational forces are 60 pounds (267 N) in pitch and 30 pounds (133 N) in roll.

Table 2 - Maximum operational forces

Force, in pounds, applied to the control wheel or rudder pedals	Pitch	Roll	Yaw
For short term application for pitch and roll control - two hands available for control	75 pounds (334 N)	50 pounds (222 N)	-
For short term application for pitch and roll control - one hand available for control	50 pounds (222 N)	25 pounds (111 N)	-
For short term application for yaw control	-	-	150 pounds (667 N)
For long term application	10 pounds (44.5 N)	5 pounds (22 N)	20 pounds (89 N)

The engine thrust levers should have an operational force of about 3 pounds (13 N) per lever. Pilots consider 5 pounds (22 N) objectionable, even though AFSC DH 2-2 allows up to 7.5 pounds (33 N) per lever and 30 pounds (133 N) for all engine thrust levers at the same time.

The brake pedal's maximum operational force of 85 pounds (378 N) is specified by MIL-B-8584 for a powered brake control system, and 125 pounds (556 N) for a manual brake system.

Maximum operating forces are not specified for other control systems; however, they should be kept low to prevent pilot complaints, but high enough to prevent actuation by vibration or acceleration forces.

4.1.2.2 Breakout Forces and Control Centering

Breakout force is that force on the control when its control surface begins to move, overcoming system friction, centering, balance, and feel forces.

The recommended breakout force ranges for the pitch, roll, and yaw flight controls from the trim position are shown in Table 3 for military aircraft. These breakout force levels are also appropriate for FAA/EASA Part 23 and 25 aircraft.

Table 3 - Breakout forces

Control		Breakout Force [pounds (N)]			
		MIL-F-8785 Aircraft Classes			
		Class I - small, light Class II-C - carrier, medium weight, low to medium maneuverability Class IV - high maneuverability		Class II-L - land, medium weight, low to medium maneuverability Class III - large, heavy, low to medium maneuverability	
		Minimum	Maximum	Minimum	Maximum
Longitudinal	Stick	1/2 (2.2)	3 (13.3)	1/2 (2.2)	5 (22.2)
	Wheel	1/2 (2.2)	4 (17.8)	1/2 (2.2)	7 (31.1)
Lateral	Stick	1/2 (2.2)	2 (8.9)	1/2 (2.2)	4 (17.8)
	Wheel	1/2 (2.2)	3 (13.3)	1/2 (2.2)	6 (26.7)
Directional		1 (4.4)	7 (31.1)	1 (4.4)	14 (62.3)

Ground measurement of breakout forces is usually considered as compliance with the requirements. Breakout forces on the ground should be measured when the trailing edge of the control surface has visibly moved.

Actual breakout forces in flight are usually lower than those measured on the ground due to aircraft vibration tending to make all friction moving, rather than static.

With absolute centering, a cockpit control will always return exactly to its trim position when released. Positive centering is a tendency to return; upon release, the control will move toward the trim position, but friction may prevent absolute centering.

Pitch, roll, and yaw controls should show positive centering in flight at any normal trim setting. Although absolute centering is not required, the combined effects of centering, breakout force, stability, and force gradient should not produce objectionable flight characteristics (see 5.10.2).

4.1.2.3 Manual Override Forces

It should always be possible for the pilot to manually overpower or countermand the automatic flight control action using the normal pilot controls. Required pilot forces should not exceed pilot capability as defined by MIL-STD-1472, AC 23-17, or 14 CFR/CS 25.143 and 25.1329 requirements. Table 4 lists recommended maximum override forces.

Table 4 - Manual override forces

Control Axis	Pilot Control	Autopilot Operation Maximum Manual Override Force [pounds (N)]			
		MIL-STD-1472		AC 23-17	14 CFR/CS 25.143(d) and 25.1329(n)(2)(ii)
		Single Channel Single Servo Engaged	Redundant Channel Servos Engaged in Redundant Configuration		
Longitudinal	Stick	20 (89)	30 (133)	-	-
	Wheel	30 (133)	50 (222)	50 (222)	50 (222)
Lateral	Stick	10 (44)	20 (89)	-	-
	Wheel	20 (89)	30 (133)	30 (133)	25 (111)
Directional	Pedals	80 (356)	120 (534)	150 (667)	150 (667)

4.1.2.4 Servoactuator Control Valve Chip Shear Forces

A servoactuator slide valve should be capable of shearing a metallic chip that may become lodged across the sleeve port and slide metering edge. The valve and its actuating linkage should sustain a maximum of 200 to 1000 pounds (890 to 4450 N), depending on application/customer requirements, at the valve slide without any damage or deformation, to shear the chip. All of the servoactuator linkage and the control system should have adequate stiffness and strength to transmit the valve chip shear force.

Damage to the valve and linkage is acceptable, but the valve and linkage should still be capable of full displacement with minimal additional friction. Some servoactuator designs have lower-level detents that break out when a slide valve becomes jammed. The breakout allows continued operation as a function of the servoactuator override features or by control of an adjacent servoactuator coupled to the same control surface.

4.2 Control System Positionability Requirements

4.2.1 Cockpit Control Travel

Cockpit controls have a high degree of commonality between cockpits of aircraft of the same type to minimize the possibility of human error as pilots transfer from one aircraft model to another. Cockpit controls are designed and located on aircraft, per specifications and airworthiness regulations such as:

- MIL-STD-203,
- AFSC DH 2-2, DN 2A1, paragraph 3 (Aircrew Controls),
- AFSC DH 2-2, DN 2A5 (Flight Controls), and
- 14 CFR/CS 23.777, 23.779, 25.777, and 25.779.

In general, the cockpit control's travel range is ergonomically determined. It should be large enough so it is not too sensitive, yet not so large that it results in uncomfortable pilot motion or requires unusual manual skill.

Typical cockpit control travels for mechanical control systems are:

- Pitch Axis
 - Control Column (Wheel or Stick)

Forward no-load travel from neutral (TED): 4.0 to 6.0 inches (10.2 to 15.2 cm)

Aft no-load travel from neutral (TEU): 5.5 to 9.0 inches (14.0 to 22.9 cm)
- Roll Axis
 - Wheel

Clockwise and counterclockwise no load rotation: ± 60 to ± 80 degrees
 - Stick

Left and right no load displacement: ± 5.0 to ± 7.0 inches (± 12.7 to ± 17.8 cm)
- Yaw Axis
 - Pedals

Forward and aft no load displacement: ± 3.0 to ± 4.0 inches (± 7.6 to ± 10.2 cm)

4.2.2 Control System Stops

Control system stops should be provided to limit system travel at the output end of the control system (or primary stops). Other auxiliary stops frequently used in control systems are output load limiting stops, input travel stops for cockpit controls (or secondary stops), autopilot authority stops, and mechanism overtravel stops. All stops should be able to withstand any expected system loads (refer to 14 CFR/CS 23.675 and 25.675). All adjustable stops should be positively locked or safety wired in the adjusted position. Plain jam nuts are not considered adequate as a locking device.

Output stops (primary stops) should be located near the item that is controlled. Each control surface should have its own travel stops. If a servoactuator is used, the output stops may be incorporated in the servoactuator. If the actuator is remotely located from the surface, a control surface should have its own stops, unless the connecting linkage can be shown to have only an extremely remote probability (1.0×10^{-9} or less) of failure.

The servoactuators should be designed with input travel stops that are set inside the actuator output piston travel limits, to minimize actuator fatigue damage. (The servoactuator output piston travel limits should be designed to withstand bottoming during ground checkout and/or wind gusts.) Output load limiting stops are also used in a servoactuator's input linkage to react to the cockpit control's design load, so that the load downstream of the stop can be reduced to that needed to shear a chip in the actuator's control valve. The stop bolt threads should be coated with a corrosion preventative compound.

Input stops (secondary stops) are installed near the cockpit controls to limit their movement after the control surfaces contact the output stops (primary stops). The input stops (secondary stops) should be located so that the cockpit controls will have enough overtravel to accommodate the system compliance due to the maximum operating loads and obtain the maximum surface angles available. The additional force to move the cockpit control to the input stop, after the output stop is contacted, is called the stop cushion force in cable systems.

With the output and input stops set for maximum control system travel, there should be clearances elsewhere in the control system between links, cranks, structure, etc.

Autopilot authority stops are used to limit the autopilot inputs into primary manually operated systems to safe levels that the pilot can override.

Mechanism overtravel stops are used to prevent a mechanism from going into an irreversible position at an extreme travel condition.

4.2.3 Control System Backlash

Control system backlash has a detrimental effect on the ability of the pilot/autopilot to control the aircraft flight path. In a mechanical control system with a single load path, backlash is generated at every pushrod and lever joint. Examples of mechanical features that generate backlash are:

- Pivot bearing radial play,
- Rod-end radial play,
- Pivot joint radial clearances, and
- Rod-end joint radial clearances.

All of these contributors to backlash can be minimized by the use of precision bearings, bolts, and fitting/bellcrank bushings. Bearing radial play can be specified and controlled to a low level, but not eliminated. Clamped pivot joints reduce the backlash under normal radial loads but can shift and ultimately loosen under repeated high loads. Typically, backlash increases as the aircraft ages. Control loads and vibration tend to increase joint clearances over time, resulting in increased overall backlash.

On some aircraft, the pushrods and levers are dualized with identical parallel paths and preloaded against one another to eliminate the control free play associated with backlash. Dualized control systems require careful design because the duality raises the overall friction level. The friction level is amplified by the pushrod preload force level. If the duality is installed downstream of the feel force generator, the preload can be controlled at a lower level and the friction can be minimized.

Preload springs have been installed on some aircraft to eliminate the effects of backlash. Preload springs are usually not a wise choice because a preload spring failure can induce uncommanded surface movement if the springs are installed at the extreme ends of a pushrod run in opposition to one another.

On some aircraft, a cable system is installed in parallel with the mechanical linkage to preload out the linkage backlash. This is usually an effective approach because a cable break or a pushrod/lever open failure results in minimal uncommanded surface movement.

The backlash associated with pushrods and cranks highlights one of the advantages of a preloaded cable system. The ideal mechanical control system utilizes as much cable control transmission as possible, limiting the pushrods and cranks to the immediate areas of the control input inceptor, autopilot, damper, feel unit, and surface/servoactuator interfaces.

4.2.4 Control System Stiffness

Mechanical control systems should be designed to have adequate end-to-end stiffness so that the aircraft can meet its operational, flight characteristic, and aeroelastic requirements (refer to 14 CFR/CS 23.629, 23.683, 25.629, and 25.683, as well as MIL-A-8870).

While the control systems must not exhibit excessive deflections under loads, their stiffness, in some cases, need to be deliberately reduced to improve the control sensitivities at high speed or to prevent possible flutter by separating the resonant frequencies of the systems from the critical airframe frequencies (refer to SAE paper 2008-01-2264).

4.3 Control System Redundancy

In general, redundancy is designed into the system as necessary to provide safe flight and landing following single and/or multiple failures. Typically, mechanical controls of pitch and roll for 14 CFR Part/CS-25 category aircraft are redundant. Mechanical control of yaw may be redundant or simplex. For minimum redundancy requirements, refer to the system safety sections of 14 CFR Part 25 and CS-25, or the redundancy consideration section of AS94900.

Redundant pitch and roll mechanical controls provide fail operative control capability after a mechanical jam or open. There are usually two parallel control systems consisting of cable, pushrod, and bellcrank runs. The two parallel control systems are coupled in the cockpit. Couplings are usually manually overridable. Either pilot can override the coupling if one parallel system jams, allowing continued fail operative control, usually with 50% control authority (see 5.12). Some systems incorporate the second coupling downstream in the system where the control paths divert to left and right. Systems with the fore and aft couplings allow either pilot to command all of the control surfaces if one of the parallel cable or pushrod systems fails open. The aft coupling also helps provide synchronization between the two half systems in normal operation.

In some pitch systems, the aft coupling is electrically controlled as a function of the airspeed. In the event of a jam on either half system at high speed, the aft coupling will remain engaged and let the horizontal stabilizer control the aircraft pitch until the airspeed goes down to a certain level. This function is for preventing a large differential deflection of the elevators at high speed from overloading the rear fuselage structure in torsion.

Some couplings reset and recouple automatically. Others have to be accessed and mechanically recoupled by maintenance. The latter is usually preferred because a jam occurs very infrequently. It is prudent to perform inspection and maintenance of the control system after a jam to minimize the potential of a jam reoccurrence. In the event of poor access to a coupling requiring a periodic operational test, a remote resetting function may be provided, electrical or other.

4.4 Vulnerability

The vulnerability of essential flight control systems should be minimized. Design should limit the degradation of these systems from any cause including those listed in Table 5. Refer to 14 CFR Part 23 and 25, CS-23 and -25, and AS94900 for the requirements.

4.5 Reliability

The reliability and flight safety requirements for the mechanical control system are based on the probability of all of those single and combined failures that would cause loss of control of the aircraft. These probabilities of failure are allocated from requirements for the maximum aircraft loss rate from flight control system failures per flight hour. The reliability requirements may require some portions of the mechanical controls to be dual.

Quantitative flight safety probability of loss of control and the equivalent maximum acceptable aircraft loss rate due to relevant flight control system failures is provided in AS94900 for military aircraft and 14 CFR Part 23 and 25, for FAA certified aircraft, and CS-23 and -25 for EASA certified aircraft.

Table 5 - Vulnerability of essential flight control systems

Factor	Cause and Effect	Design Requirements and References
Natural environment	Pressure cycling, icing, condensation and runoff, structural deflections, temperature variations, gusts and turbulence	No permanent degradation of performance except at adverse extremes of the operational envelope (not normally encountered) where temporary degradation to OS II is allowed. 14 CFR/CS 23.341 or 25.341
Bird strike	Cockpit penetration, control system damage	Prevent damage or protect control system elements for continued safe flight. 14 CFR/CS 25.631
Induced environment	Control systems and other systems generation of temperatures, thermal shocks, vibrations and buffeting, noise, shocks, induced pressures, electrical or magnetic emissions or potentials	Prevent or protect flight control system from performance degradation. MIL-STD-464 JSSG-2006 Guidance MIL-STD-461 AFSC DH 1-5, DN 1B1 and DN 1C1 Guidance 14 CFR/CS 23.251, 25.251, 23.365, or 25.365
Lightning and static electricity	Electric potential buildup and discharge	Prevent performance degradation below OS II. The temporary recoverable loss to OS III is allowed for a direct lightning strike. MIL-STD-464 and AFSC DH 1-5 Guidance 14 CFR/CS 25.581
Flight crew inaction or error	Mispositioned or maladjusted controls	Prevent improper position or sequencing of controls by positive action gates, warnings, or making the pilot's reaction to a failure instinctively correct. 14 CFR/CS 23.777, 25.777, 23.779, 25.779, 23.781, or 25.781
Maintenance error	Improper assembly or installation	Prevent installation errors by requiring two or more overt actions or modifications. Design LRUs (Line Replaceable Units) with bench adjustment only and replaceable without rerigging of the system. Minimize possibilities of jamming from mislaid tools or equipment.
Control system component failures	Jam or severance of system, loss of hydraulic system, loss of electrical power	Aircraft performance shall not be degraded below OS III. Failure analyses usually determine redundancy requirements. 14 CFR/CS 25.671, 23.672, 25.672, 23.1309, or 25.1309
Other system or equipment failures	Damage to FCS components from any failure	Prevent FCS degradation below OS III.
Loss of main landing gear	Excessive aft or up load	Complete lateral control after failure. Some gear design examples: Route lateral controls over gear trunnion near the rear spar as the forward trunnion bearing is fused to fail with an excessive gear aft load. Route lateral controls under the outboard end of the landing gear beam that is fused to fail with an excessive up load.
Engine burst	Fragments of turbine or compressor discs are sprayed across the width of the airplane; spray angles and maximum fragment sizes are defined by propulsion staff	FCS should be routed and designed to minimize damage from a single fragment in the engine burst zone: 1. Limit FCS components in the zone to those required and separate them as much as possible. 2. Use aircraft structure to shield FCS components as much as possible. 3. Fragment size determines the minimum separation of dualized systems. 14 CFR/CS 23.903 or 25.903, AC 20-128
Structural failures	Fatigue, explosions, cabin depressurization, etc.	FCS should remain operational if the aircraft is structurally capable of flight through such methods as duplication, separation, routing for max. structural protection, etc.
Tire burst in main wheel well	Pressurization of wheel well by small, destructive jet (from tire burst) whose impact pressure levels off about 9 inches (23 cm) from the tire	FCS components in wheel well shall be minimized, separated, screen shielded if within approximately 9 inches of any tire, and designed along with their supports, for tire burst impact loads. Prime airframe companies typically have tire burst test data that supports the resolution of local burst issues: 14 CFR/CS 23.729 or 25.729

4.6 Instrumentation

Mechanical flight control systems may need to be instrumented to measure and record their positional and force data for flight tests or flight data recorders (FDRs). Typical parameters to be recorded for each primary and secondary control system include:

- Cockpit control position,
- Pilot input force,
- Control surface angle, and
- Surface hinge moment (or actuator force).

Required parameters and their data accuracies for the development and certification flight tests will be determined in coordination with flight controls, aerodynamics, flight test, and instrumentation groups. System parameters required to be recorded by FDRs on production aircraft are specified in each operating rules, such as 14 CFR Part 91, 121, 135, or Commission Regulation (EU) No 965/2012, under which the aircraft is being operated.

The instrumentation for the flight control systems should be designed and installed so that the sensors, associated driving mechanisms, and connecting wires do not affect the operation, performance, or reliability of the control systems. Adequate provisions for the instrumentation should be, therefore, carefully planned from an early stage of the control system design.

5. CONTROL SYSTEM DESIGN AND INSTALLATION GUIDELINES

5.1 Control System Design Options

There are two general types of mechanical flight control systems, depending on the system's primary mechanism by which the pilot commands are transmitted to the control surfaces or actuators:

- Cable control system, and
- Pushrod control system.

These systems each have certain advantages and disadvantages as briefly compared in Table 6.

Table 6 - Comparison of cable control system and pushrod control system

System Property	Cable Control System	Pushrod Control System
Rigidity	Low	High
Friction	High	Low
Backlash	Minimal	Unavoidable
Inertia	Low	High
Weight	Light	Heavy
Installation space	Large	Small
Cost	Low	High
Wear	Common	Rare

Before deciding the system architecture for each control axis, the pros and cons of each type of system should be carefully evaluated for their effects on the system performance, aircraft handling qualities, and system manufacturability and maintainability.

Cable systems generally provide lightweight and low-cost solutions to transmit the control commands and forces. Cable systems, however, take up the space because their cables are usually installed in a loop so that they can take loads in either direction. Cables also tend to stretch under loads due to their braided construction, so the cables in the loop are pre-tensioned to obtain the desired system stiffness and to avoid cable slacking. Consequently, the backlash in the system is eliminated, but the system friction tends to be higher. Cables are also prone to wearing particularly in wing or other vibratory environments.

Pushrod systems generally provide rigid and low-friction load paths, but they are expensive and tend to be heavier as the pushrods are designed based on the compression load conditions. The consequent higher system inertia, as well as the total backlash to be accumulated through all the joints, may affect the aircraft handling qualities. Although the pushrod systems provide low-profile load paths, they may sometimes take up the space, if idler arms or walking beams need to be installed to mitigate high buckling loads or to cancel out acceleration effects respectively.

More details on the characteristics of these system types will be discussed in the rest of this document (Sections 5 and 6).

5.2 Control System Routing and Installation

Control system routing of cables, pushrods, push-pull cables, hydraulic lines, and electrical wiring should be done in the most direct manner possible taking into consideration the separation of duplicate systems, structure, other systems, hazard areas specified in 4.4, and easy access for routing maintenance.

Mechanical control systems should be run as close to the structure's neutral axis as possible to minimize the effect of structural deflections of aircraft due to maneuvers in flight and on the ground. Cable systems should keep the cables of the same system on the same side of, and at the same distance from the neutral axis of the structure to prevent control actuation due to structural deflections. Control rod systems should use reversing cranks frequently to equalize the deflections due to structural flexure and to minimize the control forces associated with accelerations.

If several different installations of components such as brackets, rods, bellcranks, splines, torque tubes, electrical connectors, trim actuators, spring struts, and cable turnbuckles are feasible, the designer should ensure that the various installations are acceptable. Installations that are not acceptable should be made physically impossible.

5.3 Control System Separation and Clearances

Control system separation for redundant cable, pushrod, push-pull cable, electrical wiring, and hydraulic systems should be the maximum possible to minimize the probability of simultaneous failure of all redundant control paths from the same cause. An example of good design is where one system is in the ceiling and the other is underneath the cabin floor.

Table 7 lists desirable and minimum clearances for cable, push-pull cable, and control rod systems.

Table 7 - Control system clearances

Type of Control System	Condition	Inches (cm) in Clearance	
		Desirable	Minimum
Cable	Between cables	2.00 (5.1)	0.50 (1.3) by supports
	Structure, electrical wiring, tubing, and fixed equipment	1.50 (3.8) down 1.00 (2.5) other directions	0.50 (1.3) fairlead ⁽¹⁾ 0.20 (0.5) rub strip ⁽¹⁾
	Gear, doors, moving components	4.00 (10.2)	2.00 (5.1)
Push-pull rods	Between push-pull rods and push-pull flexible cables	2.00 (5.1)	0.50 (1.3) other systems 0.25 (0.6) same system
Push-pull flexible cable	Structure, electrical wiring, tubing, and fixed equipment	1.00 (2.5)	0.50 (1.3)
	Gear, doors, moving components	4.00 (10.2)	2.00 (5.1)

⁽¹⁾ Under normal pre-flight and flight structural deflections (1 g ± 0.20 g).

Clearance for moving parts should be shown to be adequate for a minimum of 5 degrees overtravel or 0.50 inch (1.3 cm), whichever is greater. In each design, the amount of overtravel should be evaluated for excess of this amount. Overtravel and clearance should be shown on design layouts. This is particularly important on bellcrank clevises concerning rod-ends and similar joints.

Valve overtravel on actuators should be determined based on system travel and all tolerances to avoid the necessity for extremely precise rigging.

Quadrant overtravel should be 5 degrees beyond the maximum travel range before the cable no longer pulls the quadrant tangentially. Effect of cable stretch should be included.

Cable systems should be analyzed under all loading conditions including conditions where the cable might slack to ensure adequate clearances.

Access panels or doors, which have to be removed for inspection or maintenance should not interfere with the full freedom and functioning of the controls.

5.4 Control System Rigging Provisions

For a control system to operate properly, cable runs, levers, sectors, and bellcranks should be rigged to a definite neutral or stowed position. Rigging pins provide a quick and accurate means of establishing this position.

In a long run of pushrods, it is only required to have rigging provisions on every third bellcrank. The positions of the bellcranks on each side of one that is rigged are established by fixed-length pushrods. The third pushrod should be adjustable. Locate adjustable rods at production breaks since a dimension crossing a break has a larger than normal production tolerance. See Figure 1.

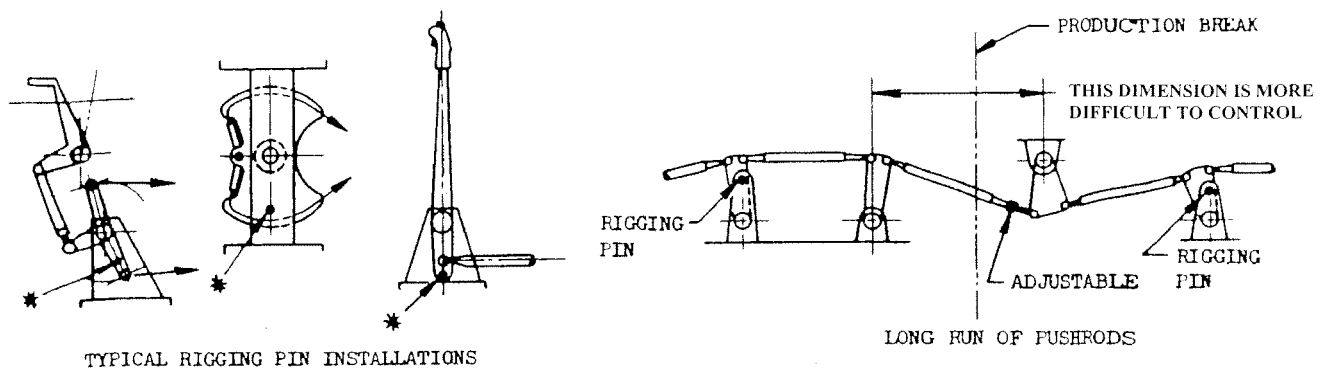


Figure 1 - Rigging pin provisions

Double shear rigging pin installations are preferred. If single shear pins must be used, one hole should be sufficiently long to prevent cocking of the pin. Avoid single shear pins if possible. See Figure 2.

To eliminate the possibility of interference in the control system, rigging pin supports should be strong enough to withstand normal ground handling without significant bending.

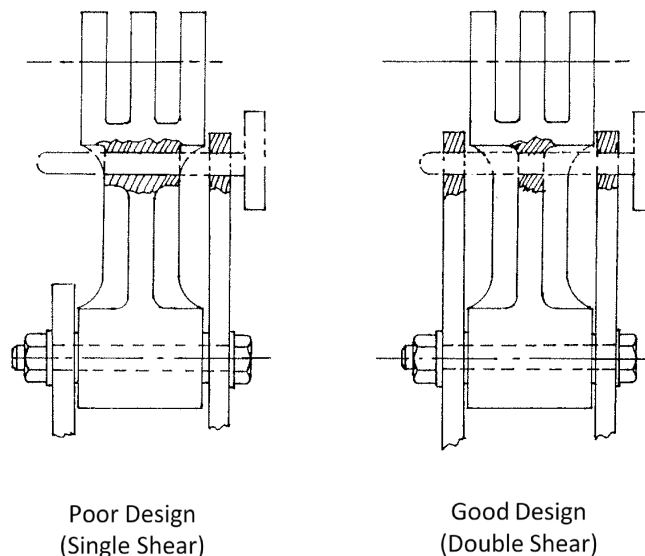


Figure 2 - Rigging pin installations

Rigging of control systems should be minimized by designing components that can be removed and replaced without affecting the system rigging. The replacement of a component in one system should not affect the rigging of another control system.

No rigging pin should be used on the power side of the system.

Complex components requiring rigging should be readily accessible and have adequate working space.

Equipment that requires sensitive or very precise adjustments, which can only be properly made when removed from the airplane, should be designed with these adjustments inaccessible with the equipment installed.

For rigging pins, use bar stock of comparable diameter or commercially available jig pins. Close tolerance pins and holes may be required if positional accuracy of the rigged components is required. Rigging pins should have a large red tag attached to highlight the presence of the installed rig pin and the need to remove it after rigging is complete.

Angular measurements should be shown in linear dimensions whenever possible.

Measurements that must be made when adjusting and rigging should be specified between easily measured features. Dimensions should be between flats, index marks, etc., not between centers of holes or centerlines of parts. Do not depend on the use of clay or putty to measure clearances, etc.

For rigging load and rigging instructions, see 6.1.11 and 6.1.13.

Considering the cable's non-linear load versus deflection characteristics, systems should be designed for tension at 2.5 times the specified rig load.

5.5 Cable System Installations

5.5.1 Cable Support Spacing

Cable wear and fatigue are accelerated if a section of cable rides on more than one sheave; therefore, the minimum spacing between sheaves is that distance that prevents a point on the cable from traveling over the groove of two adjacent sheaves plus an overtravel factor.

The maximum longitudinal cable support spacing by pulleys, fairleads or cranks is approximately 200 inches (5.1 m) in the fuselage. The maximum cable support spacing by pulleys in the wing is approximately 75 inches (1.9 m). The closer cable support spacing in the wing is to minimize cable wear from slapping fairleads and sheave grooves due to the wing bending and vibratory environment.

Cable runs in the wing (or other vibratory areas) should keep the cable restrained by positive wrap (2 degrees minimum) on pulleys or by grommets that have zero wrap unless the wing deflects. Both sheaves and grommets should bend the cable with radii greater than 15 times the cable diameter.

5.5.2 Cable Travels

No-load cable travel is defined as cable travel without stretch, due to load, to move a controlled item from one travel extreme to the other. Stop cushion force is defined as the force required at 70 °F (21.1 °C) to move the cockpit control to its input stop after the system output stop is contacted. The force is created by cable stretch, and is used to assure the output stops will be contacted with maximum system operating forces (see Table 2). These conditions normally apply to control systems with servactuators as well as purely manual control systems.

Table 8 lists the suggested no-load cable travels and stop cushion forces for PFCS. Cable travel is selected as a compromise between system friction, system stiffness, and backlash. When cable travel is reduced, system stiffness becomes more critical. Small travel also makes backlash and other lost motion more critical.

Table 8 - Suggested cable system travel and stop cushion forces

Control System	No-Load Cable Travel		Stop Cushion Force	
	Inches	m	Pounds	N
Lateral	4 to 8	0.10 to 0.20	50 min	222 min
Longitudinal	6 to 8	0.15 to 0.20	75 min	334 min
Directional	5 to 8	0.13 to 0.20	150 min	667 min
Engine (Military requirement of AFSC DH 2-2, DN 2B3)	4 min	0.10 min	200 to 250% of the normal operating force	

5.5.3 Cable Sheaves

Cable alignment with a sheave is defined as the angle between the cable centerline and the plane of the sheave groove. Design should strive for zero misalignment, although a maximum of 1/4 degree is allowed. This amount of design misalignment, along with manufacturing tolerances, still allows the shop to meet the maximum 2 degrees misalignment permitted on the aircraft, provided the cable does not rub against the side of the pulley groove. Typically, 2 degrees misalignment is permitted on the PFCS and 3 degrees misalignment is permitted on the SFCS and the UCS. Figure 3 provides a graphic indication of the impact of misalignment on cable and pulley friction.

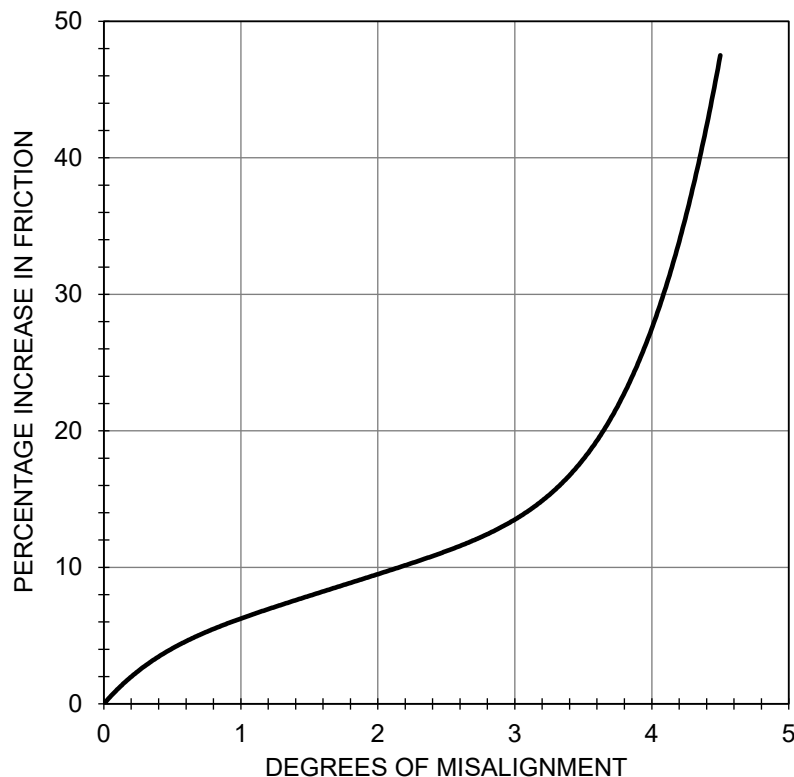


Figure 3 - Misalignment impact on cable friction

On sheave brackets that direct the cable upward, a pulley guard, similar to Figure 4, should be installed to deflect debris that might fall from above or ride down the cable.

In unpressurized areas, a sheave support structure should be designed to prevent jamming of the control system by the freezing of water or condensation flowing downward over the sheave or bracket, and the accumulation of water slush or ice. Cables routed below galleys and toilets should be protected from liquid spillage by covers. If cables pass close to waste water pipes, the cables should be routed above those pipes.

Lightening holes in the sides of pulley brackets should be placed so that the cables on sheaves are easily inspectable, and small ingested particles can drop out rather than wedge between the pulley and the bracket.

Pulleys of different systems should not be installed on the same bracket, or use the same pivot bolt unless a dual load path is provided.

Cable runs should be designed and configured so a replacement cable can be installed by pulling it into position by the cable to be replaced. Obviously, cable guards need to be removed.

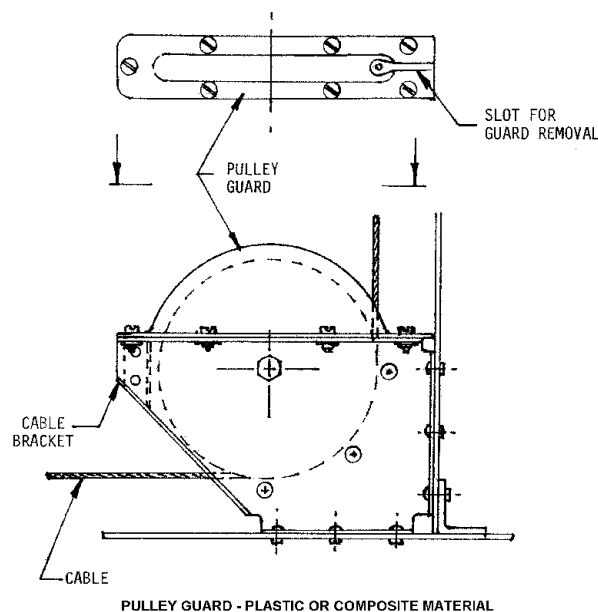


Figure 4 - Pulley guard

5.5.4 Cable and Crank Combinations

Cables can be used in combination with cranks to accomplish the same function as cables in combination with quadrants. Examples of cable and crank combinations are shown in Figure 5. Cable and crank installations generally have less friction because the cables are not being wrapped and unwrapped at the bellcrank interfaces like with cable quadrants. The anti-friction ball bearing terminals provide a very low friction interface and allow the cables to be preloaded to a higher level, resulting in increased control installation stiffness. The cable diameter can be increased in applications like the second layout in Figure 5 where there are no pulleys involved. This increases the installed stiffness with no increase in friction. The cable/crank mechanical gain can be non-linear, especially if a crank is used in combination with a conventional quadrant. This characteristic can be an advantage or a disadvantage, depending on the application. The crank and cable installation motions need to be analyzed and indexed accurately so the incremental motions of both cables are as equal as possible. Splitting the cable rise and fall, similar to the approach presented in 5.6 for pushrods and cranks, equalizes the cable incremental displacements. This incremental equality of cable strokes is necessary to maintain the cable preloads as constant as practical.

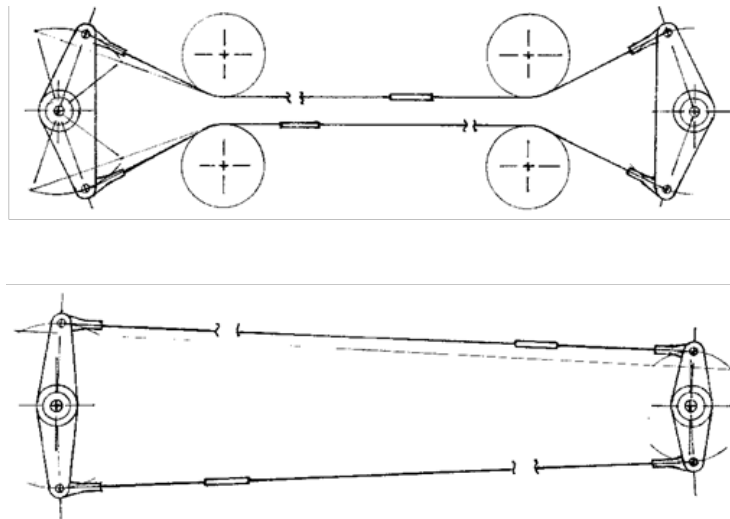


Figure 5 - Cable and crank installation

5.6 Control Pushrod Installations

5.6.1 Control Pushrod Length

The maximum length of a control pushrod is usually based on the length that will allow removal and installation without the removal of other items. Most of the time this will restrict rod length to approximately 75 inches (1.9 m).

It is preferred that control pushrods have a maximum slenderness ratio of $L/\rho = 100$, where L is the length of the rod and ρ is the mean radius of gyration. This value may be exceeded, provided that the rod is within acceptable stress limitations. The rod compressive stress, S_c , without local buckling, is calculated by use of the Euler column formula:

$$S_c = \frac{P}{A} = \frac{\pi^2 E}{(L/\rho)^2} \quad [\text{psi}] \text{ (MPa)} \quad (\text{Eq. 1})$$

where:

S_c = rod compressive stress [psi] (MPa)

P = total axial load [pounds] (N)

A = area of section [in^2] (mm^2)

E = modulus of elasticity of the material [lbs/in^2] (N/mm^2)

L/ρ = slenderness ratio [-]

L = rod length [inches] (mm)

ρ = rod mean radius of gyration [inches] (mm)

$$\rho = \frac{1}{4} \sqrt{d_o^2 + d_i^2} \quad [\text{inches}] \text{ (mm)} \quad (\text{Eq. 2})$$

where:

d_o = pushrod outside diameter [inches] (mm)

d_i = pushrod inside diameter [inches] (mm)

The most efficient rod design is a thin-walled tube whose ends are swaged down for rod-ends and whose slenderness ratio is close to 100. The minimum wall thickness is 0.035 inch (0.89 mm) for aluminum and 0.020 inch (0.51 mm) for steel.

Preliminary clearance studies can be quickly made by assuming a solid rod that has a maximum outside diameter of $d_o = 0.04L$ and a slenderness ratio of 100. For example, the maximum possible OD of a 75 inch (1900 mm) long pushrod with a slenderness ratio of 100 will be 3.00 inches (0.04×75) or 76 mm (0.04×1900). Use this maximum diameter for evaluating the clearance between the pushrod and other systems or structures during the preliminary design.

5.6.2 Control Pushrod Travel and Motion Linearity

Control pushrod travel should be set as large as practical for high mechanical advantage and low rod loads. The lower the loads, the lighter the system. Control pushrod axial travel is not linear with the angular travel of the cranks. This non-linear travel characteristic is not significant if the crank angular travel is kept within ± 30 degrees of the position where the rod centerline is normal to the crank centerline. Total crank rotation of more than 60 degrees causes rapid increase in rise and fall of the control pushrod with smaller incremental gains in linear travel. The more the angular travel, the more the rise and fall of the pushrod, and as a result, more space is required for routing the control system. For typical control pushrod systems, the clockwise and counterclockwise crank motions are split (made equal) for optimum mechanical advantage and linearity. Examples of installations with the motions not split and split are shown in Figure 6.

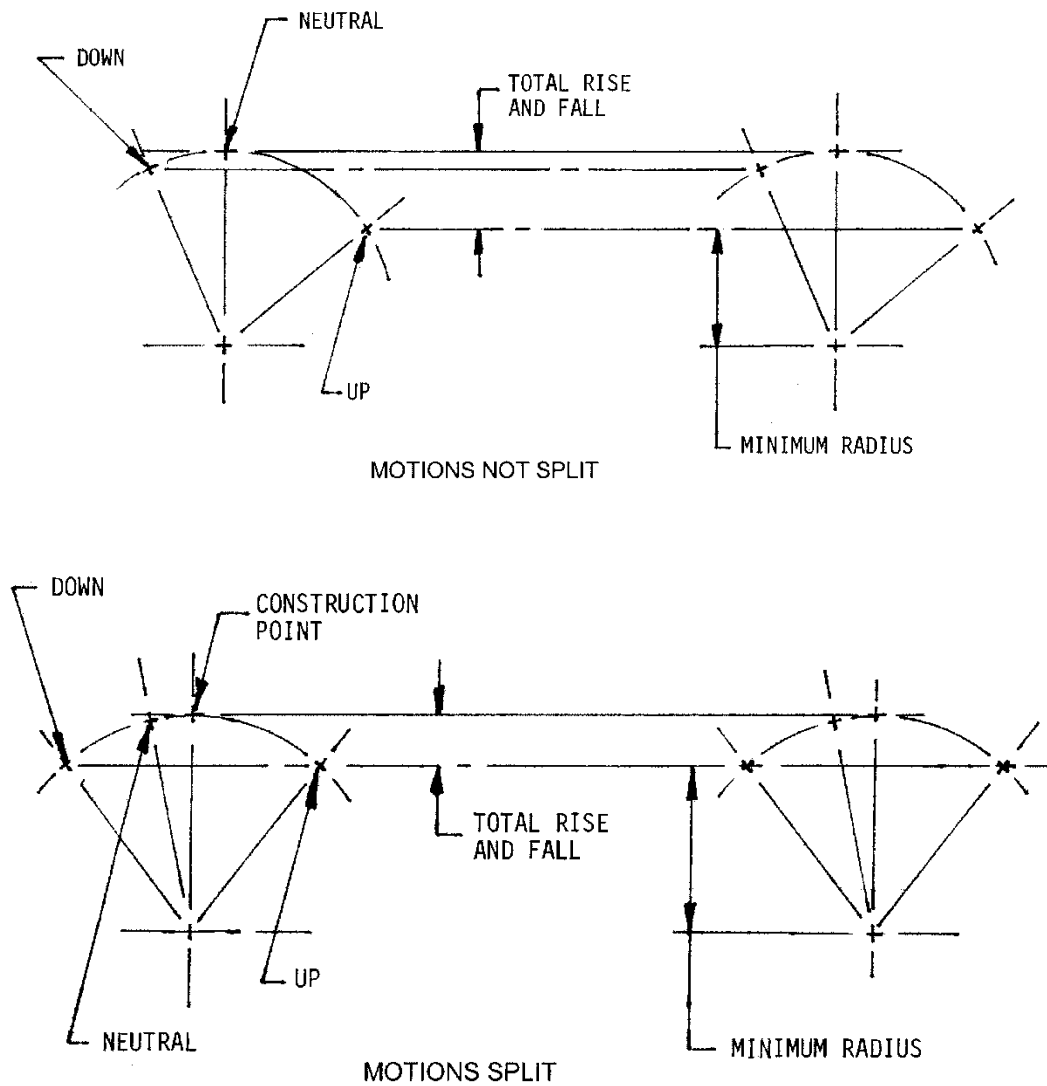


Figure 6 - Motion layouts

Split motion arrangements can be used to optimize the overall mechanical advantage with cranks of equal or unequal radii, with the cranks on the same or opposite sides of the control pushrod and with non-coplanar crank pivots. Geometric layouts are used to optimize the pushrod motions before the cranks, pushrods and pivot fitting designs are initiated. Elevator and aileron control systems are usually designed with more trailing edge up travel than trailing edge down travel. The elevator and aileron pushrod system can best be configured with the extreme endpoints of up and down surface travel split and the neutral surface position offset to the control pushrod neutral position.

5.6.3 Control Linkage Non-Linearity

On many control systems, there is a preference to keep the command motions versus surface motions as linear as possible. This is best achieved by splitting the pushrod and cranks rise and fall. But in some applications, there is a need to provide non-linear gains. This can be achieved with a pushrod and crank system, but not with a conventional cable system.

A typical example of this is a stabilator or canard command control for a high-performance jet powered aircraft. The preferred mechanical command versus surface motion is low gain at neutral and high gain at larger surface travels. An example of the preferred motions is shown in Figure 7. This motion plot provides a very low gain at neutral for accurate small output positional control at high aircraft speeds and large incremental outputs versus input at low aircraft speeds. The crank and pushrod arrangement that provides this non-linearity is shown in Figure 8.

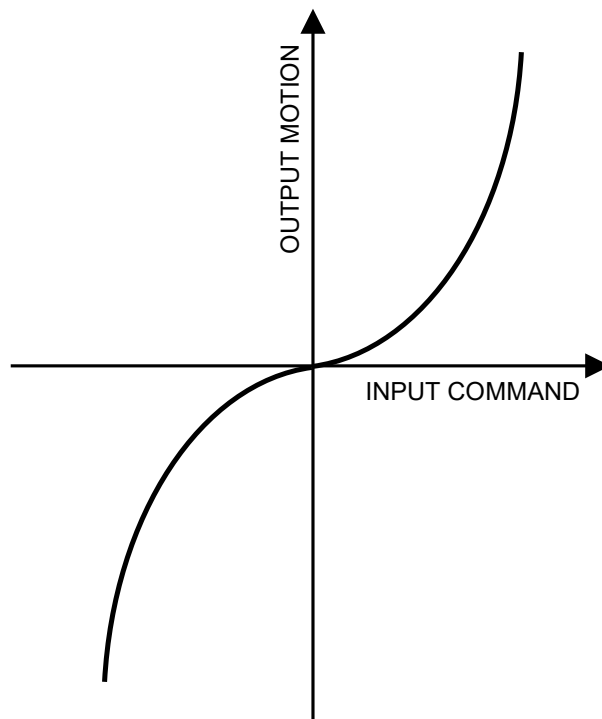


Figure 7 - Preferred motions - high performance jet

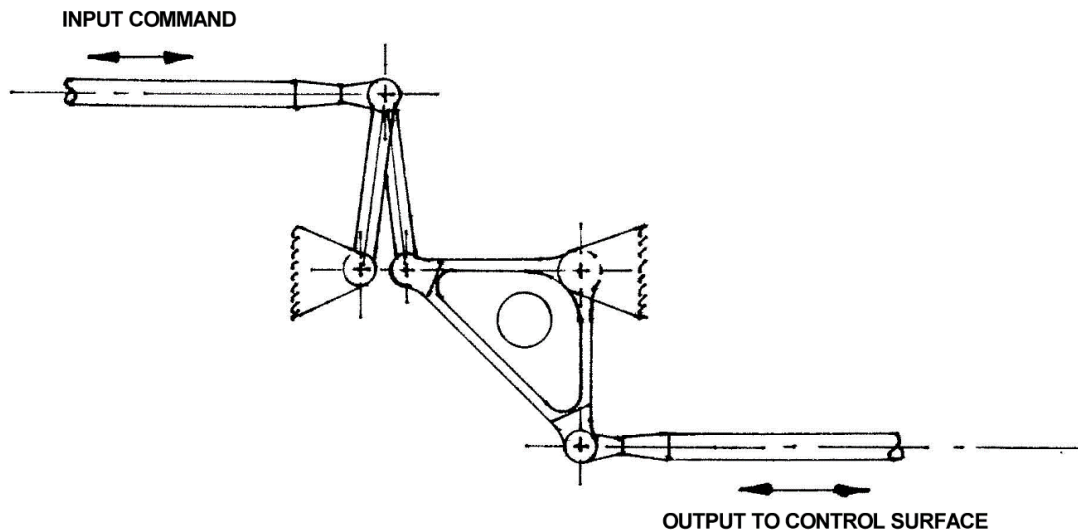


Figure 8 - Crank and pushrod arrangement

This very non-linear motion characteristic is usually used in combination with series trim so the command neutral position is held constant with the non-linear motion neutral position, regardless of trim position. Series trim actuator output motion is inserted between the non-linear linkage output and control surface input. The cockpit control and non-linear function remain motionless while the series trim output resets the control surface position. A control system schematic with the non-linear mechanization and series trim included is shown in Figure 9.

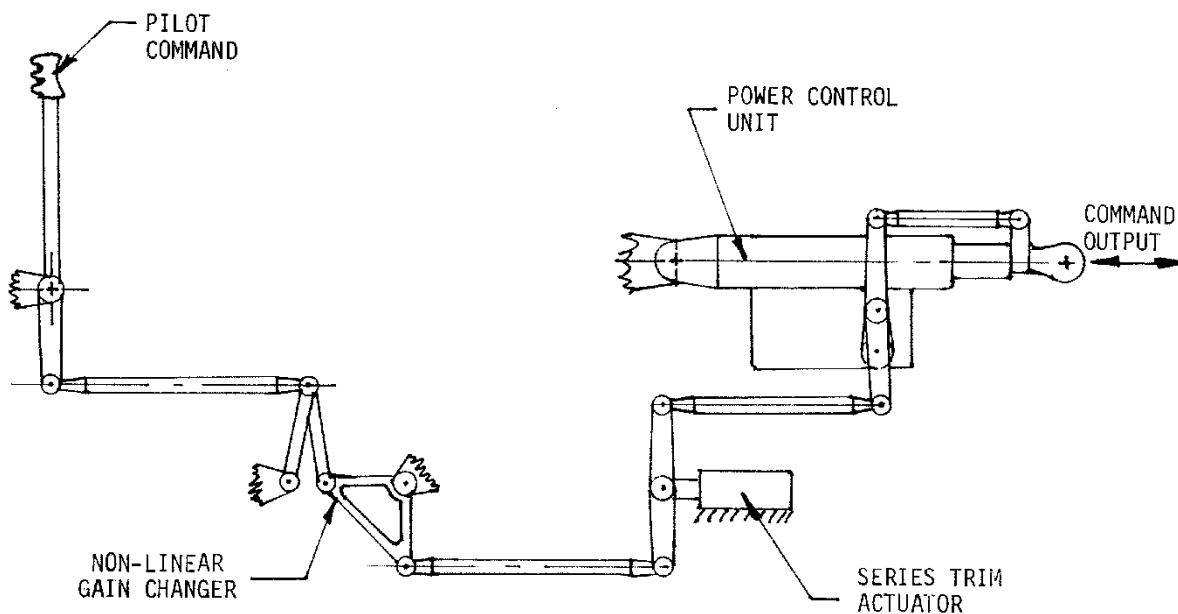


Figure 9 - System schematic with non-linear gain changer and series trim actuator

Conversely, there have been some unique control applications where the opposite motion characteristics were needed. An example of this motion plot is shown in Figure 10. This unusual non-linear gain feature was used for pitch control of a V/STOL aircraft where the pitch was induced by a propeller mounted horizontally at the aircraft's rear. The propeller provided low pitch gain around neutral. The unique linkage high gain at neutral command motion-compensated for the low propeller pitch gain. This motion arrangement is provided by the pushrod and crank arrangement shown in Figure 11. This is the reversal of the linkage arrangement shown in Figure 8.

There are computer-based four-bar linkage programs that provide a large variety of motion characteristics.

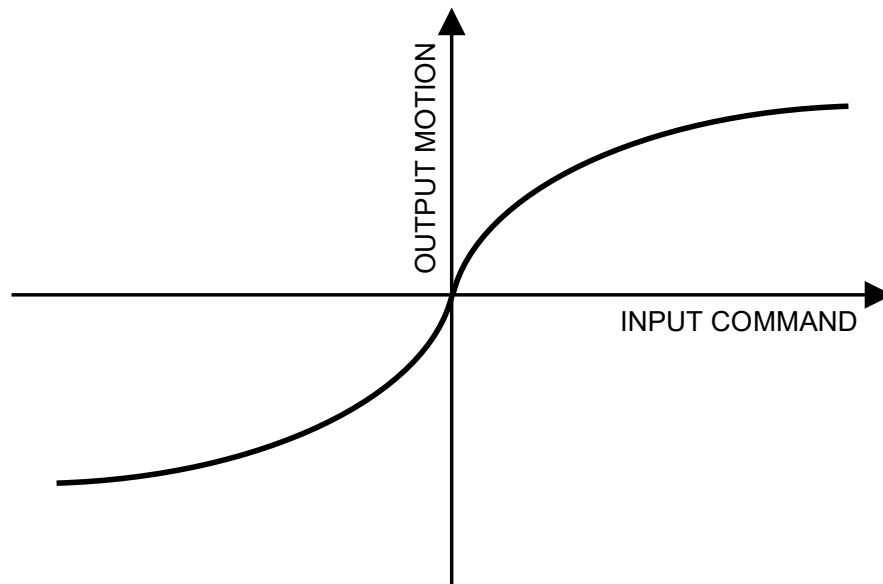


Figure 10 - Unique control motions

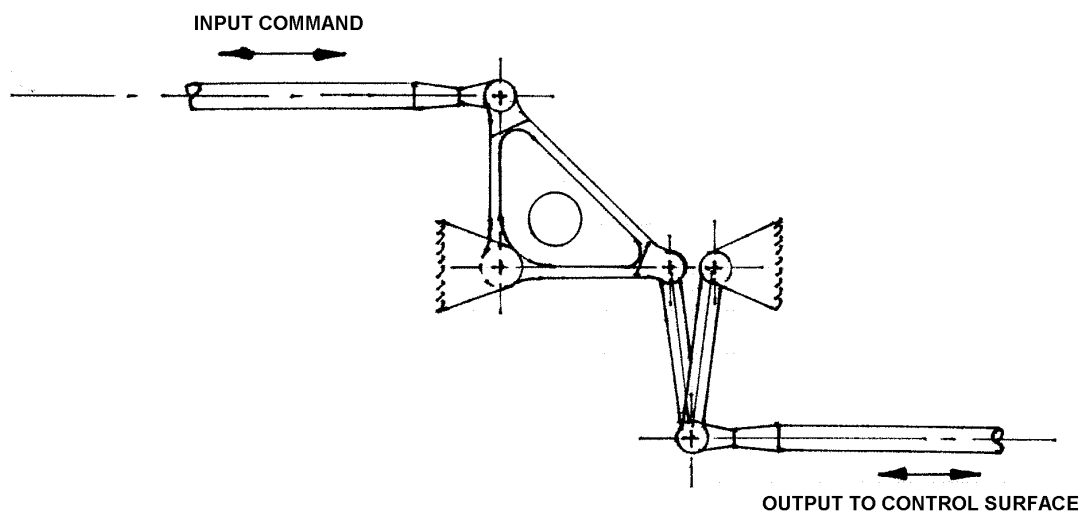


Figure 11 - Unique crank and pushrod arrangement

5.6.4 Long Pushrod Runs

Long pushrod runs are typically not used on aircraft because cable systems are usually more weight and cost effective and have less backlash. But there may be some applications where two or more pushrods are used in series. On multiple parallel pushrod runs, a series of parallelogram cranks and pushrods can be arranged as shown in Figure 12. This arrangement minimizes bearing loads, friction, and backlash because the idler bearings carry very low loads. This combination of pushrods and cranks should not be used where the rod system must deviate from a straight line because it will impose a bending load on the forks and pushrods. In such an application, a bellcrank should be used to turn the corner, then the parallelograms may be continued.

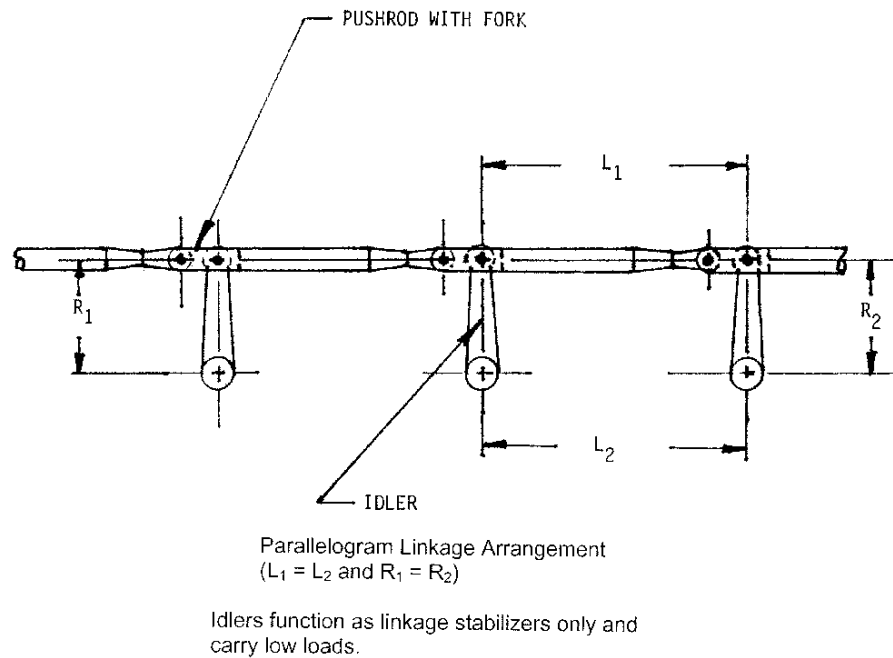


Figure 12 - Long pushrod runs

Airframe flexure, if ignored in control linkage design, can introduce unwanted signals into the control system and, in some cases, compromise aircraft safety. When airframe bending occurs, the distance between the mounting points at the ends of the linkage system will change. The linkage, however, is not subjected to the airframe loads, remains the same length, and introduces a signal into the control system. Similar unwanted signals may also be generated by the temperature change if pushrods are made of different materials from the airframe (e.g., aluminum pushrods for composite airframe, or vice versa). If a walking beam is properly located in the system, the pushrod position will then vary as required to accommodate the relative motion of the mounting points. This same walking beam may also be useful in canceling out acceleration effects. See Figure 13.

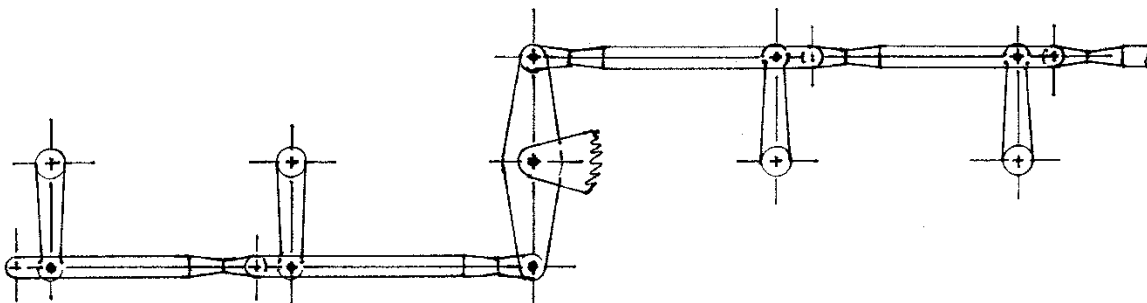


Figure 13 - Walking beam installation

5.6.5 Control Pushrod Failure Restraints

Control pushrod adjustments should be minimized, and each pushrod should be carefully evaluated to determine if a fixed-length pushrod would be satisfactory in a particular application.

Bolts with a 1/4 inch (6 mm) diameter should be the smallest fastener used for the installation of control pushrods. If a 3/16 inch diameter (5 mm) or smaller fastener is used, use a recessed head fastener to reduce the potential for over-torquing.

The effect of a jam condition should be carefully reviewed in a control pushrod system to determine whether this type of failure can be tolerated, or if an override device is required to assure adequate control at all times.

Restraints for a control pushrod should be provided if it could jam other systems should it become disconnected or severed. Any rod or link that can be used as a handhold or step during construction, maintenance, or inspection should be designed for the following ultimate lateral loads applied at any point along its length.

- Handhold - 150 pounds (667 N), and
- Step - 300 pounds (1334 N).

5.7 Push-Pull Flexible Control Installation

Push-pull flexible controls are sometimes used where the space available for the mechanical control path is restricted. They have been used occasionally for primary flight control and on numerous aircraft for secondary flight control applications. Their use for primary flight control is not recommended because of the hysteresis introduced by their combination of friction and compliance. This hysteresis can increase as a result of handling damage and installation or maintenance errors and cause flying qualities unacceptable for precision control tasks. The use of cable or pushrod approaches should be pursued energetically for primary flight control because they promise dependably acceptable friction and threshold.

Push-pull flexible controls shall comply with MIL-PRF-7958. There are two basic types of push-pull flexible controls: the sliding friction type and the ball bearing type. The ball bearing type has higher efficiency. Extreme care should be taken in the design to prevent installation errors and provide shielding so controls cannot be used as handholds or stepped on by maintenance personnel. The installation design of the sliding friction type should minimize the number of bends, use large curves, and avoid reverse bends to keep friction and backlash within acceptable limits. The installation design of the ball bearing type should keep all bends in a single plane, or the control helix at a controlled rate into another plane to prevent binding or damage. Both types should be supported at frequent intervals and on both ends, but not restrained so that motion of the internal parts may be restricted axially. Consideration of environmental conditions is very important.

5.8 System Friction and Breakout Force Calculations

System friction is critical for pitch, roll, and yaw flight control systems that have centering and low breakout force requirements. For a system with a centering device, every pound (4.45 N) of system friction, measured under static conditions on the ground, adds approximately 1.7 pounds (7.56 N) to the breakout force, the additional 0.7 pound (3.11 N) being required to overcome the centering (detent) force.

Design for a specified system breakout force requires that the friction of system components be minimized.

A careful friction analysis is required to have the actual breakout force within 10% of the calculated breakout force.

System friction is calculated, usually at 70 °F (21.1 °C), along with the control centering and any unbalance forces, to determine the breakout force for the system.

Table 9 lists the methods for calculating system friction for system components. Cable routing may be developed by using computer-graphics aided three-dimensional interactive application (CATIA).

Table 10 gives average bearing friction breakout torques of commonly used bearings at 70 °F (21.1 °C). These no-load breakout values should be used for large systems with many bearings. If the system is friction critical with a small number of bearings, these values should be increased by 25 to 50%.

Table 9 - Component friction calculation

Component	Calculation Method
Ball bearing	Use the average no-load breakout torque of bearing or similar bearing in Table 10.
Sheave and cable (carbon steel, corrosion-resistant steel, or nylon jacketed)	Compute friction from ratio F/T values from Figures 43 or 44, depending upon groove conformance with cable diameter. Interpolate F/T values for wrap angle not shown between wrap angles that are shown.
Fairlead pulley with zero wrap	Compute friction on the assumption that only half of the pulleys are contacted by the cable under two conditions: 1. The fairlead pulley bearing breakout friction. 2. The sliding friction between the cable and a non-rotating fairlead pulley. Assume a friction coefficient of 0.04 and the weight of the cable between adjacent sheaves. Take the lesser of the two values and divide by 2 to account for only half of the pulleys being contacted.
Rub strips and fixed fairleads	Friction is based on maximum anticipated deflection of supporting structure (typically wing bending) that induces cable deflection. Compute cable friction using cable tension-induced side load and 0.04 friction coefficient.
Seal and cable Eyeball pressure seal Douglas grommet Firewall seal	Compute friction using a friction coefficient of 0.04 and the weight of the cable between adjacent sheaves.
Hydraulic control valve	Use the breakout friction called out in the specification or functional test for the valve or similar valve.

Table 10 - ABMA bearing average no-load breakout torque at 70 °F (21.1 °C)

ABMA No.	SAE Designation	Average No-Load Breakout Torque ⁽¹⁾		ABMA No.	SAE Designation	Average No-Load Breakout Torque ⁽¹⁾	
		in-oz	10 ⁻³ N·m			in-oz	10 ⁻³ N·m
AS27640				AS27641			
KP3	-3	0.09	0.636	KP3A	-3	0.08	0.565
KP4	-4	0.45	3.18	KP4A	-4	0.16	1.13
KP5	-5	0.40	2.82	KP5A	-5	0.23	1.62
KP6	-6	0.58	4.10	KP6A	-6	0.74	5.23
KP8	-8	1.06	7.49	KP8A	-8	1.30	9.18
KP10	-10	1.28	9.04	KP10A	-10	1.45	10.2
AS27642				KP12A	-12	1.54	10.9
KP21B	-21	5.38	38.0	KP16A	-16	3.01	21.3
KP25B	-25	6.01	42.4	KP20A	-20	3.88	27.4
KP29B	-29	7.02	49.6	MKP4A	-4R	0.16	1.13
KP33B	-33	8.04	56.8	MKP5A	-5R	0.21	1.48
KP37B	-37	9.43	66.6	MKP12A	-12R	1.33	9.39
KP47B	-47	12.15	85.8	AS21151			
KP49B	-49	13.42	94.8	REP4M6	-8	0.47	3.32
AS27647				AS21443			
DW4K	-4	0.80	5.65	P4K	-4B	0.20	1.41
DW4	N/A	0.85	6.00	P5K	-5A	0.25	1.77
DW5	-5	0.90	6.36	PD5K	-5B	0.50	3.53
DW6	-6	1.10	7.77	P8	-8	1.30	9.18
				P10K	-10	0.80	5.65

⁽¹⁾ The average radial no-load breakout test results of multiple bearings of each size by bearing and airframe manufacturers. If the control installation is subjected to misalignment by design or installation deflections, the misalignment bearing torque needs to be accounted for. The misalignment torque can be several times greater than the radial no-load frictional torque.

The following shows a friction analysis for a hypothetical elevator control system that consists of:

- An isometric diagram of the elevator control system showing all of the friction-producing components of the system (Figure 14).
- A data sheet tabulating the friction of each component in the system (Table 11).
- Calculations (Figures 15A, 15B, and 15C) showing the typical computations for the friction of each component of the system, the resultant centering detent, and the total breakout force.

The maximum total breakout force should not exceed 7 pounds (31.1 N) based on MIL-F-8785 criteria. Most aircraft manufacturers prefer a maximum total breakout force of 5 pounds (22.2 N). Based on these latter criteria, the centering detent should be greater than total friction plus column unbalance (i.e., 2.5 pounds [11.1 N] max), but not less than 70% of the total friction with no column unbalance. If friction cannot be minimized to achieve this condition, consideration should be given to the use of cable tension regulators that reduce friction by permitting a lower rigging load. This hypothetical elevator control system utilizes tension regulators with a 70 pounds (311 N) cable preload.

Examination of the summary of calculated component friction levels in Table 11 highlights the magnitude of the friction associated with control assemblies such as the pitch autopilot actuators, force feel unit, and servoactuators.

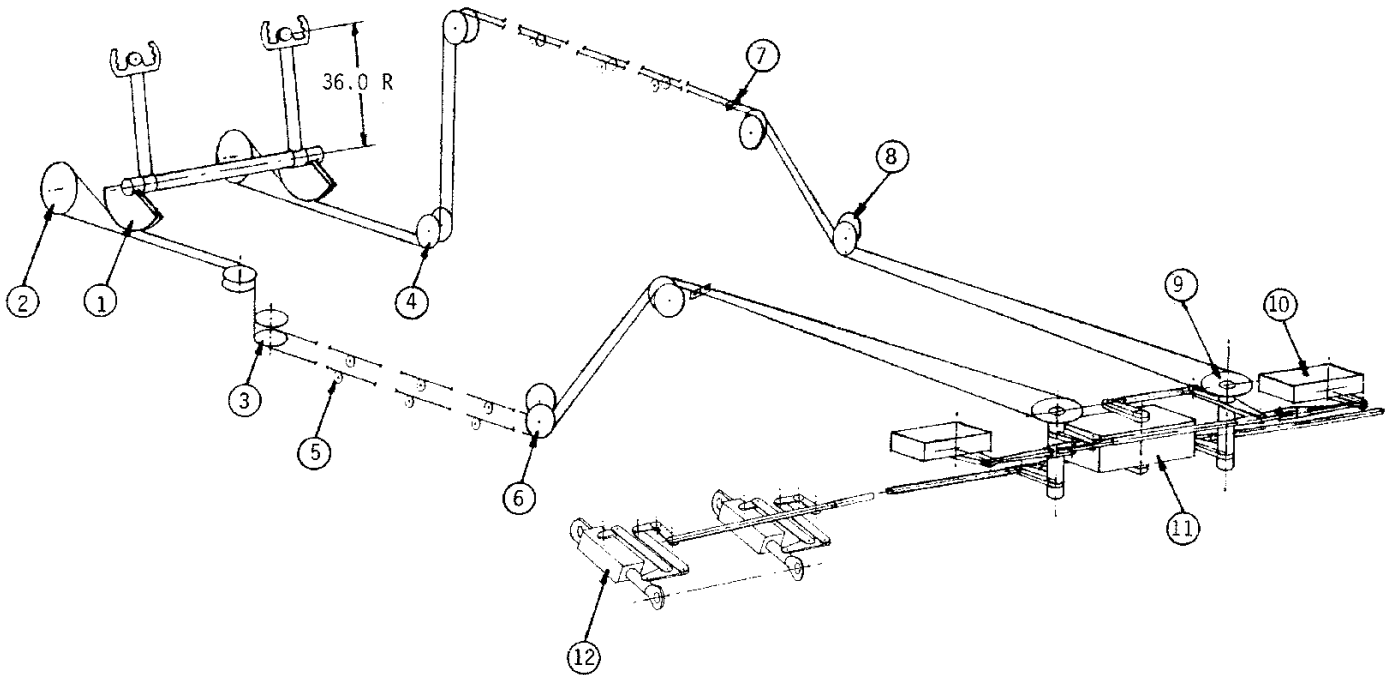


Figure 14 - Characteristic transport aircraft elevator control system isometric

Table 11 - Characteristic elevator control system component friction analysis

Item	Item	No. of Items	Friction at Column	
			pounds	N
1	Control Columns	2	0.155	0.689
2	Forward Pulleys	2	0.051	0.227
3	Intermediate Pulleys - Pilot Side	4	0.109	0.485
4	Intermediate Pulleys - Copilot Side	4	0.117	0.520
5	Fairlead Pulleys	24	0.036	0.160
6	Intermediate Pulleys - Pilot Side	4	0.109	0.485
7	Eyeball Pressure Seals	4	0.027	0.120
8	Intermediate Pulleys - Copilot Side	4	0.097	0.431
9	Rear Quadrants	4	0.077	0.342
10	Pitch Autopilot Actuators	2	0.196	0.872
11	Force Feel Unit	1	0.185	0.823
12	Servoactuator Linkage and Valves	4	1.584	7.045
Subtotal:			2.743 pounds	12.199 N
70% Detent:			<u>1.920 pounds</u>	<u>8.539 N</u>
Total Pitch Axis Breakout:			4.663 pounds	20.738 N

Control Column Arm Length	- 36.00 in R (0.914 m R)
Control Column Cable Quadrants	- 10.00 in R/20.00 in pitch dia (0.254 m R /0.508 m pitch dia)
Forward Pulleys and Rear Quadrants	- 12.00 in pitch dia (0.305 m pitch dia)
Intermediate Pulleys	- 8.00 in pitch dia (0.203 m pitch dia)
Idler Pulleys	- 3.00 in pitch dia (0.0762 m pitch dia)
Cable Diameter	- 0.125 in dia (0.00318 m dia)
Cable Tension	- 70.0 pounds (311 N)

1. Control Columns

2 - Column Boots	- 0.45 pound at 4.00 in R (2.00 N at 0.102 m R)
2 - Column Bearings	- KP8A - 1.30 in-oz (0.00918 N·m)
2 - Column Quadrant Assemblies	- 20.00 in (0.508 m) dia x 30 degree wrap (two wraps per quadrant assembly)
4 - Remove PD5K Pulley Bearing Friction	- 0.50 in-oz (0.00353 N·m)

$$\text{Quadrant } D/d = (20 - 0.125)/0.125 = 159, F/T = 0.0007$$

$$\text{Friction} = \frac{2 \times 0.45 \times 4}{36} + \frac{2 \times 1.30 - 4 \times 0.5}{36 \times 16} + \frac{4 \times 0.0007 \times 70 \times 10}{36}$$

$$= 0.1000 + 0.0010 + 0.0544 = 0.155 \text{ lb (0.689 N)}$$

2. Forward Pulleys

2 - Pulleys	- 12.0 in (0.305 m) pitch dia x 210 degree wrap
$D/d = (12 - 0.125)/0.125 = 95, F/T = 0.0012 \times 1.08 = 0.0013$ (Extrapolated from 180 to 210 degrees)	

$$\text{Friction} = \frac{2 \times 0.0013 \times 70 \times 10}{36} = 0.051 \text{ lb (0.227 N)}$$

3. Intermediate Pulleys - Pilot Side

4 - Pulleys	- 8.0 in (0.203 m) pitch dia x 60 degree wrap
$D/d = (8 - 0.125)/0.125 = 63, F/T = 0.0014$	

$$\text{Friction} = \frac{4 \times 0.0014 \times 70 \times 10}{36} = 0.109 \text{ lb (0.485 N)}$$

4. Intermediate Pulleys - Copilot Side

4 - Pulleys	- 8.0 in (0.203 m) pitch dia x 90 degree wrap
$D/d = 63, F/T = 0.0015$	

$$\text{Friction} = \frac{4 \times 0.0015 \times 70 \times 10}{36} = 0.117 \text{ lb (0.520 N)}$$

Figure 15A - Elevator control system friction analysis (1 of 3)

5. Fairlead Pulleys - Select lesser value of sliding or pulley bearing friction assuming one-half of pulleys contacted.

- 24 - Pulleys - 3.0 in (0.0762 m) pitch dia x 0 degree wrap
 24 - Pulley Bearings - P5K - 0.25 in-oz (0.00177 N·m)

$$\text{Bearing Friction} = \frac{0.25}{16} \times \frac{2}{3.00 - 0.125} \times \frac{24}{2} \times \frac{10}{36} = 0.036 \text{ lb (0.160 N)}$$

Sliding Friction

$$\mu = 0.04$$

$$\text{Weight of jacketed cable} = 3.62 \text{ lb/100 ft (0.528 N/m)}$$

$$\text{Average weight/every other pulley} = \frac{3.62}{100} \times 16 = 0.579 \text{ lb (2.575 N)}$$

$$\text{Sliding Friction} = 12 \times 0.579 \times 0.04 \times \frac{10}{36} = 0.077 \text{ lb (0.342 N)}$$

Use the bearing friction = 0.036 lb (0.160 N)

6. Intermediate Pulleys - Pilot Side

- 4 - Pulleys - 8.0 in (0.203 m) pitch dia x 60 degree wrap
 $D/d = (8 - 0.125)/0.125 = 63$, $F/T = 0.0014$

$$\text{Friction} = \frac{4 \times 0.0014 \times 70 \times 10}{36} = 0.109 \text{ lb (0.485 N)}$$

7. Eyeball Pressure Seals

- 4 - Seals - Friction Coefficient - 0.04

Weight of 200 inches (5.08 m) of cable at 3.62 lb/100 ft (0.528 N/m) - 0.6033 lb (2.683 N)

$$\text{Seal Friction} = 4 \times 0.04 \times 0.6033 \times \frac{10}{36} = 0.027 \text{ lb (0.120 N)}$$

8. Intermediate Pulleys - Copilot Side

- 4 - Pulleys - 8.0 in (0.203 m) pitch dia x 30 degree wrap
 $D/d = 63$, $F/T = 0.00125$

$$\text{Friction} = \frac{4 \times 0.00125 \times 70 \times 10}{36} = 0.097 \text{ lb (0.431 N)}$$

9. Rear Quadrants

- 2 - Quadrant Assemblies - 12.0 in (0.305 m) pitch dia x 28 degree wrap (two wraps/quadrant assy)
 4 - Pivot Bearings - KP8A - 1.30 in-oz (0.00918 N·m)
 4 - Remove PD5K Pulley Bearing Friction - 0.50 in-oz (0.00353 N·m)
 10 - Rod-End Bearings on 8 inch cranks - REP4M6 - 0.47 in-oz (0.00332 N·m)
 Quadrant $D/d = 95$, $F/T = 0.0007$

$$\text{Friction} = \frac{4 \times 0.0007 \times 70 \times 10}{36} + \frac{4 \times 1.30 - 4 \times 0.50 + 10 \times 0.47}{16 \times 6} \times \frac{10}{36} = 0.077 \text{ lb (0.342 N)}$$

Figure 15B - Elevator control system friction analysis (2 of 3)



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10. Pitch Autopilot Actuators

2 - Actuators - 34 in-oz (0.240 N·m) breakout friction with 8.0 in (0.203 m) crank

$$\text{Friction} = \frac{2 \times 34 \times 8}{16 \times 8} \times \frac{10}{6} \times \frac{1}{36} = 0.196 \text{ lb (0.872 N)}$$

11. Force Feel Unit

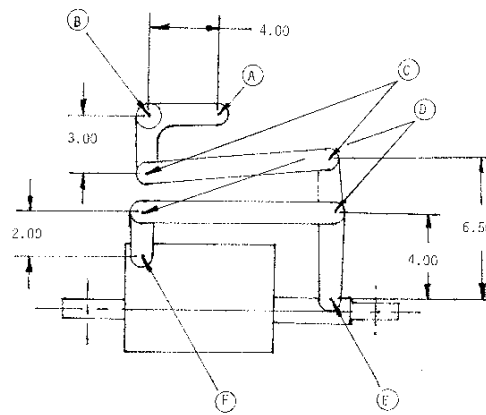
1 - Feel Unit

2 - Inputs - Internal friction at breakout - 2 in-lb (0.226 N·m)

$$\text{Friction} = \frac{2 \times 2}{8} \times 8 \times \frac{10}{6} \times \frac{1}{36} = 0.185 \text{ lb (0.823 N)}$$

12. Servoactuator Linkage and Valve

4 Servoactuators/ Aircraft



A - REP4M6 Bearing
 B - 2 MKP5A Bearings
 C - 2 MKP4A Bearings
 D - 2 MKP4A Bearings
 E - 2 MKP4A Bearings
 F - Valve Breakout Friction

0.47 in-oz (0.00332 N·m)
 0.42 in-oz (0.00297 N·m)
 0.32 in-oz (0.00226 N·m)
 0.32 in-oz (0.00226 N·m)
 0.32 in-oz (0.00226 N·m)
 72.00 in-oz (0.508 N·m)

$$\begin{aligned} \text{Friction}_{\text{ACTUATOR}} &= \left[\frac{0.47}{16 \times 4} + \frac{0.42}{16 \times 4} + \frac{0.32}{16 \times 4} + \frac{0.32 \times 3}{16 \times 6.5 \times 4} + \frac{0.32 \times 3}{16 \times 6.5 \times 4} + \frac{0.32 \times 3}{16 \times 6.5 \times 2} + \frac{0.32 \times 3}{16 \times 6.5 \times 4} + \frac{72 \times 4 \times 3}{16 \times 2 \times 6.5 \times 4} \right] \\ &= 0.0073 + 0.0066 + 0.0050 + 0.0023 + 0.0023 + 0.0046 + 0.0023 + 1.0385 \\ &= 1.069 \text{ lb (4.755 N)} \end{aligned}$$

$$\text{Friction}_{\text{COLUMN}} = 4 \times 1.069 \times \frac{8}{6} \times \frac{10}{36} = 1.584 \text{ lb (7.045 N)}$$

Figure 15C - Elevator control system friction analysis (3 of 3)

5.9 Control System Gearing Ratio

5.9.1 General

In the manually powered PFCS, the pilot force required at the cockpit control is determined by the aerodynamic hinge moment at the control surface and the gearing ratio between the control surface and the cockpit control. The gearing ratio of the control system should be carefully designed, as it affects the handling quality of the airplane, along with the control surface's hinge moment characteristics.

5.9.2 Definition of Gearing Ratio

The gearing ratio of the control system is defined as a ratio of the pilot force to the hinge moment at the control surface as follows:

$$G = \frac{PE}{HM} \quad [1/ft] (1/m) \quad (\text{Eq. 3})$$

where:

G = control system gearing ratio $[1/ft] (1/m)$

PE = pilot effort at the cockpit control (+ve in pull, CW, or RH pedal push) [pounds] (N)

HM = control surface aerodynamic hinge moment (+ve in trailing edge down or left) [ft-lbs] (N·m)

The gearing ratio is conventionally expressed in the unit of 1/ft. Figure 16 schematically represents a control system consisting of a cockpit control and a control surface connected by a mechanical control system.

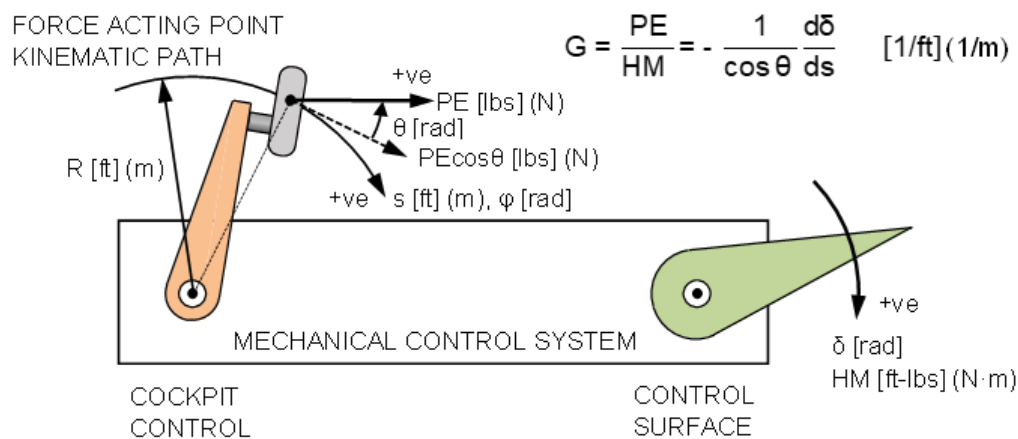


Figure 16 - Control system schematic diagram

It should be noted that, for ergonomic reasons, the direction of the pilot force application does not necessarily coincide with the kinematic trajectory of the force acting point on the cockpit control. The force acting point and direction, however, are both subjective, and they should be determined by a variety of human factors. It should be also paid attention that the flight test instrumentation is installed so that the measured control forces are consistent with the actual forces the pilot exerted.

Assuming that the control system is rigid and there is no system friction, the equilibrium of the virtual work done on the system is expressed as follows:

$$dW = PE \cos \theta ds + HM d\delta = 0 \quad [\text{ft-lbs}] \text{ (N}\cdot\text{m)} \quad (\text{Eq. 4})$$

where:

W = work done on the system [ft-lbs] (N·m)

θ = pilot force angle against the kinematic path of the force acting point [rad]

s = displacement of the pilot force acting point along its kinematic path (+ve direction shown in Figure 16) [ft] (m)

δ = control surface deflection (+ve direction shown in Figure 16) [rad]

At the cockpit control, only the component of the pilot force projected in the direction of the displacement does work. The system gearing ratio is then expressed as:

$$G = \frac{PE}{HM} = - \frac{1}{\cos \theta} \frac{d\delta}{ds} \quad [1/\text{ft}] \text{ (1/m)} \quad (\text{Eq. 5})$$

The $d\delta/ds$ is a gradient of a curve of the control surface angle, δ , versus the cockpit control deflection, s . It should be aware that the values of $d\delta/ds$ and θ are functions of the s . If the kinematic path of the pilot force acting point is confined to a single pivot motion, the deflection, s , is calculated as:

$$s = R\phi \quad [\text{feet}] \text{ (m)} \quad (\text{Eq. 6})$$

where:

R = cockpit control arm length to the pilot force acting point [ft] (m)

ϕ = cockpit control angular deflection [rad]

A curve of the kinematic relationship between δ and s can be approximated by a multi-degree polynomial as follows:

$$\delta(s) = \delta_0 + C_1s + C_2s^2 + C_3s^3 + C_4s^4 + \dots \quad (\text{Eq. 7})$$

where:

δ_0 = control surface offset angle (if necessary) [rad]

C_n = polynomial coefficients [-]

The polynomial should be at least the fourth degree for reasonable accuracy. The gradient, $d\delta/ds$, can be obtained by differentiating the given polynomial of $\delta(s)$ with respect to the s .

$$\frac{d\delta(s)}{ds} = C_1 + 2C_2s + 3C_3s^2 + 4C_4s^3 + \dots \quad (\text{Eq. 8})$$

If the variables, θ and δ , are expressed in degrees [θ° , δ°], the expression of the gearing ratio becomes:

$$G = \frac{PE}{HM} = - \frac{1}{\cos \theta^\circ} \frac{1}{57.3} \frac{d\delta^\circ}{ds} \quad [1/\text{ft}] \text{ (1/m)} \quad (\text{Eq. 9})$$

5.9.3 Pilot Force

The pilot force required to counteract the surface hinge moment at a certain system deflection can now be calculated by the following equation:

$$PE = G \cdot HM = - \frac{1}{\cos \theta} \frac{d\delta}{ds} HM \quad [\text{pounds}] \text{ (N)} \quad (\text{Eq. 10})$$

or

$$PE = G \cdot HM = - \frac{1}{\cos \theta^\circ} \frac{1}{57.3} \frac{d\delta^\circ}{ds} HM \quad [\text{pounds}] \text{ (N)} \quad (\text{Eq. 11})$$

Using the hinge moment coefficient, C_h , the surface hinge moment can be expressed as follows:

$$HM = C_h q S c \quad [\text{ft-lbs}] \text{ (N}\cdot\text{m)} \quad (\text{Eq. 12})$$

where:

C_h = hinge moment coefficient [-]

q = dynamic pressure ($=1/2 \rho V^2$) [lbs/ft²] (Pa)

S = control surface area aft of hinge line [ft²] (m²)

c = control surface mean aerodynamic chord (MAC) aft of hinge line [ft] (m)

The gearing ratio and the hinge moment are determined so that the pilot obtains proper feel of the airplane control, and the required pilot strength will not exceed the values specified in 14 CFR/CS 23.143(c), 25.143(c), or MIL-F-8785 (see Table 2). When the control force characteristics are not acceptable, either the gearing ratio or the hinge moment, or both, need to be modified.

The possible magnitude of the gearing ratio, however, is restricted to a certain range, as the parameters of the gearing ratio have similar values for most airplanes for aerodynamic and ergonomic reasons. The maximum control surface travel normally ranges between 10 and 35 degrees to maintain its control effectiveness. The range of the cockpit control deflection will be much the same for any airplane as it is designed considering human factors (see 4.2.1). Typical values of the gearing ratio for each control system are:

- Elevator Control System: 0.6 - 1.6 [1/ft] (1.97 - 5.25 [1/m])
- Aileron Control System (with Wheel): 0.2 - 1.2 [1/ft] (0.66 - 3.94 [1/m])
- Rudder Control System: 1.2 - 2.6 [1/ft] (3.94 - 8.53 [1/m])

With the adjustability of the gearing ratio limited to a relatively narrow range, the aerodynamic design of the control surface should be carefully conducted to achieve the desired hinge moment characteristics, which, along with the gearing ratio, provides an adequate pilot control feel. The design parameters of the control surface that affect the hinge moment characteristics include:

- Geared tab (or geared function on trim tab),
- Surface leading edge shape and gap,
- Surface trailing edge cross section angle, and
- Aerodynamic balance (overhang, horn, etc.).