WIEFP 2014

A review of aircraft antiskid system and hydraulics application for brake system

Mário Maia Neto, M.Eng.
Luiz Carlos Sandoval Góes, PhD.

Aeronautical Institute of Technology (ITA)
Department of Mechanical Engineering
São José dos Campos, Brazil

Agenda

- Aircraft brake systems
- Hydraulics for brake system operation
- Review of antiskid systems
- Main antiskid system requirements
- Hydraulic dynamics-related issues
- Modeling and simulation
- Conclusions
- References

Agenda

- **Aircraft brake systems**
- Hydraulics for brake system operation
- Review of antiskid systems
- Main antiskid system requirements
- Hydraulic dynamics-related issues
- Modeling and simulation
- Conclusions
- References

Aircraft Brake Systems

- Aircraft brake system functions:
  - Stop the aircraft during landing or rejected take-off runs;
  - Allow aircraft ground maneuvers during taxiing;
  - Park the aircraft;
  - Halt the wheels rotation during landing gear retraction.

- Brake system types:
  - Drum-and-Shoe Brakes:
    - Early brakes, similar to automobile ones.
    - Drum-and-shoe types:
      - Metal shoe with a riveted lining of asbestos composition.
      - Cast iron drum.
    - Brake actuation:
      - Mechanical actuation (cables, coil springs).
      - Hydrostatic pressure (master cylinders).
    - A/C Examples: Piper Cub, Boeing B-29, etc.

Aircraft Brake Systems

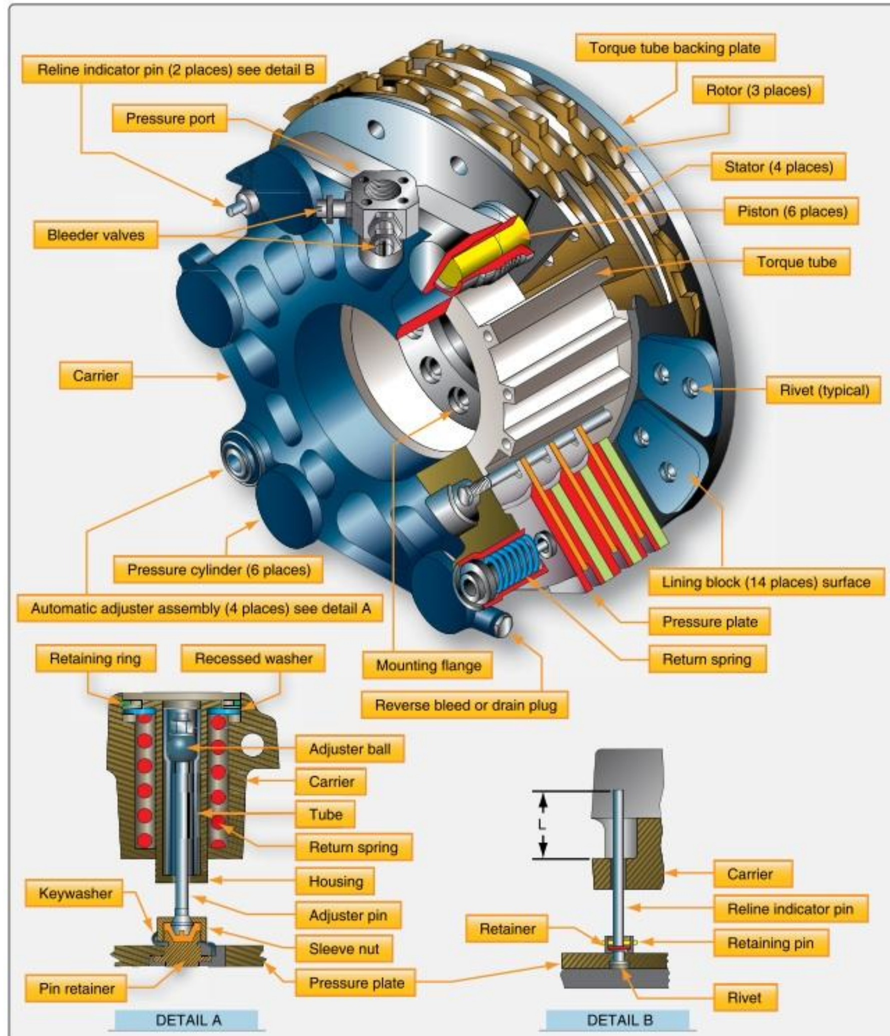
- Brake system types:
  - Disk-Types Brakes
    - Higher thermal energy dissipation capacity.
    - Single-disk brakes:
      - Small aircraft.
      - A/C Examples: EMB-312, etc.
    - Multiple-disk brakes
      - Large aircraft.
      - A/C Examples: EMB-170, Boeing 747, etc.
    - Disk materials
      - Steel, berilium, carbon composite.
    - Brake actuation:
      - Hydraulic system pressure.
      - Pilot input by means of brake pedals.
      - Pressure modulation through proportional valves (hydraulically or electrically operated).

Photo: www.faa.gov

Photo: www.boeing.com

Aircraft Brake Systems

- Brake system types:
  - <u>Disk-Types Brakes</u>
    - Boeing 737 brake assembly.



Source: [UNITED STATES, 2012b]

Aircraft Brake Systems

- Brake system types:
  - Electric Brakes
    - Current studies and inovative applications.
    - Brake actuation and control:
      - Digital electronics.
      - Electromechanical actuators.
    - Claimed advantages:
      - Absence of hydraulic leakages (maintenance gains).
      - Good reliability.
      - Data record and monitoring facilities.
    - A/C Examples: RQ-4B Global Hawk, Boeing 787 Dreamliner, etc.

Photo: www.utcaerospacesystems.com

Agenda

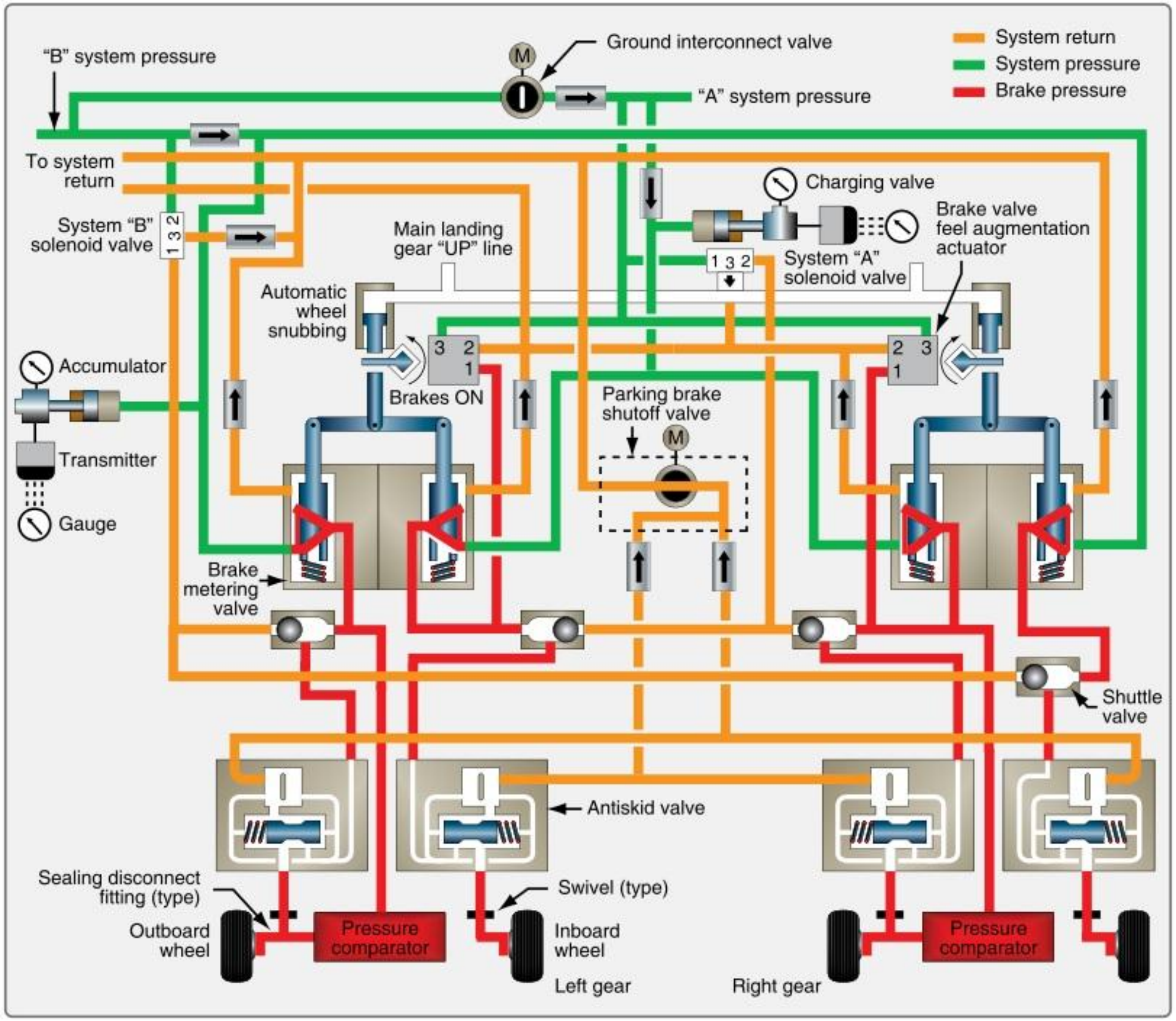
- Aircraft brake systems
- **Hydraulics for brake system operation**
- Review of antiskid systems
- Main antiskid system requirements
- Hydraulic dynamics-related issues
- Modeling and simulation
- Conclusions
- References

Hydraulics for Brake System Operation

- Characteristics:
  - Introduction on aircraft in the early 1930s.
  - Most currently applied throughout the world.
- Hydraulic power advantages:
  - High power-to-weight ratio;
  - Relatively low initial costs;
  - Acceptable maintenance costs;
  - Flexibility of installation;
  - Good reliability;
  - Self-lubrication.
- Main components found:
  - Tubing, hoses, fittings.
  - Hydraulic accumulators.
  - Several types of valves: proportional, check, shuttle, restrictor, shutoff, etc.
  - Master cylinders.

Hydraulics for Brake System Operation

Boeing 737 brake system



Source: [UNITED STATES, 2012b]

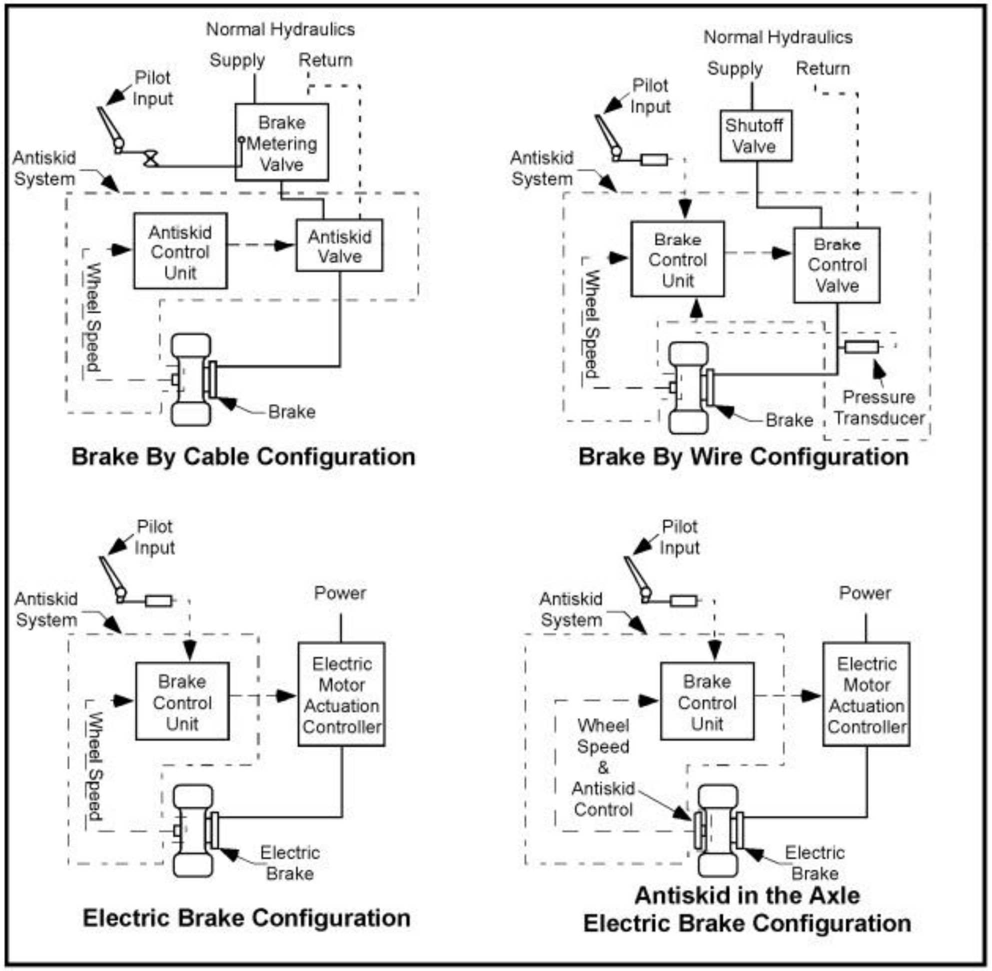
Agenda

- Aircraft brake systems
- Hydraulics for brake system operation
- **Review of antiskid systems**
- Main antiskid system requirements
- Hydraulic dynamics-related issues
- Modeling and simulation
- Conclusions
- References

Review of Antiskid Systems

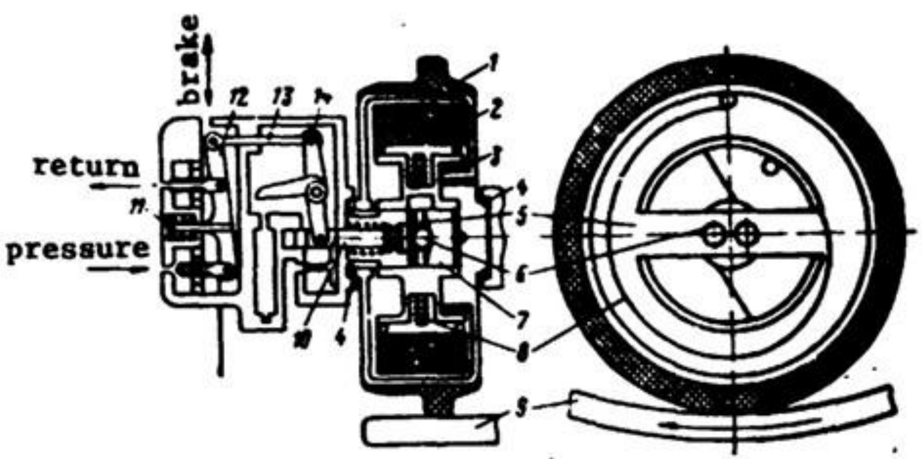
- Antiskid system schematics:

Source: [SOCIETY OF AUTOMOTIVE ENGINEERS, 2012]

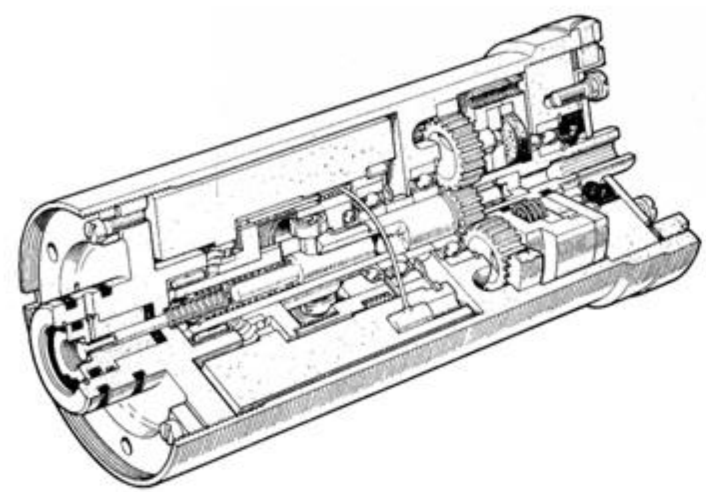


Review of Antiskid Systems

- Early systems:
  - Remote actuation
    - Electrical or electroinertial controller.
    - Hydro-Aire Mark I (1948): mechanical device or relay-operated solenoid valve.
  - Direct actuation
    - Sensor and valve: unique component on brake assembly.
    - Dunlop Maxaret.



Source: [ZVEREV; KOKONIN, 1975]



Source: [MOIR; SEABRIDGE, 2001]

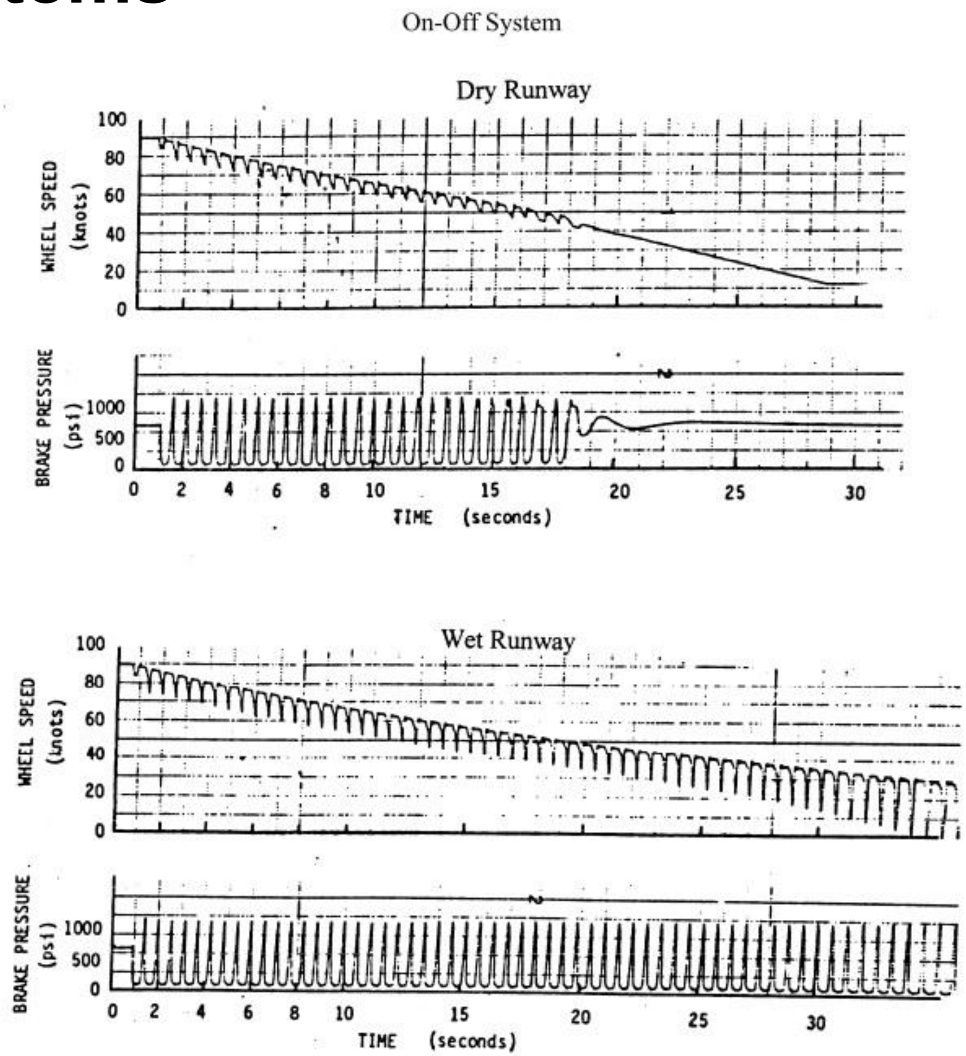
Review of Antiskid Systems

- Eletronics development (20th century):
  - Segregation between controller and sensors:
    - Electronic controller: input circuit and power amplifier.
    - Tachogenerators: DC or AC generator (AC/DC converter).
  - More complex control algorithm:
    - Hydro-Aire Mark II (1958).
    - Hydro-Aire Mark III (1967).
    - Goodyear Adaptive Brake Control System.

- Digital systems:
  - Microprocessor-based system:
    - Control over a broader range of aircraft performance.
  - Improved control algorithm:
    - Hydro-Aire Mark IV and V.

Review of Antiskid Systems

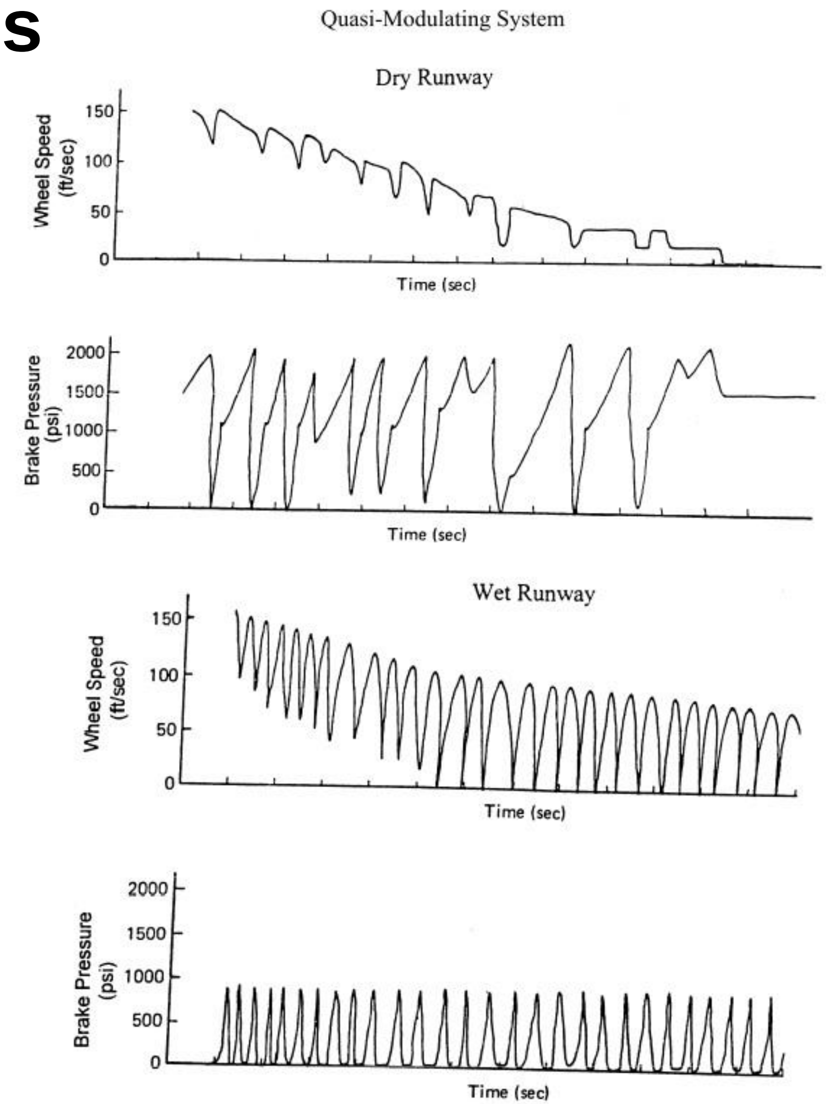
- Antiskid system types:
  - ON-OFF (Open-closed) Systems:
    - Incipient locked-wheel condition: brake pressure release.
    - Spin-up to synchronous speed: brake pressure reapplication.
    - Significant brake pressure oscillation and slow time response.
    - A/C example: B-52.



Source: [UNITED STATES, 2012a]

Review of Antiskid Systems

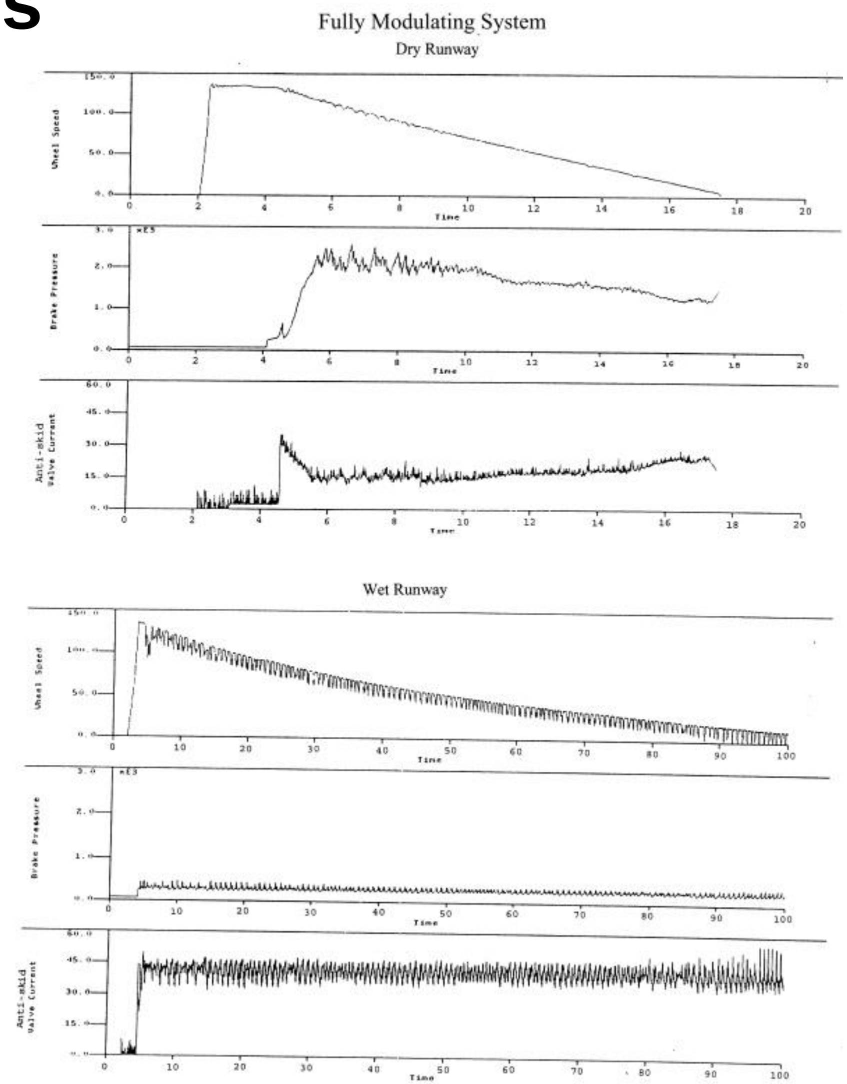
- Antiskid system types:
  - Modulating (Quasi-Modulating) Systems:
    - Pre-programmed sequence.
    - Incipient locked-wheel condition: brake pressure release.
    - Brake pressure held off according to skid depth.
    - Brake pressure reapplied to a lower level and ramped up until a new skid starts: Pressure Bias Modulation (PBM).
    - Efficient on dry runways.
    - A/C example: Convair 990.



Source: [UNITED STATES, 2012a]

Review of Antiskid Systems

- Antiskid system types:
  - Adaptive (Fully-Modulating) Systems:
    - Advanced control logic: high frequency wheel speed transducers, multiple data control functions and nonlinear computing elements.
    - Based on wheel-speed time history.
    - Control over the optimum braking: slip ratio.
    - Efficient on dry and wet runways.
    - A/C examples: DC9-30, Boeing 747, B757 and B767.



Source: [UNITED STATES, 2012a]

Review of Antiskid Systems

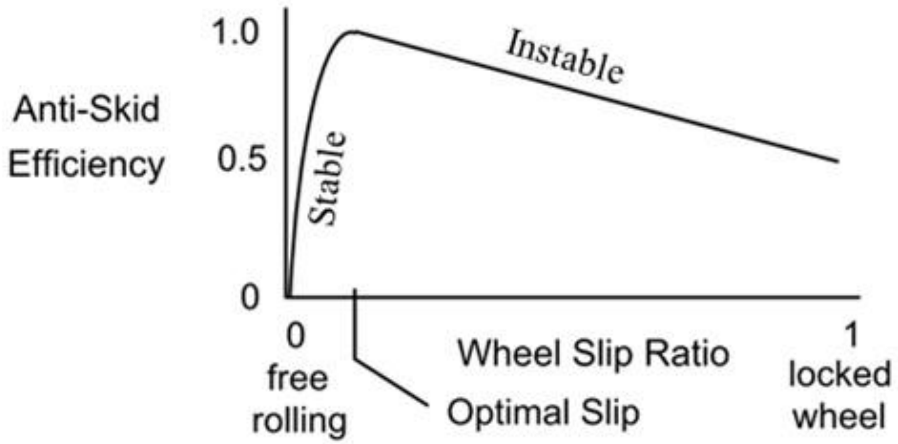
- Antiskid system functionalities:
  - Basic function:
    - Prevent a locked-wheel condition and optimize braking performance (“ABS”).
    - Control criterion:
      - Deceleration rate / Slip velocity / Slip ratio.
  - Additional functions:
    - Touchdown Protection:
      - Prevent brake application during touchdown at wheels spin-up;
      - Tires subjected to a high load / acceleration condition.
    - Locked-Wheel Protection:
      - Compare the deceleration of paired-wheels or combination of wheels;
      - Avoid inadvertent yaw moments due to assymetrical braking.
    - Hydroplaning Protection:
      - Hydroplaning condition;
      - Release brake pressure in the wheel whose speed is inferior to a percentage of aircraft speed.
    - Drop-out Function:
      - System becomes inative below a threshold value (10 kt to 20 kt);
      - Allow ground taxiing maneuvers.
    - BIT (Built-in Test) Function:
      - System monitoring circuit;
      - Identify electrical failures.

Agenda

- Aircraft brake systems
- Hydraulics for brake system operation
- Review of antiskid systems
- **Main antiskid system requirements**
- Hydraulic dynamics-related issues
- Modeling and simulation
- Conclusions
- References

Main Antiskid System Requirements

- System performance:
  - Stop the aircraft within the required runway length;
  - Operation on dry and wet runways;
  - Good efficiency for all hydraulic system operational conditions.



Source: [Adapted from UNITED STATES, 2012a]

- Comfort:
  - Smooth braking.

Main Antiskid System Requirements

- Tire wear:
  - Avoid uneven tire wear;
  - Prevent a locked-wheel condition and tire blow-out.

Heavy Braking Skid

Source: [GOODYEAR, 2011]

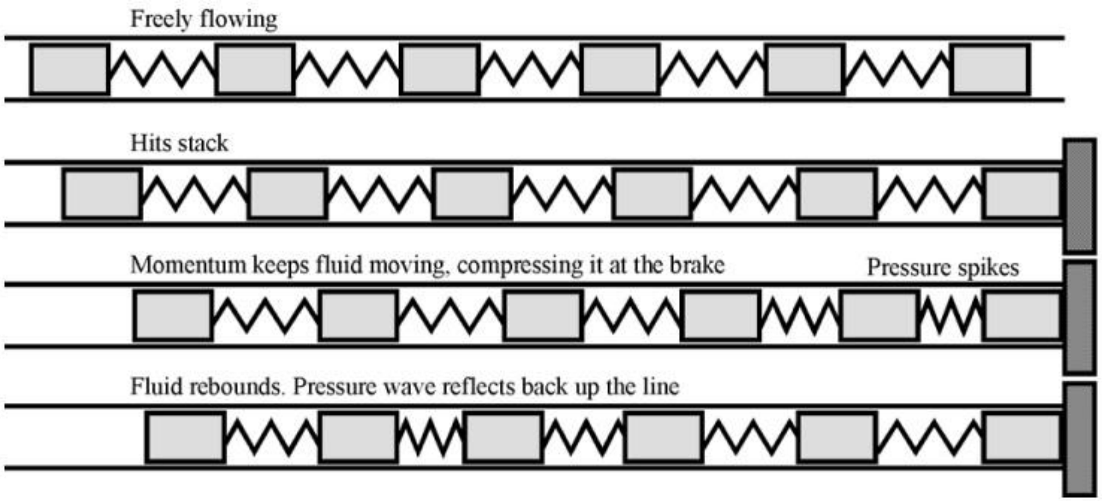
- Safety Assessment:
  - Reliability, adequate installation and robust design.
- Landing gear interaction:
  - Do not result in landing gear instabilities.

Agenda

- Aircraft brake systems
- Hydraulics for brake system operation
- Review of antiskid systems
- Main antiskid system requirements
- **Hydraulic dynamics-related issues**
- Modeling and simulation
- Conclusions
- References

Hydraulic Dynamics-Related Issues

- Hydraulic installation layout:
  - High tubing length:
    - Pressure drop, fluid inertance and fluid compliance:
      - Influence on system frequency and time response;
      - Impacts on antiskid efficiency.
    - Water hammer effect:
      - Pressure surge (deep skid);
      - Loss of antiskid efficiency or asymmetric braking;
      - Delta pressure varies with temperature: control algorithm difficulties.



Source: [SOCIETY OF AUTOMOTIVE ENGINEERS, 2012]

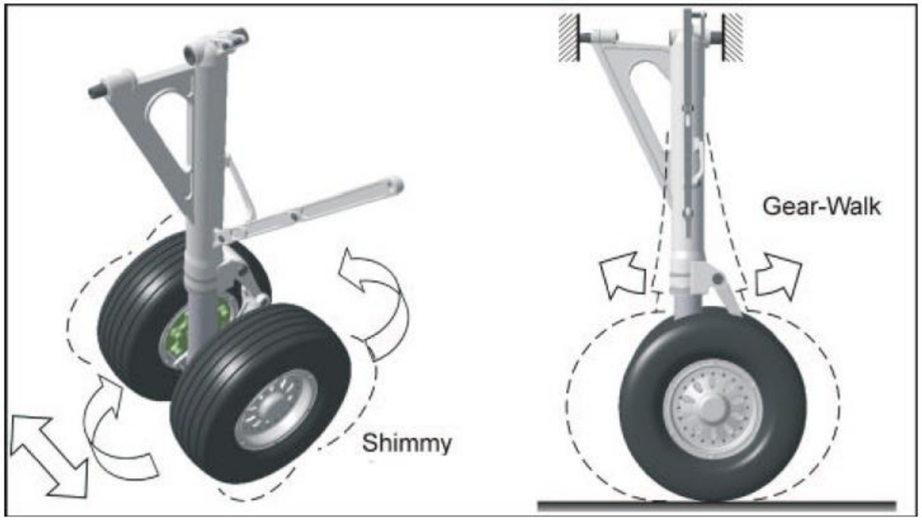
Hydraulic Dynamics-Related Issues

- Hydraulic installation components:
  - May reduce antiskid system efficiency:
    - Flexible lines and hoses;
    - Tubing with too small or too large diameter;
    - Components with high pressure drop: valves, swivel fittings, etc.
    - Line entrapped air;
    - Inadequate hydraulic system return line design.

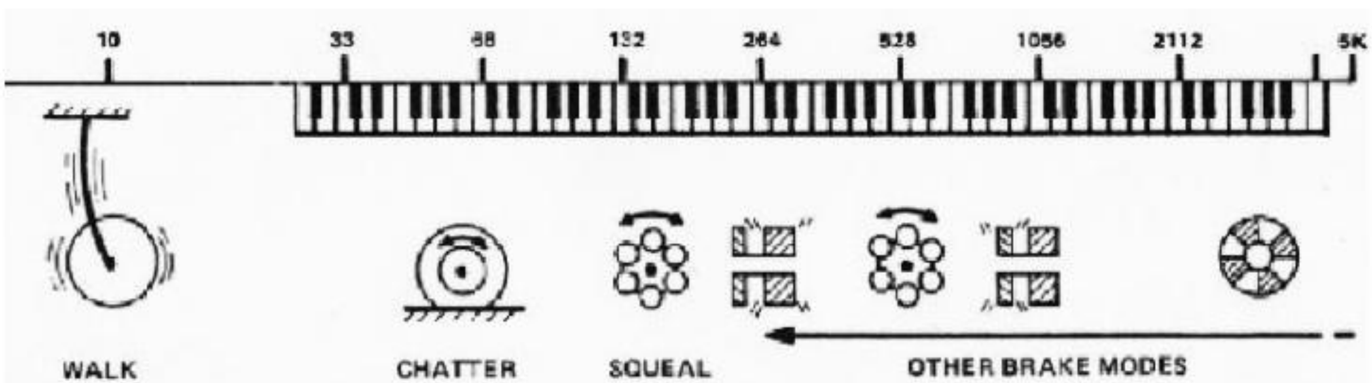
- Landing gear instabilities:
  - Hydro-Aire Mark I / II: not a concern (f = 3.5 Hz);
  - From Hydro-Aire Mark III on: a significant concern (f > 50 Hz);
  - Brake system hydraulic dynamics influence;
  - Main phenomena: shimmy, gear walk, brake squeal, brake chatter.

Hydraulic Dynamics-Related Issues

- Landing gear instabilities:



Source: [LERNBEISS, 2003 apud KHAPANE, 2008]



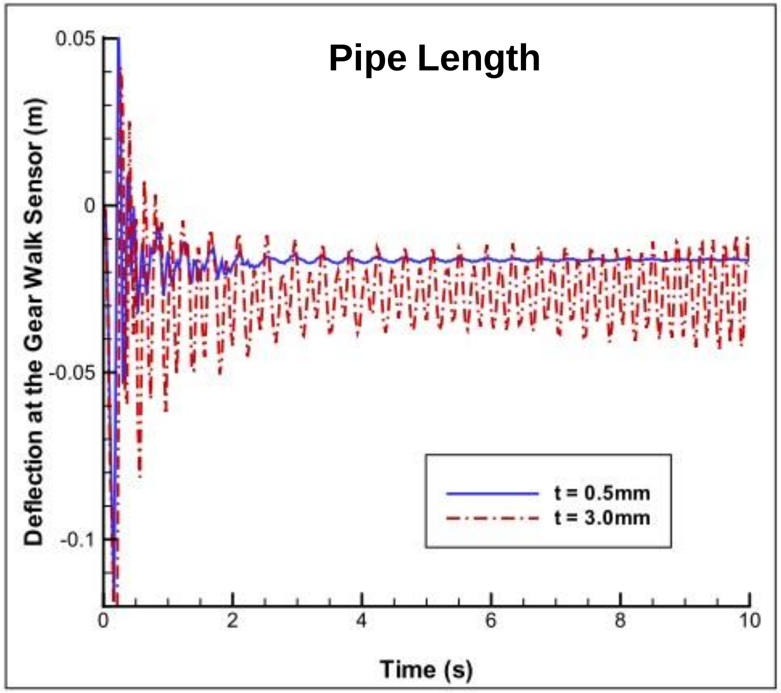
Source: [ENRIGHT, 1985 apud KHAPANE, 2008]

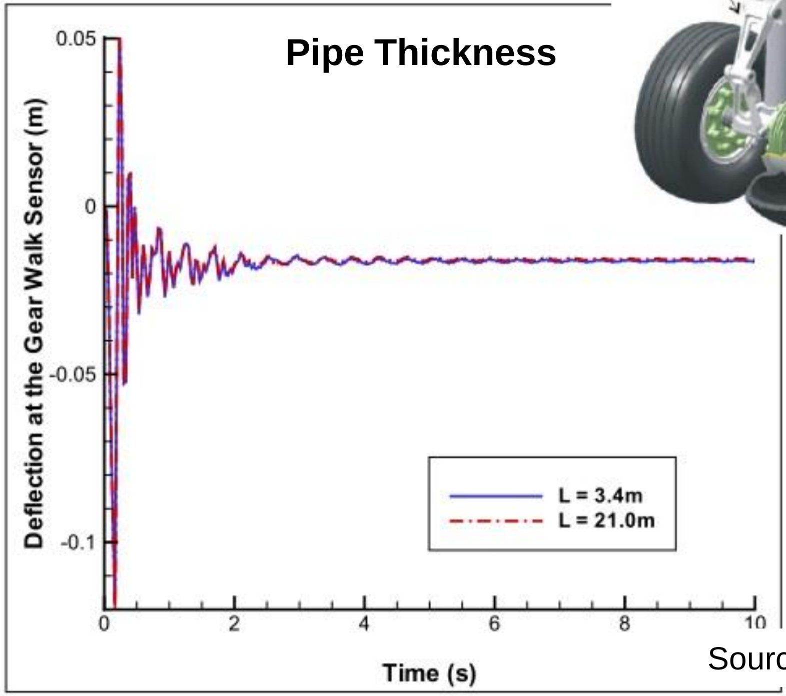
Hydraulic Dynamics-Related Issues

- Landing gear instabilities:
  - Case Study (KHAPANE, 2008):
    - Two-mass model of a flexible landing gear;
    - Hydraulic line parameters considered: pipe length and thickness;
    - Effect evaluated: gear walking.

Landing gear type:

Source: [KHAPANE, 2008]





Source: [KHAPANE, 2008]

Agenda

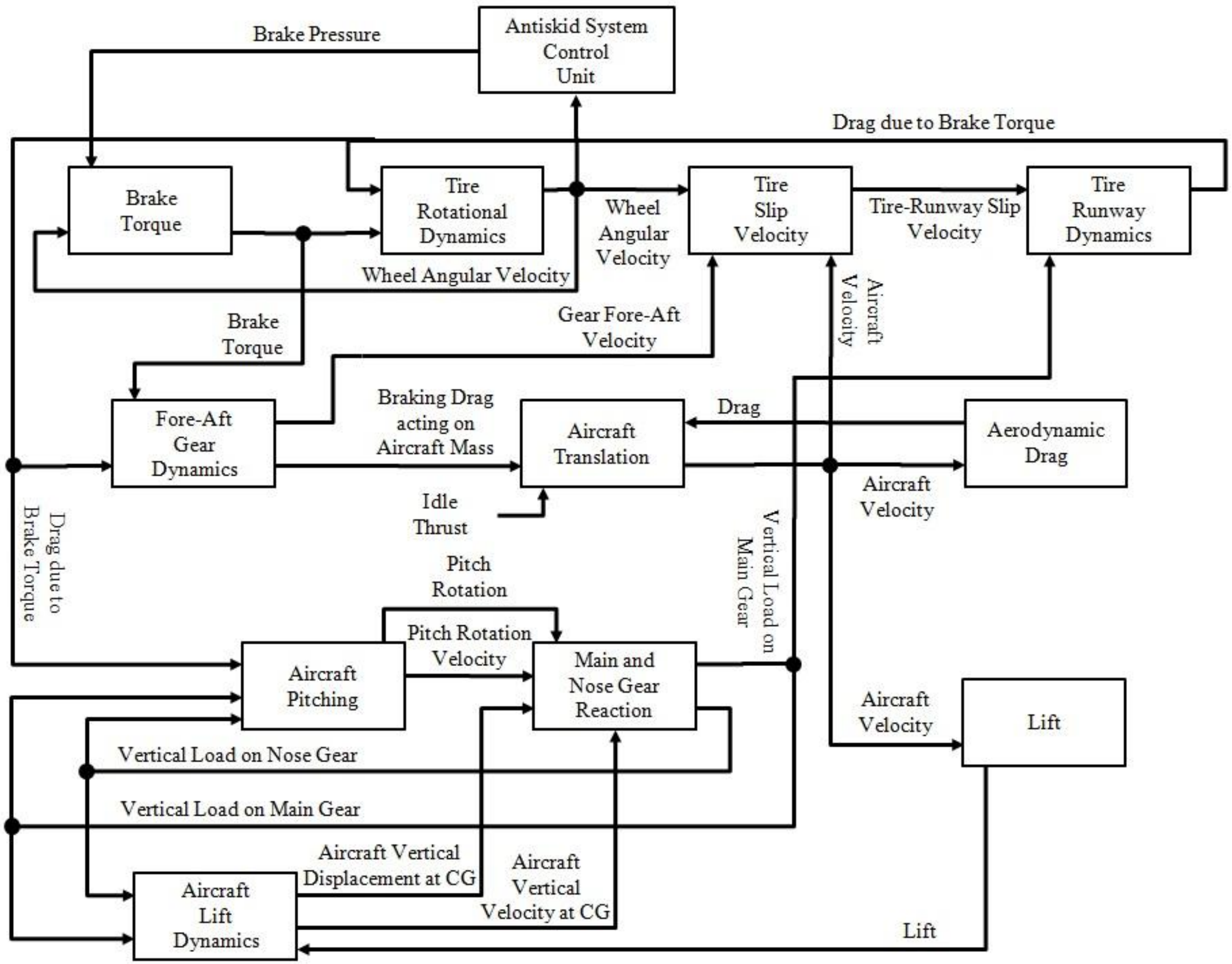
- Aircraft brake systems
- Hydraulics for brake system operation
- Review of antiskid systems
- Main antiskid system requirements
- Hydraulic dynamics-related issues
- **Modeling and simulation**
- Conclusions
- References

Modeling and Simulation

- System Model:
  - “Executable specification” (ANTHONY; FRIEDMAN, 2014).
- Industry application:
  - Early systems: cut-and-try methods with extensive test campaign;
  - Modulated systems: introduction of system simulation (system interface).
- Current Practices:
  - System tuning:
    - Use of simulation to adjust system controller gains;
    - Optimize system performance throughout operational envelope.
  - Failure simulation:
    - Simulation of critical conditions and/or component failures.
  - Simulation types:
    - “Pure” simulation;
    - “Hardware in the loop”: rig (mock-up).

Modeling and Simulation

- Complete Block Diagram:



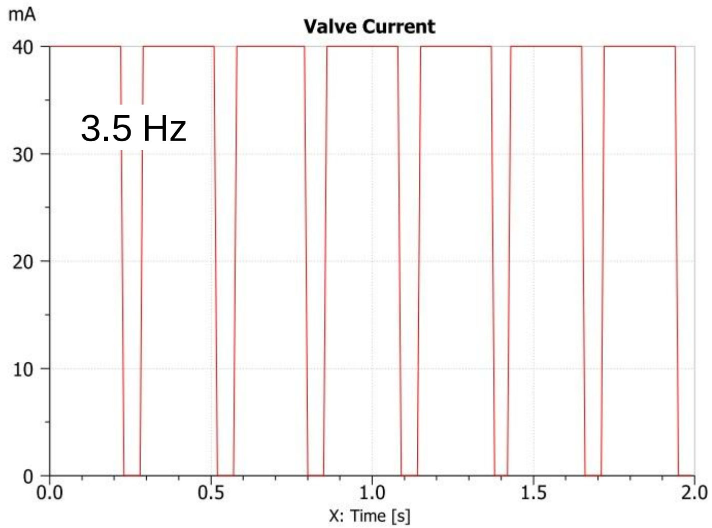
Source: [Adapted from SOCIETY OF AUTOMOTIVE ENGINEERS, 2008]

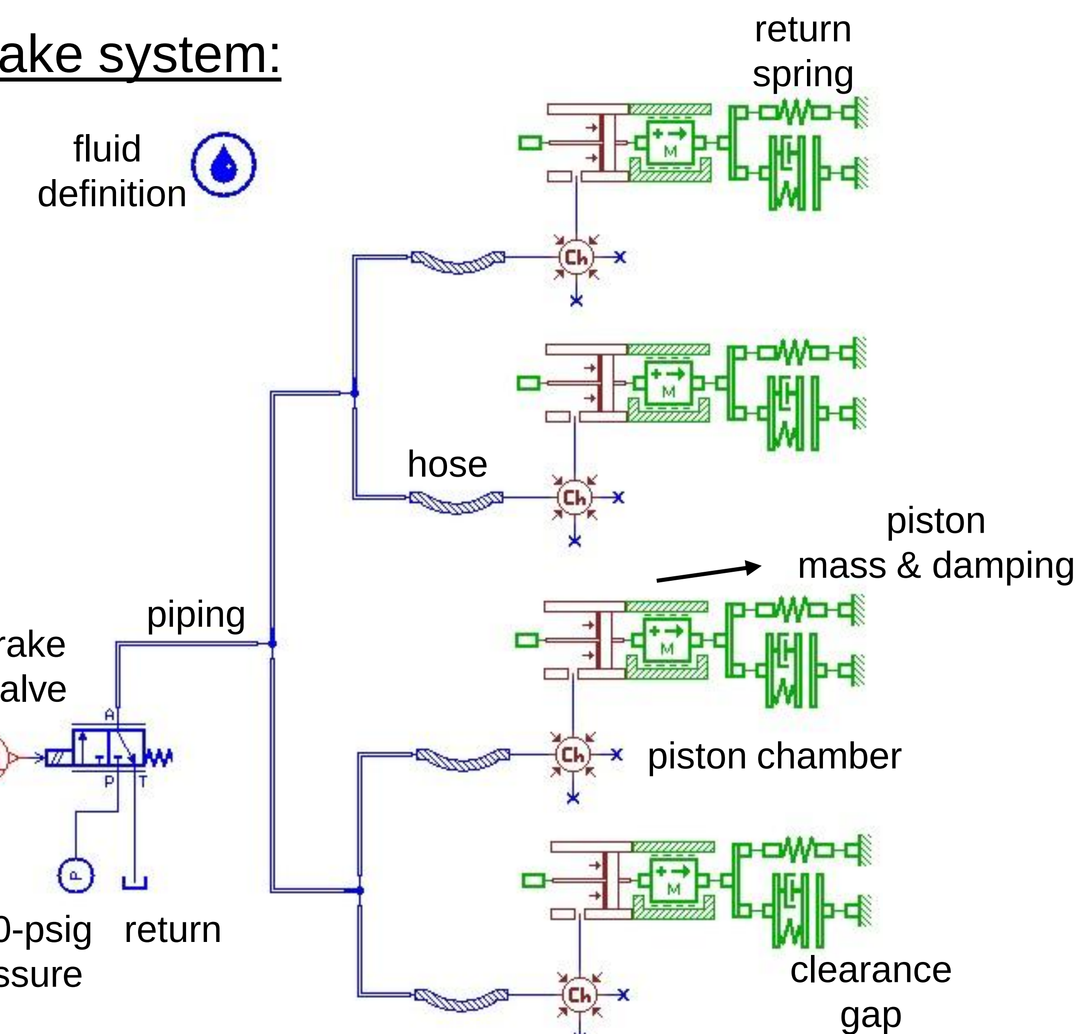
Modeling and Simulation

- Example of a simplified brake system:
  - Impacts of hydraulic system geometry on system response.
    - Software: LMS® Imagine.Lab AMESim
    - Brake assembly: 4 piston multiple-disk type.
    - Pipe model: HLG0020D (hydraulic line CFD 1D Lax-Wendroff):
      - Continuous model;
      - Rigid tube;
      - 1D Navier-Stokes equations;
      - Developed to compute wave effects with a high level of accuracy.
    - Hose model: HH04R (simple wave equation hydraulic pipe/hose: C-IR):
      - Lumped model;
      - Compressibility, friction and fluid inertia are considered;
      - Effective bulk modulus: fluid compressibility and hose wall flexibility.
    - Valve Actuation: Square wave.
      - Frequency: 3.5 Hz;
      - Pulse ratio: 80% (1 cycle: 80% operated, 20% no signal);
      - Simulates an "on-off" antiskid system.

Modeling and Simulation

- <u>Example of a simplified brake system:</u>

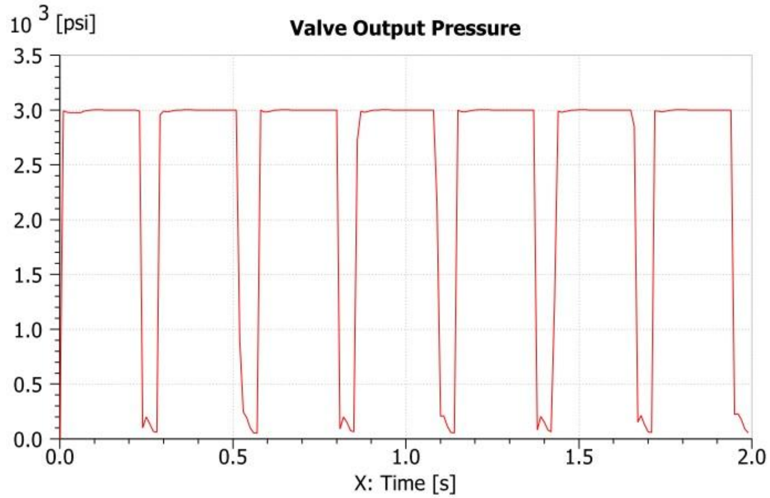


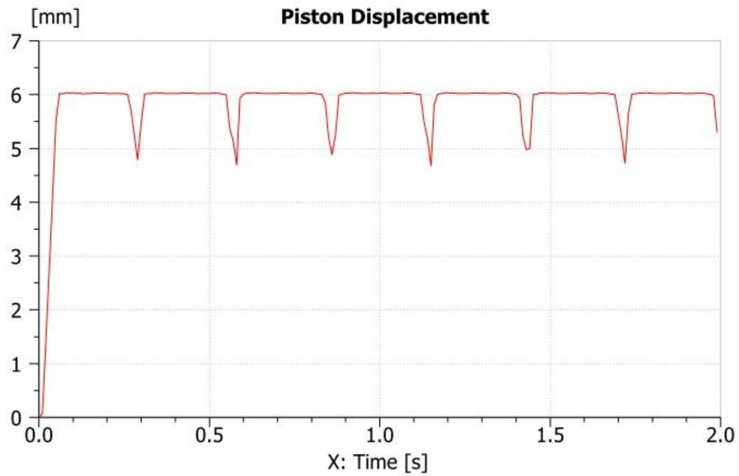


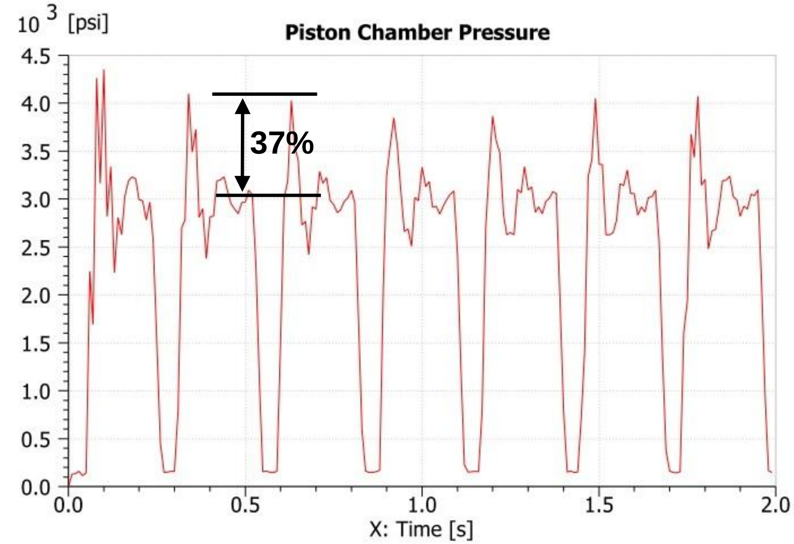
AMESim Model

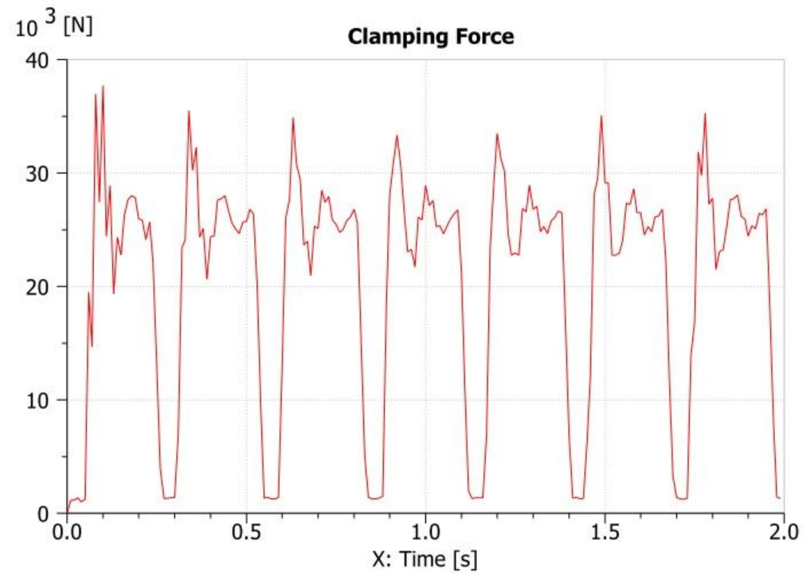
Modeling and Simulation

- Nominal conditions.



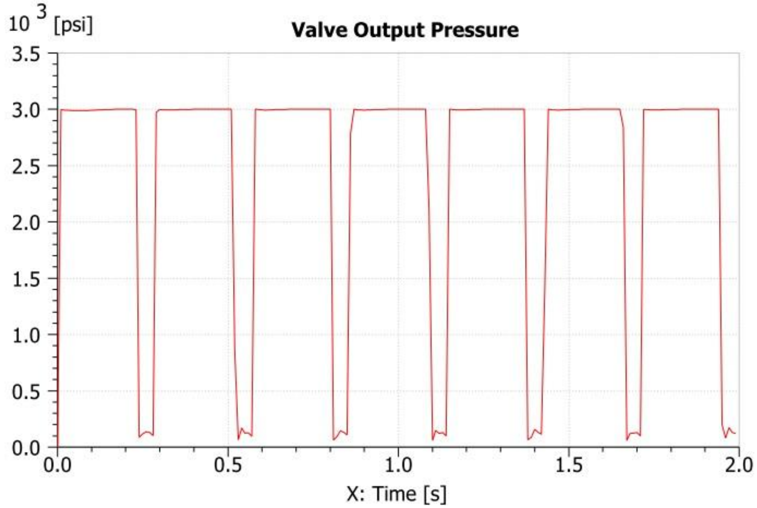


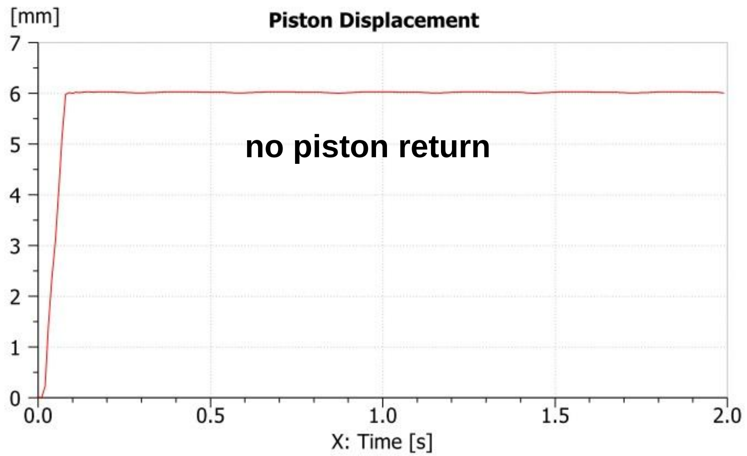


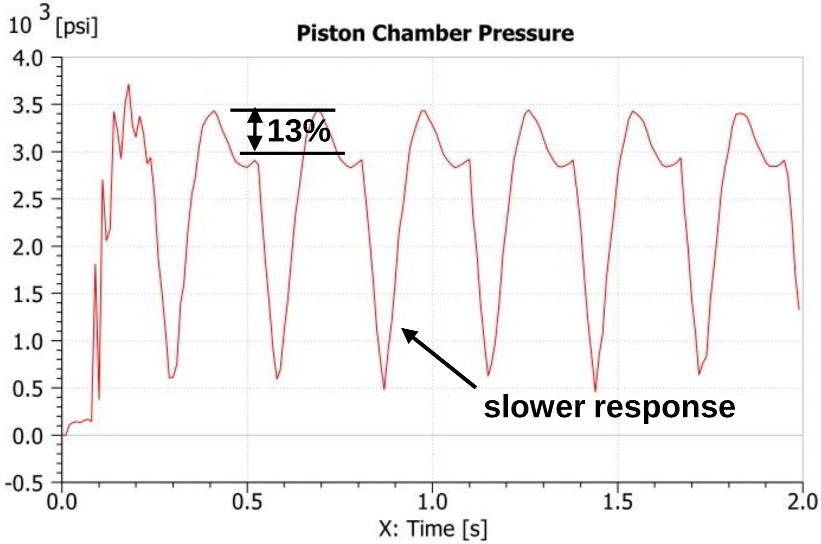


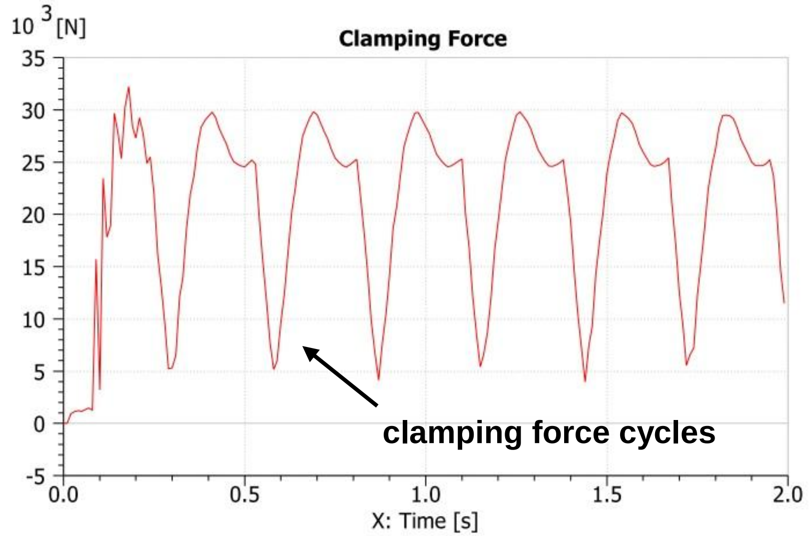
Modeling and Simulation

- Tubes/Hoses: 100% increased length.



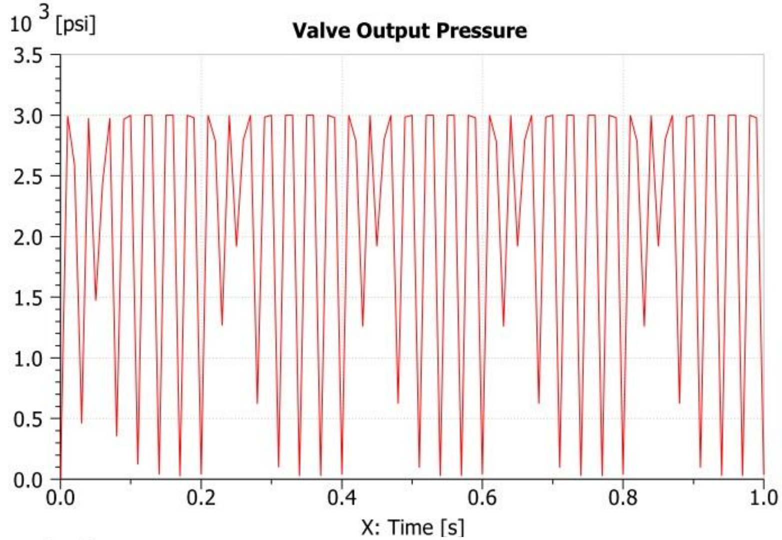


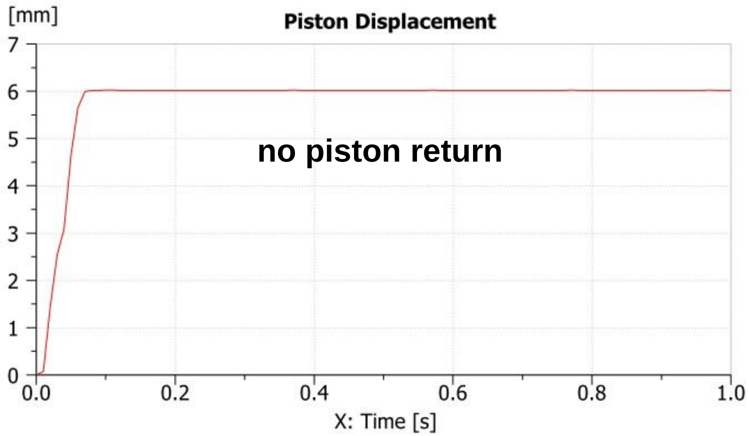


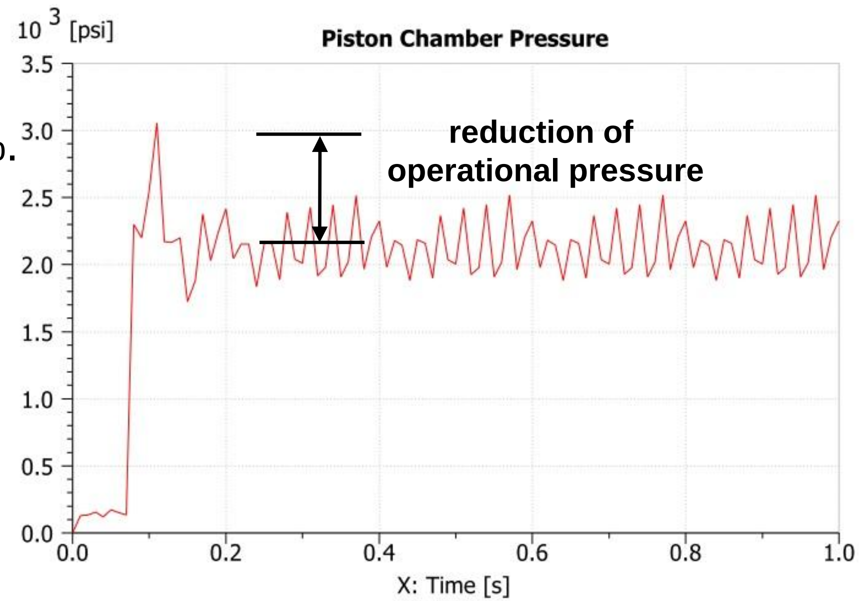


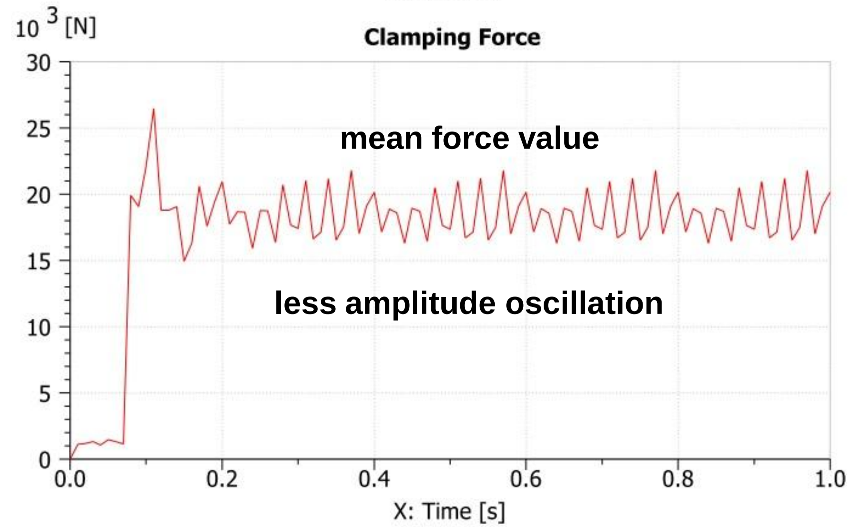
Modeling and Simulation

- Nominal dimensions, 35 Hz, pulse ratio = 60 %.



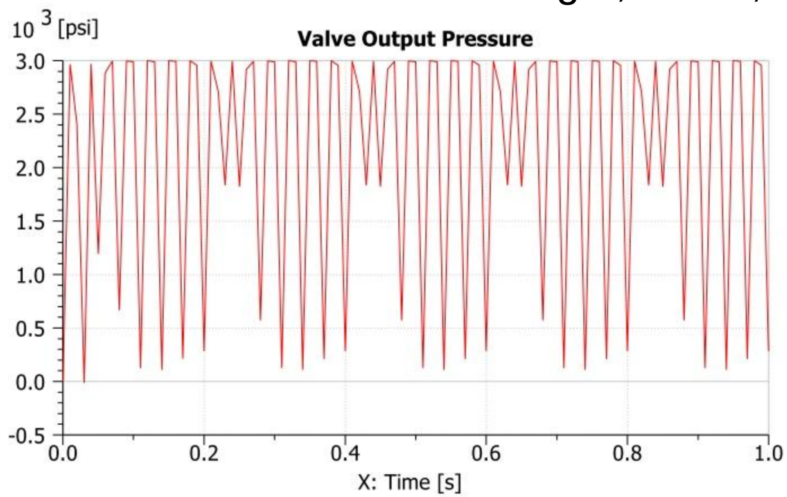


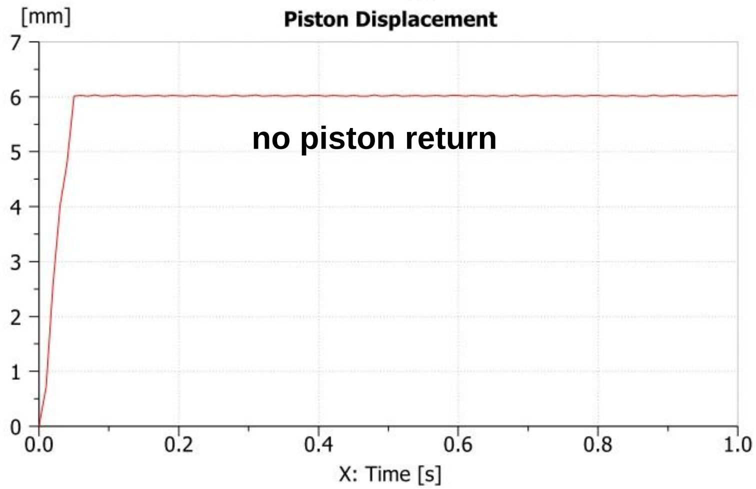


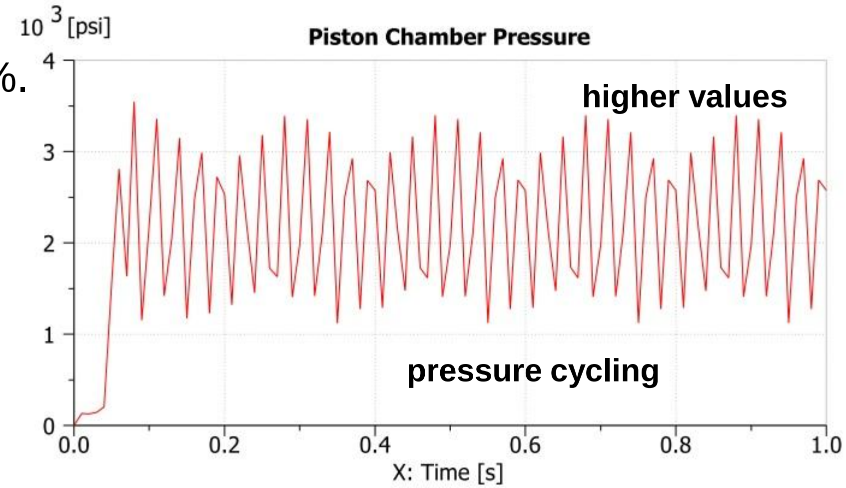


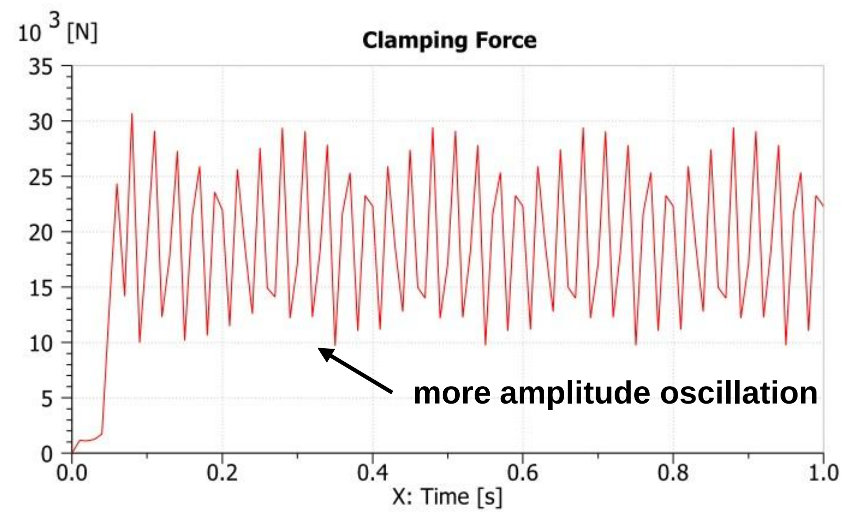
Modeling and Simulation

- Tubes/Hoses: 50% reduced length, 35 Hz, 60 %.









Agenda

- Aircraft brake systems
- Hydraulics for brake system operation
- Review of antiskid systems
- Main antiskid system requirements
- Hydraulic dynamics-related issues
- Modeling and simulation
- **Conclusions**
- References

Conclusions

- Hydraulic power for aircraft brake systems:
  - Most currently applied throughout the world;
  - Considerable advantages.
- Antiskid system:
  - Significant development since early systems;
  - Several functionalities;
  - Important requirements: efficiency, safety, comfort, tire wear, landing gear stability.
- Impacts of hydraulic dynamics on antiskid system:
  - May affect system response and its efficiency;
  - May result in landing gear instability problems.
- System modeling and simulation:
  - Powerful tool for antiskid system design, tuning and sensibility analysis;
  - An example of the impacts of hydraulic system geometry on system response has been provided: shows the importance of system optimization.

Agenda

- Aircraft brake systems
- Hydraulics for brake system operation
- Review of antiskid systems
- Main antiskid system requirements
- Hydraulic dynamics-related issues
- Modeling and simulation
- Conclusions
- **References**

References

- ANTHONY, Mike; FRIEDMAN, Jon. **Model-Based Design for Large Safety-Critical Systems**: A Discussion Regarding Model Architecture. Natick: The MathWorks, Inc. Available at: <http://www.mathworks.com/ tagteam/49608_MBD_ModelArchitecture.pdf>. Access in January, 2014.
- COOK, Harold; FIELDS, Elbert. MARK II Anti-Skid for Hercules Aircraft: a reliable system that stops a skid before it starts. **Service News**, Marietta, v. 8, n. 1, p. 3-12, January/March 1981.
- CRANE, Dale. **Aircraft Wheels, Brakes, and Antiskid Systems**. Order No. EA-AWB. Basin: Aviation Maintenance Publishers, Inc., 1979. 61 p. (An Aviation Maintenance Publishers, Inc. Training Manual).
- CURREY, Norman S. **Aircraft Landing Gear Design**: Principles and Practices. Washington, DC: AIAA Education Series, 1988. 373 p.
- DANIELSON, Leibert. Electric braking debuts in military and commercial applications**. Aerospace Engineering**, Warrendale, p. 42, Sept. 2005.
- ENRIGHT, John. Laboratory Simulation of Landing Gear Pitch-Plane Dynamics. **SAE – Aircraft Landing Gear Systems, PT-37-851937**, 1985. ISBN 1-56091-074-7.
- GOODYEAR. **Aircraft Tire Care & Maintenance**. Akron, 2011. Available at: <http://www.goodyearaviation. com/resources/tirecare.html>.
- HIRZEL, E. A. Antiskid and Modern Aircraft. In: NATIONAL AEROSPACE ENGINEERING AND MANUFACTURING MEETING, 1972, San Diego. **SAE Technical Paper 720868**. New York: Society of Automotive Engineers Inc., 1972. 8 p.
- KHAPANE, Prashant. **Simulation of Landing Gear Dynamics and Brake-Gear Interaction**. 2008. 108f. Thesis (Doctor of Engineering) – Technischen Universität Carolo-Wilhelmina zu Braunschweig, Braunschweig.
- LERNBEISS, R. **Simulation eines Flugzeugfahrwerks bei Elasticher Betrachtung des Federbeines**. Dipl. Arb., 2003.
- LMS Imagine. **Imagine.Lab AMESim Training – HYD2**: Design of Hydraulic System and Components, 2012.

References

- LMS Imagine. **Imagine.Lab AMESim Help**, 2014.
- MOIR, Ian; SEABRIDGE, Allan. **Aircraft Systems**: Mechanical, electrical, and avionics subsystems integration. 2. ed. Bury St Edmunds: Professional Engineering Publishing, 2001. p. 91-124.
- SOCIETY OF AUTOMOTIVE ENGINEERS. SAE Aerospace. **AIR1739B**: Information on Antiskid Systems. Warrendale, 2012. 56 p.
- SOCIETY OF AUTOMOTIVE ENGINEERS. SAE Aerospace. **ARP1070C**: Design and Testing of Antiskid Brake Control Systems for Total Aircraft Compatibility. Warrendale, 2008. 43 p.
- UNITED STATES. Department of the Air Force. **MIL-B-8075D**: Brake Control Systems, Antiskid, Aircraft Wheels, General Specification for. Ogden, 1971. 25 p.
- UNITED STATES. Department of the Navy. **MIL-B-8584C**: Brake Systems, Wheel, Aircraft, Design of. Lakehurst, 1970. 13 p.
- UNITED STATES. Federal Aviation Administration. Advisory Circular. **AC 25-7C**: Flight Test Guide for Certification of Transport Category Airplanes, Washington, DC, 2012a. p. 32-58.
- UNITED STATES. Federal Aviation Administration. **Aviation Maintenance Technician Handbook – Airframe**. Washington, DC, Vol. II, 2012b. p. 1-96 (chapter 13).
- UNITED STATES. Federal Aviation Administration. Federal Aviation Regulations. **14 CFR Part 25 - Airworthiness Standards: Transport Category Airplanes**. Washington, DC, (e-CFR), 2013a. Available at: <http://www.faa.gov>.
- ZVEREV, I. I.; KOKONIN, S. S. **Design of aircraft wheels and brake systems**. Washington, DC: National Aeronautics and Space Administration, 1975. 253 p. (NASA TT F-15764).

Thank You!

contact: mario.maia.neto@gmail.com