ISSN 0509-6669

TRANSACTIONS
OF THE INSTITUTE OF AVIATION

Scientific Quarterly
2 / 2005 (181)

STATE OF THE ART IN LANDING GEAR SHOCK ABSORBERS

Zbigniew WOLEJSZA
Wojciech KOWALSKI
Institute of Aviation, Warsaw
Arnaud LAFITTE
Messier Dowty SA, Vélizy
Grzegorz MIKULOWSKI
Institute of Fundamental Technological Research, Warsaw
Lars REMMERS
EADS Deutschland GmbH, Munich

Edition is sponsored by State Comittee for Scientific Research

Summary

This report describes the state of the art in landing gear design with a particular focus on shock absorbers. It gives an overview on the general design solutions and installation of landing gears into the airframe. An emphasis is placed on the function and calculation of loads acting on oleopneumatic shock absorbers, which are the main type of shock absorber considered within ADLAND. One part of this document covers the requirements which are the basis of the shock absorber design, materials used and related future developments within aerospace industry. A brief summary is given on research performed on active shock absorbers so far.

Project EU ADLAND No. IST-FP&-2002-Aero 1-502793-STREP

Publisher**:** Institute of Aviation
Scientific Publications Group

Al. Krakowska 110/114, 02-256 Warszawa, phone (48 22) 846 00 11 ext. 442
Edition, revision and computer typesetting: Iwonna Olesińska, Tadeusz Korsak
Printers: ALKOR, 05-070 Sulejówek, Krucza 4

ISSN 0509-6669

CONTENTS

1. INTRODUCTION 5
  1.1. Functional Groups of Aircraft 5
    1.1.1. Commercial aircraft 5
    1.1.2. Light aircraft 6
    1.1.3. Military aircraft 6
  1.2. Landing Gears 7
    1.2.1. Commercial aircraft 7
    1.2.2. Light Aircraft 8
    1.2.3. Military Aircraft 8
  1.3. General Arrangement of Landing Gears 8
    1.3.1. Landing gear arrangement in commercial aircraft 8
    1.3.2. Landing gear arrangement in light aircraft 10
    1.3.3. Landing gear arrangement in military aircraft 10
  1.4. Landing geartypes 11

2. SHOCK ABSORBERS 14
  2.1. Air-Spring Function 21
  2.2. Air Spring Tuning 22
  2.3. Single-Stage Shock Absorber 23
  2.4. Double-Stage Shock Absorber 24
  2.5. Damping Function 25
  2.6. Materials 26

3. LOADS 28
  3.1. Overview 28
  3.2. Landing loads 28
  3.3. Ground loads 31
    3.3.1. Taxiing 31
    3.3.2. Braking 32
    3.3.3. Turning 32
    3.3.4. Pivoting 32
    3.3.5. Shimmy 32
  3.4. Calculation of Landing Gear Ground Loads 33
    3.4.1. Shock Absorbers Loads 37

4. ADDITIONAL REQUIREMENTS 38
  4.1. Introduction 38
    4.1.1. Environmental Requirements 38
    4.1.2. Other general requirements 41
    4.1.3. Additional Requirements for Military Aircraft 41
    4.1.4. Additional for Requirements for Commercial Aircraft 42

5. TRENDS WITHIN INDUSTRY 43

6. ACTIVELY CONTROLLED LANDING GEARS 43
  6.1. Introduction 43
  6.2. Variable Orifice Diameter 44
  6.3. Control of Differential Pressure in Internal Chambers of the Shock Absorber 44
  6.4. Control realization by introducing fluid accumulators 45
  6.5. Research at Messier Dowty 50

REFERENCES 53

1. INTRODUCTION

This document describes the ‘state of the art’ of aircraft landing gear design. Special emphasis is given to the design and application of Shock Absorbers.

The presented information is related to three functional groups of aircraft:

- large commercial,
- light & commuter,
- military.

Special requirements valid for the mentioned groups are also discussed within this document.

1.1. Functional Groups of Aircraft

1.1.1. Commercial aircraft

Large, turbine-powered aircraft with a higher weight than 5,700 kg are covered by FAA (Federal Aviation Administration) Transport Category Aircraft regulations, the FAR 25, and their European equivalents, the Certification Specification CS 25 issued by EASA (European Aviation Safety Agency). They are then applied to a wide range of airplanes from business jets to large passenger aircraft like Airbus A380. Their gross weights range from 18,000 kg for Falcon 50 to almost 550 metric tons for an Airbus A380.

Fig. 1. I-23 Executive airplane with piston engine and cantilever retractable landing gear – nose and main (take-off mass 1150 kg)

Fig. 2. Skytruck – commuter airplane with turbo engines and trailing arm type nonretractable landing gear (take-off mass 7500 kg)

Fig. 3. PZL-130 TC Orlik military primary trainer – airplane with turbo engine and telescopic nose landing gear and trailing arm main landing gear both retractable (take-off mass 2700 kg)

Fig. 4. Cessna CitationJet – commercial airplane with jet engines and telescopic retractable type landing gear (take-off mass 4717 kg)

1.1.2. Light aircraft

Light airplanes are designed according to regulations stated in documents FAR 23 & EASA CS part 23. The group of aircraft described as „light” covers airplanes with maximum take-off mass up to 5670 kg (12500 lb) and for the commuter category 8164 kg (18000 lb).

Minimum masses are in principle not characterized but 750 kg (1650 lb) is taken as a lower limit. In general aircraft from the group of light airplanes are in service as commuter or as general aviation planes; in civil and military applications (Fig. 1, 2, 3, 4).

1.1.3. Military aircraft

The group of Military Aircraft may be divided into two main classes according to the mission they are dedicated to:

- Combat Aircraft
  - Fighters / Bombers
  - Strategic Bombers
- Transport Aircraft.

The class of fighter / bomber aircraft consists of planes that have gross weights up to approximately 35 tons (Fig. 5÷6). The second class within the combat aircraft group, the strategic bombers, are for example represented by B1-B or B-52. (Fig. 7). Maximum Takeoff weight of these aircraft may rise to 220 tons. The last group of the military airplane are transport aircraft like C-5 Galaxy or A400M, which have take off weights up to 380 tons (Fig. 8).

Military aircraft are primarily designed to standards which are issued by national governmental agencies, e.g. the Ministries of Defense or the Forces themselves of the UK or US.

The mainly used baselines are

MIL STANDARDS (US-origin)
MIL SPECS (US-origin)
DEF STD (UK-origin)

Most MIL specifications and standards date back to the 1950’s and are becoming obsolete or withdrawn due to the cost and effort involved in updating them. Therefore the military industry is looking to replace them by using civil standards for design purposes where possible. MIL publications are more and more frequently replaced with FAR, CS and SAE standards.

The list below mentions the main documents, that lay down the general requirements (e.g. loads due to ground handling, maneuver loads, sink rate distribution, limit and ultimate load cases, etc.) to which military aircraft are currently designed. Derived from that general requirement s are the constrains which apply to Landing Gears in particular:

- *MIL-A-8870 Airplane Strength & Rigidity, Flutter, Divergence to the Aeroelastic Instabilities* (inter alia: determination the influence of Landing Gears on the whole A/C structure w.r.t. vibration)
- *MIL-A-8863 Airplane Strength & Rigidity, Ground Loads for Navy acquired Airplanes* (general specification for ground loads)
- *MIL-A-8862 Airplane Strength & Rigidity, Landplane Landing & Ground Landing Loads (replaced by MIL-A-8863)*
- *MIL-A-8860 General Specification For Airplane Strength and Rigidity* (inter alia: The shock-absorption characteristics and strength of landing-gear units incl. their control systems)
- *DEF-STAN 00-970 Design and Airworthiness Requirements for Service Aircraft*
  (Complete set of requirements to be met in designing a military aircraft)

Fig. 5. Eurofighter Combat Aircraft

Fig. 6. Tornado combat aircraft

Fig. 7. B-52 Strategic Long Range Bomber

Fig. 8. C-5 Galaxy Transport aircraft

1.2. Landing Gears

Landing Gears can be distinguished into two groups by their way of being mounted into the Aircraft:

- fuselage-mounted landing gear (Fig. 9),
- wing-mounted landing gear (Fig. 10).

1.2.1. Commercial aircraft

Fuselage mounted landing gears are used for high wing airplanes like for example BAe 146, Do28 and ATR 42/72. Wing mounted gears are installed on low wing aircraft, in which category we find almost all large commercial vehicles (FAR 25).

Fig. 9. ATR 42

Fig. 10. Airbus A320

1.2.2. Light aircraft

The undercarriage configuration of light aircraft is decided based upon the purpose that the aircraft was designed for. In many cases fuselage-mounted landing gear are chosen for small high wing transport aircraft (like Skytruck Fig. 2). Small commuter aircraft may have both: either wing or fuselage mounted landing gear.

The main reasons driving particular solutions for light aircraft are:
- stability of the aircraft during ground operations,
- available storage space for the landing gear,
- strength of the wing structures in case of wing mounted landing gear.

1.2.3. Military aircraft

The configuration of landing gear in military combat aircraft is mainly driven by space constraints which apply to the airframe. According the final position of the landing gears, the design is developed and adjusted to satisfy the requirements of aircraft stability during ground operations, take-off and landing.

For military transport aircraft one main objective is to optimize holding space. Therefore and due to the fact that most transport Aircraft have a high wing configuration, they have landing gears mounted to the fuselage. Some of them have sponsons (external bays) on the side of the fuselage where the undercarriage is attached.

1.3. General arrangement of landing gear

In terms of landing gear configuration, the tricycle – or nose wheel – layout is mainly used. It indeed can be considered as virtually standardized. Its numerous advantages over the tail-wheel layout greatly offset its few disadvantages. For example:
- The floor line of the aircraft is always horizontal, which is advantageous to the passengers, crews and luggage/cargo loading.
- High braking can be applied without flipping over.
- When landing in a crosswind the aircraft is stable.
- No take-off performance lost due to the drag from a tail down attitude.

1.3.1. Landing gear arrangement in commercial aircraft

With the increasing size and weight of commercial aircraft, new configurations have appeared. To operate on an airfield of defined strength, some additional struts and wheels are required to spread the load over a larger area. Good examples are the Airbus A340 (Fig 1.11) and Ilyushin Il-96 with their belly undercarriage gears and the Boeing B747 and Airbus A380 with their four under-wing and under-fuselage struts.

Fig. 11. Airbus A340

The arrangement of wheels, their number and pattern vary from one aircraft to another. However most aircraft have typical configurations as listed below (Fig. 12):

- Dual arrangement for nose landing gear.
- Dual, dual tandem or tri-twin tandem for main landing gear.

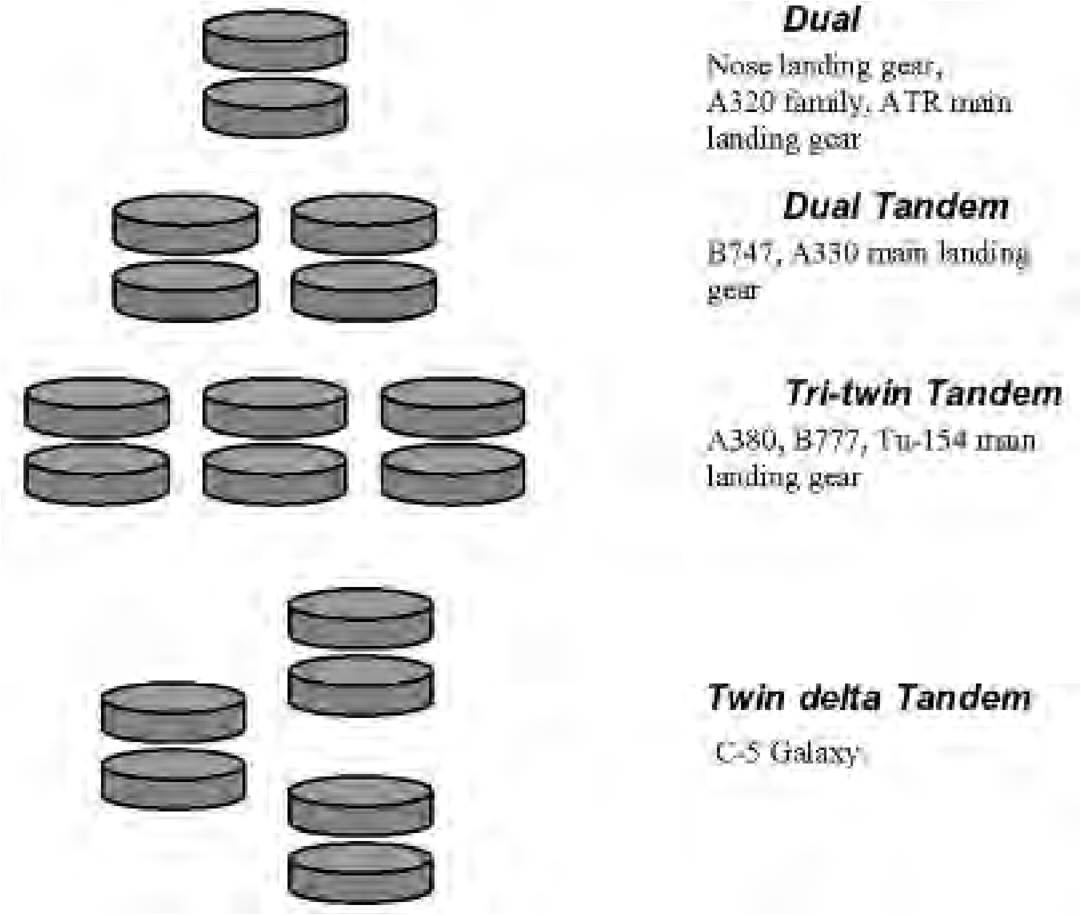


Fig. 12. Main types of wheels arrangement

1.3.2. Landing gear arrangement in light aircraft

Airplanes of the light category have landing gear that is designed to cover two basic criteria: low mass of landing gear structure and low cost of manufacturing. Therefore it is a very important directive of the design process to aim towards simplicity of the product. An important feature of the small aircraft design is also its maximum air speed. Depending on the maximum speed, designers have to decide between retractable or fixed configuration of the landing gear. Another aspect that must be taken into account during the design process is the kind of runway surfaces that the airplane is going to be operated off. Different requirements must be considered in case of paved or unpaved airfields.

The factors mentioned above determine a basic layout and allow choosing a landing gear system as well as elements responsible for energy absorption, which are essential for the landing gear performance. Most common for light aircraft is also the tricycle landing gear layout but with single wheel per strut only.

1.3.3. Landing gear arrangement in military aircraft

Typically in military combat aircraft the following layout for landing gear is used:

- single wheel for main landing gear,
- single or twin wheels for nose landing gear.

The most common reason of using the single wheel configuration in MLG in combat aircraft is lack of space where the landing gear bay may be placed. Nevertheless there are exceptions from that, especially within the Russian Military Aircraft.

Military transport aircraft have usually also a tricycle configuration where the nose landing gear is a twin wheel and main landing gear is mounted on both sides of the fuselage in dual tandem or tri-twin tandem configurations.

Specific conditions may drive exceptional solutions in undercarriage layout. An example of an unusual configuration of landing gear is the American strategic-bomber B-52 (Fig. 13): A solution was realized where main and nose landing gear of the airplane is placed on the basis of an rectangle, which allows to open the whole length of the fuselage to release the bomb-load without a shift of the C of G in x-direction, which would force the aircraft in a dangerous nose-up or -down attitude.

This kind of arrangement required to mount additional small gear to the wing tips to ensure the stability of the aircraft during ground operations.

One main aim for landing gear layout of heavy military transport aircraft is spreading the wheel-load to satisfy limitations in strength of airfields. This leads to configurations like on C-5 Galaxy (Fig. 13) Transport aircraft that has a main landing gear in twin delta tandem configuration and a nose landing gear with double dual wheel configuration.

Photo courtesy of Estelle Calleja

Photo courtesy of Christoher Hammarborg

Fig. 13. Undercarriages of B52 and C-5 Galaxy transport aircraft

1.4. Landing gear types

Basically two different types of landing gears are used:

- cantilever gear (Figs 14 to 16),
- trailing arm suspension gear (Fig. 17).

The cantilever configuration is the most widely used and is the most cost and weight effective. In this configuration the shock absorber is a part of the main fitting. It is a structural part. This configuration has however one main disadvantage. During spin-up, the shock absorber works in bending mode what induces high bearing friction.

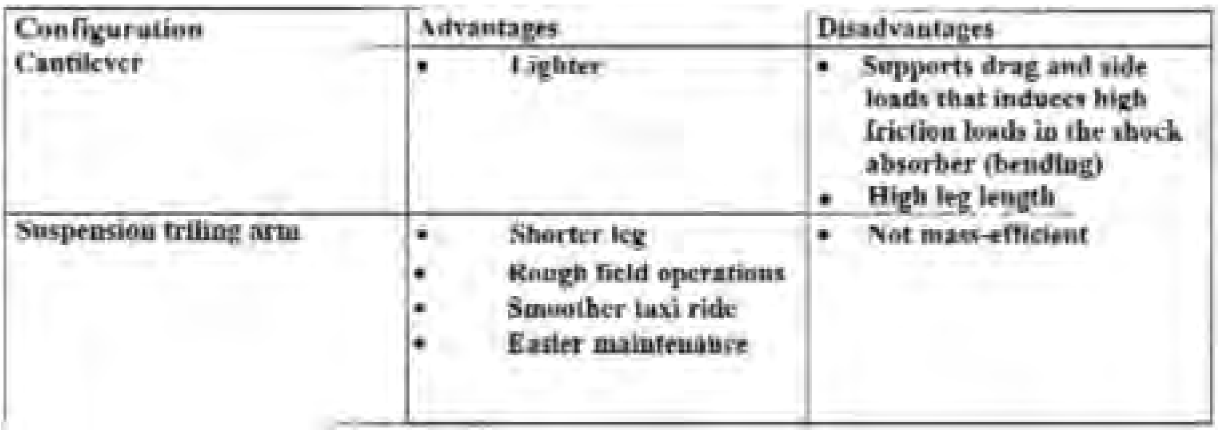
Fig. 14. Nose retractable cantilever type landing gear for light aircraft – 3D model

Fig. 15. Airbus A340 Main Landing Gear
- *shock absorber*
- *main strut*

Fig. 16. Main retractable cantilever type landing gear for light aircraft – 3D model

Fig. 17. Bombardier Global Express main landing gear
a) shock absorber
b) main strut

The trailing arm suspension(Fig. 17) is less common for commercial airplanes and, above all, it is heavier. It is used when ground clearance is low and stowage room limited and to get a smoother taxi ride over bumpy runways, which makes it predestined for Military Transport aircraft like C160 or A400M. The shock absorber is mounted between the main strut and the trailing arm. A long stroke is obtained for relatively short leg length



Configuration	**Advantages**	**Disadvantages**
Cantilever	• Lighter	• Supports drag and side loads that induces high friction loads in the shock absorber (bending) • High leg length
Suspension triling arm	• Shorter leg • Rough field operations • Smoother taxi ride • Easier maintenance	• Not mass-efficient

However, in some cases, centre of gravity positions and attachment points are incompatible with a cantilever gear and the trailing arm landing gear imposes itself as the unique available solution.

2. SHOCK ABSORBERS

The main functions of the landing gear are:

- to absorb the kinetic energy of the vertical velocity,
- to provide elastic suspension during taxiing and ground manoeuvres.

These tasks are fulfilled on landing gear by the shock absorbers and the tyres, the later will not be covered in this document.

Several different designs exist to perform those functions.

In modern light airplanes elements responsible for energy absorption can be chosen from the following solutions: spring beams (spring landing gear – Fig. 18), flexible elements - elastomers (Fig. 19), steel ring springs (Fig. 20) and ole-pneumatic shock absorbers, as presented below.

Fig. 18. Spring type non-retractable landing gear

Fig. 19. Retractable landing gear with spring rubber elements

Fig. 20. Non-retractable landing gear landing gear with steel ring spring

The solutions mentioned above are preferred because of their low cost, reliability, low weight and high efficiency rates.

A comparison of different types of „energy absorbers" is presented in Fig. 21 and Fig. 22 (according to Norman S. Currey – „Landing Gear Design: Principles and Practices").

Although the remaining solutions are not as efficient as oleo-pneumatic shock absorbers, they are in use because of low costs of production and low costs of maintenance.

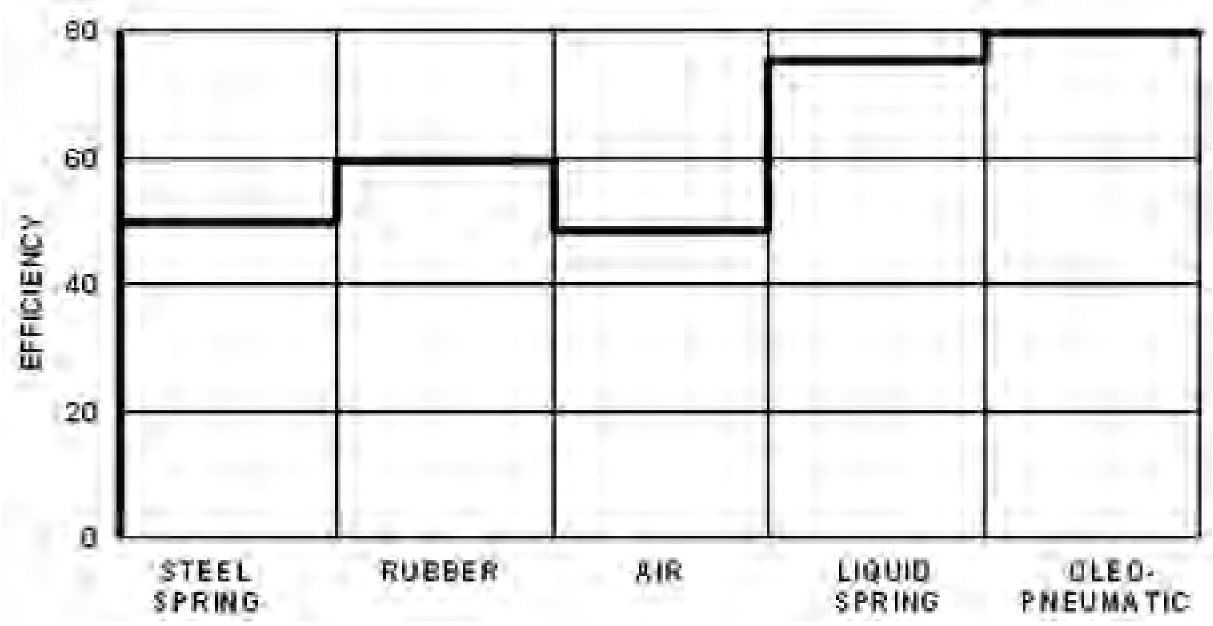


Fig. 21. Shock absorbers efficiency – differences

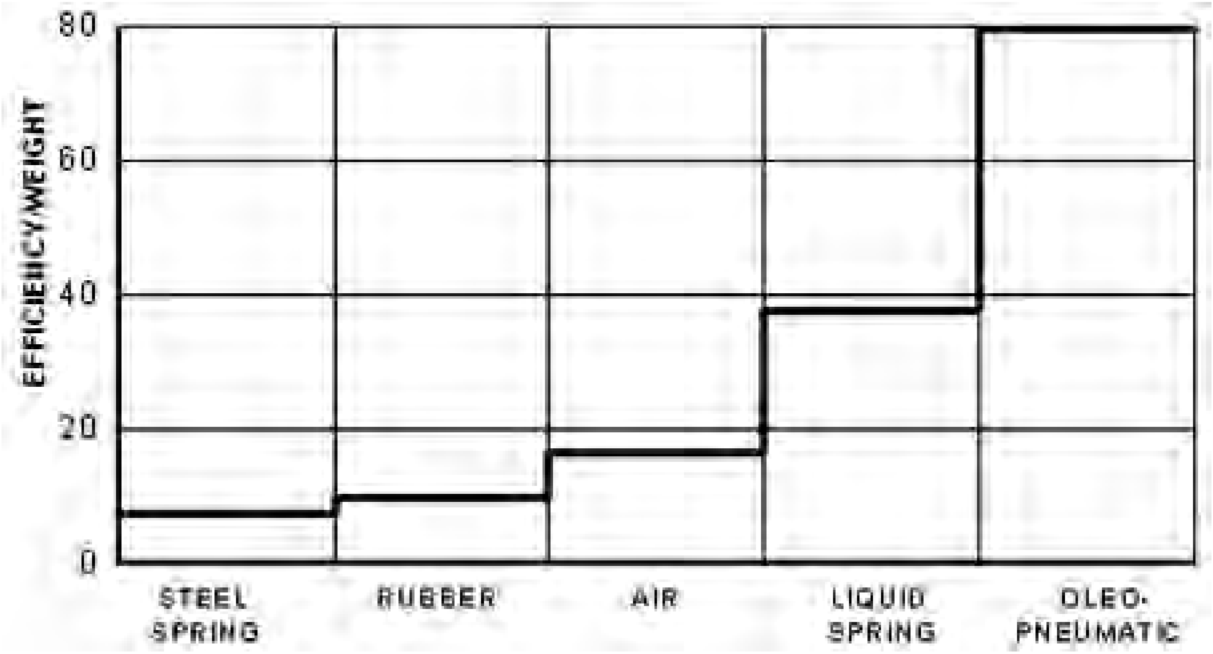


Fig. 22. Shock absorbers efficiency - differences in accordance to masses of amortization system

In military and commercial aircraft where efficiency is the highest priority, only the oleo pneumatic shock absorbers are used.

However, only one is used on FAR 25 commercial aircraft. All the modern transport aircraft have an oleo-pneumatic shock absorber. This shock absorber type has the highest efficiency and the best energy dissipation. Its role is to limit the impact loads by transmitting the lowest and most bearable acceleration level to the aircraft structure and passengers. An oleo-pneumatic shock absorber absorbs energy by „pushing" a volume of hydraulic fluid against a volume of gas (nitrogen or dry air) and compressing it.

Oleo-pneumatic shock absorbers carry out two functions:

- a spring or stiffness function, which provides the elastic suspension by the compression of a gas volume,
- a damping function, which dissipates energy by forcing hydraulic fluid through one or more small orifices.

Oleo-pneumatic shock absorbers applied in contemporary airplanes can be classified in 3 different groups

A. Depending on piston position
   – piston in up position
   – piston in down position

B. Depending on separation of liquid and gas
   – without separation
   – with separation

C. Depending on number of chambers
   – single acting shock absorbers
   – double acting shock absorbers

According to group A

Shock absorbers with piston in upper position (Fig. 23) are applied only in trailing arm type of landing gear. Sometimes it is necessary to locate shock absorber as close as possible to the leg. The diameter of the piston is smaller than diameter of cylinder and this fact allow reaching the design target.

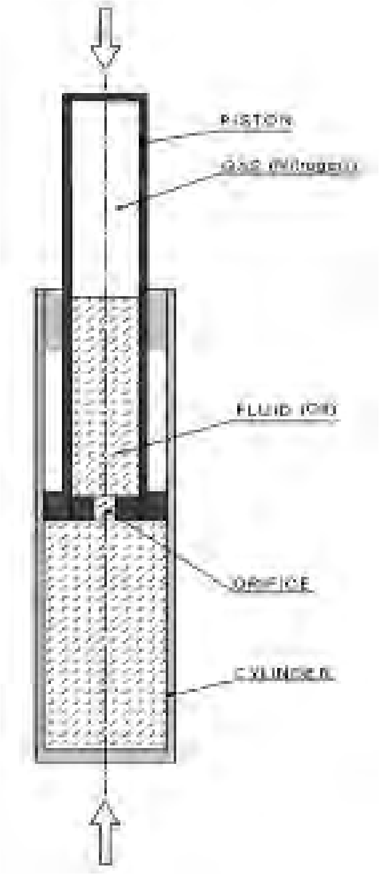


Fig. 23. Shock absorber with piston in up side position

Shock absorbers with piston in lower position (Fig. 24) are applied in trailing arm type and in cantilever type of landing gear. The inside gas chamber can be bigger and it gives more possibility of optimizing filling of shock absorber (liquid and gas). This is the only type of shock absorber used in cantilever gears.

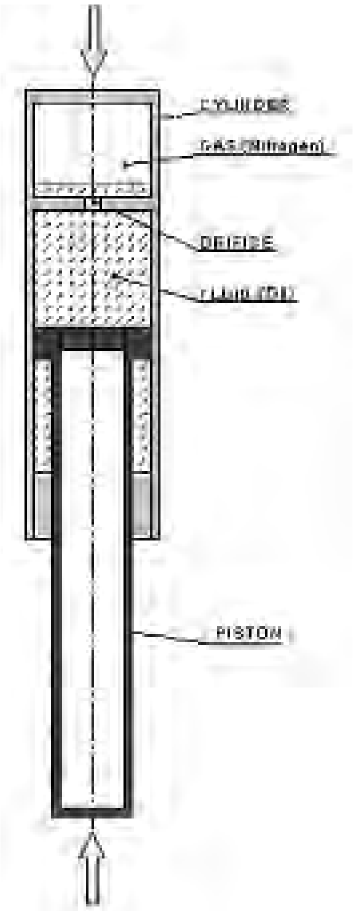


Fig. 24. Shock absorber with piston in down position

According to group B

Shock absorbers in which liquid and gas are not separated (Fig. 25) are the most popular in small airplanes because of lower costs and more simplicity (no additional pistons with seals).

But such shock absorbers have characteristics that are not repeatable, because of oil and gas mixing during operation.

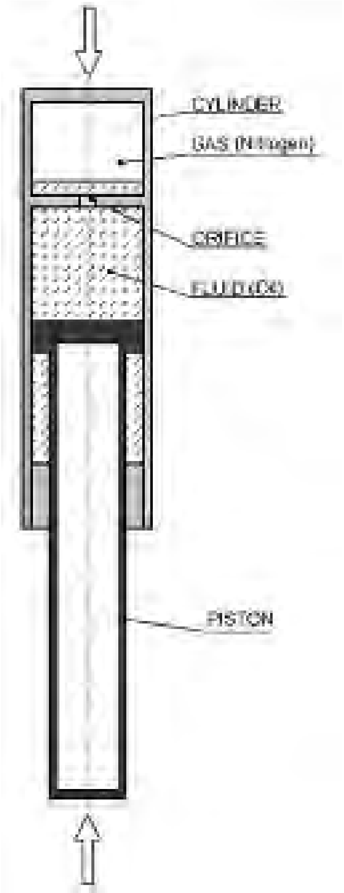


Fig. 25. Shock absorber without liquid and oil separated

Shock absorbers in which liquid and gas are separated (Fig. 26) are sometimes applied in small airplanes, but it is related with higher cost of production and a little higher total mass of the structure.

Their functional characteristics are repeatable.

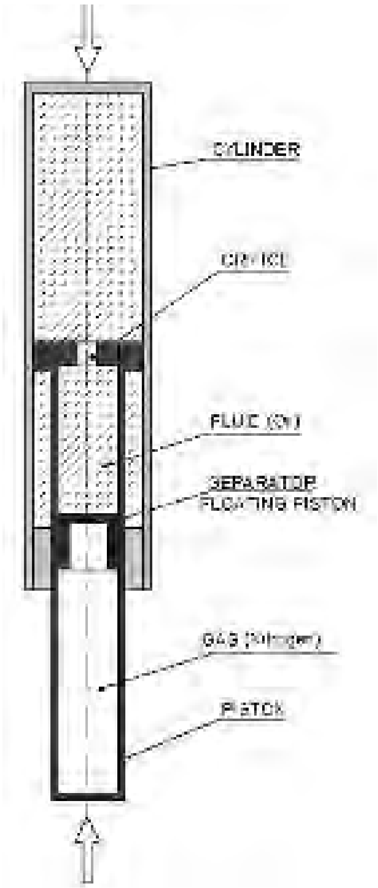


Fig. 26. Shock absorber with liquid and oil separation

According to group C

Single-stage shock absorbers (Fig. 27) are mostly used on airplanes, because of lower cost of production and more simplicity (no additional piston, seals etc.) and less total mass. They have only one chamber of gas.

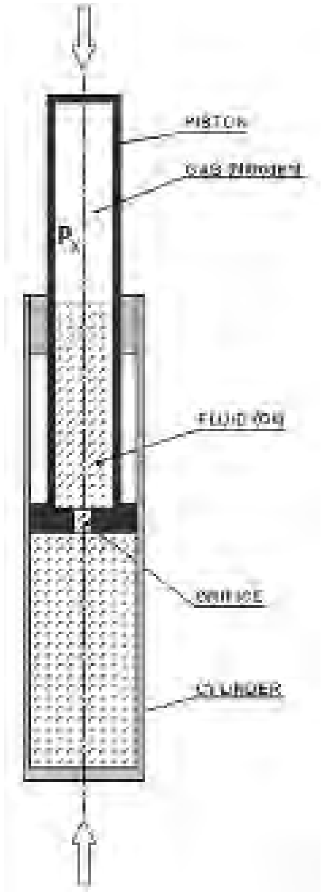


Fig. 27. Single-Stage shock absorber

Double Stage shock absorbers (Fig. 28) are applied in airplanes, where improving of shock absorption characteristics during taxing conditions over unpaved or rough fields is required.

They have two gas chambers:

- primary chamber with lower pressure with or without separation liquid and gas,
- secondary chamber with higher pressure always with separation liquid and gas.

The separation is realized by separator piston (floating piston).

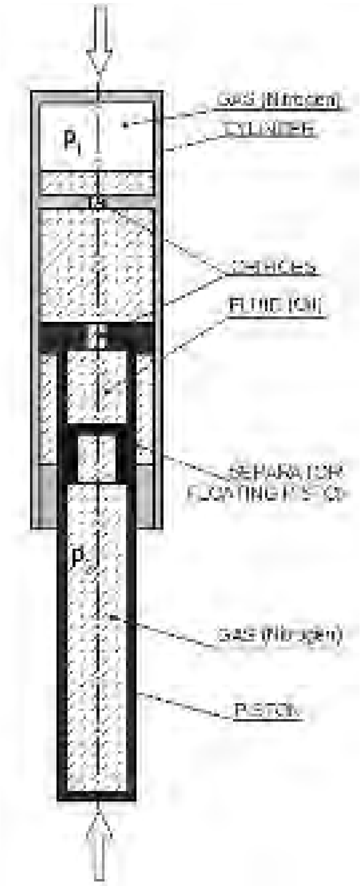


Fig. 28. Double - Stage shock absorber

Figure 29 shows a typical shock absorber load-stroke curve. The shock absorber load can be divided into two parts:

- one from the hydraulic fluid forced through the damping orifices ($F_{damping}$)
- an other from the gas, typically nitrogen, compression (F_{air})

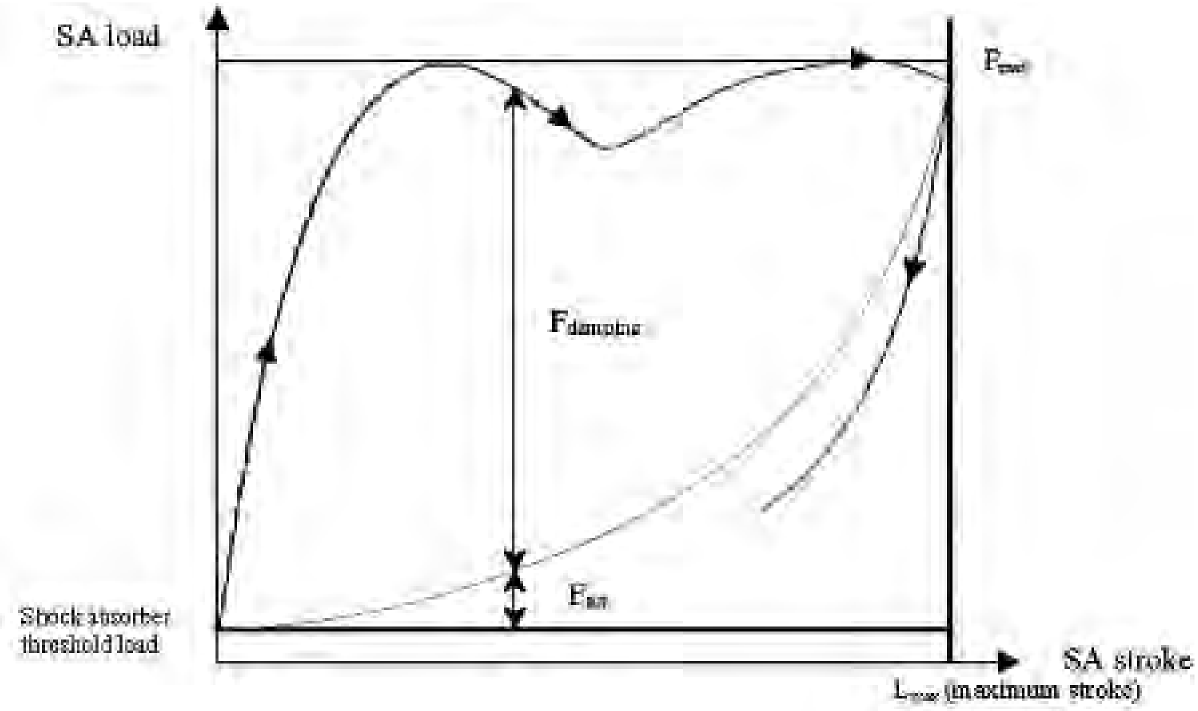


Fig. 29. Shock absorber load versus stroke law

From Figure 29, we can define one of the shock absorber characteristics, the shock absorber efficiency. It is obtained using the following formula:

$$Efficiency \quad \eta = \frac{W}{F_{max} \cdot L_{max}}$$

where

W is the energy absorbed by the shock absorber during its stroke,

F_{max} is the maximum load,

L_{max} is the maximum stroke.

With oleo-pneumatic shock absorbers, 0.8-efficiency can be easily achieved. With stroke-variable damping, efficiencies greater than 0.85 and even above 0.9 can be reached. However the research of the best efficiency is not necessarily the criterion of optimization for the structure.

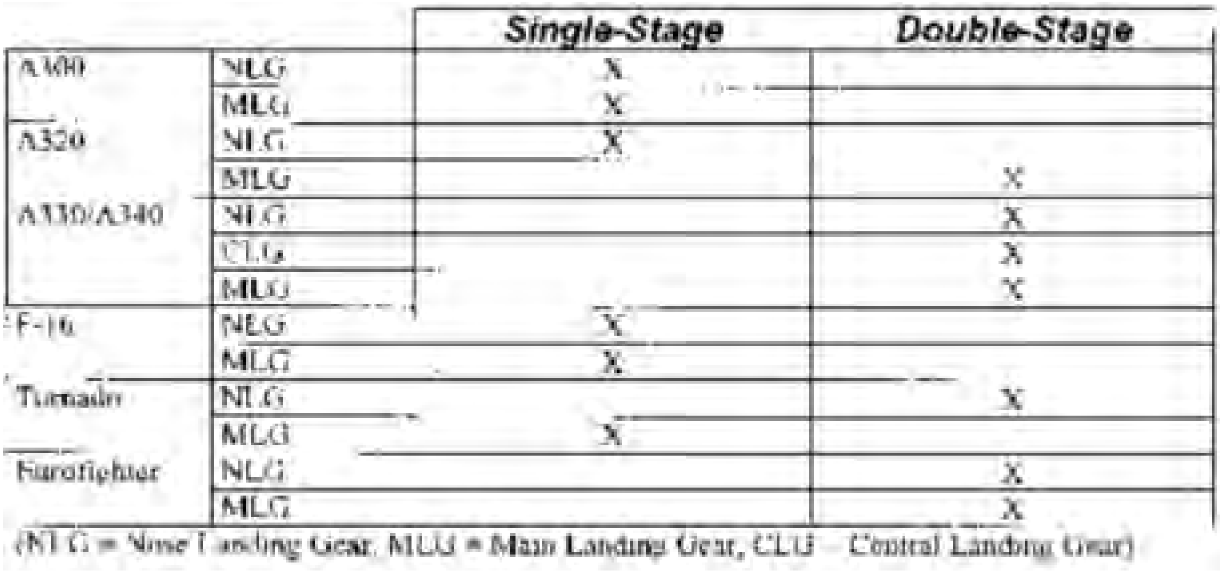
The single-stage shock absorber is the preferred one. It is more weight and cost effective, easier to manufacture and more reliable. However, in some particular cases, a second chamber is needed to perform more advanced gas law.

These cases are:

- improved characteristics during taxi conditions over rough or unpaved runways,
- low attitude variations, whatever weight and balance are.

Among double-stage shock absorbers, we can again distinguish two categories according to the respective positions of the two chambers: with adjacent chambers or with chambers in opposition. In both cases, a separator piston has to be added, between the two gas chambers in the former and between the hydraulic fluid and the lower gas chamber for the latter.

The following table presents the types of shock absorber (single-stage or double-stage) for some airplanes of the Airbus family and examples of military aircrafts.



		Single-Stage	Double-Stage
A300	NLG	X	
	MLG	X	
A320	NLG	X	
	MLG		X
A330/A340	NLG		X
	CLG		X
	MLG		X
F-16	NLG	X	
	MLG	X	
Tornado	NLG		X
	MLG	X	
Eurofighter	NLG		X
	MLG		X

(NLG = Nose Landing Gear, MLG = Main Landing Gear, CLG = Central Landing Gear)

2.1. Air-spring function

When the shock absorber is fully extended, the volume occupied by the gas, under an initial pressure p_0, is V_0. Those first values define the shock absorber threshold load $F_0 = p_0S$, where S is the piston area. On one hand this spring pre-load has to be as low as possible in order to minimise forces needed to initiate the shock absorber closure (soft landing). On the other hand it can’t be too low to give some stiffness to the landing gear when retracted. The stiffness, as shown on Figure 30, is not a constant with respect to the piston stroke.

This spring function is ruled by the ideal gas equation

$$PV = nRT$$

and defined by the gas curve.

For a given stroke, the following relation gives the „air effort”

$$PV^{\gamma} = P_0V_0^{\gamma}$$

with $\gamma = \frac{C_p}{C_v}$

	Isothermal (slow displacement)	Polytropic (quick displacement)	Adiabatic (theoretical)
γ	1	$1<\gamma<1.408$	1.408

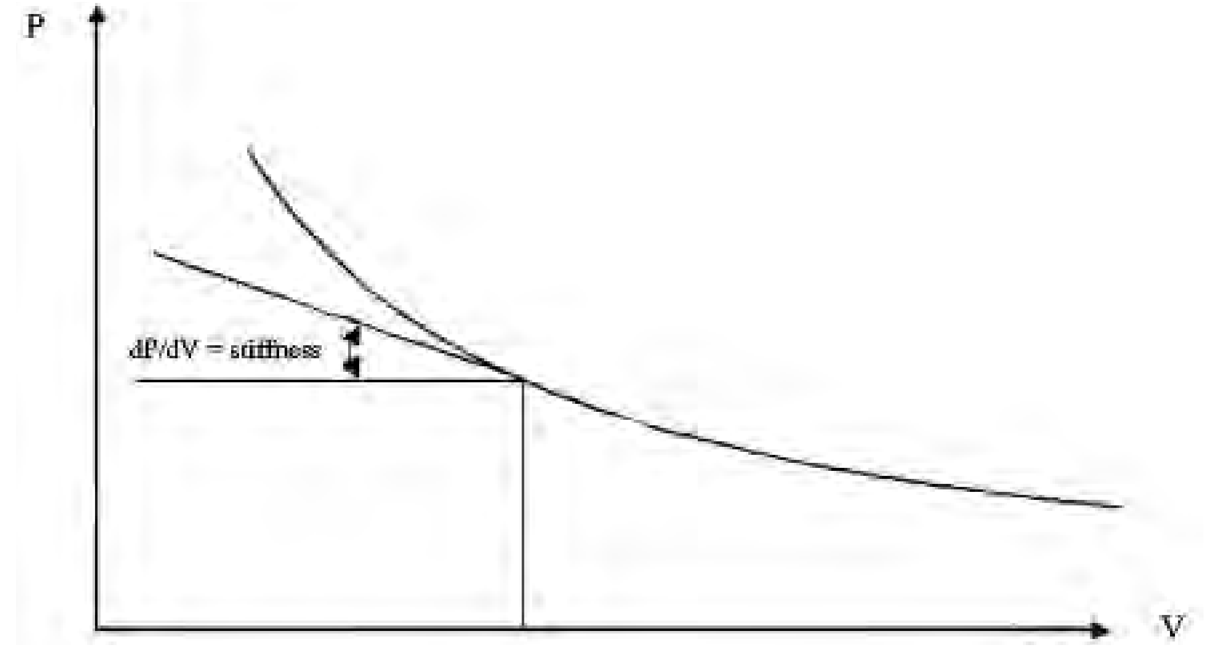


Fig. 30. Isothermal gas curve

Values of γ

- Under static loads and/or during ground operations, we consider slow displacements. Isothermal air spring law is used (**$\gamma = 1$**).
- For the landing impact, quick displacements are considered
  1) with a separator piston between the air and hydraulic fluid, **$\gamma = 1.3$**
  2) without a separator piston, **$\gamma = 1.1$** (hydraulic fluid cools the nitrogen down)
- during hard braking
  1) for a main landing gear **$\gamma = 1$**
  2) for a nose landing gear
     - with a separator piston **$\gamma = 1.2$**
     - without **$\gamma = 1.1$**

These values are only presented here to give an order of magnitude. The thermo dynamical phenomenon is more complex and the value of **γ** depends on several other parameters.

2.2. Air spring tuning

Before tuning this function, two parameters have to be defined, the maximum mechanical stroke and the shock absorber section.

The FAA and EASA require that a transport-type aircraft be able to withstand the shock of a landing at 3.05 m · s^{-1} (10 ft.s-1) at the design landing weight and 1.83 m · s^{-1} at maximum gross weight. At the limit sink rate (3.05 m · s^{-1}), the airframe manufacturer limits the load factor. This maximum load gives the maximum mechanical stroke.

$$F_{vmax} \Rightarrow W = \frac{1}{2} M_R V_z^2 \Rightarrow F_v \cdot l \Rightarrow l$$

where

F_{vmax}	the maximum load,
W	the energy to be absorbed by the shock absorber,
M_R	the considered mass,
V_z	the vertical velocity,
l	the maximum mechanical stroke.

Moreover, this stroke had to be sufficient to ensure no abutment during ultimate sinking speed test ($3.65\ m \cdot s^{-1}$, $12\ ft \cdot s^{-1}$).

The shock absorber section is such as the pressure does not exceed a given pressure (typically around 200 bars) under maximum static load. Under maximum dynamic load, the maximum pressure is checked. The shock absorber section is a trade-off between size and weight.

When these values are fixed, several conditions and constraints are used to size the gas chamber. These constraints depend on the position and the role of the concerned shock absorber. For example, for FAR 25-type aircraft, „flat" air curves, but not too flat to avoid large roll excursions, are searched to improve the comfort during taxi conditions.

The sizing of a shock absorber is based on a trade-off process. The commonest initial assumptions are typically:

- a ratio of the static stroke divided by the total stroke between 0.60 and 0.65 for a nose landing gear (NLG),
- a ratio of the static stroke divided by the total stroke between 0.80 and 0.85 for a main landing gear (MLG).

Considering these constraints, two load-stroke curves for the spring function can be drawn: isothermal and polytrophic. They will be shown for single and double-stage shock absorbers in the next paragraphs.

2.3. Single-stage shock absorber

The following shock absorber (Fig. 31) is representative of a single-stage shock absorber with metering pin and no separator piston.

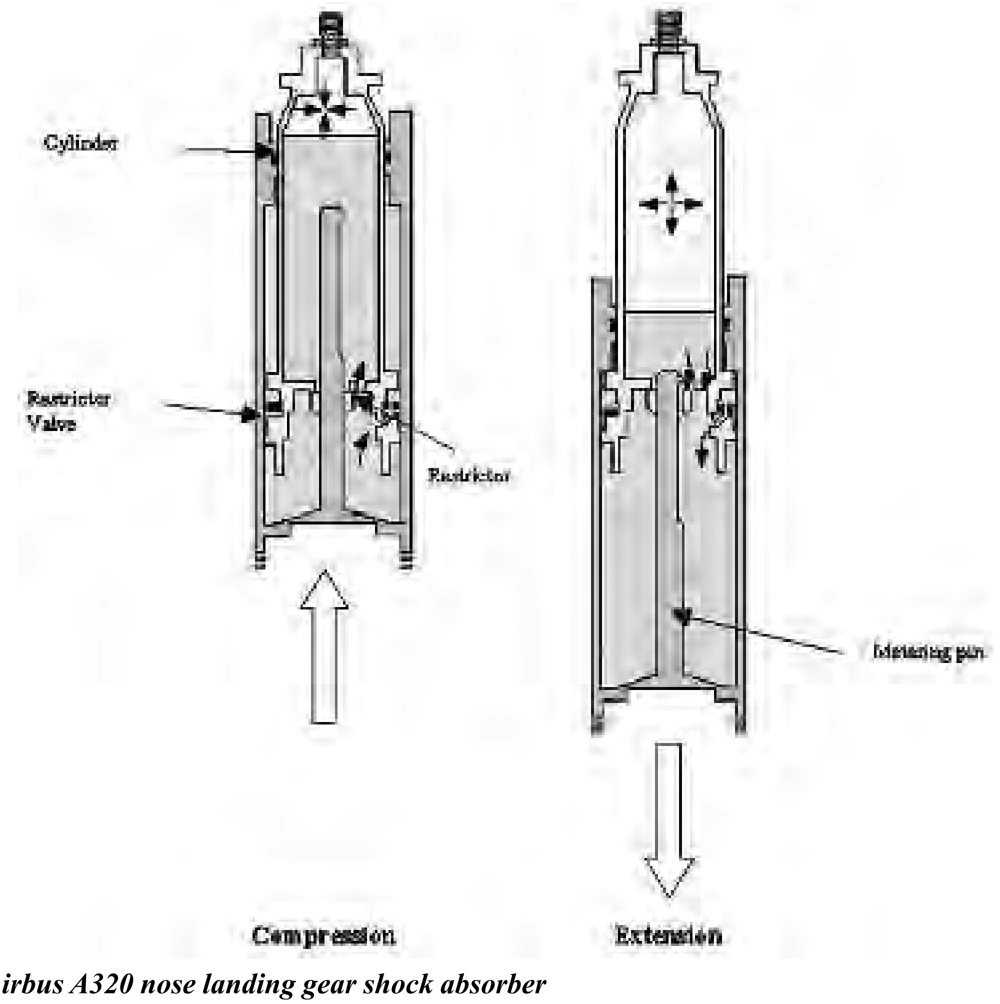


Fig. 31. Airbus A320 nose landing gear shock absorber

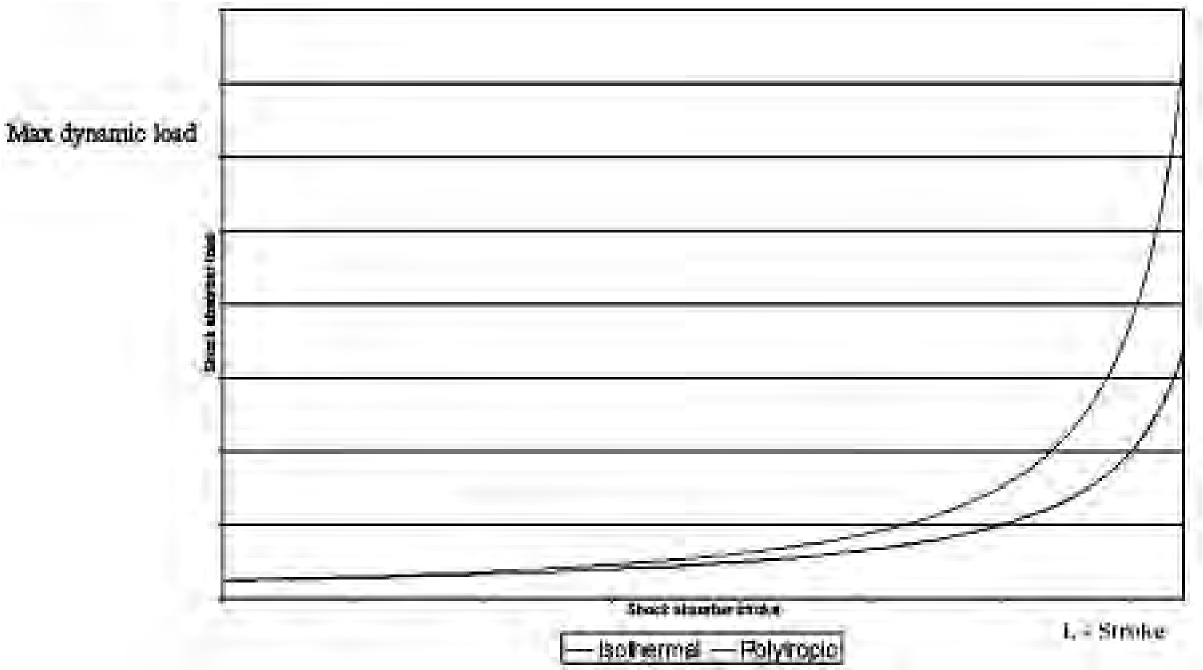


Fig. 32. Isothermal and polytropic gas curve for a single-stage shock absorber

2.4. Double-stage shock absorber

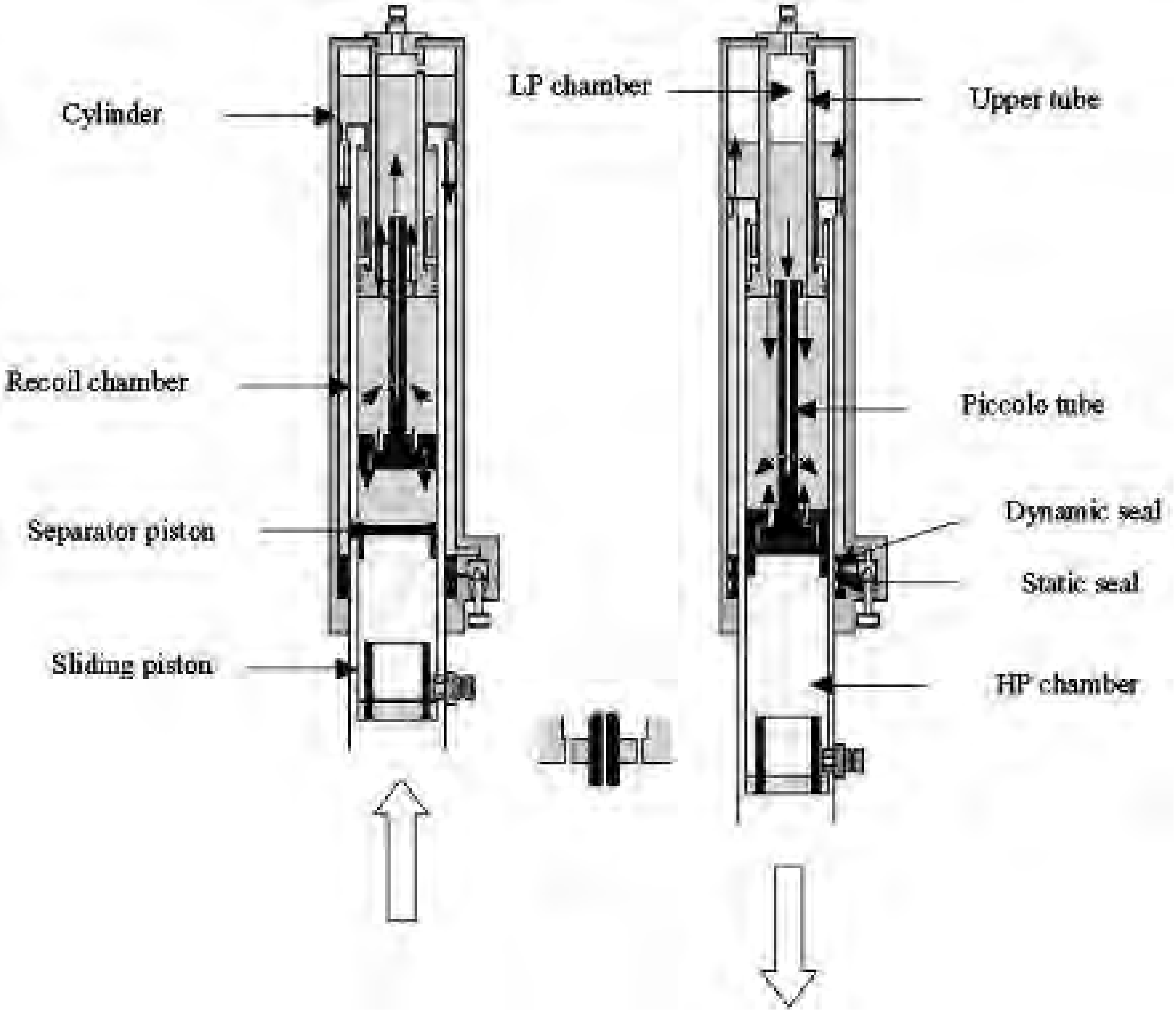


Fig. 33. Airbus A340 central landing gear shock absorber

For isothermal working the low-pressure chamber works alone for 50 to 65% of the shock absorber stroke.

If low variations of aircraft attitude and/or increased stability (case 1) are looked for, then static loads will be positioned on the low-pressure air curve. The pre-load pressure of the second chamber will be typically chosen equal to 1.25 or 1.3 times the maximum static load.

If an aircraft is to be operated on rough and unpaved runways (case 2), static loads will be placed on the second part of the gas curve (where the two chambers are working) – Fig. 34. With this adjustment, we obtain an increased flexibility and a reduction of the load variations from the crossing of obstacles. The high-pressure chamber pre-load is typically chosen around the minimum static load (+10%). Thus it could be taken around 40% of the total stroke of the shock absorber.

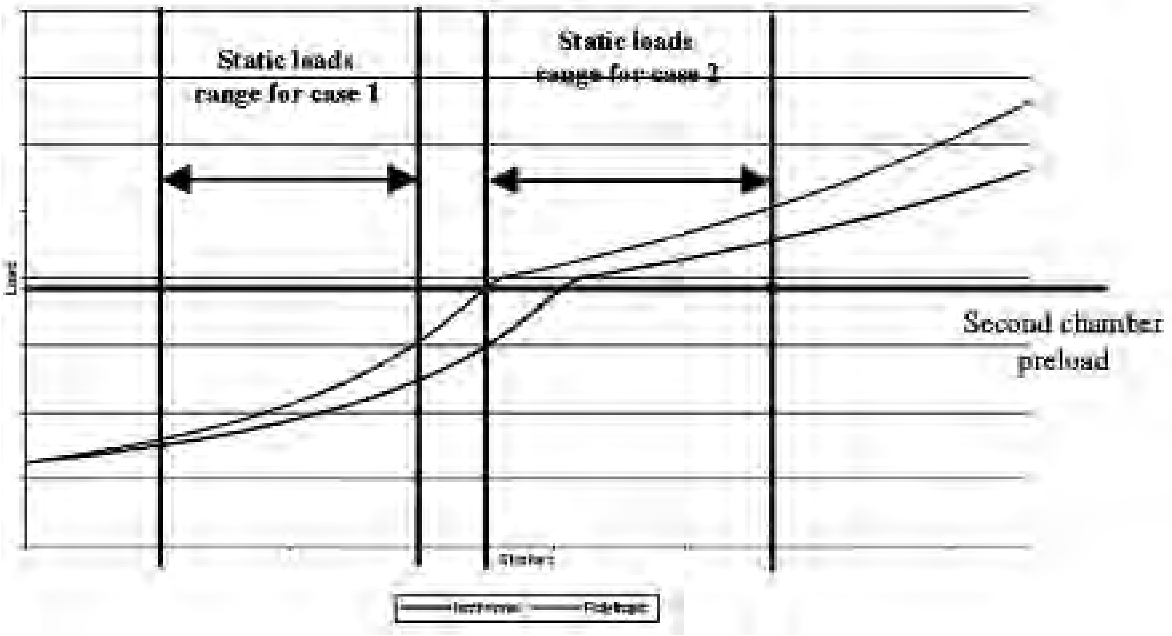


Fig. 34. Isothermal and polytropic gas curve for a double-stage shock absorber

2.5. Damping function

The damping function dissipates the kinetic energy of the vertical velocity in form of heat by forcing hydraulic fluid through small orifices. The pressure loss created by these orifices is proportional to the square of the shock absorber compression velocity. The hydraulic damping force can be written

$$F_H = K' v^2 \quad \text{with} \quad K' = \frac{1}{2}\rho\frac{S_H^3}{\sigma^2}$$

where

ρ is the hydraulic fluid density

S_H is the hydraulic section area of the shock absorber

σ is the orifice area

Paper and, more and more, computer drop tests are performed to size orifices to achieve energy absorption requirements. Many rules of thumb exist for guessing orifice area.

The results are then checked with actual drop tests and refined. The usual way is to change at least once the orifice definition after the tests.

Constant orifice design is today limited for efficiency. Metering pins are then introduced to improve efficiency and carry out position dependant damping. The damping is then a function of the stroke. The metering pin is sized to give high damping on initial closure then shaped to a profile that provides optimal performance for the critical case (limit landing speed). A metering pin is in the

Airbus A320 nose landing gear shock absorber. Another used design is the „Piccolo tube" (see A340 CLG). It can provide several levels of damping with orifices that increase the damping with stroke.

The damping function is also active during the recoil of the landing gear. The energy to be absorbed when recoiling is much less than during the impact. It is only due to the spring effect of the compressed gas. However tuning is more difficult than for impact. The nitrogen forcing the hydraulic fluid to flow back into its chamber or into a recoil chamber through recoil orifices damps the rebound. If hydraulic fluid is able to flow back quickly, the aircraft will bounce upward. If it flows back too slowly, a short wavelength bump will not be damped and high loads will appear. The recoil orifice area is typically smaller than the impact orifice area. When recoiling, the hydraulic fluid flow often flattens valve plates against the damping piston to partially close the orifices. Moreover some shock absorbers achieve a recoil control by using some annulus chamber between the main fitting and the sliding tube.

2.6. Materials

In this paragraph we discuss materials used to manufacture the shock absorbers and more generally the landing gear. Like for all the aeronautical equipment, landing gear materials have to be of high strength and high stiffness. But they also must have low cost and density. Some other requirements have to be completed.

Landing gears for airplanes with oleo-pneumatic shock absorbers in most solutions are made of metals like: steel, aluminum alloys or titanium alloys. Used are high strength steels with tensile strength from 1200 to 2000 MPa. For not welded parts, steels are used with higher then 1500 MPa tensile strength, such as steel 4340, 300M, NC310, 35NCD16, AerMet 100, and for welding (mostly common on small aircraft) the most popular – steel 4330V. In shock absorbers, such parts are made of steel: pistons, inner tubes, cylinders, pins, bolts.

A lot of parts are made of aluminum alloys that are also applied in landing gear structures. The most common landing gear aluminum alloys are 7175, 7050, 7049, 7155, and 7010. The tensile strength is about 450 MPa with elongation higher then 7%.

Recently titanium alloys are more often used for landing gears/shock absorbers production. The most popular are WT23, Ti-6A1-6V-2Sn, Ti-10-2-3, Ti-4-4-2, Ti-6-22-22. Titanium alloys offer good relation between strength and weight, but due to difficult manufacturing and machining processes, they are not in broad use yet.

At present producers of high strength steel, aluminum alloys and titanium alloys offer a lot of good materials for landing gears / shock absorbers production. Manufacturers of landing gears should pay special attention to:

- stress corrosion resistance,
- low/high cycle fatigue strength,
- high cycle fatigue strength,
- weldability,
- crack initiation, propagation behavior,
- forgeability,
- machinability,
- and to production processes themselves.

Besides the traditional materials military industry is trying to reduce weight of their airplanes with new technologies like Metal Matrix Composites. The composites are metals that are locally reinforced with fibres, particles or other forms of reinforcement (Fig. 35, 36).

For the highly loaded landing gear components, Titanium (Ti) with continuous Silicon Carbide (SiC) fibres provide an optimal combination. This variant is called TMC (Titanium Matrix Composite). Especially in stiffness driven applications this leads to extreme weight savings, because of the high stiffness to weight ratio. The fibre material SCS-6 is manufactured using a CVD process, depositing SiC on a carbon core. Titanium 6Al-4Sn-2Zr- 4Mo was chosen as a matrix material. The fibres and matrix were combined using Plasma Spray process, resulting in tapes with longitudinal fibres at well defined distances. Layers of these tapes were stacked and consolidated in a HIP (Hot Isostatic Press) to form the basic material for machining.

Using the MMC can result in large weight savings compared to Ultra high strength steel parts. Over 40% weight reduction was achieved on the F16 lower drag brace, where the material was primarily tested. Additionally this material has many advantages due to its better corrosion and fatigue resistance in comparison to commonly used steel and aluminium alloys.

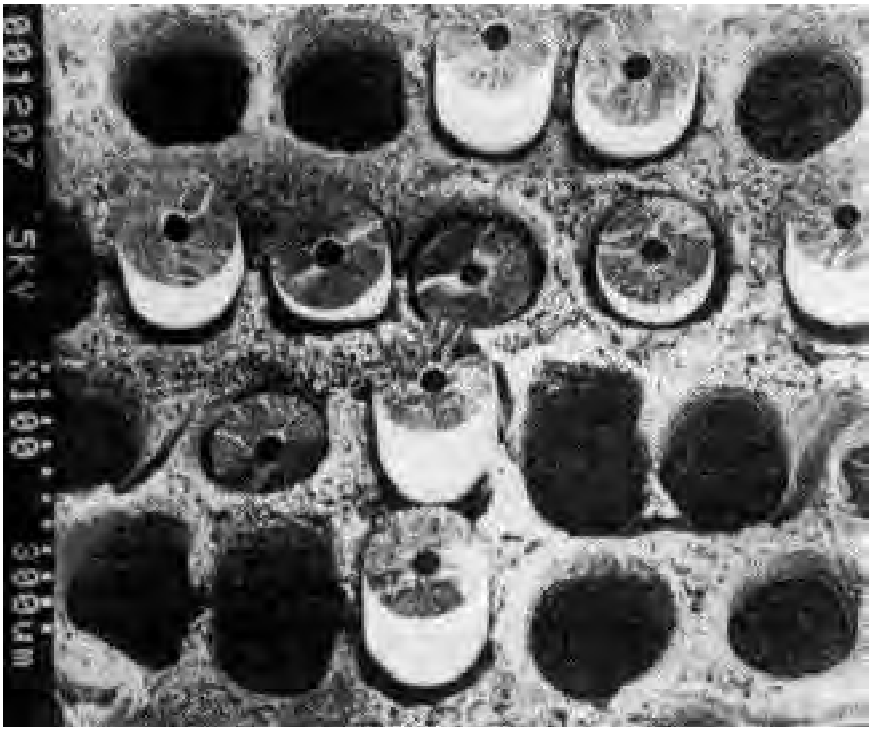


Fig. 35. SEM (Scanning Elecron Microscopy) picture of TMC coupon fracture surface

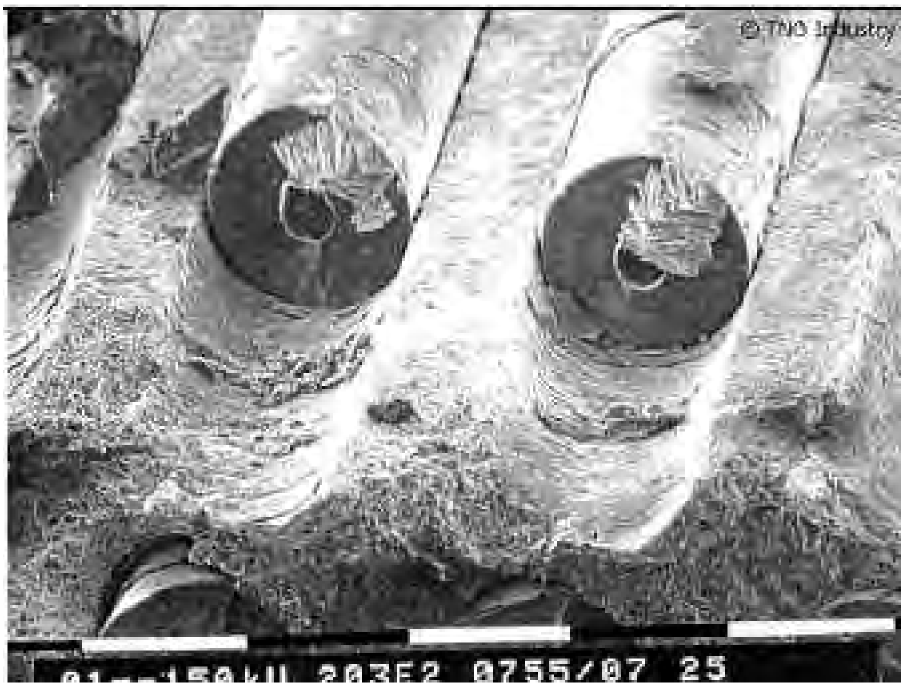


Fig. 36. Fracture and failure mode analysis of coupons. The SCS-6 fibers are clearly visible, as well as the fractured titanium matrix

3. LOADS

3.1. Overview

A landing gear has mainly to withstand two types of loads: the landing impact loads and the ground operation loads. The landing conditions themselves are critical for only a small part of the landing gear structure. Taxiing, turning and pivoting are critical for the majority of the structure.

The major part of the loads affecting a landing gear is dynamic. Static loads are only used to check shock absorber internal pressure and flotation requirements.

Concerning the fatigue, landing gears are designed according to the safe-life approach, redundancies are difficult to obtain for obvious reasons like mass or space constrains. Therefore the selected materials usually have to present the best fatigue behaviour. To reduce the probability of fatigue failures to a minimum, inspection techniques and frequencies are defined.

The critical load conditions can be classified into three categories:

Critical landing load conditions

- maximum sink speed landing,
  - tail landing,
  - level landing,
- landing with a burst tyre (associated to lower sinking speeds),
- lateral drift landing.

Critical ground handling load conditions

- towing/push-back,
- taxiing,
- braking,
- turning/pivoting,
- jacking.

Other critical load conditions

- loads from shimmy (has to be avoided)

3.2. Landing loads

To explain loads that act on a landing gear, different test results will be showed. The tested gear is a cantilever type one representative of a FAR 25-type aircraft.

The data of interest are:

- the vertical load FV1,
- the longitudinal load FH1,
- the lateral load FL1.

These loads are measured at the attachment points of the landing gear to the aircraft structure.

The vertical load (FV1 on Fig. 37), which is equal to zero at t = 0 s, increases very quickly until 0.04 s. It reaches a maximum at t = 0.3 s., when the shock absorber stroke (CAP on Fig. 38) is maximum. The longitudinal force FH1 on Figure 37 is damped-sinus-shaped. This aspect can be explained as follow. At t = 0 s, the wheels are motionless and come into contact with the runway. A friction force is created because of slipping. This force increases as the vertical effort FV1. Under its influence the wheels are spun up, the leg bends and stores a large amount of energy. At t = 0.2 s, wheels are accelerated, the shock absorber bending is maximum. There is no more sliding and the friction force goes to zero. The cantilever leg then works as a spring, oscillates at its first modal frequency and produces a longitudinal forward force. This is the „spin-up/spring back” phenomenon.

On Figure 38, we can see that the sink rate of the shock absorber (marked in red on Fig. 38, i.e. first derivative of the shock absorber displacement [CAP]) is nearly constant until 0.2 s. Between 0.2 and 0.32 s (light blue zone), the sink rate decreases and tends towards zero. The load is then only pneumatic.

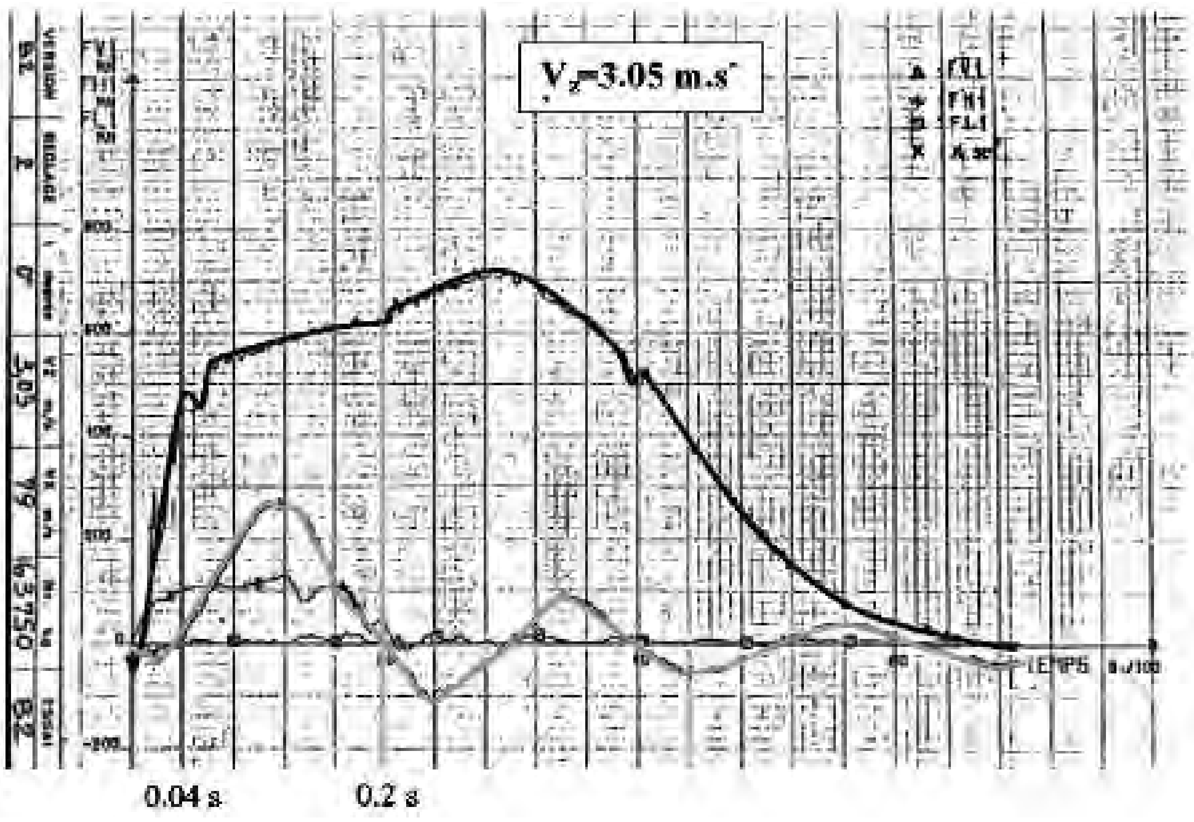


Fig. 37. Loads during impact

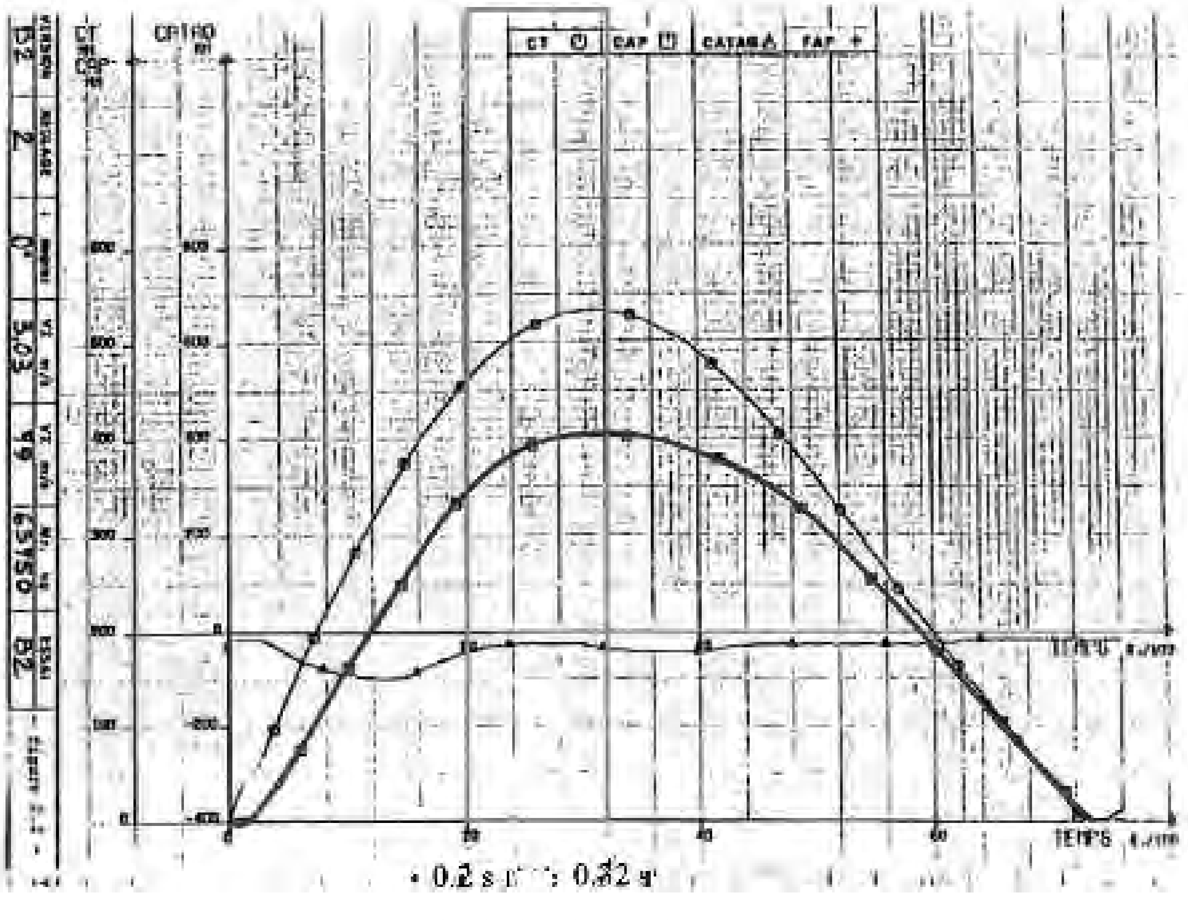


Fig. 38. Displacement during impact (shock absorber stroke versus time)

„Spring back” load = 0.8 „Spin-up” load

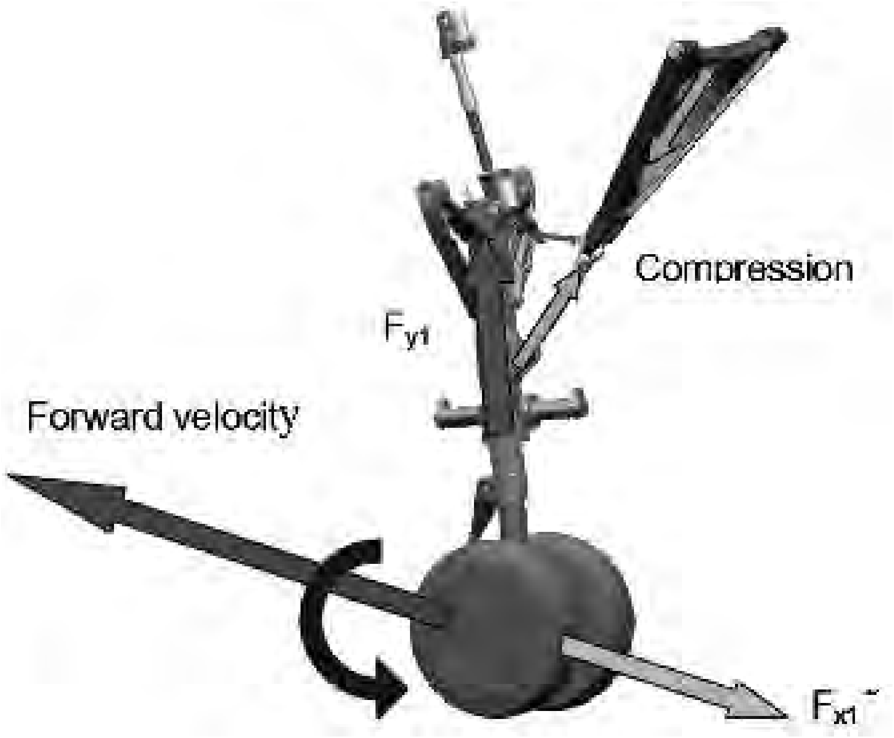


Fig. 39. Spin-up

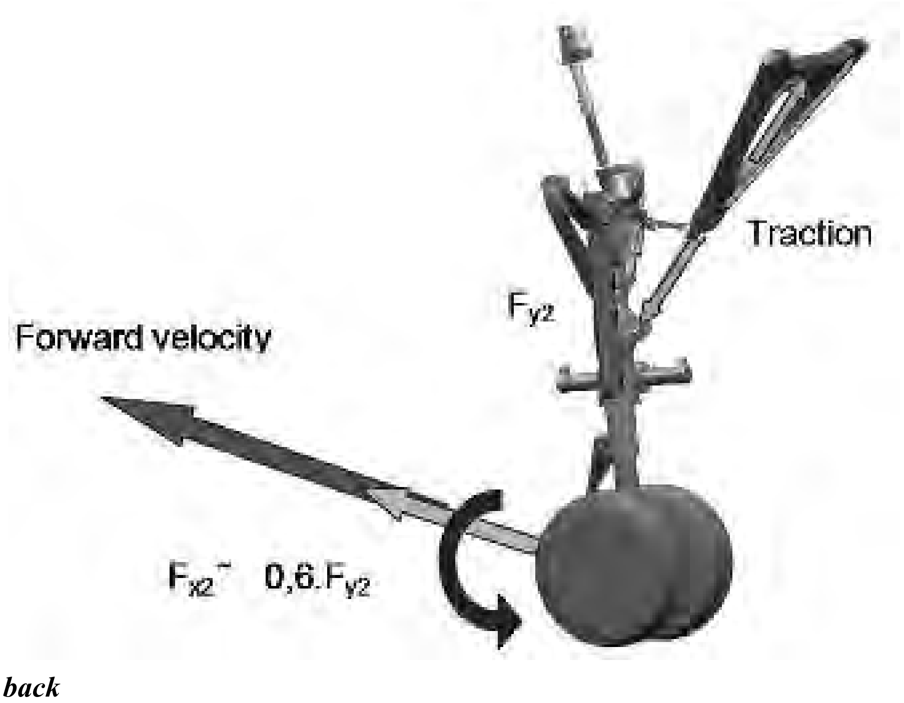


Fig. 40. Spring back

This load case is one of the design drivers considered for the sizing of several parts, like: main fitting, sliding tube, side stay, torque links.

Figure 41 displays the results of a drop test for a main landing gear of a small aircraft conducted for two attitudes. It shows that the process of dissipating energy has a significantly different character depending on the pitch angle during landing.

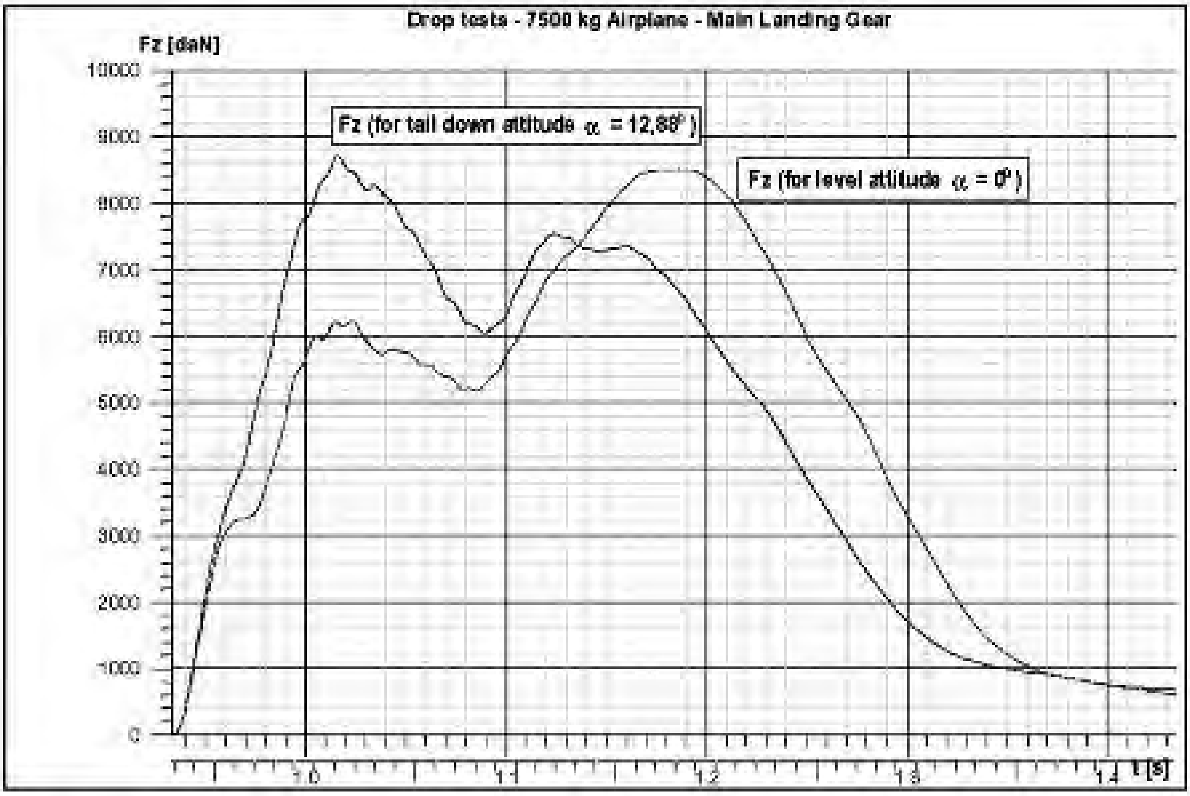


Fig. 41. Results of a main landing gear drop test shown for two attitudes (data – Institute of Aviation, Warsaw)

During the design phase, limit landing loads are calculated according to the following process.

- Calculation of limit loads for some basic cases, e.g. symmetrical landing. FAR 25 regulations or MIL-Standard provide standard coefficients to compute loads in other cases, such as drift landing, from these initial values.
- The calculated loads are then cross-checked by representative tests.

3.3. Ground loads

In this paragra ph, the FAR 25 requirements for the four main critical ground load conditions will be summed up: high speed taxiing, braking, turning and pivoting. These ground operations lead to critical static and fatigue loads for large MLG. They are the main drivers for large parts of the design. Therefore there is a need for evaluating manoeuvring loads through rational exploitation of in-service data statistics.

3.3.1. Taxiing

Taxiing, especially at high speed, induces high loads on landing gears and aircraft structures. So the critical condition generally appears in take-off configuration. When on the runway, each landing gear strut undergoes incremental loads with respect to its static load.

The FAR25 or CS25 requirements are the following:

The shock absorbing mechanism may not damage the structure of the airplane when the aeroplane is taxied on the roughest ground that may reasonably be expected in normal operation. (25.235)

Within the range of appropriate ground speeds and approved weights, the aeroplane structure and landing gear are assumed to be subjected to loads not less than those obtained when the aircraft is operating over the roughest ground that may reasonably be expected in normal operation. (25.491)

This vague text is completed by an additional paragraph in CS 25.

- For the main landing gear, the loads are:

$$Z = 1{,}5\frac{M_{to}\,g}{2} \quad X = 0.2 \cdot Z \quad Y = \pm 0.2\,Z$$

where

Z	is the vertical force
Y	is the lateral force
X	is the drag force
Mto	is the take-off mass

- For all the gears, a case for which the vertical load on each strut is equal to 1,7 times the static load at MTOW (Maximum Take-Off Weight) with the engine thrust taken into account has to be studied.

3.3.2. Braking

Braking is a significant source of dynamic loads. For several components of the landing gear, it is even often dimensioning, mainly for the NLG due to the pitching effect. Basically for all aircraft, brakes are typically mounted on the main landing gears (except some military aircraft). A strong brake application generates a pitch-down torque. The latter creates a very significant load on the nose landing gear. This dynamic load is usually a design driver for vertical loads, or if asymmetric braking is considered also for side loads. Loads created by braking are in most cases more severe than those created during derotation. This is of course specific for the NLG.

According to FAR & CS 25, three load cases have to be considered.

- Dynamic braking:
  Vertical loads and drag loads equal to 0.8 time the vertical are applied. The aircraft sustains a load factor of 1.2 at landing weight and 1 at take-off weight.
- Asymmetrical braking:
  It concerns the nose landing gear. A lateral load equal to 0.8 times the vertical load is applied.

3.3.3. Turning

To curve the aircraft trajectory, centripetal forces are needed. These appear thanks to the drift of the tyres, which generates lateral loads. They are proportional to the centrifugal acceleration. It is generally admitted that they are distributed on the level of each tyre proportionally to the local vertical reaction.

The most loaded landing gear is the one outside the turn. Turning at high speed is often dimensioning for the main landing gears.

3.3.4. Pivoting

Pivoting is a turn carried out at very low speed, with a very small radius. The minimum radius of the turn is obtained while pivoting around one of the main landing gears which wheels are braked. The resulting movement being very slow, the yaw torque is balanced by a moment of vertical axis, which appears by friction between the tyres and the ground.

Pivoting induces lateral and torsion loads.

3.3.5. Shimmy

Shimmy is the one thing to be avoided on landing gears. It is sinusoidal, combined lateral yaw motion of the landing gear. It comes from the interaction between the structural dynamics of the landing gear and the dynamic tyre behaviour. The typical frequency of this phenomenon is in the range of 10 to 30 Hz. In some cases it can become divergent. The motion amplitude then grows and induces annoying vibrations affecting the visibility of the pilot and comfort. They can even result in severe structural damage or landing gear collapse.

3.4. Calculation of landing gear ground loads

The loads calculation method will be presented on example of light aircraft. The ground loads appearing during landing process (landing loads) are determined and described on the basis of FAR 23 § 23.471 to 23.483 and additionally can be calculated according to FAR 23 Appendix C.

The landing loads include limit loads with descent vertical velocity for „level" landing conditions, for „tail down" landing conditions and for one-wheel landing conditions.

The base for determination of the loads is the correct definition of the load factor *n*. This factor is a function of the vertical velocity, vertical displacement of axle and of the wheel and tyre deflection.

If:

V_Z – sink velocity,

U_{AW} – max wheel vertical displacement,

U_T – max tyre deflection,

L – lift ratio,

m_R – mass of airplane reduced to landing gear,

η_{AW}, η_T – shock strut and tyre efficiency,

η_{WAW}, η_{WT} – displacement efficiency of shock strut and tyre,

where:

η_{WAW} = displacement of wheel's axle / max. displacement of wheel's axle

η_{WT} = deflection of tire / max. available deflection of tyre

than the energetic balance described as:

$$m_R V_Z^2/2 + m_R(1-L)g(\eta_{WAW} U_{AW} + \eta_{WT} U_T) = n \cdot m_R \cdot g \ \eta_{WAW} U_{AW} \eta_{AW} + n \ m_R \ g \cdot \eta_{WT} \eta_T U_T \quad (1)$$

and after transformation the limit inertia load factor *n* is obtained.

It can be seen, that the load-factor *n* is not a function of m_R.

The vertical ground reaction is:

$$P_Z = n \cdot m_R \cdot g$$

In general it is an aim to minimize the load factor *n* but according to FAR 23 § 23.473(g) it shall not be less than 2.67.

On the other side, the aircraft structure is designed to the inertia load factor *n*, which results from the aircraft maneuvering envelope.

Resulting from (1): if the inertia load factor *n* decreases than the vertical displacement of the axle and the wheel and tyre deflection increases. This can lead to the increase of landing gear parts geometry and finally – the mass.

Limit drop velocity, which is a function of the airplane landing weight and wing surface area, is defined in FAR 23 § 23.473(d).

Modified to SI units:

$$V = 0.509788\ (W / S)^{1/4} \quad [m/s]$$

where:

W – the airplane landing weight in [N]

S – wing surface area in [m^2]

For light airplanes this velocity can not be less than 2.12 [m/s] not be bigger than 3.05 [m/s].

The airplane landing weight is quantified in FAR 23 § 23.473(b) and (c).

The efficiencies η_{AW} and η_T for small airplanes are:

η_{AW} = 0.8÷0.9, (for oleo-pneumatic shock absorbers should not be less than 0.75)

η_T = 0.47÷0.5

Besides limit drop energy the landing gears have to absorb reserve energy equal to 1.44 times limit drop energy, according to FAR 23 § 23.727(a) and DEF-STAN 00-950.

To assure absorption of limit and reserve energy wheel and tyre must not bottom out. The values should be: $\eta_{WOK} < 0.9$ and $\eta_{WOP} < 0.95$.

The factor of lift wing load according to FAR 23 § 23.725(b) and § 23.727(b) is:

L = 2/3 for limit drop energy,
L = 1 for reserve drop energy.

Correctness of defining above coefficients and design parameters must be confirmed during drop tests that should be conducted according to FAR 23 § 23.725 to 727, using a proper landing gear unit attitude.

Typical graphs of the forces generated during drop tests are shown on Figure 42 and on Figure 43.

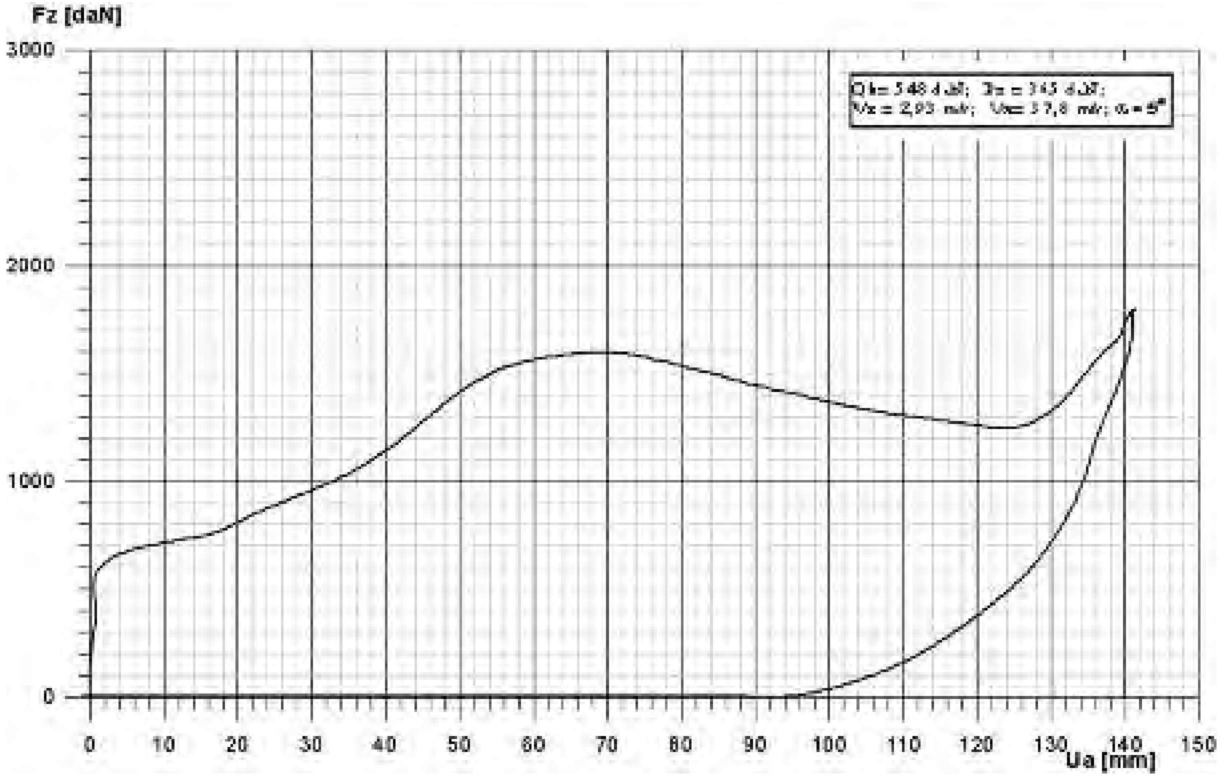


Fig. 42. Graph of the vertical force generated during drop tests for cantilever type L/G. Limit vertical velocity V_z = 3,05 [m/s] (data – Institute of Aviation, Warsaw)

It can be observed that the landing gear with the conventional oleo-pneumatic shock absorber, which has the damping orifice with fixed diameter or with applying a metering pin, may be optimize for only one drop velocity.

It is usually limit drop velocity.

For the other drop velocities efficiency of absorption can fall even to $\eta_{OK} = 0.5$.

So, there are generated loads bigger than optimized with efficiency $\eta_{OK} = 0.8 \div 0.9$.

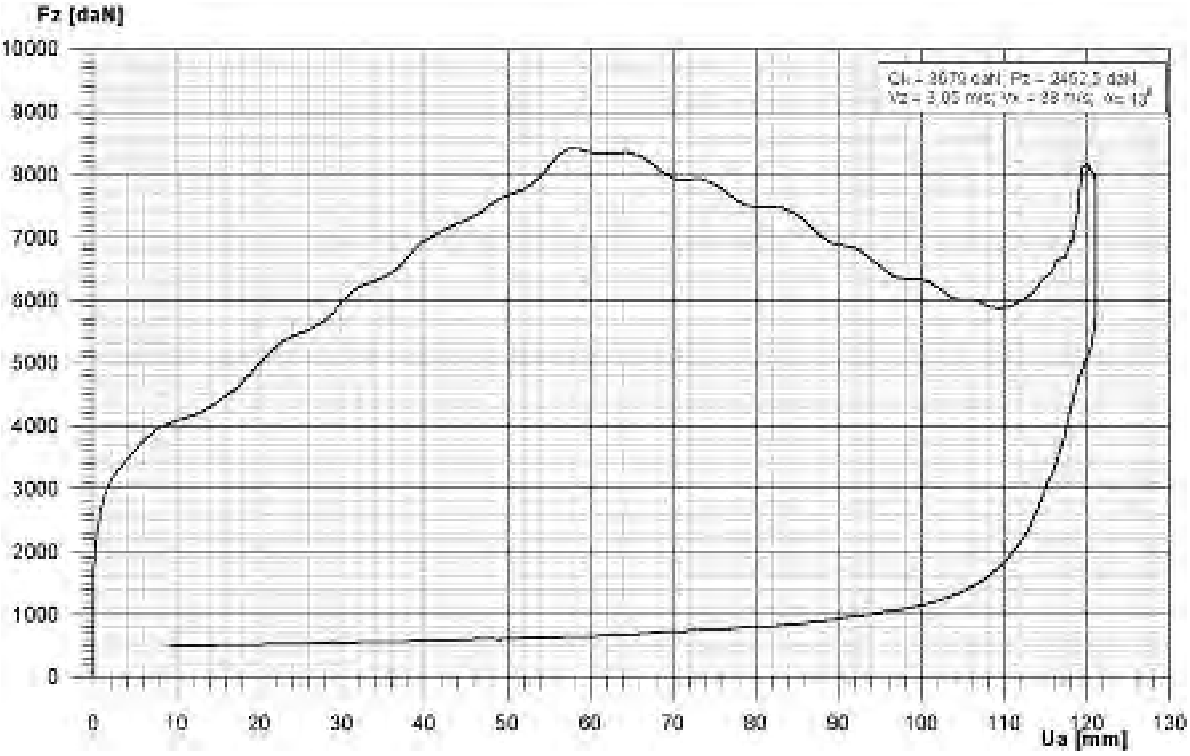


Fig. 43. Graph of the vertical force generated during drop tests for trailing arm type L/G. Limit vertical velocity $V_z = 3{,}05$ [m/s] (data – Institute of Aviation, Warsaw)

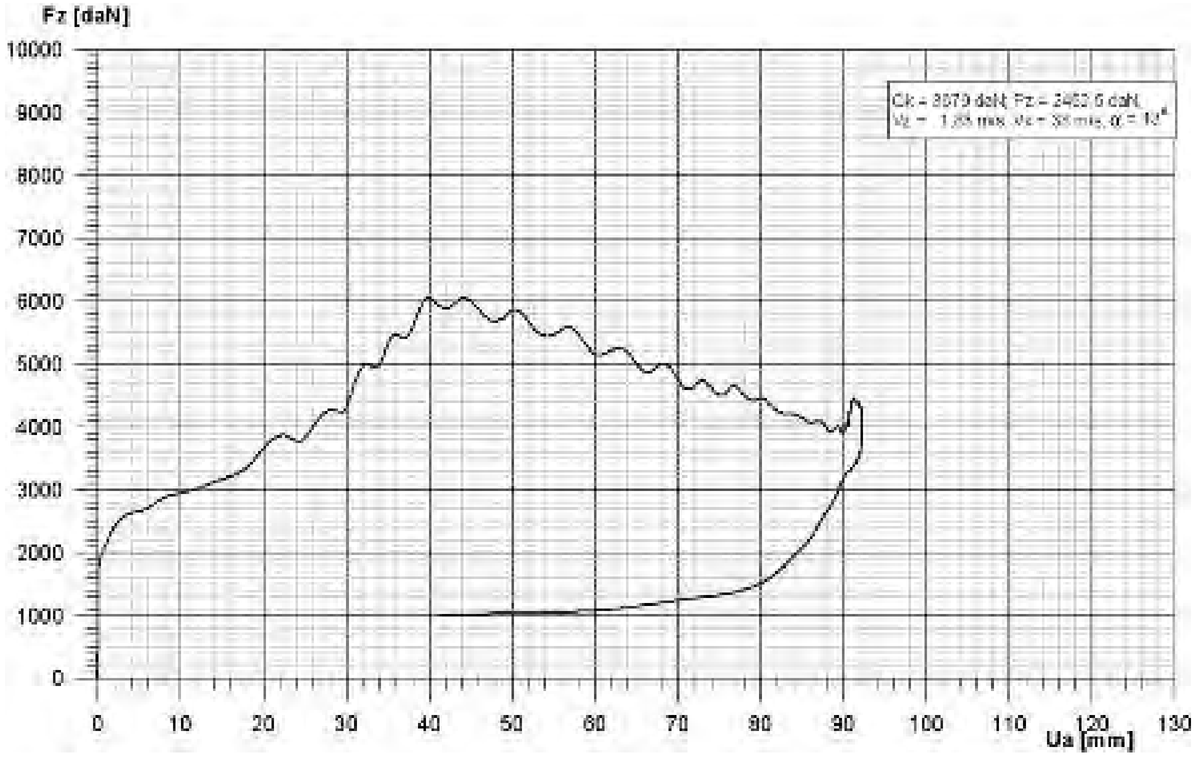


Fig. 44. Graph of the vertical force generated during drop tests for trailing arm type L/G. $V_z = 1{,}83$ [m/s] (data – Institute of Aviation, Warsaw)

Landings with limit drop velocities are a rather rare phenomenon that is proved by the table quoted below. The solution we look for should be supposed to result of optimal work of the shock absorber and to minimize load factor for each condition. This can have advantageous influence on fatigue durability of the landing gears.

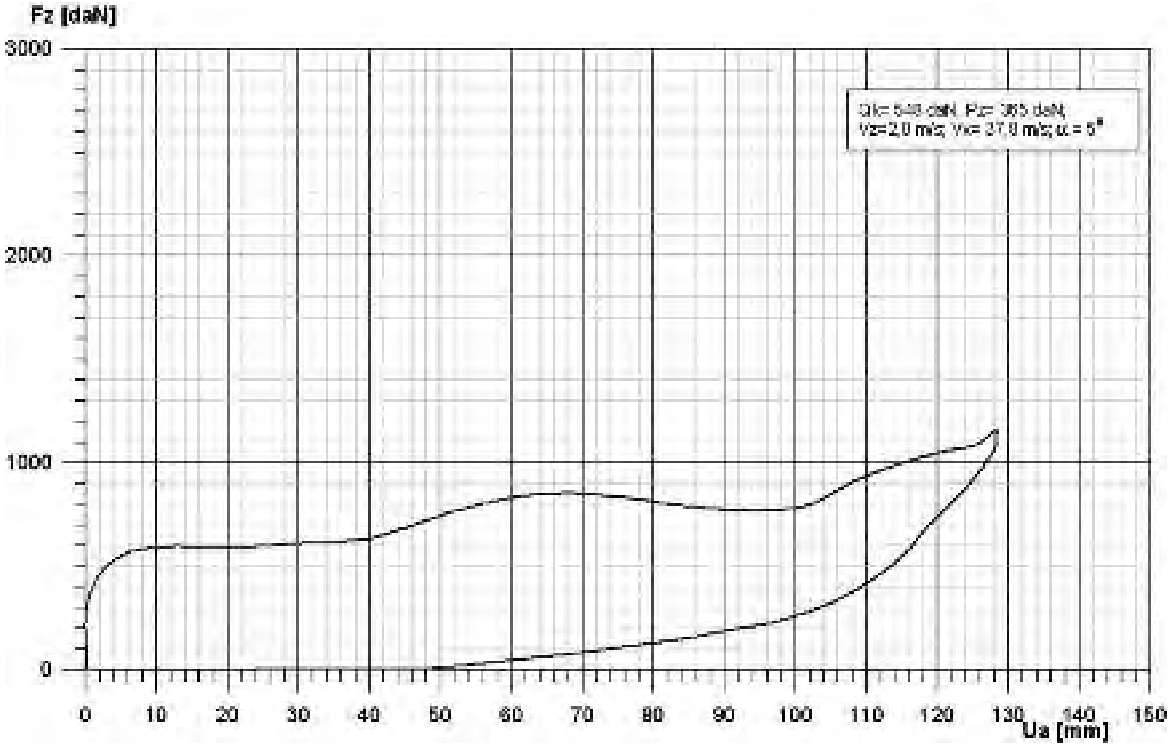
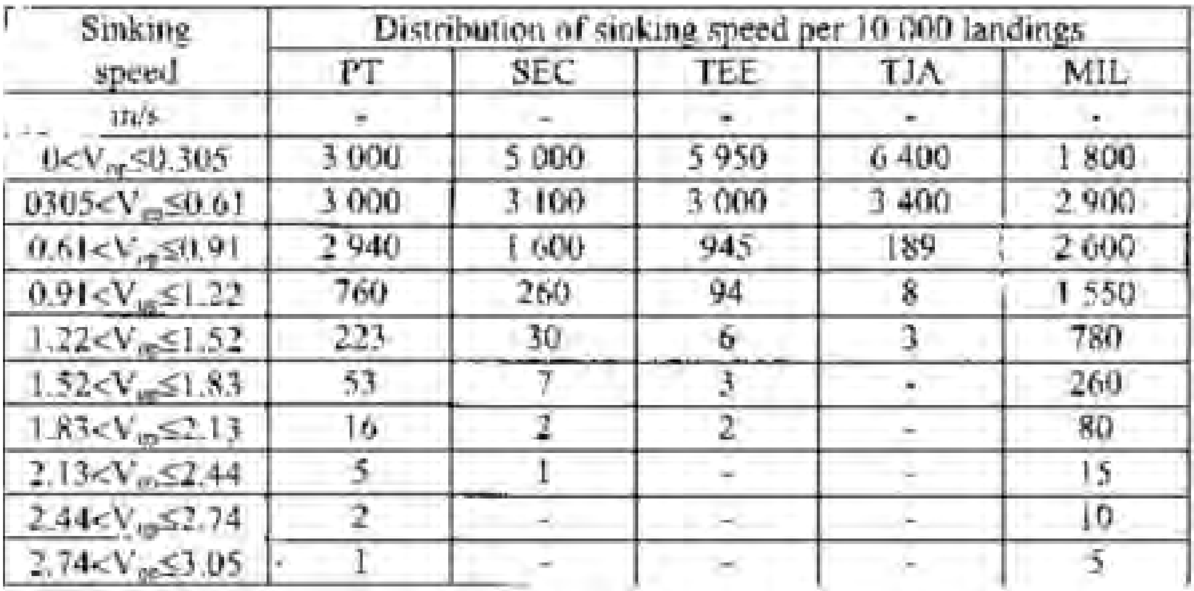


Fig. 45. Graph of the vertical forces generated during drop tests for cantilever type L/G. V_z = 2,00 [m/s] (data – Institute of Aviation, Warsaw)

Comparison of landing impact spectra



Sinking speed	Distribution of sinking speed per 10 000 landings				
	PT	SEC	TEE	TJA	MIL
m/s	-	-	-	-	-
$0<V_{op}\leq0.305$	3 000	5 000	5 950	6 400	1 800
$0305<V_{op}\leq0.61$	3 000	3 100	3 000	3 400	2 900
$0.61<V_{op}\leq0.91$	2 940	1 600	945	189	2 600
$0.91<V_{op}\leq1.22$	760	260	94	8	1 550
$1.22<V_{op}\leq1.52$	223	30	6	3	780
$1.52<V_{op}\leq1.83$	53	7	3	-	260
$1.83<V_{op}\leq2.13$	16	2	2	-	80
$2.13<V_{op}\leq2.44$	5	1	-	-	15
$2.44<V_{op}\leq2.74$	2	-	-	-	10
$2.74<V_{op}\leq3.05$	1	-	-	-	5

where:
PT – privat trainer – AFS-120-73-2
SEE – single engine exec. – ”
TEE – twin engine exec. – ”
TJA – twin jet airliner – ”
MIL – field – MIL-A-8866(ASG)

3.4.1. Shock absorbers loads

Loads generated during compression of gas.

If:

p – gas pressure,

A_p – effective surface area of piston.

Therefore the balances of force and the pressure is:

$$P_g = p \cdot A_p$$

At the same time with the change of shock absorber stroke changes of gas pressure appear as:

$$p = p_0 (V_0/V)^\gamma = p_0 (V_0/V - A_p S_p)^\gamma$$

where

p_0 – gas pressure in non compressed shock absorber

V_0 – volume of gas in non compressed shock absorber

V – volume of gas in compressed shock absorber

S_p – stroke of piston

γ – exponent of polytropic (see chapter 2)

The „gas force" in shock absorber is:

$$P_g = A_p p_0 (V_0/V_0 - A_p S_p)^\gamma$$

and the absorbed energy is:

$$E_g = \int_0^s P_g \cdot ds = \frac{p_0 \cdot V_0}{\gamma - 1}\left[\left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

The loads generated during flow of liquid through orifices

If:

Δp – difference of pressures between chambers on both sides of orifice,

V_c – speed of liquid flow through a small hole (orifice),

A_p – effective surface area of piston,

A_h – area of small hole,

ρ – density of liquid,

V_p – velocity of piston displacement,

P_d – the load of hydraulic resistance,

μ – coefficient conditioned by shape of orifice and the fluid viscosity.

Then:

$$P_d = \Delta p \cdot A_p$$

$$\Delta p = (\rho/2)V_c^2$$

$$V_p = ds/dt$$

$$V_p A_h \mu = V_p A_p$$

and

$$P_d = (\rho/2)(V_p^2 A_p^3/\mu A_h^2)$$

The friction loads

The friction loads appear between pairs of moving parts, especially between:

- head and cylinder of shock absorber,
- seals located in cylinder (no movement) and piston,
- seals located in floating piston and the inside area of the cylinder or of the piston.

The loads depend on geometry of the landing gear and on pressures in the shock absorber. They are bigger in cantilever type of landing gear/shock absorbers then in lever type.

For the first approximation it can be assumed that friction forces are proportional to the pressure of gas inside of a shock absorber:

$$P_{fr} = k \cdot P_g$$

For cantilever type landing gears k can be assumed: $k = 0{,}1 \div 0{,}15$
For lever type of landing gears k can be assumed: $k = 0{,}06 \div 0{,}08$

The total load

The total load generated by a shock absorber is the sum of all above described forces, so:

$$P_{\text{shock absorber}} = P_g + P_d + P_{fr}$$

4. ADDITIONAL REQUIREMENTS

4.1. Introduction

Landing gear used in airplanes certified according to FAR, respectively EASA CS or military standards must be capable of meeting requirements described in above regulations as well as special requirements determined by the airframer (aircraft requirements).

Additional requirements include environmental specifications and durability criteria.

4.1.1. Environmental requirements

Shock absorber should be capable of operating and/or being stored within environmental conditions under ambient parameters and in increased critical conditions.

The covering environmental conditions are specified in EUROCAE ED-14C/ RTCA DO-160C (1989) and RTCA/DO-160D (1997) standard “Environmental conditions and test procedures for airborne equipment” as well as in MIL-STD 810.

Ambient conditions:

These standards specify ambient conditions as:

- Temperature: +15 to +35 degrees Celsius with tolerances ±3 degrees Celsius.
- Relative humidity: not greater them 85 percent.
- Ambient pressure: 84 to 107 kPa with tolerances ±5 percent of specified pressure.

Temperatures

One of the most important parameters is the operating temperature. Critical items in Shock Absorbers are seals. They should be tested in the Shock Absorber Assembly for the specified temperature ranges.

Depending on the type of aircraft – the landing gears can be attributed to equipment categories.

The categories cover the range of environments known to exist in the majority of aircraft types and the locations where landing gears are installed.

The categories related to landing gears are:

- B2–for installation in non - pressurized and non controlled temperature locations on airplane that is operated at altitudes up to 7 620 m (25 000ft) MSL.

- C2–for installation in non - pressurized and non controlled temperature locations on airplane that is operated at altitudes up to 10 700 m (35 000ft) MSL.
- D2–for installation in non - pressurized and non controlled temperature locations on airplane that is operated at altitudes up to 15 200 m (50 000ft) MSL.

The temperature conditions connected with above categories are presented in the table below:

Categories	B2	C2	D2
Operating Low Temperature (^{0}C)	-45	-55	-55
Operating High Temperature (^{0}C)	+70	+70	+70
Ground Survival High Temperature (^{0}C)	+85	+85	+85

The rates applicable to the temperature variation are minimum 10 degrees Celsius per minute. According to the applicable requirements and standards special tests should be conducted. The methodology of tests are specify in RTCA/DO-160D.

Humidity/Corrosion

Another problem is connected with humidity. Tests should determine the ability of landing gears/shock absorbers to withstand either natural or induced humid atmospheres.

The main effect to be anticipated is corrosion, especially for airplanes that are in service in maritime environment.

According to the category landing gears may be required to be operated under conditions that are subjected to direct contact with outside air for periods of time in excess of that specified for the standard humidity environment.

The moisture should be provided by steam or by evaporation of water having a pH value between 6.5 and 7.5. Figure 46 shows an external humidity environment test.

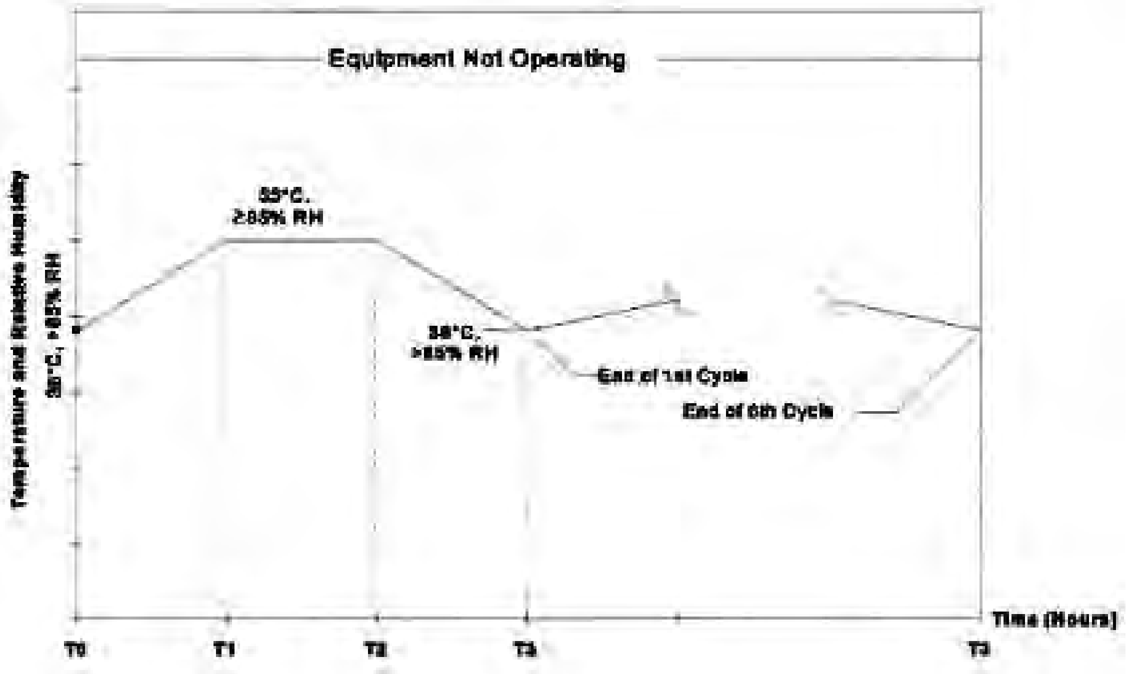


Fig. 46. External humidity enviroment test

The total test includes 6 cycles (144 hours of exposure). The Shock Absorber structure should be capable of providing resistance to corrosion during and after exposure to humidity up to 100% in a salty environment. It should include conditions with condensation of liquid and/or frost. All parts of Shock Absorbers have to be protected against corrosion.

Ozone

Shock absorber exposed to ozone have to withstand without deterioration. Usually this requirement is applied for non retractable L/G.

Fungus resistance

Aircraft equipment should not support fungal growth and any fungal growth should affect performance or use of the material. The primary objectives of the fungus test are to determine:

a. if the materials comprising the material, or the assembled combination of same, will support fungal growth, and if so, of what species,
b. how rapidly fungus will grow on the materiel,
c. how fungus affects the materiel, its mission, and its safety for use following the growth of fungus on the material,
d. if the materiel can be stored effectively in a field environment,
e. if there are simple reversal processes, e.g., wiping off fungal growth.

Sand and dust

Landing gears are installed in locations where the equipment is subjected to blowing sand und dust carried by air movement at moderate speeds. The main adverse effects to be anticipated in such conditions are:

- penetration into cracks, bearings and joints, causing interferences and,
- clogging of moving parts,
- this might act as nucleus for the collection of water vapour, resulting in a secondary effect of possible corrosion.

Sand and dust used in a suitable test chamber vented to the atmosphere shall be raised and maintained at concentration of 3.5 to 8.8 g/m^3. The jet velocity shall be maintained between 0.5 and 2.5 m/s. Special scrapers have to be applied to exclude sand and dust from moving parts (pistons, bearings, etc.). The structure of shock absorbers have to work without getting stuck during contact with sand and/or dust.

Rain

Aircraft equipment should be resistant with respect to rain, water spray, or dripping water. The features that should be checked are:

a. the effectiveness of protective covers, cases, and seals in preventing the penetration of water into the material.
b. the capability of the material to satisfy its performance requirements during and after exposure to water,
c. any physical deterioration of the material caused by the rain,
d. the effectiveness of any water removal system,
e. the effectiveness of protection offered to a packaged material.

Acoustic noise

Materials should resist the specified acoustic environment without unacceptable degradation of its functional performance and/or structural integrity.

Mechanical shock

Materials should physically and functionally withstand the relatively infrequent, nonrepetitive shocks encountered in handling, transportation, and service environments.

Accelerations

Equipment of military aircraft should structurally withstand the steady state inertia loads that are induced by platform acceleration, and manoeuvre in the service environment and function without degradation. The acceleration level that military equipment has to withstand is up to 15g, depend on the role of the aircraft.

Temperature shock

Materials should withstand sudden changes in the temperature of the surrounding atmosphere without experiencing physical damage or deterioration in performance. For the purpose of military applications „sudden changes" is defined as „greater than 10°C per minute".

Electromagnetic compatibility

The equipment shall be designed such that electromagnetic radiation originating from internal or external sources does not influence the correct function of the equipment nor shall the equipment influence other equipments.

Equipment should be tested for:

- conducted/radiated susceptibility,
- magnetic induction fields susceptibility,
- lightning strike.

Environment friendly materials

Today some materials or treatments are harmful for the environment and health. Some industry-wide developments to find replacement technologies are on their way. One of the best examples is the effort done to replace cadmium and chrome plating with alternative surface treatments.

Cadmium is used on many landing gear parts to provide protection against corrosion. Chrome is used to improve friction/wear properties as well as corrosion. Chrome itself is not toxic but the hexavalent chromium products found in the hard chrome plate process is. So, new processes have appeared. The most promising is the HVOF (High Velocity Oxygenated Fuel). It uses metal ceramic powder sprayed at very high speeds (~3000 km/h^{-1}) onto landing gears components. It then consolidates to form a resistant and protective coating.

4.1.2. Other general requirements

Durability / Life cycle

The life of an aircraft is in the order of 25 years. Equipments installed on an A/C shall sustain the same life, with as less scheduled maintenance work as possible. For a landing gear this equates to approximately 20.000 to 70.000 landings, depending on the use of the aircraft (long- or short haul).

Software design

The software code for control of the active circuits must be free of errors this shall be ensured by following the applicable software design guidelines. The software code shall contain fail safe functionalities.

4.1.3. Additional requirements for military aircraft

Military Aircraft in addition what is stated above to satisfy additional requirements that result from their purpose.

Temperatures

Landing gear equipments should not be adversely affected with following outside air temperatures:

	lower limit	upper limit
non operating temperatures	-30°C at sea level	+96°C at sea level for 25 min
	-34°C at 40 kft	+40°C at 40 kft
operating temperatures	-31°C at ground level	+70°C at ground level

Hydraulic equipment should function for the following temperatures of hydraulic fluid:

	lower limit		upper limit
operational	no continous flow during operation	-54 °C	+135°C
	continous flow during operation	-31°C	
non operational	-54°C		

Gunfire vibrations

Vibrations which origin from gunfire must not damage the installed equipment.

Nuclear hardening

The equipment shall be designed such that it functions throughout a nuclear event without any degradations in specified performance.

Biological/chemical (BC) hardening

The effects of contamination by BC agents shall not cause any short term (e.g. within 4 weeks) deterioration of materials such as to affect the equipment reliability or performance, nor shall it result in corrosion or damage to painted surfaces.

Battle damage

The equipment parts shall be designed to be easily salvaged after the equipment is battle damaged. The undamaged parts/modules will be considered as spares and reutilized. A modular equipment design should be considered

4.1.4. Additional for requirements for commercial aircraft

Today environmental requirements take a greater and greater importance. Respecting the environment, as well as safeguarding the health and safety are a crucial concern. There are numerous ways to achieve these goals. We will be interested here only on two great subjects under development in the world of the landing gears: the reduction of the noise and the elimination of some products such as chromium VI.

Noise reduction

Until the 1960s, engine noise dominated overall aircraft noise levels. Airframe noise was negligible by comparison and, moreover, noise wasn't a real concern. In the early '70s, the introduction of new engine technologies such as the high bypass ration turbofan led to a drastic reduction of engine noise level. Consequently, the airframe, including the landing gear, noise component became more important. During the approach, landing gear noise is up to one third of the total aircraft noise.

In 1971, ICAO (International Civil Aviation Organization) has adopted a series of standards and recommended practices. Those are gathered in Chapter 16 of the ICAO convention. The current trend is to constantly decrease the authorised noise levels.

Two major work axis are studied today:

- to find ways of reducing noise generated by current landing gears. They could be modified and fairings could be attached,
- to investigate alternative landing gear configurations with noise reduction taken as a primary design driver.

Chrome and Cadmium are not the only materials to be deleted from landing gear parts. In the „black list”, beryllium, nickel or VOCs (Volatile Organic Compounds) can be found.

5. TRENDS WITHIN INDUSTRY

The first remarkable trend within the world of the landing gears is the transition from the trade of equipment manufacturer to that of system provider / system manager. The landing gear suppliers are more and more often responsible for the system integration. The responsibility of a landing gear supplier will now extend from the tyre on the ground to the Landing Gear selector switch inside the cockpit.

The second way, which has been recently opened, is the introduction of smart materials and structures. These structures will carry micro-gauges to monitor stresses, strains and other data. Indeed, health monitoring of aging aircraft is more and more important. Those data will be useful from a maintenance point of view. Moreover they will give an insight view of the real operational life of a landing gear. This knowledge is very useful to create more realistic fatigue spectra.

The introduction of new materials with higher strength and toughness is also progressing. New steels, titanium and aluminum alloys are developed just as high strength composites. Organic and metallic matrices are both studied without distinction. The aim is always the same: to improve material characteristics and cost/weight efficiency (refer to section 2.6 Materials for details).

Another significant evolution is the electrification of the landing gear. After a long period during which hydraulics was the privileged source of power of aeronautics, the electric output makes a return in strength. After a noticed return within the flight controls, the landing gear designers take interest in its use to perform actuation and steering as well as even braking. The removal of hydraulics will lead to an increase in safety as a flammable liquid gets banned from e.g. hot parts as brakes are.

Additional research is aimed in the following directions:

- using active control systems for controlling ground loads (ADLAND - see chapter 6),
- using the friction phenomenon in energy absorption,
- introducing more welding technologies into landing gear production process.

6. ACTIVELY CONTROLLED LANDING GEARS

Paragraphs 6.1 to 6.4 refer to a literature survey on actively controlled landing gears, paragraph 6.5 briefly reflects Messier Dowty work done on that subject.

6.1. Introduction

For many years aircraft industry considered the possibility of introduction of controlled landing gears into airplanes. Motivation for these efforts was always depended on the branch of industry that the research was started by. Works conducted by civil transportation research centres took the safety of airplanes operations and passengers and crew comfort as a main aim to achieve. Military companies were also interested in introduction of controlled landing gears into their aircraft. The most basic motivation for military purposes were obtaining a more versatile device, which would be capable of landing on partly destroyed or repaired landing fields and introduce less loads into the aircraft structure.

Following the separation it was important for civil purposes to control the behavior of the nose landing gear, which induces high frequency vibrations into the fuselage during taxiing and for military applications main landing gears were the units that should be controlled because these work with highest vertical and horizontal velocities during landings on uneven pavements. In the following report the state of the art for military applications is presented.

Nowadays basically only oleo-pneumatic shock absorbers are in use, which are the most popular because of relatively high efficiency rates that can be obtained with these. The primary aim for each aircraft shock absorber is to dissipate kinetic impact energy by converting it into other forms of energy. Traditional passive oleo-pneumatic shock struts transform kinetic energy of a plane into work by forcing fluid to flow turbulently between internal chambers of the strut. The value of damping force generated by the device, depends on difference between fluid pressures values in internal chambers of hydraulic shock absorbers. By influencing the time characteristics of damping force, one can regulate an amount of energy dissipated by the shock absorber. Control of internal pressures in shock absorbers can be introduced in a number of ways: by changing of an orifice diameter through which the fluid is forced from one chamber of shock absorber to another; by adding an external hydraulic system connected to the chambers of shock absorber with capability of influencing the internal pressure; and by changing the properties of fluid itself. The last possibility can be obtained with use for example of magnetorheological fluids, which properties can be changed depending on an applied external magnetic field.

A review of the above mentioned solutions will be presented in the following sections.

6.2. Variable orifice diameter

Simple and the most widely used in current designs is a shock absorber which performance depends directly on the shock strut deflection. The dependence is obtained by introducing a so called metering pin inside of the shock absorber housing (Fig. 26). During deflection of the device, the metering pin fixed to the lower part of shock absorber, moves in orifice that is bored in upper part of shock absorber. Due to the variation of pin diameter the desired course of net orifice area can be obtained. Time characteristics of generated damping force in this kind of device are dependent only on deflection of the piston and do not correspond to changes in velocity. That is the reason why these are not able to react properly for wide range of landing cases e.g. for very high or very low impact energies that may occur during landing operations. Due to the concept limitations each landing gear must optimised for certain landing conditions, which are usually chosen as the most frequently noticed case.

6.3. Control of differential pressure in internal chambers of the shock absorber

The idea of introducing active systems with capability of controlling the behaviour of landing gear struts was considered since the 1970s [1]. Most of the propositions were based on the idea of influencing the shock absorber performance by regulating the internal fluid pressure over time. In reference 1 the authors present a simple classification of control systems that may be potentially used for active control of landing gear struts. Figure 47 shows three concepts of influencing the shock absorber forces. The first proposal is controlling the pressure level in the upper chamber by regulating the gas pressure. In the solution two gas accumulators were mounted to the upper part of the system and connected to the gas chamber. One of them was a low-pressure accumulator and the other was a high-pressure accumulator. A pair of electronically controlled valves controlled a pressure difference between both chambers to be on the required level. The second concept took into consideration introducing an additional hydraulic actuator, which paralleled the shock strut itself. In the third proposal the control unit was connected to the lower chamber of the shock strut and regulated the fluid pressure level. For all cases it was considered to accomplish control by means of a digital controller controlling the valves. The design that realized the idea of controlling the lower chamber fluid pressure was reconfigured in a way shown in figure 47. Finally the researchers chose the last approach, which they called Series Hydraulic Active Control Gear Model, for developing during further research.

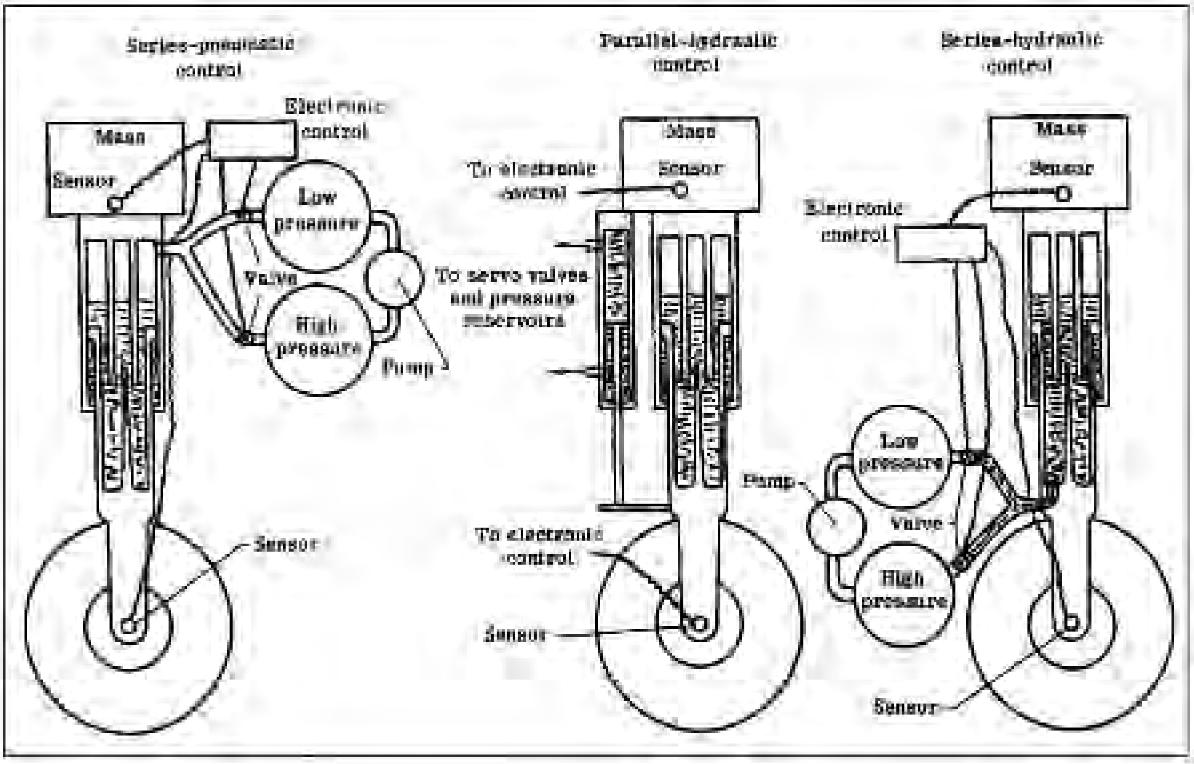


Fig. 47. Active control concepts for landing gears [7]

6.4. Control realization by introducing fluid accumulators

J. McGhee and H. Carden published in 1976 a report [2] giving an overall layout for operating landing systems actively controlled via using a hydraulic system connected in series to the shock strut (Fig. 48). The following example illustrates the active control landing gear during a landing impact and roll-out. The mass at the wing-gear interface was assumed to remain constant during landing; thus, the acceleration of the wing-gear interface reflected the force applied at this position. For a specific airplane design and the measured sink rate, the limit force, defined from the limit acceleration, was determined as a product of the mass and the square of the sink rate divided by the available shock strut stroke. A signal corresponding to the limit acceleration was input to the electronic control circuit. The electronic control circuit continuously monitored the acceleration signal at the wing gear interface and compared this signal with the limit acceleration signal. The control was actuated when the wing gear accelerometer signal exceeded the acceleration limit signal by a preset tolerance.

The report of J. McGhee and R. Dreher from 1982 [3] presents results of experimental testing of series hydraulic active control system for landing gear of small aircraft. The tests were performed on an experimental setup that consisted of a landing gear strut with assembled apparatus for changing the oil pressure inside of the upper chamber (Fig. 49). The apparatus contained two fluid accumulators and a servo valve connected to the shock strut in a series configuration. The tests that were performed, aimed on determination of the effectiveness of the existing control system. The unit was subjected to vertical drop tests , touchdown impact tests and traversing-the-step-tests.

Results showed that, during the impact phase of a landing, the active gear was effective in reducing ground loads applied to the simulated airplane relative to those generated by the passive gear. Data from the vertical drop tests showed that the effectiveness of the active gear increased with increase in touchdown sink rate. For example it was noted that the improvement was on a level of 8% for a sink rate of 0.9 m/s and on a level 32% for a sink rate of 1.7 m/s. However, the effectiveness decreased dramatically when a horizontal (ground) speed was increased. For example 31% of loads reduction for ground speed of 8 knots and only 9% percent of dynamic loads reduction at 40 knots.

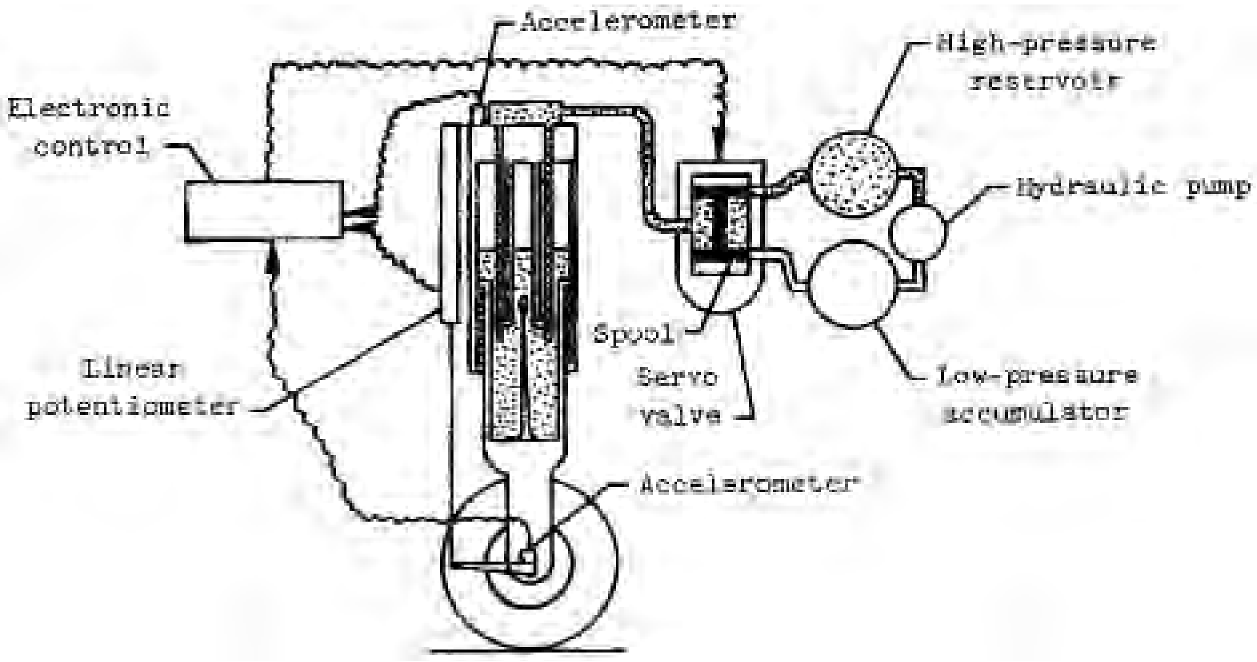


Fig. 48. Series hydraulic active control gear model [1]

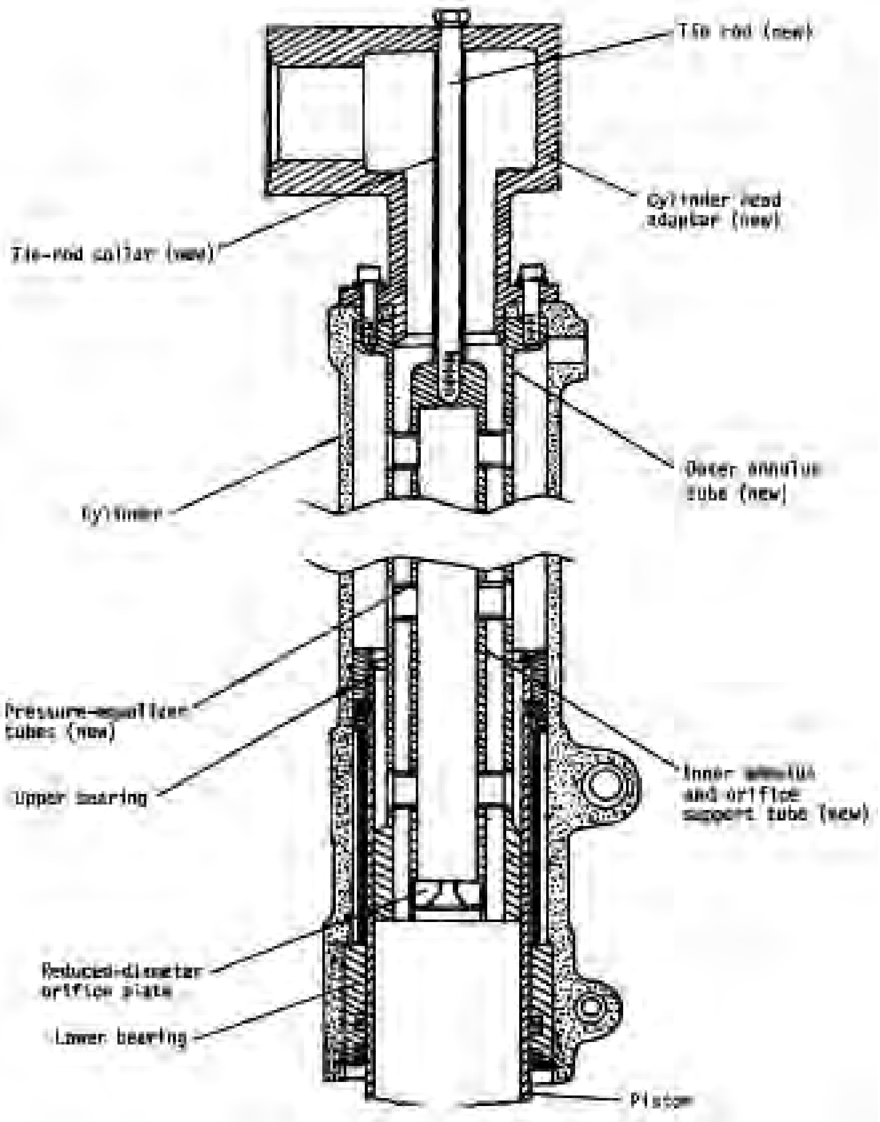


Fig. 49. Details of McGhee strut assembly [3]

These reductions in effectiveness may have been attributed due to increase in shock-strut „stiction" (= stick and friction effects) forces resulting from increased wheel „spin up" drag at the higher ground speeds.

The results indicated also that a hydraulic system is not fast enough to perform an efficient control procedure during impact phase of the landing. Fig. 50 and Fig. 51 present the results of drop tests that were performed in NASA laboratories. Figure 6.4 presents loads forces and stroke versus time. The graph showing the forces contains three lines: a solid line describing forces obtained with using an active gear, a dotted line describing forces obtained using a traditional landing gear and a dash-dotted line depicting the calculated desired force limit. The drop test was conducted assuming a horizontal velocity equal to 0 m/s so with minimal internal friction forces. It can be seen that the control unit starts to regulate after around 50 ms from the beginning of the process and around 25 ms after receiving control signals. This latency was too large for introduction of a closed loop control system.

Figure 51 shows results of a test with a horizontal velocity of about 40 knots. Only slight differences between force-levels for active and passive tests proved that internal friction of the shock strut is a very important factor influencing the behavior of the landing gear. It was concluded that a control system for landing gears should take into account friction forces as forces acting in parallel to the damping force generated by the shock strut.

In 1984 McGhee and Morris [4] proposed a complete control system for landing gears designated for reducing dynamic loads transmitted to airplanes fuselages during ground operations. This hydraulically based active system adjusted damping forces during taxiing. The system operation was briefly described as follows. The electronic controller determined the operating mode (take-off or landing), amplified and shaped feedback transducer signals, and implemented control laws. The control laws programmed into the controller were based on the following logic. Assuming the airplane mass remained constant during landing, the controller employed the sink rate to compute the touchdown energy of the airplane. During landing impact the gear compressed as the shock strut deflected, the hydraulic force in the shock strut increased, and the controller computed and compared the remaining work capability of the shock strut (determined from the accelerometer and linear potentiometer signals) with touch down energy. When the instantaneous work capability of the shock strut equaled or exceeded the touch down energy, the controller stored in memory the instantaneous value of the scaled acceleration (wing – gear interface force) for use as an impact limit force and enabled the servo loop. This force was maintained by removal/addition of hydraulic fluid from/to the shock strut piston.

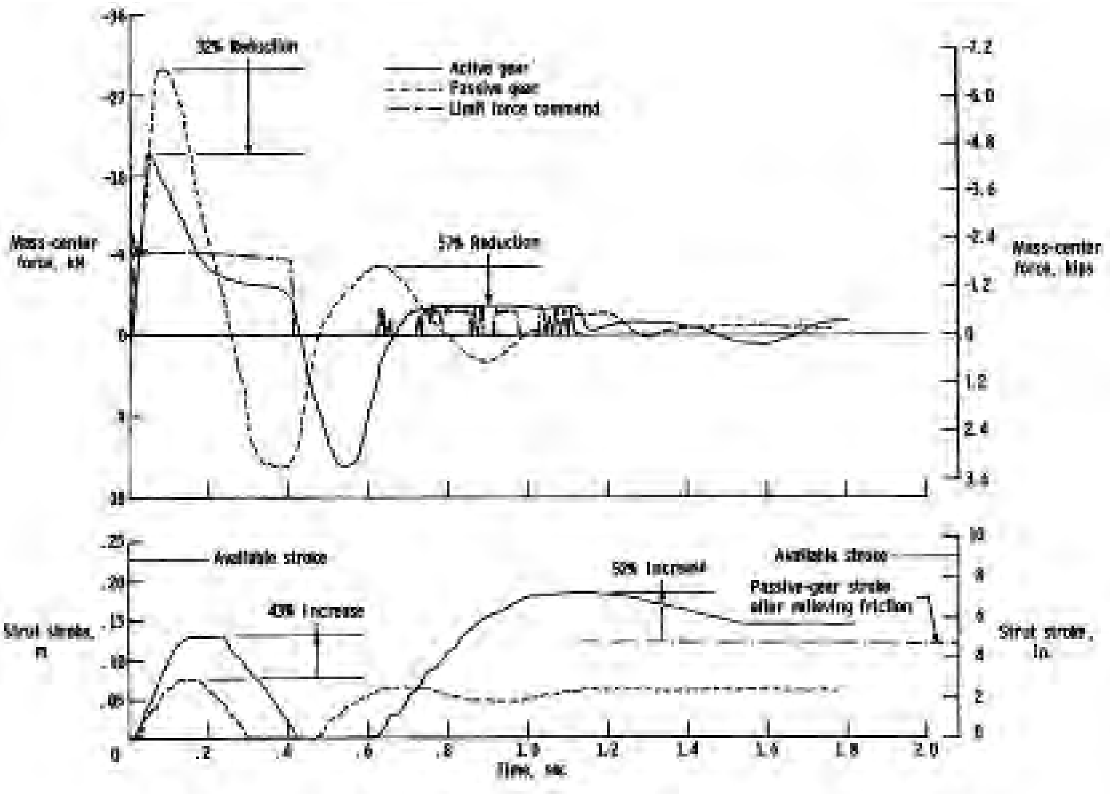
At a programmed value of momentum, for a specific airplane gear design, the controller linearly transitioned the impact limit force to a value of zero for rollout control. During rollout and taxi the control maintained the wing – gear interface force within a designed tolerance about zero force. After control initiation at touchdown, the controller continuously operated with a long time constant (10 seconds) control to return the gear stroke to the designed static equilibrium position.

By the proposed approach the authors obtained a slight decrease of touchdown loads and significant improvement of the ground operation performance.

In 1999 NASA Langley Research Centre [5] presented results of an active landing system developed for Navy aircraft. The main effort of the work was to propose an efficient way to solve a problem of operating military aircrafts on repaired bomb damaged landing fields.

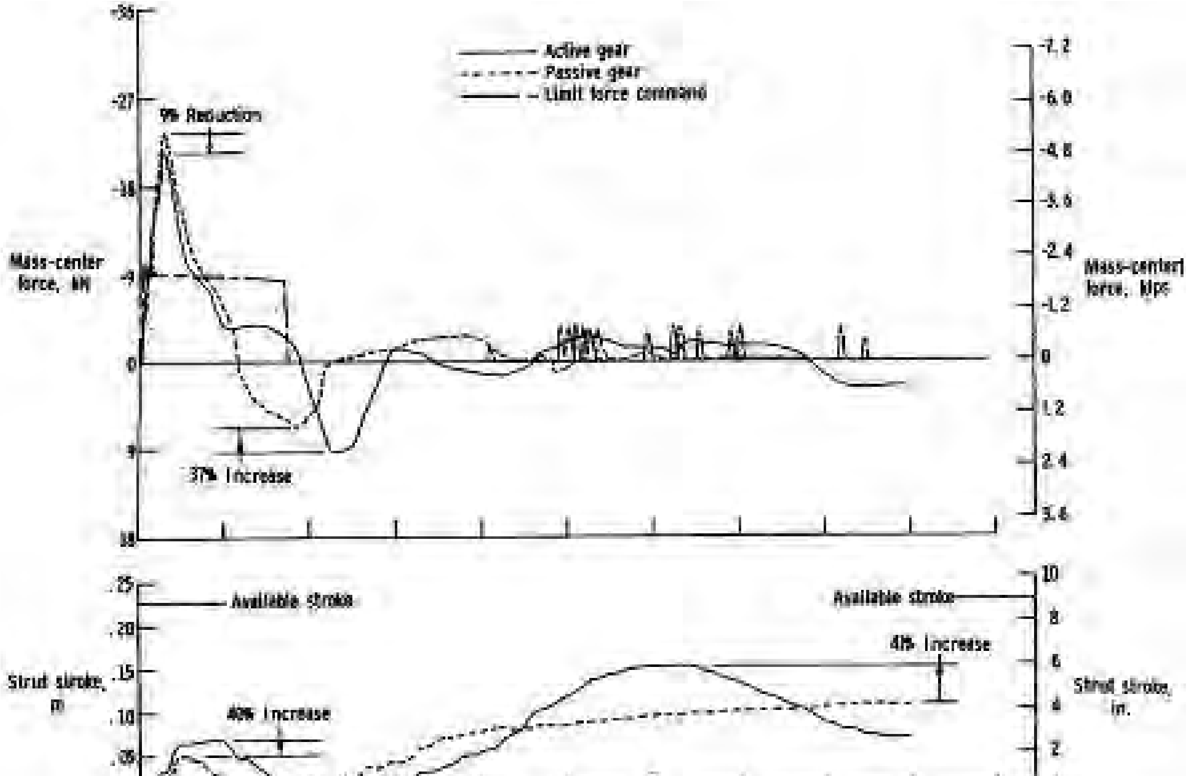
A prototype of active landing gear presented by the authors was based on an idea of series hydraulic active control system proposed in 70's. Possibility of fluctuating the pressure levels was reached by introducing pressure accumulators connected to both: upper and lower oil chamber and steered by electro servo valves. Figure 52 presents the general scheme of the proposed solution. The idea of influencing both upper and lower chamber simultaneously might have come from problems with operational delays that were determined by previous research.

The goal for control design was to minimize disturbance propagation from the ground into the fuselage. The control law was realized by means of steering the electronic valves.



(d) V_v = 1.7 m/sec (5.5 ft/sec); $p_a = p_p$ = 1834 kPa (266 psig); tests 51 and 49.

Fig. 50. Series hydraulic active landing gear – drop tests results



(b) V_h = 48 knots; V_v = 1.5 m/sec (5.0 ft/sec); p_a = 1328 kPa (192 psig);
p_p = 1407 kPa (204 psig); θ = 0°; tests 16 and 14.

Fig. 51. Series hydraulic active landing gear – drop tests results

Experiments were conducted on a typical landing gear, which was modified in a number of ways. Two electro hydraulic servo valves were attached to lower and upper chamber of the landing gear in a way, which enabled them to transfer pressurized fluid either into or out of the desired chamber. Both valves were designed to have flow-rates of at least 26 gal/min (98÷42 l/min) at 600 psi (4.137 MPa) with a response approaching 100 Hz. A high-pressure accumulator was mounted on the upper mass and was kept charged to a pressure approximately twice that of the static pressure in the landing gear. A low pressure accumulator was also installed in a way that when desired, pressurized hydraulic fluid in the landing gear could be directed there, reducing the transient back pressure that would tend to restrict the outward flow of the hydraulic fluid. The low- pressure accumulator was maintained at essentially atmospheric pressure. Ultimately the low-pressure accumulator was attached to an atmospheric pressure reservoir where the pump used to supply high pressure accumulator was located. The system was then pressure balanced evenly around the nominal static pressure of the landing gear, permitting roughly equal flow rates into or out of the gear at similar servo command levels. The piston head of the shock absorber was modified in order to obtain the same damping characteristics for both directions of the fluid motion. Control of the system was performed in a closed loop routine.

As a result authors obtained reduction of accelerations of a suspended mass by a factor of 4 with the proposed methodology. The control of impact forces was not performed.

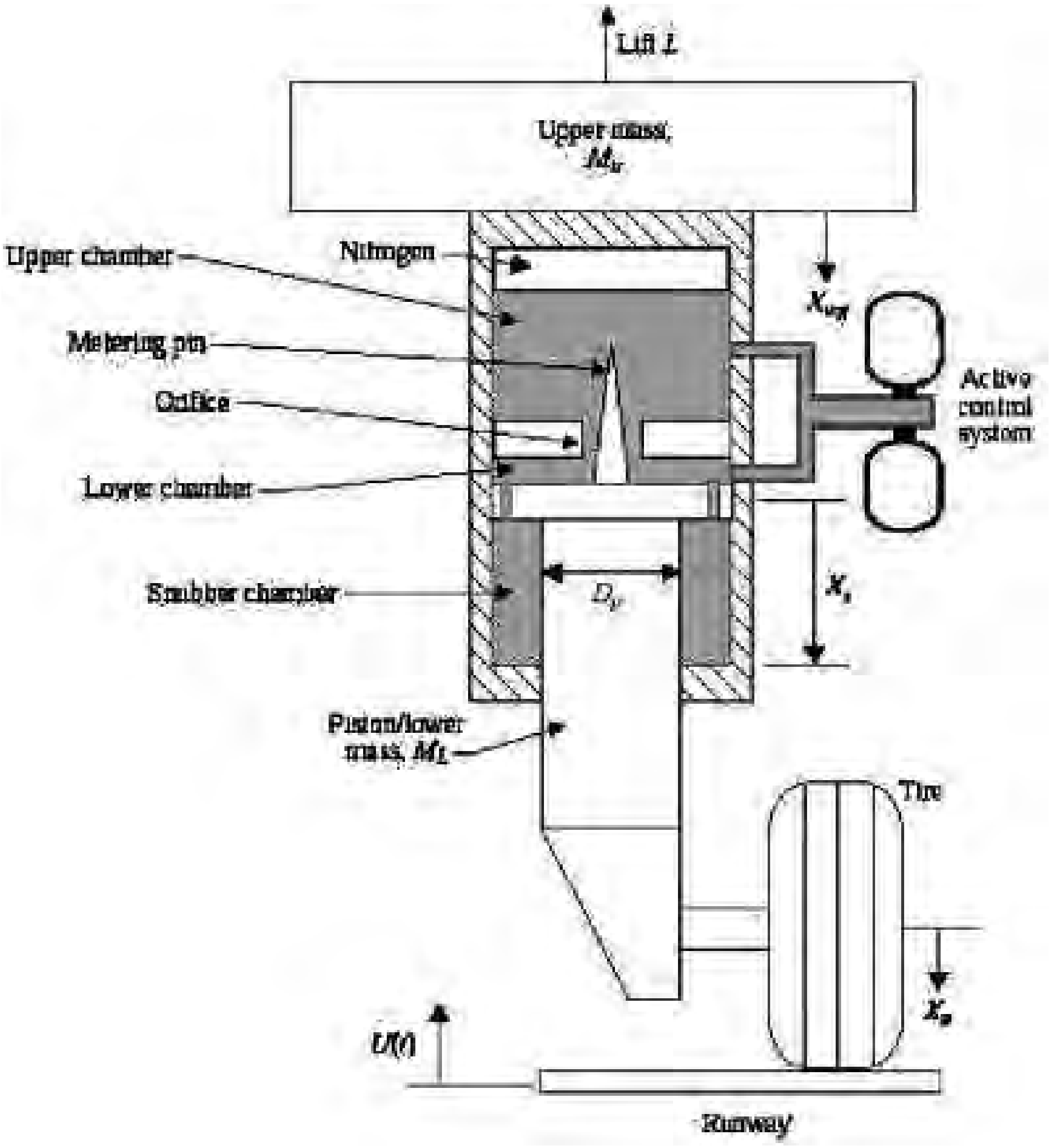


Fig. 52. Scheme of active landing gear system

6.5. Research at Messier Dowty

Three main programs dealt with active control of shock absorbers within Messier-Dowty. All three were based on the Dassault Mirage 2000 size fighter aircraft (Fig. 53) and carried out between 1984 and 1995.

Fig. 53. Mirage 2000

In detail the programs were split like shown below:

1. MLG with active control (1984¸1987).
2. Adaptive NLG (1990).
3. Optimized double stage shock absorber (1995).

Ad. 1)

The shock absorber functionality was controlled by modifying the diameter of the orifices between oil and gas chamber. The control was realized by use of a servo valve (Fig. 54).

118 different tests have been conducted (landing impact tests and the crossing of obstacles with fixed and variable orifice area) at CEAT test facilities in Toulouse. The results obtained showed that the predominating factor for optimization is rather the stiffness than the damping shock absorber and that a continuous control of the stiffness requires very significant hydraulic power. The load-reduction obtained during the tests was negligible, even though the hydraulic, mechanic and electrical portion of the system worked well.

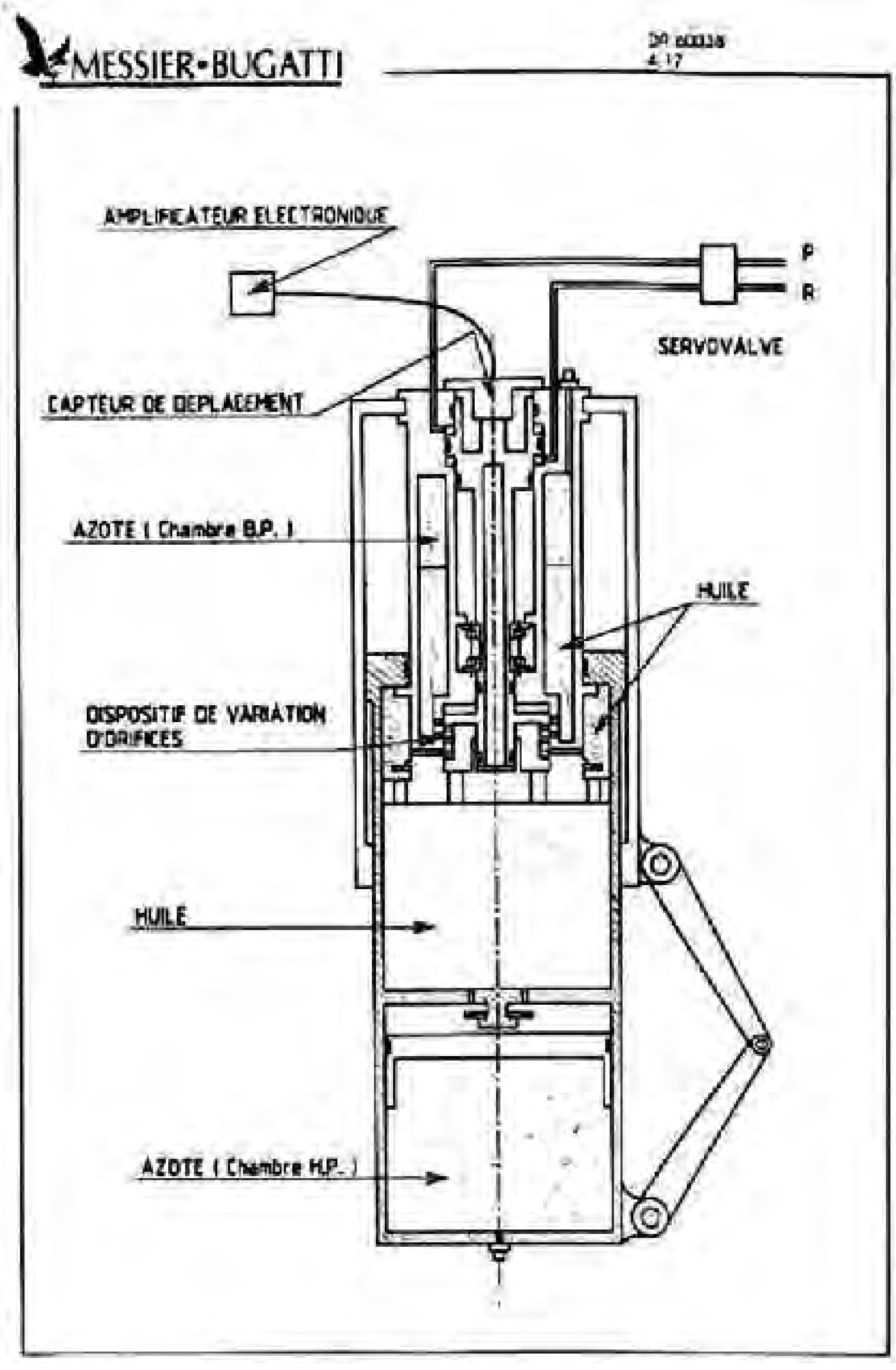


Fig. 54. Shock absorber with controll (servo valve)

Ad. 2)

The NLG was designed (based on the outcome of the above experience) in such a way, that the pilot could switch the unit form a single stage functionality (during landing impact – spring curve I (Fig. 55)) to a double stage functionality for take-off and/or taxi on unprepared or repaired runways (spring curve II (Fig. 55)). In case of a failure the system would still act as a traditional shock absorber (fail-safe).

Advantages were gained for taxiing and ground handling, e.g. for operation on repaired runways a load decrease for 20% was achieved with an active NLG shock absorber, on unprepared runways the gain was still 8%, so the operational capability of the aircraft was improved by that technology.

The disadvantages were an mass increase of about 20% and costs which were 10% higher than for the conventional design, taking the additional hydraulic supply not into consideration.

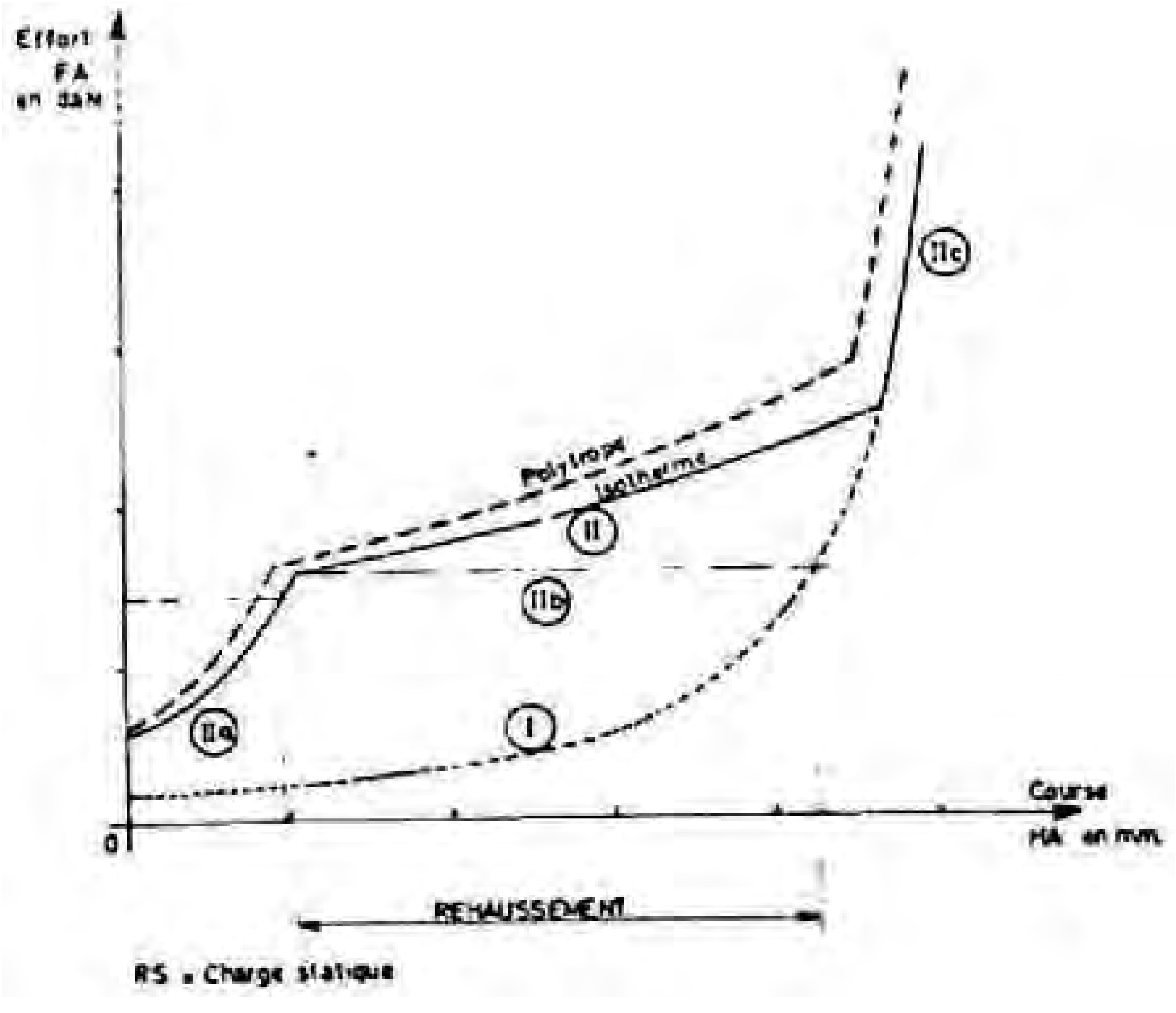
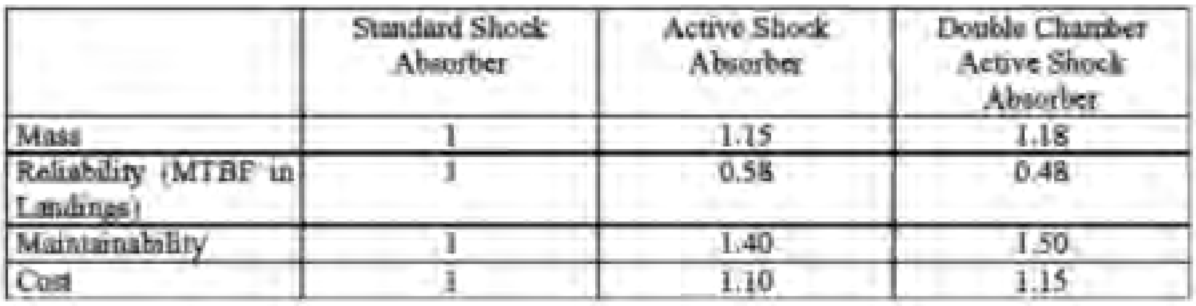


Fig. 55. Spring curve of active NLG

Ad. 3)

Here the economic side of active control was investigated. The results are shown in the table below:



	Standard Shock Absorber	Active Shock Absorber	Double Chamber Active Shock Absorber
Mass	1	1.15	1.18
Reliability (MTBF in Landings)	1	0.58	0.48
Maintainability	1	1.40	1.50
Cost	1	1.10	1.15

The results above illustrate that the active control can lead to a decrease in load introduction, but it could up to now not compete with respect to mass, reliability, maintainability and costs.

REFERENCES

[1] Ross I., Flight worthy Active Control Landing Gear System for a Supersonic Aircraft, NASA Contractor Report 3298, 1980.

[2] McGhee J.R., Carden H.D., A Mathematical Model of an Active Landing Gear for Load Control during Impact and Roll-out, NASA Technical Note, NASA TN D-8080, 1976.

[3] McGhee J.R., Dreher R.C., Experimental Investigation of Active Loads Control for Aircraft Landing Gear, NASA Technical Paper 2042, 1982.

[4] McGhee J. R., Morris D.L., Active Control Landing Gear for Ground Load Alleviation, AGARD 384, FMP Symposium, Toronto, Canada, 1984.

[5] Horta L.G., Daugherty R.H., Martinson V.J., Modelling and Validation of a Navy A6- Intruder Actively Controlled Landing Gear System, Langley Research Centre, Haumpton, Virginia, NASA/TP-1999-209124.

[6] Wang X., Carl U., Fuzzy Control of Aircraft Semi-active Landing Gear System, Proceedings of 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, 1999.

[7] Currey Norman S., Aircraft Landing Gear Design: Principles and Practices, AIAA Education Series, 1989.