3016 AERONAUTICAL ENGINEERING I

RESEARCH PROJECT:

LANDING GEAR SHOCK ABSORBER

Benjamin Chartier (1118519)
Brandon Tuohy (1106083)
Jefferson Retallack (1120801)
Stephen Tennant (1104453)
1 Abstract

The following report on landing gear shock absorbers is constructed in response to an aeronautical engineering research task.

The task is accomplished through a thorough analysis of available resources, and multiple consultations with the lecturer-in-charge.

The outcome of the investigation is a thorough understanding of the available landing gear shock absorption systems, including their performance attributes and relevant application. The most effective system was found to be the oleo-pneumatic shock absorber, and is therefore analysed in detail.
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2 Acronyms

FAR  Federal Aviation Regulations (United States)
USN  United States Navy
USAF  United States Air Force
LCN  Load Classification Number
FPS  Feet per second
UTS  Ultimate Tensile Strength
3 Introduction

The purpose of this report is to submit the findings of an investigation into landing gear shock absorbers.

The material included within the submissions include an overview of the various types of shock absorbers and the general equations pertinent to these designs, an in depth technical investigation of the oleo-pneumatic shock absorber, an analysis of multiple case studies, in addition to a discussion of future innovations.

The technical information contained within the report has been collected from a number of locations. Resources include internet-based technical document databases, the Barr Smith Library, and the lecturer-in-charge.
4 History

Shock absorption that implemented a wheeled landing gear was first evident in aircraft in October of 1906. Santos-Dumont’s ‘No. 14 bis’ first applied this design (refer Figure 1), as it was flown throughout Europe.

![Figure 1: Santos Dumont’s ‘No. 14 bis’ [16]](image)

Eight years later, wheeled landing gears, particularly those encompassing a tail wheel, were common in aircraft design. Landing gear configurations often contained primitive shock absorption on soft surfaces such as grass fields, which was achieved through a series of bungee cords wrapped around the main axles. The simple, rugged struts that supported such axles were attached to the fuselage, offering very limited energy absorption as supporting members.

The rapid progression of aviation as a weapon of war resulted in significant advances in shock absorption. World War 2 first saw retractable landing gears, in addition to various shock absorption methods such as restricted-flow hydraulic cylinders.

Post World War II technological advancements have resulted in improvements in shock absorber design, in addition to a number of other landing gear components. Shock absorption has advanced through avenues such as radial tyres and high strength aluminum alloys, while beryllium materials and fiber optic control systems have improved braking systems.
5 Background

The landing gear shock absorber is an integral component of an aircraft’s landing gear. The role of the shock absorber is to absorb and dissipate energy upon impact, such that the forces imposed on the aircraft’s frame are tolerable. These accelerations must be acceptable not only to structural components, but also to everything contained within the aircraft (passengers, cargo, weapons, avionics etc). The shock absorber may be an independent element, or integrated with the landing gear strut (refer Figure 2).

![Figure 2: Example of shock absorber and tyres [15]](image)

In order to achieve sufficient energy absorption, landing gear designers must consider all circumstances in which its shock absorbers are concerned. Such contingencies may be divided into landing cases and ground maneuvering cases.

5.1 Landing Cases

The examination of landing cases that an aircraft may endure involves analysis of the forces that the landing gear may endure upon numerous touchdown circumstances. Investigation of landing performance is critical to the shock absorber design, as the greatest energy absorption requirements are during
landing touchdown. A landing gear must perform to an adequate level during level landings, tail down landings, one-wheel landings, in addition to crabbed landings. In such situations, vertical, longitudinal, and lateral loads are exerted on the landing gear.

Vertical loads during landing (refer Figure 3) are the result of a non-zero vertical touchdown speed, and are dissipated by shock absorbers and tyres. The shock absorbers and tyres must absorb the maximum energy at the relevant design vertical velocity, such that the design reaction into the airframe is not exceeded, thereby avoiding deformation.

![Figure 3: Change of ground reaction force during landing [15]](image)

Longitudinal loads during landing are due to ‘spin up’ loads*, and braking and rolling friction. Lateral loads are a result of crabbed landings, cross wind taxiing, in addition to ground turning. Lateral and longitudinal loads are often resisted by a side brace and drag brace (refer Figure 2).

* ‘Spin up’ loads relate to the forces due to wheels spinning up. This force can be up to half of the vertical force due to landing, and occurs because the landing gear’s wheels are not spinning prior to touchdown.
5.2 Ground Manoeuvring

Shock absorbers are also essential in effective ground manoeuvring. Ground manoeuvring includes scenarios such as braking, taxiing, take off roll, landing roll, steering, and towing. Instances during ground manoeuvring that often pertain to shock absorbers include taxiing and take off/landing roll, as an aircraft often experiences shock loads due to uneven surfaces. Care is taken in considering such shocks, however, as ‘soft’ shock absorbers may induce motion sickness, whilst ‘hard’ shock absorbers may cause heaving or sudden jerks may be unpleasant to passengers.
6 Technical Aspects

6.1 Shock Absorber Types

One of the most critical parts of an aircraft is the landing gear arrangement, as this system is responsible for ensuring the safety of those onboard during take-off and landing. These sections of flight only account for a short period of time, and yet are the most susceptible to accidents.

For this reason significant time and effort is spent to ensure the reliability and functionality of these systems, with much of this time spent on an important component of the landing gear arrangement: the shock absorber system.

Shock absorbers are not only of significant importance to aircraft performance, but are also of significant cost. There are many different types of shock absorbers, with the most effective discussed in this report along with other less conventional methods of shock absorption.

The main types of shock absorption used in aircraft are:

- Rigid axle
- Solid spring
- Levered bungee
- Oleo-pneumatic shock strut
- Telescopic strut
- Articulating strut
- Semi-Articulating strut
- Tyres
- Reserve energy dissipation devices
- Controlled crashes
6.1.1 Rigid Axle

Rigid axle shock absorbers were used early in aeronautical history, and relied predominantly on two areas of shock absorption.

1. The first area of shock absorption is the axle that the tyres are fitted to. The axle is usually mounted to the fuselage with some vertical deflection capability in the form of a cushioned mounting pad, located above the axle. As the axle moves vertically upward, the pad is squeezed, thereby dissipating energy [14]. An alternate arrangement is mounting the axle on a spring, which is capable of larger deflection than a rubber pad.

2. The second area of shock absorption is in the form of the tyres, and are discussed in detail in Section 6.1.5. Tyres as shock absorbers vary in many factors depending on the aircraft they are fitted to, which may include the diameter, width, ply rating and internal pressure.

These two shock absorber methods are clearly seen in Figure 4 below:

![Figure 4: Rigid axle shock absorber [15]](image-url)
6.1.2 Solid Spring

The solid spring arrangement uses a solid but flexible strut, which connects the wheel arrangement to the fuselage. This strut is mounted at a lateral angle to enable some vertical displacement of the aircraft through bending in the strut, thus enabling shock absorption. As these struts are deflected, the wheel undergoes an angle of travel, as the wheel stroke is non-vertical (refer Figure 5). This motion causes excess wear on the sides of the tires, and is known as ‘scrubbing’.

An additional difficulty with this shock absorber arrangement is that there is no damping of the shock-induced vibration. Similar to an undamped spring system, the strut reverberates up and down causing the aircraft to ‘bounce’ during landing [14]. This type of shock absorber is appropriate for light aircraft where sink speeds are low and shock absorption is non-critical. The simplicity, combined with the low cost associated with solid spring shock absorbing systems justifies their suitability for light aircraft.

![Diagram of Solid Spring Shock Absorber](image)

**Figure 5:** Solid spring shock absorber with deflection [14]
6.1.3 Levered Bungee

The levered bungee system implements a rubber shock cord, which is essentially a rope made by binding a multitude of thin rubber strands in a woven arrangement, in conjunction with a metal strut to absorb energy. This configuration is similar to that of the solid spring arrangement, as the vertical displacement of the aircraft also induces an outward movement of the landing gear wheel, causing tyre scrubbing. [14]. However in contrast to its solid spring counterpart, the levered bungee system utilizes a rubber, porous shock absorber in addition to a metal strut. The result is improved energy absorption and damping abilities due to frictional forces between rubber strands. These systems, however, are purely historical in existence, and are never considered for modern designs.

Figure 6: Levered bungee shock absorber [15]
6.1.4 Oleo-Pneumatic Shock Absorbers

This shock absorber system is currently one of the most common in medium to large aircraft, as it provides shock absorption as well as effective damping. The basic structure of an oleo-pneumatic shock strut is outlined in Figure 7 below.

![Figure 7: Simple oleo-pneumatic shock strut [14]](image)

This type of shock absorber contains two integral components. The first is the compressed gaseous chamber that acts as a spring, absorbing the shock of the aircraft’s vertical movement. The second is the damping that acts by forcing hydraulic fluid through small holes (orifices), causing friction and thus slowing the oil. The integration of an oleo-pneumatic shock absorber into the landing gear system provides the most efficient shock absorption option.

There are three common configurations that implement the oleo shock absorber. These are telescopic strut, articulating strut and semi-articulating strut. The main difference between these three types of oleo shock absorbers is the positioning of the landing gear strut relative to the wheel and whether the shock absorber is structurally rigid with respect to the airframe.
6.1.4.1 Telescopic Strut

In a telescopic oleo strut arrangement, the shock absorber is positioned such that the shock absorber is housed within the main vertical strut of the landing gear. In this configuration the wheel deflects in the same line of action as the shock absorber as can be seen diagrammatically in Figure 8 below.

This arrangement has two distinct disadvantages. Firstly, when the shock absorber requires maintenance the entire landing gear system must be removed as the oleo-pneumatic shock absorber is housed within the main strut [14]. Secondly, as the oleo-pneumatic shock absorber is positioned in a vertical fashion and connected directly to the wheels, the shock strut must be of adequate length to absorb the landing energy. This means that a relatively long, imposing oleo-pneumatic shock strut is required.

6.1.4.2 Articulating Strut

In an articulating oleo-pneumatic strut configuration, the oleo-pneumatic shock strut is the link between airframe and a linkage on which the wheel is connected. This configuration causes the wheel to deflect in a circular arc around the axis of rotation, as seen in Figure 9. This allows the wheel stroke length to be larger than the shock
absorber stroke due to the mechanical advantage of the linkage. The drawback, however, is that the oleo-pneumatic strut must carry a greater load. Notice also that during the travel of the wheel the shock strut moves with respect to the airframe, as the linkage moves about the pivot point.

![Diagram of shock absorber](image)

**Figure 9: Articulating oleo-pneumatic strut configuration [15]**

**Triangulated**

This triangulated system is comparable to the levered bungee system, however the shock absorbing device is located above the triangulated structure and acts in compression. This system often incorporates an oleo-pneumatic strut in an articulating configuration, as can be seen in Figure 10 below. This arrangement, similarly to the rubber bungee and solid spring shock absorber, causes wheel scrubbing [14]. Due to the improved damping effect of the oleo-pneumatic shock absorber, this wear is reduced, as the arc of the travel is smaller, thus limiting the wear on the tyre.
6.1.4.3 Semi-Articulating

In a semi articulating oleo-pneumatic configuration (refer Figure 11), the shock absorber is positioned in the main support strut of the landing gear system. Such an arrangement is similar to the telescopic configuration, however the semi articulating system has a linkage connecting the oleo strut to the wheel. In this way the semi articulating arrangement can be thought of as a combination of both the telescopic and the articulating. The semi articulating oleo set up allows the wheel to traverse an arc around the pivot point of the gear linkage.
Figure 11: Semi-articulating OLEO configuration [15]

Trailing link

The combination of a high efficiency oleo-pneumatic shock absorber in conjunction with a hinged lever system provides arguably the best performing shock absorption system. The hinged lever system (refer to Figures 9 and 11) operates in the direction of travel and so prevents the scrubbing phenomenon associated with triangular arrangements. Uneven surfaces are more effectively traversed, as the lever action about the hinge aids the motion about obstructions and inconsistencies in the landing surface. This layout also minimises the ‘shimmy’ effect that is associated with telescopic strut layouts (similar to the rapid vibration of a worn shopping trolley wheel). This setup may be installed with either an articulating or semi articulating oleo strut.

One other advantage that this system has over its counterparts is that the design allows for the oleo-pneumatic strut to be removed during maintenance, whilst keeping the majority of the landing gear system in tact, thus minimising servicing time and labour.
6.1.5 Tyres

6.1.5.1 Introduction to Tyres

Tyres are a critical part of a landing gear setup, as they are involved in landing and ground maneuvering cases.

Aircraft tyres are much stronger and durable than tyres of similar sizes used for automobiles. The reasons for this are that aircraft tyres are subjected to high take-off and landing speeds (approximately double that of automobile tyre speeds), and large shock loads upon landing. For this reason the design of aircraft tyres is very detailed, ensuring that aircraft tyres will not blow out during take-off and landing, so that the tyres can withstand the rigors of landing loads, including tyre deflection and spin-up loads.

The geometry of an aircraft tyre is defined by the following parameters:

- $D$ = Bead Seat Diameter
- $D_F$ = Flange Diameter
- $D_O$ = Outside Diameter — Tire
- $D_S$ = Shoulder Diameter — Tire
- $W$ = Section Width — Tire
- $W_S$ = Shoulder Width — Tire
- $H$ = Section Height — Tire
- $W_S (max)$ = 0.85 $W$ (max) for Type III Tires
- $W_S (max)$ = 0.88 $W$ (max) for all other Types
- $D_S (max)$ = $1.64H + D$
- $H = \frac{D_O - D}{2}$

Figure 12: Tyre geometric parts list [15]
6.1.5.2 Performance Measures of tyres

Tyre manufacturers grade tyres in terms of the following four performance measures [15]:

1. **Ply Rating**

Ply rating is an indicator of tyre strength, and is defined by the maximum (recommended) static load that a tyre may carry and the corresponding internal pressure of the tyre. For instance, a 49x17 tyre (49 inch tyre diameter x 17 inch tyre width) with a 32 ply rating may actually only have 18 plies built into the carcass to accommodate the maximum static load at the corresponding inflation pressure, but as stated in the tyre description has a 32 ply rating (Dunlop Tyre Manual) and not an 18 ply rating.

2. **Max allowable static loading**

The maximum allowable static loading is the maximum load the tyre can carry when the aircraft is stationary. This value is smaller than the maximum allowable dynamic loading of the tyre during landing as in landings, the tyre experiences greater loads associated with shock absorption. The static load can be calculated from the equation $s_t = D_0 - 2(\text{loaded radius})$ and will vary from different manufacturers depending on the type of tyre and its associated ply rating [15].

3. **Recommended Unloaded Inflation Pressure**

The recommended unloaded inflation pressure is the maximum pressure (or preferably the recommended pressure) of the tyre when it is unloaded. Note that this pressure is not the maximum allowable pressure the tyre can safely withstand, as in loaded conditions the tyre volume decreases due to tyre displacement and thus the pressure increases, as seen in Figure 13 below.
Another key issue in inflating tyres is knowing the correct inflation pressure as inappropriate inflation can result in uneven wear of the tyre tread as in Figure 14 below.

![Figure 13: Tyre print area [14]](image)

![Figure 14: Uneven tyre wear caused by incorrect inflation pressure [6]](image)
The inflation pressure of tyres varies between higher pressure, lower volume tyres, used in military fighters and most new aircraft applications, and lower pressure higher volume tyres, used in older aircraft and applications needing softer landings to provide more leeway for rough landing surfaces such as military transports [15].

4. Max allowable runway speed

The maximum allowable runway speed of a tyre will depend on the application of the tyre and should be higher in heavier aircraft as these aircraft need greater speeds to allow them to achieve the required lift needed for takeoff.

6.1.5.3 Tyre Clearances

Tyres must be able to fulfill certain clearance requirements. During take-off and landing the tyres experience centrifugal forces causing the diameter to increase and the width to decrease and during the working life of a tyre, due to creep and stress relaxation, tyres increase in size by approximately 4 percent in width and 10 percent in diameter (Roskam). Tyres must have a clearances to accomodate these growth factors.

6.1.6 Reserve energy dissipation devices

In some cases design sink speeds are exceeded, due to variables such as wind gusts, fluctuations in ground surface and human error, so larger loads may be applied to shock absorbing elements. To compensate for these rare occasions an extra energy absorbing device is fitted between the conventional shock absorbing element and the aircraft structure. These reserve energy dissipation devices absorb energy by plastically deforming in preference to the aircraft structure and landing gear elements, similar to ‘crumple zones’ found in modern cars. The device may take the form of a composite plastic tube or an additional fluid damper with an energy release blow-off valve. The devices are most convenient when implemented such that they can easily be replaced during maintenance as the removal of the whole landing gear assembly is both time consuming and labour intensive [10].
6.1.7 Controlled Crashes

This is last resort in shock absorption as this type of shock absorption can result in damage to the aircraft fuselage, or worse, a complete crash.

This form of shock absorption utilises the fact that all other forms of shock absorption have been unsuccessful in dampening the vertical energy of the aircraft and this form of shock absorption is reserved for crash landings only.

6.1.8 Conclusion

Oleo-pneumatic shock absorbers offer the best option for shock absorption in aircraft, in general. Figure 15 below shows the difference in efficiency between the alternative shock absorbing elements. It is clear the oleo-pneumatic shock absorbers are the most efficient shock absorbing elements and are thus the most common type of shock absorber in production today, especially for the mid to large sized aircraft. Solid spring shock absorbers are still very common as the main landing gear on light civil aviation craft, such as Cessna aircraft, due to their simplicity and low cost. For any application involving a combination of high aircraft weight, high sink speed or minimum gear space an oleo pneumatic strut should be considered for its obvious gains in performance, small size and low weight.

![Figure 15: Efficiencies for alternative shock absorbing elements (Jenkins, 1989)](image)
6.2 Shock Absorber Equations

Designing a shock absorber is an iterative process, as each aircraft is individual and the shock absorber must be optimised to reduce size and weight, whilst maintaining the desired performance. The following set of equations offer a general starting point for this design process. The conceptual design is tested using a drop test and its performance is measured. Often the design must be altered from the initial conception to find an optimum balance between performance, weight and size. These equations have been derived from a basic energy analysis of an aircraft during landing and have been adapted from Roskam’s book *Airplane Design: Part IV*.

The touchdown kinetic energy or the kinetic energy in the vertical direction at touchdown can be approximated from:

\[
E_t = 0.5 W_L \left( \frac{v_z^2}{g} \right) \tag{Equation 6.1}
\]

Where:

- \( E_t \) – touchdown kinetic energy of the aircraft
- \( W_L \) – weight of the aircraft at landing
- \( v_z \) – design vertical touch rate

This equation may be further extended to include potential energy term for completeness. Touchdown energy, \( E_t \), becomes:

\[
E_t = 0.5 W_L \left( \frac{v_z^2}{g} \right) + (W_L - L)(s_s + s_t) \tag{Equation 6.2}
\]

Where:

- \( L \) – the lift at landing
- \( s_s \) – the shock absorber stroke
- \( s_t \) – the tyre deflection
For conservative design it is assumed that all of the energy at touchdown is absorbed by the main landing gear. The energy that can be absorbed by the shock absorber and the tyres is as follows:

\[ E_{\text{absorbed}} = W_L N_g (\eta_i s_i + \eta_s s_s) \]  
(Equation 6.3)

Where:

- \( N_g \) – The landing gear load factor (the ratio of maximum load per leg to the maximum static load)
- \( \eta_i \) – tyre efficiency
- \( \eta_s \) – shock absorber efficiency

It is assumed that by definition: \( W_L = n_s P_m \)

As: \( n_s \) – number of main gear struts

\( P_m \) – the maximum static load per main gear

\[ E_{\text{absorbed}} = n_s P_m N_g (\eta_i s_i + \eta_s s_s) \]  
(Equation 6.4)

Thus shock absorber energy can be equated to the touchdown energy, \( E_t \).

\[ n_s P_m N_g (\eta_i s_i + \eta_s s_s) = 0.5 \left( W_L \left( \frac{v^2}{g} \right) \right) + (W_L - L)(S + S_i) \]  
(Equation 6.5)

Design touchdown rates can be found in Section 6.2.1. Some rough values of efficiencies and landing gear load factors can be approximated from Sections 6.2.2 and 6.2.3. By using these values the required stroke length of the shock absorber can be determined. If we assume that the potential energy term is negligible, if the lift generated is approximately equal to the weight of the aircraft during landing, then the stroke length is determined by:

\[ s_s = \left[ \left( \frac{0.5 \left( W_L \left( \frac{v^2}{g} \right) \right)}{n_s P_m N_g} \right) - \eta_i s_i \right] / \eta_s \]  
(Equation 6.6)
This above equation can further be simplified as \( W_L = n_s P_m \) by definition:

\[
s_s = \left[ \frac{v_z^2}{2gN_f} - \eta_s s_s \right] \eta_s
\]

(Equation 6.7)

Note that the shock absorber stroke length does not depend on the aircraft’s weight, but only on its vertical sink speed, load gear factor, the tyre parameters, and overall shock absorber efficiency [10]. For design length an inch is added to this length as an additional safety margin.

\[
s_{s,\text{design}} = s_s + 1/12 \text{ ft}
\]

(Equation 6.8)

The diameter of the shock absorber strut can be estimated from:

\[
d_s = 0.041 + 0.0025P_m^{0.5} \text{ in feet, where } P_m \text{ is in pounds. (Equation 6.9)}
\]

This analysis is only valid for telescopic strut or similar shock absorbers where the shock absorber stroke is equal to that of the wheel stroke. For articulating and semi articulating configurations an independent analysis must be undertaken to incorporate the relationship between stroke length and wheel travel [15].

6.2.1 Design Touchdown Rates

<table>
<thead>
<tr>
<th>Design touchdown rates</th>
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<tbody>
<tr>
<td><strong>FAR 23</strong></td>
</tr>
<tr>
<td><strong>FAR 25</strong></td>
</tr>
<tr>
<td><strong>USAF</strong></td>
</tr>
<tr>
<td><strong>USN</strong></td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
</tr>
</tbody>
</table>

* no less than 7 fps and no more than 10 fps
6.2.2 Gear Load Factors

<table>
<thead>
<tr>
<th>Aircraft type</th>
<th>N_{gear}</th>
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<tbody>
<tr>
<td>Large bomber</td>
<td>2.0-3.0</td>
</tr>
<tr>
<td>Commercial</td>
<td>2.7-3.0</td>
</tr>
<tr>
<td>General aviation</td>
<td>3.0</td>
</tr>
<tr>
<td>Air Force fighter</td>
<td>3.0-4.0</td>
</tr>
<tr>
<td>Navy fighter</td>
<td>5.0-6.0</td>
</tr>
</tbody>
</table>

6.2.3 Shock Absorber Efficiency

<table>
<thead>
<tr>
<th>Type</th>
<th>Efficiency, ( \cdot )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel leaf spring</td>
<td>0.50</td>
</tr>
<tr>
<td>Steel coil spring</td>
<td>0.62</td>
</tr>
<tr>
<td>Air spring</td>
<td>0.45</td>
</tr>
<tr>
<td>Rubber block</td>
<td>0.60</td>
</tr>
<tr>
<td>Rubber bungee</td>
<td>0.58</td>
</tr>
<tr>
<td>Oleo-pneumatic</td>
<td></td>
</tr>
<tr>
<td>-Fixed orifice</td>
<td>0.65-0.80</td>
</tr>
<tr>
<td>-Metered orifice</td>
<td>0.75-0.90</td>
</tr>
<tr>
<td>Tyre</td>
<td>0.47</td>
</tr>
</tbody>
</table>

6.2.4 Drop test Equations:

To test a given landing gear a drop test is conducted. Each landing gear must pass this test in order to meet safety regulations, and demonstrate its reserve energy absorption capacity. The vertical kinetic energy can be calculated from the aircrafts sink speed and its weight and is given by equation 6.1:

\[
E_v = 0.5(W_L) \left( \frac{v_z^2}{g} \right)
\]

The drop test on the landing gear is conducted with the same mass. At a given height the potential energy is given by:

\[
E_p = W_L H
\]  
(Equation 6.10)
If we equate the potential energy of the drop test (Equation 6.10) to the vertical kinetic energy of the aircraft (Equation 6.1) then we get:

\[ 0.5(W_L) \left( \frac{v_z^2}{g} \right) = W_L H \]  

(Equation 6.11)

\[ \therefore H = \frac{v_z^2}{2g} \]  

(Equation 6.12)

For a given sink speed the drop test height can be calculated accordingly.

For a sink speed: \( v_z = 12 \) fps = 3.6 m/s

Equivalent drop test height:

\[ H = \frac{3.6^2}{2 \times 9.81} = 0.66m \]
7 Oleo-Pneumatic Shock Absorber

7.1 Introduction

Oleo-pneumatic shock absorbers are highly efficient as they can absorb and remove vertical kinetic energy simultaneously. This is due to the combination of the spring force, due to the compression of the gas, the damping or removal of energy, due to the flow of hydraulic fluid through an orifice element. This combination of elements allows the system to be compact and highly efficient. Figure 16 below shows a comparison of all shock absorber types based on a weight-normalised efficiency calculation. This plot shows the significant advantage of using an oleo-pneumatic system.

The three layouts of an oleo-pneumatic shock absorbers, telescopic strut, articulating and semi-articulating, were discussed in detail in section 6.1.4 under types of shock absorbers.

![Efficiency - weight ratios for various shock absorbers](image)

Figure16: Efficiency - weight ratios for various shock absorbers
7.2 Parts

The oleo pneumatic shock absorber comprises several key parts that dynamically interact to absorb the landing energy of aircraft. Typical Oleo pneumatic shock absorbers contain:

- An outer cylinder
- An inner cylinder
- A piston
  - Piston rod
  - Piston head
- Working Fluids
  - Gas
  - Liquid

The outer cylinder encases the whole shock absorber and remains static with respect to the airframe during operation. This cylinder must be able to withstand the internal pressure created by the working fluid and gas during operation [14]. The inner cylinder is free to move in an axial direction with respect to the outer cylinder. The inner cylinder must also be able to withstand significant internal pressure, due to both static and dynamic loading. The piston and piston rod are situated within the outer cylinder and remain stationary. The piston head has a series of holes in it, which act like an orifice plate, and is critical in absorbing the energy of the landing [14]. The inner cylinder is filled entirely with the hydraulic fluid, usually some type of oil, and the outer cylinder contains a combination of working fluid and working gas, which is most commonly pure nitrogen. Variations on this setup exist however they all contain a cylinder, an orifice plate, hydraulic fluid and a pure gas.

7.3 Kinematics of Operation

Oleo pneumatic shock absorbers comprise of an outer cylinder in which a piston sits which absorbs the excess energy. The piston is fully submerged in a hydraulic fluid, or oil, and the outer cylinder contains part hydraulic fluid and the rest is gas.
The piston, or inner cylinder, has a series of holes in the top which act like an orifice plate.

When not loaded the inner cylinder is fully extended with respect to the outer cylinder, due to the excess pressure of the gas inside the outer cylinder. When the landing load is applied to the bottom of the inner cylinder it forces it to move in a longitudinal direction, into the outer cylinder, as seen in the middle diagram of Figure 17. This places pressure on the hydraulic fluid within the inner cylinder, and forces it through the holes in the piston head. This is effectively the dampening of the system where the majority of the landing energy is absorbed, as the vertical kinetic energy is converted to heat energy within the hydraulic fluid. As the hydraulic fluid passes through the piston head it reduces the volume of the gas within the outer cylinder. This provides substantial resistive force, and forces the hydraulic fluid back through the piston head, which removes more energy, in a recoil motion, thus acting effectively like a spring. The three stages of operation can be seen in Figure 17 above [15].
7.4 Load Deflection Curves

Load deflection curves, or work diagrams, are critical in the design and testing of landing gear. These diagrams are a plot of the resistive force of a given shock absorber against its stroke displacement. The plots are easily determined during testing, by attaching an accelerometer to the shock absorber, and a simple displacement sensor to the inner cylinder. These plots give an accurate means of determining the shock absorbers performance, and are critical to the design process of shock absorbers and/or shock absorber selection. Performance statistics such as maximum loading, maximum deflection and efficiency can all be determined from these curves. The efficiency of the shock absorber is critical as a more efficient shock absorber is inherently lighter and more compact, and thus reduces the weight and maximises the cargo volume of the aircraft. However the efficiency, size and weight of each shock absorber must all be considered simultaneously during landing gear design.

Figure 18: Typical load deflection curve [15]
The two components of the force can be determined from Figure 18 above. If a polytropic force line is plotted on the load deflection curve then the two components of the force can be determined. This is easily plotted as the initial force, or y intercept of the plot, corresponds to the initial internal pressure force on the shock absorber, and using the relationship of a polytropic gas, the spring force at varying strut deflections can be calculated. It is assumed that the gas behaves like an ideal gas so the pressure follows a polytropic curve. The rest of the shock absorber force corresponds to the force of dampening, due to the motion of the hydraulic fluid through the piston head holes.

7.4.1 Efficiency Calculation

The efficiency of the shock absorber can be determined from the load deflection curves. The efficiency is defined as the ratio of area under the load deflection curve to the area of the maximum load deflection. This is expressed mathematically in Equation 7.1 below. This can easily be calculated with numerical means on computer based plots, and accurately determines the efficiency of the shock absorber. The efficiency only refers to the period between no external loading, and the maximum deflection of the shock absorber, thus any recoil motion is not required for the efficiency calculations.

\[
\eta_{\text{shock absorber}} = \frac{\int_{0}^{x} Fds}{F_{\text{max}} \times s_{\text{max}}}
\]  

(Equation 7.1)

7.5 Metered Orifice

To improve the functionality of the entire oleo-pneumatic system a varying orifice cross section is employed. The simple oleo-pneumatic system, with a fixed orifice area, is fairly straightforward to understand in principle and performs accordingly. A metering device is a mechanical system which varies the orifice cross section according to the applied load, to improve the efficiency and performance of the system. During light loadings, such as during taxiing, the orifice cross section is large, thus reducing the forces during these perturbations. During high loading the orifice cross section reduces accordingly and the dampening force increases.
There are many metered orifice configurations ranging in complexity. The most complex systems are used in critical applications where weight and size limitations are paramount, such as military applications. Typical efficiencies of such systems are between 75-90%, which is at least a 10% gain on fixed orifice oleo-pneumatic systems.

A simple metered orifice system contains a pin similar in shape to that shown in Figure 19 above. This pin is attached to the orifice plate by a simple spring. Under compression motion, the inner cylinder travels vertically resulting in a higher pressure on the lower side of the orifice plate. This difference in pressure forces the orifice pin to move upwards thus constricting the flow through the orifice section as can be seen on the left schematic in Figure 20 below. With a higher loading, the pressure difference about the orifice plate is greater and so the pin is further displaced, reducing orifice cross section thus further reducing the fluid flow. This means that during soft landings and subtle shocks the damping force is
significantly less than when the applied force is great. This allows for lower loads to be transmitted to the airframe thus increasing passenger comfort. During the recoil phase the pressure difference reverses forcing the orifice pin downwards, as seen in Figure 20 below, thus increasing the orifice cross section, lowering the dampening force under recoil. The orifice pin, in some cases, may have a hole through its axis, and so it works as a simple orifice hole, and constrains the fluid flow around it with a variable flow effect.

![Metering Pin Schematic](image)

Figure 20: Metering pin schematic (not to scale)

Metering systems become vastly more complex as maximum efficiency is pursued. A duplex system is shown in Figure 21 below. The fundamental components of an oleo strut are evident; an inner cylinder, denoted ‘1’ in diagram, an outer cylinder, an piston, denoted ‘2’ in diagram, an orifice plate, denoted ‘3’, a liquid, symbolised by horizontal dotted lines and a gas, symbolised by series of dots in the upper section. The diagram illustrates the fluid kinematics, shown by curved arrows, under compression on the left hand side and upon recoil on the right. In this particular case the main orifice plate, denoted ‘3’ in the diagram, is connected to the inner cylinder. As these components move vertically the fluid situated immediately above the orifice element is forced downwards through the orifice, providing a dampening force. This element is metered with the metering device,
denoted ‘4’ in the diagram. A detailed drawing of this system’s function is seen in figure 21 below. Under compression the metering element slides down the inner cylinder, constricting fluid flow. Under recoil the metering element returns to a position where the orifice holes are aligned, thus reducing the viscous forces on the fluid, and thus reducing damping of the system. During the compression phase, the inner cylinder moves vertically and the piston remains stationary. The fluid in the reservoir between the piston and inner cylinder is forced through orifice at the top, created by the tapered pin, denoted 5 in the diagram, and the piston, and the bottom of the inner cylinder. The opposite motion occurs during the recoil phase. The tapered pin is designed to vary the cross section of the orifice throughout the stroke length, thus creating damping force depending on the strut displacement. The curve on this taper is intricate so that the optimum performance characteristics can be achieved. This is clearly complex system; however it is this complexity that permits such high efficiencies.

<table>
<thead>
<tr>
<th>Item number</th>
<th>Description of Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inner Cylinder</td>
</tr>
<tr>
<td>2</td>
<td>Piston</td>
</tr>
<tr>
<td>3</td>
<td>Main Orifice Element</td>
</tr>
<tr>
<td>4</td>
<td>Metering Device</td>
</tr>
<tr>
<td>5</td>
<td>Tapered Pin</td>
</tr>
</tbody>
</table>

Figure 21: Duplex metered orifice system (reference)
7.6 Materials

Most aircraft materials are chosen for their high specific strength, such as the many aluminium alloys. Steel is not generally considered an aircraft material, but it is chosen for load-bearing structures such as landing gear, which require low volume and high strength, as size is important. It can also be made corrosion resistant, which can be beneficial in certain applications.

The greatest disadvantage is the weight of the steel. This is currently a relatively small fraction of the total weight of an aircraft, but as more high strength low weight alloys are being used in the aircraft industry this fraction is always increasing. This is why it is becoming more important for an optimum design to be utilised.

Aluminium alloys are now being produced such that the specific strength is greater than that of most titanium-based alloys. These new materials may be considered for landing gear and other critical aircraft components where high strength is required in combination with smaller geometry or lighter weight and will most likely take the place of steel in high performance components.

To ensure that the landing gear will not fail under design conditions, each structural member is sized such that the maximum stresses at limit loads will not result in plastic deformation.

<table>
<thead>
<tr>
<th>Material</th>
<th>U.T.S (MPa)</th>
<th>Density (Mg/m³)</th>
<th>E (GPa)</th>
<th>G (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum alloy 7010 T 736</td>
<td>500</td>
<td>2.82</td>
<td>69</td>
<td>26</td>
</tr>
<tr>
<td>Aluminium alloy BS L161</td>
<td>385</td>
<td>2.80</td>
<td>69</td>
<td>26</td>
</tr>
<tr>
<td>Titanium AMS 4967 TA13</td>
<td>830</td>
<td>4.42</td>
<td>113</td>
<td>42</td>
</tr>
<tr>
<td>Steel BS S99</td>
<td>1080</td>
<td>7.83</td>
<td>200</td>
<td>76</td>
</tr>
<tr>
<td>Ultra-high-tensile steels</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 M</td>
<td>1550</td>
<td>7.83</td>
<td>200</td>
<td>76</td>
</tr>
<tr>
<td>HY-TUF AMS 6418</td>
<td>1275</td>
<td>7.83</td>
<td>200</td>
<td>76</td>
</tr>
<tr>
<td>35 NC D16 THQ</td>
<td>1420</td>
<td>7.85</td>
<td>203</td>
<td>79</td>
</tr>
<tr>
<td>4330 M AMS 6411</td>
<td>1276</td>
<td>7.83</td>
<td>200</td>
<td>76</td>
</tr>
</tbody>
</table>

Table 1: Some material properties of landing gears
8 Case Studies

8.1 Cessna 172

The Cessna 172 is a general aviation aircraft that is primarily operated by private individuals and organizations. Production of this aircraft began in 1957, and continues today. More than 35,000 Cessna 172s have been produced, making it the most built aircraft to date. The aircraft may carry 4 persons (including 1 crew), utilizes a high wing configuration, and is powered by a single engine. The maximum takeoff weight of the Cessna 172 is 1110 kg.

The main landing gear of the Cessna 172 consists of a simple, solid spring landing gear (refer Figure 23), in addition to a single wheel. Although such a system is cost effective and therefore appropriate for general aviation aircraft, it offers relatively poor shock performance. Apart from tyre scrubbing that results from lateral motion of the landing gear, the solid spring landing gear offers no shock absorption. The result is an aircraft that tends to bounce, similar to a car with poor shock absorbers.
Unlike the main landing gear system, the nose landing gear implements a telescopic, oleo-pneumatic shock absorber. A more effective shock absorber is implemented, as it must support the Cessna 172 engine. In contrast to the main landing gear, this landing gear offers superior shock absorption. Note that in comparison to the oleo-pneumatic struts used on the Boeing 757, the nose landing gear shock absorber of the Cessna 172 is much smaller. This is due to the relatively low mass and design touchdown rate of the aircraft.
8.1.1 Stroke Calculation

An estimation of the Cessna 172 stroke length may be provided using Equation 6.7:

\[
\text{shock absorber stroke, } s_s = \left[ 0.5 \left( \frac{v_z^2}{g} \right) \left( N_g \right) - \eta_s s_s \right] / \eta_s
\]

\textbf{Assumptions:}

All energy at landing is absorbed by shock absorber

Lift at landing is equal to weight of aircraft

Acceleration due to gravity, \( g = 9.81 \text{ m/s}^2 \)

Tyre deflection is negligible (data is unavailable)

\textbf{Data}

Design touchdown rate, \( v_z = 12 \text{ fps} = 3.6576 \text{ m/s} \) (FAR 23) \hspace{1cm} (Section 6.2.1)

Gear load factor, \( N_g = 3.0 \) \hspace{1cm} (Section 6.2.2)

Shock absorber efficiency, \( \eta_s = 0.50 \) \hspace{1cm} (Section 6.2.3)

\textbf{Results}

\[
s_s = \left[ 0.5 \left( \frac{v_z^2}{g} \right) \left( N_g \right) - \eta_s s_s \right] / \eta_s
\]

\[
= \left[ 0.5 \left( \frac{3.048^2}{9.81} \right) \right. \\
= 0.210450 \text{m}
\]

\[
= 8.28542 \text{ in} + 1 \text{ in} = 9.3 \text{ in}
\]
8.2 Boeing 757

The Boeing 757 is a medium range, transcontinental airliner, produced by Boeing Commercial Airplanes. The aircraft was produced from 1982 to 2004, during which a total of 1050 were manufactured. The maximum takeoff weight of a Boeing 757 is as much as 123,600 kg, and may carry up to 280 passengers. Today the aircraft is commonly used for transatlantic routes between the Eastern United States and Western Europe, as it is one of the first of its class to meet the extended range twin-engine operational performance standards.

The landing gear of the Boeing 757 is comprised of a retractable tricycle configuration. Such an arrangement allows for favorable ground maneuvering, due to high visibility over the nose, a level floor attitude, and proficient steering (including take-off rotation).

The main landing gears (refer Figures 25 and 26), located underneath each wing, consist of dual tandem wheel layouts. Multiple tyres not only disperse the load and therefore pressure within each tyre, but also increase shock absorption and protect
the surface of the runway. Each of the main landing gears consist of a side brace and drag brace for lateral and longitudinal loads (respectively), and a telescopic, oleo-pneumatic shock absorber for vertical loads. This shock absorber has a relatively high stroke distance, due to the high aircraft weight, and the importance of energy dissipation for commercial aircraft.

![Diagram of Boeing 757 Main Landing Gear](image)

Figure 25: Boeing 757 Main Landing Gear [15]
Figure 26: Boeing 757 Main Landing Gear [15]

The nose landing gear of the Boeing 757 consists of a twin wheel layout, at the end of a telescopic landing gear. In comparison to the main landing gear, the nose landing gear contains fewer wheels and a smaller oleo-pneumatic shock absorber, due to the relatively small loads induced to the forward landing gear.
8.2.1 Stroke Calculation

An estimation of the Boeing 757 main landing gear stroke length may be provided using Equation 6.7:

\[ s = \left[ 0.5 \left( \frac{v_z^2}{g} \right) \left( \frac{1}{N_s} \right) - \eta_s \right] / \eta_s \]

**Assumptions:**

- All energy at landing is absorbed by shock absorber
- Lift at landing is equal to weight of aircraft
- Acceleration due to gravity, \( g = 9.81 \text{ m/s}^2 \)
- Tyre deflection is negligible (data is unavailable)

**Data**

- Design touchdown rate, \( v_z = 12 \text{ fps} = 3.6576 \text{ m/s} \) (FAR 25) (Section 6.2.1)
- Gear load factor, \( N_g = 2.85 \) (Section 6.2.2)
- Shock absorber efficiency, \( \eta_s = 0.75 \) (Section 6.2.3)

**Results**

\[ s = \left[ 0.5 \left( \frac{3.6576^2}{9.81} \right) / 2.85 \right] / 0.75 \]
\[ = 0.318998 \text{ m} \]
\[ = 12.5590 \text{ in} + 1 \text{ in} = 13.6 \text{ in} \]
8.3 F-14 Tomcat

The F-14 Tomcat is a supersonic, twin-engine, variable sweep fighter, bomber and tactical reconnaissance aircraft, manufactured by the Grumman Aircraft Engineering Corporation. The aircraft was introduced in to the USN in 1972, and operated for more than 30 years. Its maximum takeoff weight is 32,805kg.

The F-14 landing gear is composed of a retractable tricycle configuration. This configuration facilitates favourable ground manoeuvring (important for carrier based aircraft), due to high visibility over the nose, a level floor attitude, and proficient steering (including takeoff rotation). As illustrated in Figure 27 above, the relative size of the landing gear system is considerably larger in comparison with the Cessna 172 and Boeing 757. This is a result of the large design vertical velocities of carrier based aircraft (refer Section 6.2.1).

Each main landing gear of the F-14 consists of a retractable, OLEO pneumatic shock absorber attached to a single wheel. This system is implemented for its high efficiency, which is required for high vertical velocity landings.
Similarly to the main landing gear, the F-14 Tomcat nose landing gear consists of a telescopic OLEO pneumatic shock absorber, however in a twin wheel arrangement.

Figure 28: F-14 Tomcat main landing gear [7]
8.3.1 Stroke Calculation

An estimation of the F-14 Tomcat stroke length may be provided using Equation 6.7:

\[
\text{shock absorber stroke, } s_s = \left[ 0.5 \left( \frac{v_z^2}{g} \right) N_g \right] \eta_s \eta_s
\]

Assumptions:

All energy at landing is absorbed by shock absorber

Lift at landing is equal to weight of aircraft

Acceleration due to gravity, \( g = 9.81 \text{ m/s}^2 \)

Tyre deflection is negligible (data is unavailable)

Data

Design touchdown rate, \( v_z = 22 \text{ fps} = 6.7056 \text{ m/s (USN)} \) (Section 6.2.1)

Gear load factor, \( N_g = 5.0 \) (Section 6.2.2)

Shock absorber efficiency, \( \eta_s = 0.75 \) (oleo-pneumatic) (Section 6.2.3)

Results

\[
\begin{align*}
\text{stroke, absorbershock} & = \left[ 0.5 \left( \frac{6.7056^2}{9.81} \right) / 5.5 \right] / 0.75 \\
& = 0.555587 \text{ m} \\
& = 21.8735 \text{ in} + 1 \text{ in} = 22.9 \text{ in}
\end{align*}
\]
8.4 Discussion

The outcome of the stroke length calculations for the Cessna 172, Boeing 757, and F-14 Tomcat are summarised in Table 2 below:

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Shock Absorber Stroke, $s_s$ (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cessna 172</td>
<td>9.3</td>
</tr>
<tr>
<td>Boeing 757</td>
<td>13.6</td>
</tr>
<tr>
<td>F-14 Tomcat</td>
<td>22.9</td>
</tr>
</tbody>
</table>

Table 2: Shock absorber stroke estimations

As expected, the shock absorber stroke length of the Cessna 172 is the smallest stroke estimation of the three aircraft. Although the main landing gear is relatively inefficient, the effect that the lower design speed has on decreasing the stroke length is of greater significance.

The stroke length of the Boeing 757 is in-between that of the Cessna 172 and F-14 Tomcat. This result is due to the low design vertical speed in comparison to the F-14 Tomcat, and the high speed relative to the Cessna.

The stroke length of the F-14 Tomcat exceeds that of the Cessna 172 and Boeing 757 by a significant margin. This can be explained by the large design vertical velocity that such aircraft landing gears must tolerate upon landing.

Note that the above discussion does not indicate any relationship between the shock absorber stroke length and the weight of the aircraft. Although this variable is critical in landing gear design, it simply ‘cancels’ in the energy analysis of aircraft at landing (refer Section 6.2).
9 Conclusion

There are a multitude of shock absorption devices and configurations with the ability to absorb the vertical kinetic energy of aircraft due to non-vertical sink speeds during landing. Different aircraft have different design requirements and an appropriate shock absorption device should be selected. The best design meets the necessary performance obligations whilst taking into account weight and size restrictions. Oleo-pneumatic shock absorbers are the most popular shock absorber for medium and large aircraft, as their ability to absorb and remove kinetic energy gives rise to highly efficient systems. Only in light civil aircraft, where shock absorption is not critical, weight is lower, and sink speeds are lower, do the additional cost of oleo-pneumatic systems outweigh the performance advantage. In these cases a solid spring element is most commonly used.

Under design conditions, passive oleo-pneumatic shock absorbers with metered orifice systems can reach very high efficiencies, up to 80-90%[6]. However, their performance deteriorates rapidly in off-design conditions, such as taxiing or typical landings, thus transmitting unnecessarily high loads to the aircraft's structure. The challenge of this work is therefore to decrease the overall load levels applied to the airframe. Semi-active control offers a method of reducing the transmitted load over a wide range of loading condition, thereby offering a promising shock absorption system for the not too distant future. This system works by varying the viscosity, or dampening, element of the shock absorber to suit the applied loading. The performance seems to be only marginally inferior with respect to that of a fully active system, which acts on both stiffness and damping characteristics, thereby requiring a larger, heavier system. Once an adequate control law has been developed for the semi-active system it may be lighter and more cost-efficient than the classical passive solution, which nowadays is a highly sophisticated with its complex valve layout. By employing a semi-active control system an extended range of operational conditions in which the energy absorption efficiency is high can be achieved.

The future holds many new developments in landing gear shock absorbers, as we strive towards an endless pursuit of performance. There are many innovative energy absorption principles capable of shock absorption in aircraft landing gear.
The most promising innovative concept is viscoelastic damping which uses a material characterised by possessing both viscous and elastic behaviour. Thus as the material compresses part of the kinetic energy is dissipated instead of just stored momentarily and released in the opposite direction, as in an elastic material. A viscoelastic system could reduce the required size and weight of the landing gear shock absorber significantly, thus leading to lower flying costs and larger cargo volume.

Whilst these technological developments are still in the development phase oleo-pneumatic shock absorbers with metered orifice sections still offer the highest shock absorption efficiency, and are currently the best technology for modern landing gear.
10 References


