FIGURE 6.31 Cantilever shock absorber bearing overlap.

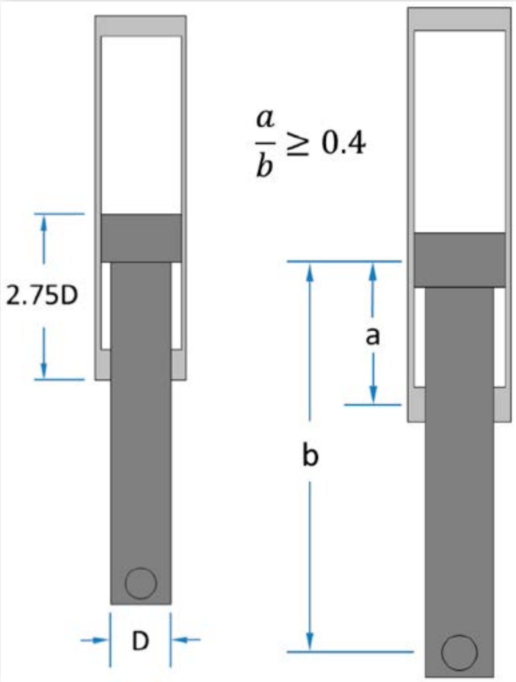
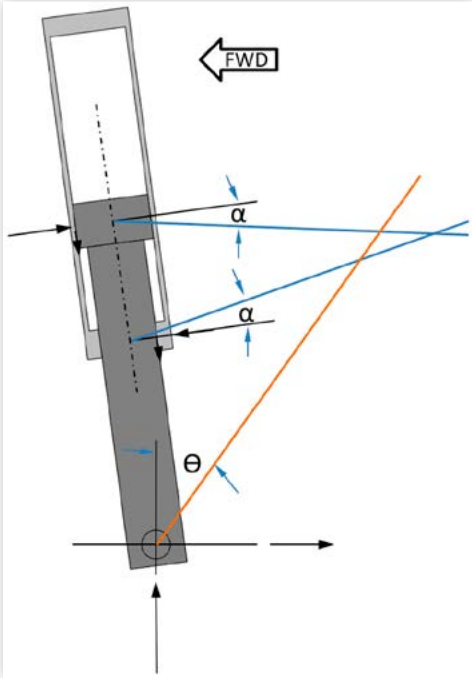


FIGURE 6.32 Cantilever bearing overlap, friction vector approach.



The ground load vector is considered with a ground coefficient of friction of 0.8 (usually considered to be the worst-case friction coefficient). The angle, θ, from the vertical is:

$$\theta = \tan^{-1} \mu_g$$

$$\alpha = \tan^{-1} 0.8 = 38.7°$$

As the ground force vector intersects the bearing friction vectors with margin, this shock absorber arrangement will be free from binding. In the use of this method, the selection of an appropriate bearing friction coefficient is critical. Many self-lubricated bearing manufacturers claim friction coefficient values near or less than 0.1. However, the friction value considered must include the impact of temperature, component ovalization under load, counterface surface roughness, and so on. The use of a friction value of 0.25 is considered conservative for oil-immersed upper bearings as well as greased bronze and self-lubricated lower bearings. It is better to take some conservatism in the selection of the friction coefficient value than be surprised when the assembly does not behave as a bearing catalog value suggested it would. With experience and confidence in a self-lubricated bearing assembly, a friction coefficient of 0.15 has been used by some designers with success.

The bearing friction vectors are shown in the example to originate at the shock absorber centerline while it may be considered that they should originate at the contact surface. Either approach is valid (the reality lies somewhere between) as the resulting difference is usually insignificant. The ground contact vector originates at the piston/axle intersection in this example as a dual wheel gear is considered. If the landing gear featured mechanical trail, the method is valid with the ground force vector originating at the axle centerline (offset from the piston centerline). For bogie landing gears, the force is considered to originate at the bogie pivot point.

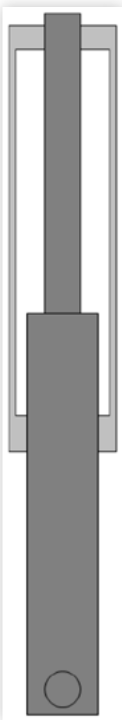
The vector method can be conducted at any shock absorber closure value. If the full ground to tire friction can be developed with the shock absorber fully extended, it is appropriate to conduct the analysis at that point. For oleo-pneumatic shock absorbers, this may occur during a low sink rate landing or during the second touchdown following a bounce. For a normal descent rate landing, the effect of tire spin-up means that a certain amount of shock absorber closure will occur before the peak ground to tire friction is developed—performing the analysis at around 15% closure is often a good approximation for the maximum drag force to be developed during landing. Often, the bearing overlap is based on the friction vector method conducted with the maximum loads at 15% closure and the risk that a high load occurs with the shock absorber more extended is accepted: momentary sticking of the bearings being accommodated in the resilience of the tire.

While the example shown in Figure 6.32 develops a two-dimensional approach, the approach can be extended to three dimensions in order to address the moment generated by offset wheel attachments. In the three dimensional case, the ground force vector is extended from the wheel center while the bearing force vectors are projected as cones revolved around the shock strut axis. The criterion for acceptable operation is the same—the ground force vector must cut through the bearing cones prior to their intersection.

POGO-STICK DESIGN

A special case of the cantilever gear, which can be used when a conventional cantilever would be too long, is the "pogo-stick" gear. In shock absorbers of this type, the piston is permitted to extend beyond the top of the cylinder. The upper bearing is fixed at the top of the cylinder, permitting a reduced overall length for a given bearing overlap. A schematic of the arrangement is shown in Figure 6.33. As the working area of the shock absorber is the annular area of the step in the piston, the overall diameter of this type of shock absorber is larger than an equivalent cantilever shock absorber. While offering a more compact arrangement, the pogo-stick design has more seals and greater weight than an equivalent telescopic cantilever.

FIGURE 6.33 Pogo-stick configuration.



When incorporating a pogo-stick landing gear, space must be reserved for the piston when the shock absorber is compressed. In addition, a portion of the piston will protrude when fully extended. The typical application for this landing gear type is in a helicopter sponson, as shown in Figure 6.34.

TORQUE LINKS AND SPLINES

Unless free castering rotation is desired, a means is needed to resist rotation of the piston within the cylinder. There are two different approaches: splines and torque links. There are a limited number of splined shock absorbers in service; Figure 6.35 illustrates one approach [6].

The spline must resist the applied torque while sliding. In the illustration, an external spline (37) is provided on the innermost tube (24). The piston (12) slides vertically and rotation of the piston is resisted by the spline block (34) which is fixed to the piston and has internal splines (36) which engage and slide over the external splines (37). The remainder of the layout is reasonably conventional. With an arrangement such as that in Figure 6.35, the rotation of the piston can be restrained or controlled from the top of the cylinder by a mechanism (or restraint) applied to the innermost tube (24). An arrangement similar to this is used on the Lockheed C-5 main landing gears to provide steering on the ground as well as rotation of the piston (and attached bogie beam) during the retraction sequence. The North American XB-70 main landing gear (Figure 6.36) used

FIGURE 6.34 Westland Super Lynx; note main landing gear piston extending above sponson (detail, right).

FIGURE 6.35 Splined shock absorber from US Patent 3,027,122.

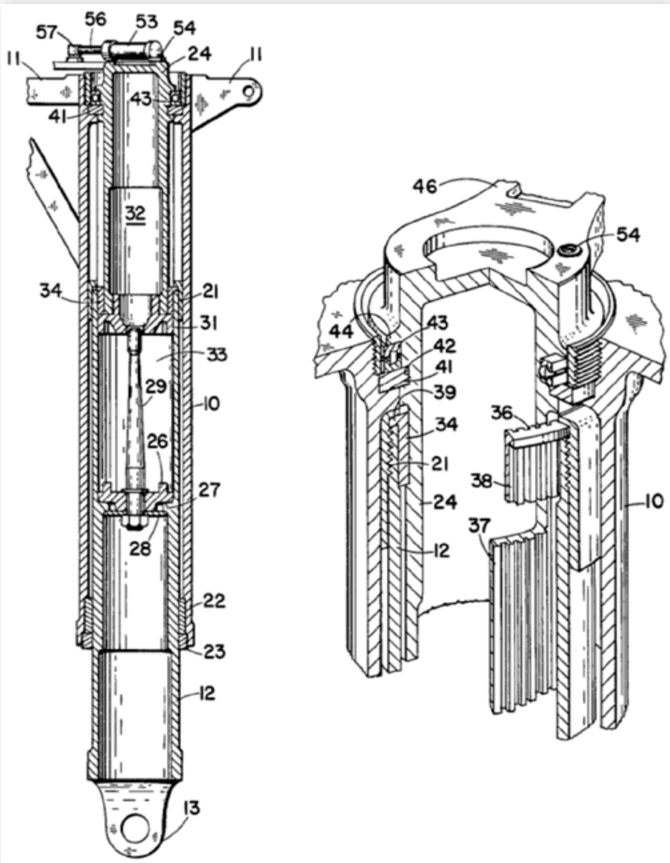


FIGURE 6.36 North American XB-70 main landing gear.

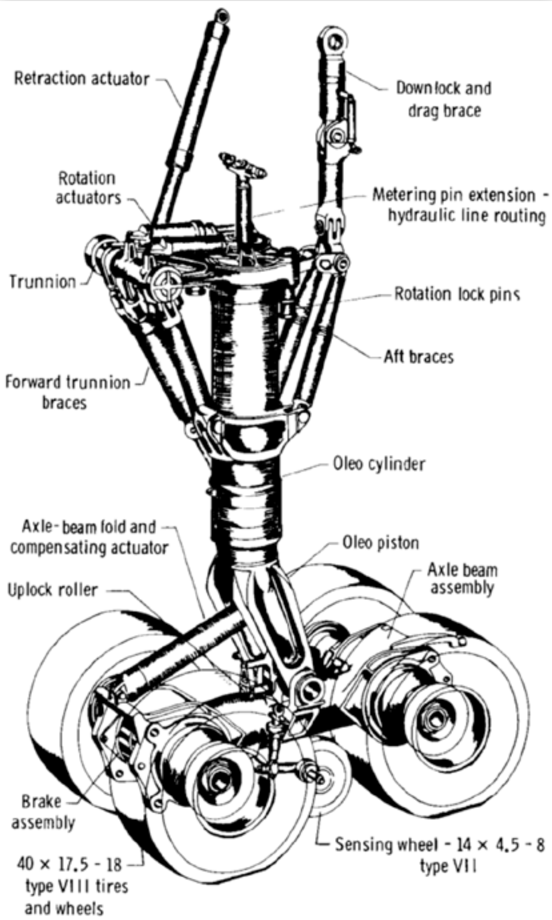


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FIGURE 6.37 Boeing 777 nose landing gear torque links.

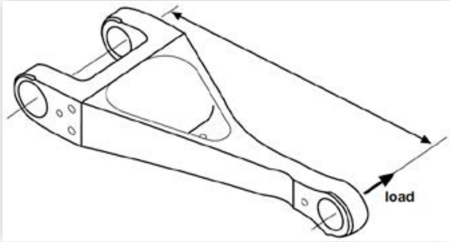
a similar arrangement to provide 90° of piston (and bogie) rotation during the retraction sequence.

A 1951 paper [7] compares the performance of Supermarine Spitfire landing gears: some with internal splines and the others with conventional torque links. The paper notes that splined shock absorbers were already at that time no longer in common use due to high sliding friction. A number of torque link equipped shock absorbers were drop tested and showed 7%–8% coefficient of variation. A similar number of splined shock absorbers were drop tested and showed up to 18% coefficient of variation. During static compression on an inclined plate, the splined shock absorber did not compress at all due to internal friction while the torque link equipped shock absorbers functioned acceptably. Torque links should be selected except when extraordinary operations require steering or positioning the piston from the top of the landing gear.

Torque links, such as those pictured (Figure 6.37), are the lowest friction, lowest cost means to resist rotation of the piston while permitting it free translation. The location of the torque links on the gear structure is driven primarily by the available stowage space. Torque links are routinely placed on either the front or back of the shock strut but have also been placed on the side and at arbitrary angles for clearance reasons.

A variety of shapes for torque links exist. Figure 6.37 shows an asymmetric arrangement: the top torque link is shorter than the bottom torque link. This can be helpful when limiting the variation in the distance of the torque link apex from the piston centerline; in this case, the steering torque is transmitted through the upper torque link. The apex joint can be arranged as shown for the 777 nose landing gear, with a clevis joint, which necessitates two separate part numbers for the upper and lower torque link (even if they have the same length). An alternative approach (preferred where possible to minimize cost and complexity) is a symmetrical torque link design where the upper torque link and the lower torque link are the same part number, with one installed inverted. Figure 6.38 shows the general layout required for a symmetrical torque link design.

FIGURE 6.38 Symmetrical torque link layout.



Reprinted from NLR-TP-99026Development of a composite torque link for helicopter landing gear applications H.G.S.J. Thuis. https://reports.nlr.nl/xmlui/bitstream/handle/10921/1111/TP-1999-026.pdf

Some historical aircraft used two sets of torque links (e.g., Concorde). In general, this was done for strength reasons as a sufficiently strong single set would not fit in the space available. A single set of torque links is the standard approach on modern designs. In order to ensure that torque links do not bind, it is mandatory to respect a maximum included angle of 135° in the layout of the links with the shock strut fully extended (Figure 6.39).

Semi-Articulated

A semi-articulated landing gear (Figure 6.40) attaches the wheel or wheels to a lever arm. The lever arm is connected to the shock absorber piston around the midpoint and to a drop link at its far extremity. The drop link is connected to the cylinder. The arrangement permits an increase in the possible axle travel for a given shock absorber. It can be used where a very short landing gear is required or where rough runway compatibility is desired.

FIGURE 6.39 Maximum torque link included angle.

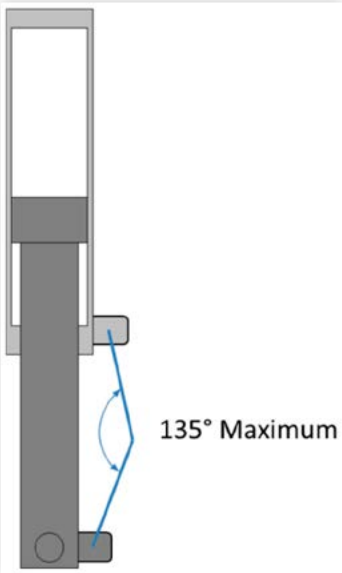


FIGURE 6.40 Semi-articulated landing gear.

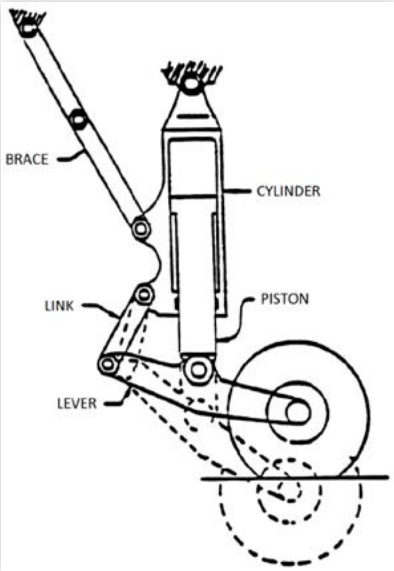
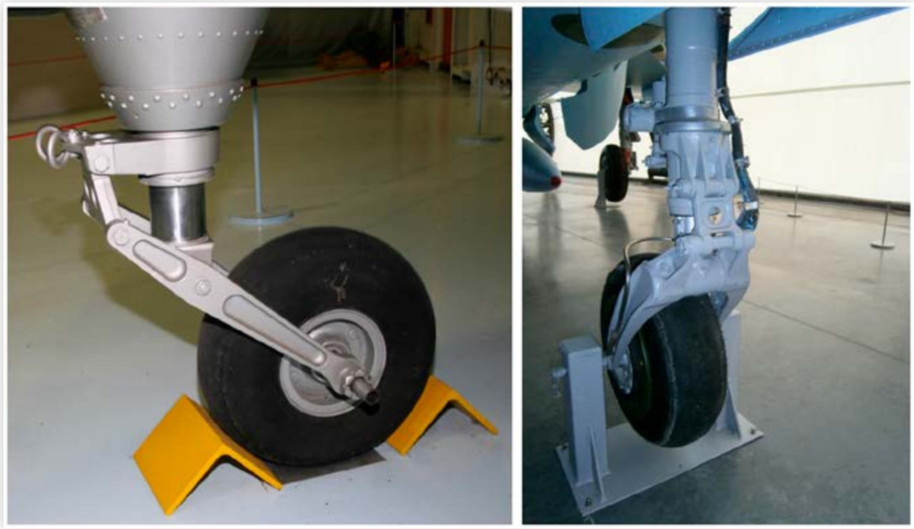


FIGURE 6.41 Westland Dragonfly nose landing gear (left); MiG-21 nose landing gear (right).



The semi-articulated geometry has been widely used as a nose landing gear on helicopters and on military aircraft designed by Mikoyan-Gurevich, where the additional travel offered by the arrangement has been of benefit for compatibility with airfield roughness requirements (Figure 6.41).

There are a number of variations on the semi-articulated landing gear configuration, as illustrated in Figure 6.42 [8]. Of these configurations, only (c), which has already been discussed, and (a) are in common usage. Configuration (a) is used on some small commuter nose landing gears, such as the Bombardier Q400, and has been widely used by the Ilyushin design bureau in order to achieve compliance with airfield roughness requirements. Both are illustrated in Figure 6.43. The configuration shown in (b) was used on the Handley Page Halifax V main landing gear; a semi-articulated configuration adapted late in the aircraft's development.

Depending on the type of semi-articulated configuration employed, the shock absorber may or may not experience bending as a result of applied ground loads. Designs following configuration (c) do see drag load and require bearing overlap as per a cantilever

FIGURE 6.42 Semi-articulated landing gear configurations.

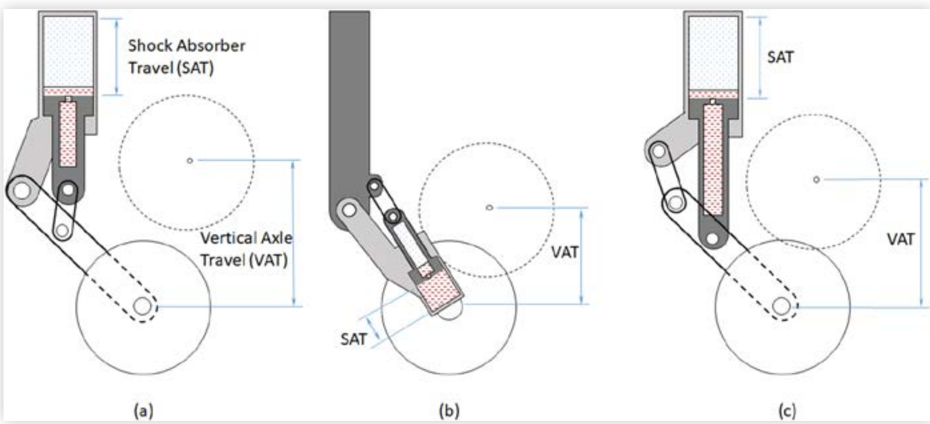


FIGURE 6.43 Bombardier Q400 nose landing gear (left); Ilyushin Il-76 nose landing gear (right).

shock strut. Those designs following configuration (a) do not transmit drag load to the shock absorber piston and if a spherical bearing is used in the connection linkage, side load will not be imparted either. In this case, a reduced shock absorber bearing overlap (measured from the top of the upper bearing to the bottom of the lower bearing at full extension) equaling 1.25 times the piston diameter is sufficient (MIL-L-8552 guidance).

Articulated

The articulated landing gear configuration, also known as a trailing arm landing gear, is often used as a main landing gear, especially on low wing aircraft with aft fuselage mounted engines, such as business jets. Articulated landing gears (Figure 6.44) are characterized by a main fitting, which attaches to the aircraft at the upper end, and

FIGURE 6.44 Articulated landing gear.

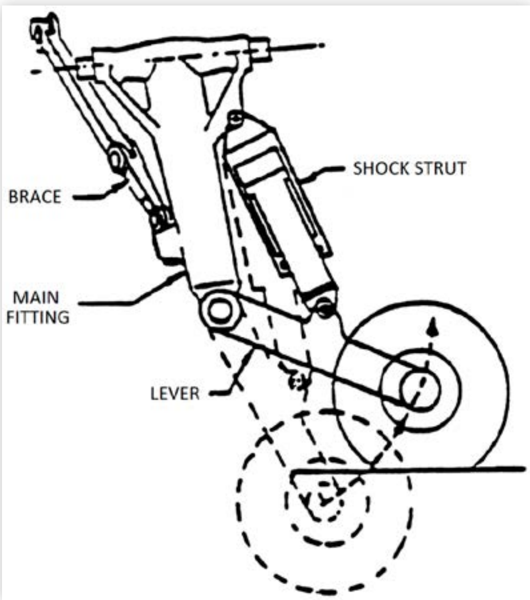
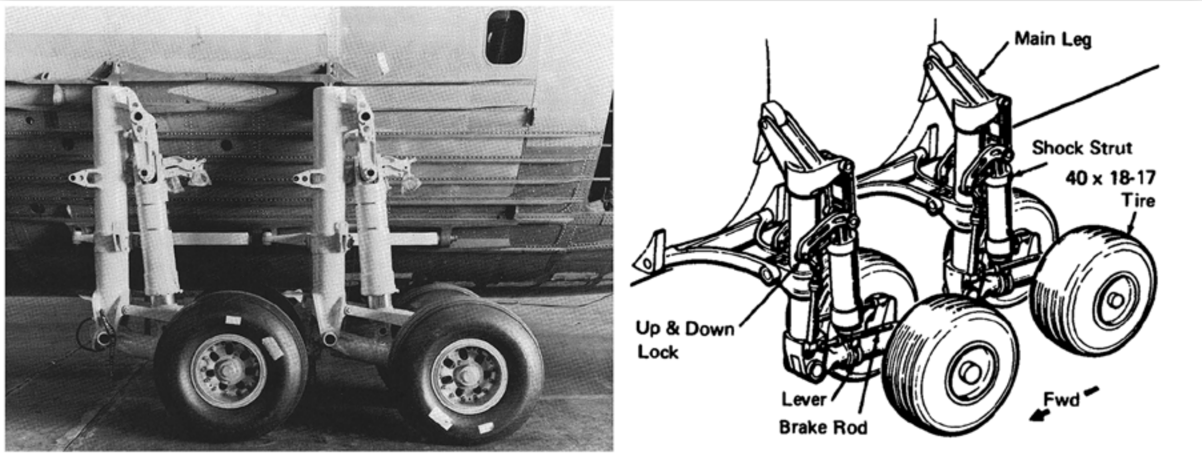


FIGURE 6.45 Boeing YC-14 main landing gear.



provides a pivot for a lever at the lower end. The wheel or wheels are attached to the far extremity of the lever. A shock absorber is pinned between the lever and the main fitting. A significant mechanical advantage is provided, permitting a compact shock absorber while maintaining large vertical axle travel.

While a trailing arm configuration is generally heavier than an equivalent cantilever arrangement, the trailing arm permits the tire contact position to be arranged significantly behind the main fitting aircraft attachments. When the aircraft takes off and the landing gear extends, the package size can be similar to a cantilever gear. This attribute can assist in solving a number of gear location and stowage problems. An example articulated main landing gear is that of the Boeing YC-14, shown in Figure 6.45.

Alternative arrangements of the articulated layout are possible, as shown in Figure 6.46. Option (a) was used as the Gloster Meteor main landing gear. Option (b), employing a tension shock absorber, was used on the Meteor nose landing gear.

A shock absorber bearing overlap (measured from the top of the upper bearing to the bottom of the lower bearing at full extension) equaling 1.25 times the piston diameter is sufficient, in accordance with MIL-L-8552. This permits a compact shock absorber unit which, by virtue of being pin jointed, is readily removed and replaced if required without requiring jacking of the aircraft to a significant height. Spherical joints are recommended at the ends of the shock absorber to avoid transmitting loads due to deflection. When the trailing arm is not directly in line with the main fitting attachment point, a Cardan joint may be required at one of the shock absorber attachments, as illustrated for the Alpha Jet in Figure 6.47.

When the shock absorber is not in the same plane as the trailing arm (lever) and main fitting attachment points, such as on the Alpha Jet, the ATR family, and the BAe 146, an outwards thrust is produced which acts to toe-in the tire under load. This toe-in can increase the rate of tire wear; it is recommended that the amount of deflection at maximum load be calculated during the design phase and the gear be designed such that under no load it has an equal measure of toe-out. As load is applied, the tire will approach the desired zero toe angle condition. Both the ATR family of aircraft and the BAe 146 family of aircraft are adjusted in this way to improve tire life.

FIGURE 6.46 Alternative articulated landing gear designs.

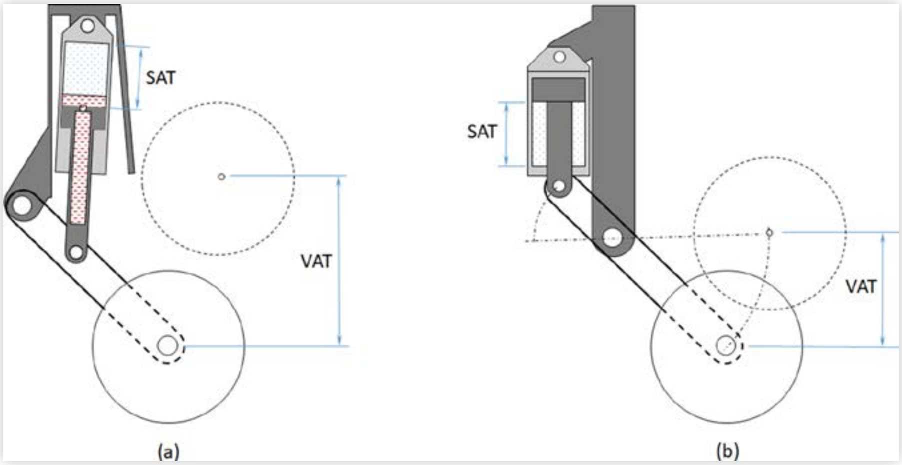


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FIGURE 6.47 Dassault-Dornier Alpha Jet main landing gear.

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A significant advantage of the trailing arm articulated arrangement is that drag loads, such as those arising from spin-up of the wheels on landing and spring back of the structure once the wheels have reached synchronous speed, are at least partly absorbed by the shock absorber. The combination of this feature and the generous travel afforded by the arrangement make the articulated configuration well known for ride comfort. Most pilot reviews of aircraft with trailing link landing gears will praise the configuration for bestowing smooth landings.

While most articulated arrangements place the lever in the trailing position, it is possible to place the lever in a leading position, when the required wheel position must be ahead of the aircraft structure. Examples include the Ryan PT-22 Recruit and the Kaman Seasprite (Figure 6.48).

FIGURE 6.48 Kaman SH-2 Seasprite.

While articulated landing gears are generally used for main landing gears without steering, a steered variant is possible if the shock absorber is housed within a turning tube and given freedom to move (similar to configuration b in Figure 6.42). The articulated geometry can be used for tail gears if the tail gear pivot is mounted on the trailing arm, as on the AH-64 Apache attack helicopter (Figure 6.49).

When computing the required vertical axle travel, attention should be paid to the tail-down condition, which can result in a reduction of available travel for a given shock absorber stroke. The analysis is similar to that presented in Figure 6.29 for cantilever arrangements. An example of the varying mechanical advantage with compression and fuselage angle is shown in Figure 6.50 for the OV-10 main landing gear.

FIGURE 6.49 AH-64 Apache Tail landing gear.

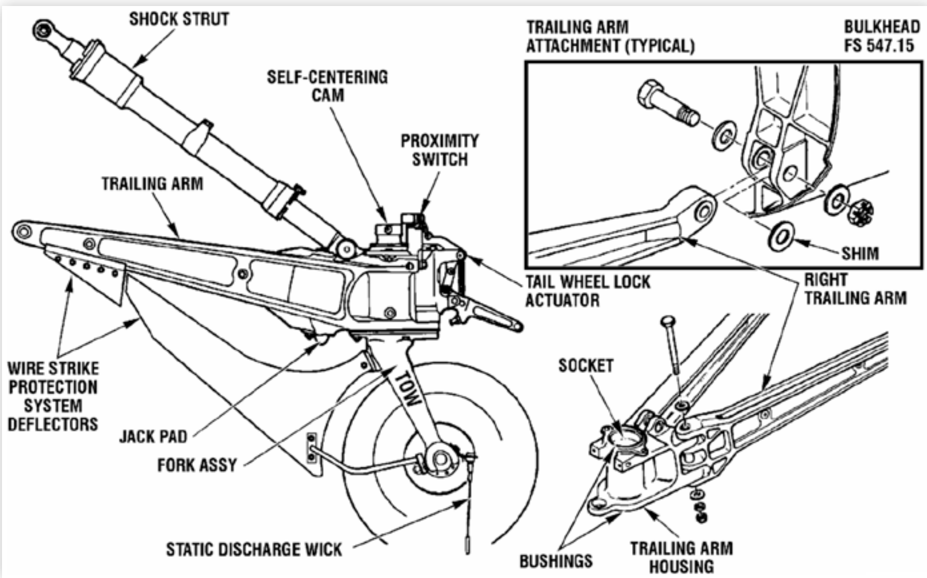
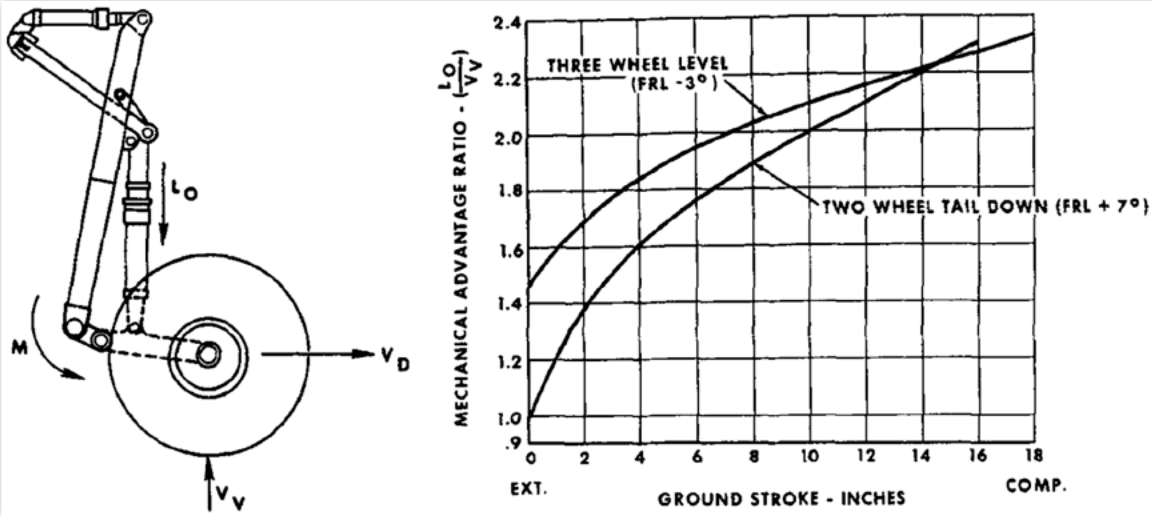


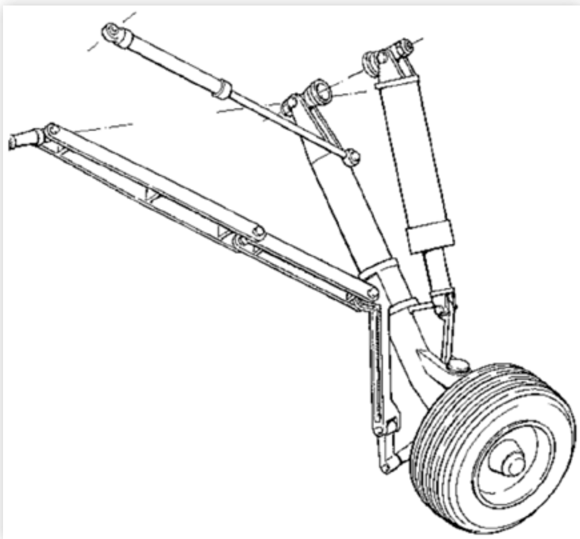
FIGURE 6.50 North American OV-10 Bronco main landing gear.



Side-Hinged Articulated

The side-hinged articulated landing gear (Figure 6.51) is a variant of the articulated gear, particularly adapted to fuselage mounting. Landing gears of this variety tend to be found on military aircraft, such as the F-16 (Figure 6.52). The landing gear can be forward or rearward retracting, depending on the space available. In some configurations, the axle is integral with the lower arm (as shown in Figure 6.53), while in others, it is pivoted with a radius rod to trim the wheel position during retraction. While this configuration can provide a significant track for a fuselage mounted landing gear, the position of the wheel moves in an arc during shock absorber compression. This results in the wheel track varying and the tire camber angle changing as a function of applied load. While often considered to lead to excessive tire wear, the large lateral motion of the tire during landing appears to the tire contact patch as yawed rolling, which occurs in more conventional landing gear design when landing with a crab angle or during steering of nose wheels. However, spin-up wear can be asymmetrical due to the initial spin-up event occurring with the tire at a significant camber angle. Anecdotal information suggests that tire wear on US Navy aircraft carrier airplanes with side-hinged articulated landing gears such as the Lockheed S-3 and Vought A-7 was no worse than the wear on aircraft with cantilever landing gears.

FIGURE 6.51 Side-hinged articulated configuration.



Multi-Wheel Bogie Arrangements

The architectures discussed to this point are capable of supporting a single axle, generally limiting them to one or two wheels (although there are a few cases of three