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AIR4846

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Extraordinary and Special Purpose Landing Gear Systems

RATIONALE

This document has been prepared to gather and document technical information on unique landing gear designs for historical purposes. The information provided may be used in the design of landing gear for future aircraft as applicable.

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1. SCOPE

A landing gear system comprises the most compelling assembly of engineering skills. Its importance to the successful design of an aircraft can be favorably compared with that of the aircraft's wings and engines. A landing gear system consists of several different engineering disciplines, and is continually in the public eye especially with regard to safety.

The primary objective of AIR4846 is to present a record of a variety of interesting gears, gear/aircraft systems and patents, and to discuss wherever possible the lessons learned, and the reasons for the design. Thus, the document is not only a historical account, but a means of recording technical knowledge for the practical benefit of future landing gear designers.

Commendable efforts have been made over the years by several individuals to make such recordings, and AIR4846 will make continual reference to them. This applies to all books, papers, or specifications that have the approval of the SAE A-5 Committee.

AIR4846 also accepts the premise that an essential aircraft requirement can often justify a gears' complexity and consequent weight. However, the document's purpose is not to recommend, but to provide reliable, authenticated information. Hence, the gear designer would be better equipped to adjudicate trade studies rationally, while not restricting his/her innovative skills.

Each gear design feature will be associated with as many aircraft examples as possible, and every effort will be made to ensure accuracy, authenticity, and detail clarity.

Section 2 of this document describes the features of landing gear which are addressed in the specific descriptions of various landing gears (Category A). Also, special types of landing gear are categorized as Category B.

2. CATEGORY DEFINITIONS

Category A (Gear Features)

- Oleo shock absorber integral with cantilevered post
- Simple folding drag or side strut
- Single or twin wheel arrangements
- Main gear truck beams (4 wheels max.)
- Nose gears with linear hydraulic actuator steering
- Nose gear steering (rack & pinion)
- Nose gear steering (rotary actuator)
- Main shock absorber separate from cantilevered post
- Gears that shorten, lengthen, or twist during retraction
- Telescopic side or drag strut)
- Retraction with skew axes
- Folding & rolling drag & side braces

- Truck beams with more than 4 wheels
- Truck beams with 2 or 3 wheels
- Main gear steering
- Gears with side drift landing correction
- Aft C.G. tip-back devices
- Gears that kneel
- Two stage shock absorber struts

Category B (Aircraft with specific landing gear requirements)

- Aircraft with outrigger (or wing tip) gears
- Aircraft with tail bumpers
- Aircraft with nose gear towing (Naval)
- Aircraft with arrester hooks (Naval)
- Aircraft with arrester hooks (land based)
- Aircraft on skis and floats
- Aircraft on skids and floats (pop-outs)

3. CATEGORY "A" (LANDING GEAR FEATURES)

3.1 S-3A - Tripod Main Landing Gear

3.1.1 Applications for Tripod Landing Gears

3.1.1.1 Tripod main landing gears are rugged and structurally efficient. They are well suited for hard landings such as those experienced on aircraft carriers. The Tripod configuration provides excellent load paths for drag, side, and vertical loads. Loads are carried by three legs loaded essentially in tension or compression. Two members, the shock strut and drag brace strut, are two force members. Structural bending loads in the third member, (the tension strut) are minimized by the aiming of the two other members. The Tripod landing gear has the benefit of a pinned ended shock strut and hence eliminates the variability of piston bearing friction from the struts' load/stroke curve. The shock strut piston can therefore be sized to provide a more realistic air spring curve/area that does not include the affect of structural bending. The length of piston bearing overlap and length of piston are reduced, since the piston stroke may be only a 1/3 of the axle stroke. Customarily, a cantilevered strut piston overlap is set at 2.75 $\times$ the piston diameter, where a pin-ended strut is set at only 1.5 $\times$ the piston diameter.

3.1.1.2 Compared with normal cantilevered gears, the Tripod configuration enables the wheel to be located more outboard, thereby improving the turnover angle for carrier operation.

3.1.1.3 A disadvantage of the Tripod gear is the large stowage volume required. In its simplest form, the Tripod main gear retracts the tire such that it presents almost its full diameter to the aircraft frontal cross section. The doors remain stationary as the gear strokes on landing. This is accomplished by proper positioning of the link between the tension strut and the forward torque tube. The upper length of the link lies on the strut-stroking axis. Since no motion is transmitted to the forward torque tube, the doors remain stationary. Time elapsed during gear extension and locking is a maximum of 15 seconds.

3.1.1.4 The Tripod gear also requires an airframe with low ground clearance. An aircraft with more than approximately 4 feet of ground clearance at static, would require struts of excessively long lengths in order to maintain a fairly shallow angle to the ground. If this angle is too steep, the gear may not stroke when high drift landings are encountered.

3.1.1.5 A common concern with Tripod landing gears is adverse tire wear, since the angle of the tire plane changes as the gear strokes. However, service experience has shown that tire wear is more a function of tire size than gear type, and in any case, all taxiing is performed with the axle near the horizontal position. The S-3A main landing gear is a good example of a Tripod landing gear.

3.1.2 Structural Configuration

3.1.2.1 The S-3A main landing gear has three structural members which form a tripod. See Figure 1 and 2. It consists of a pinned-ended shock strut, tension strut and a drag brace. All three members are attached to the fuselage with universal joints. The shock strut and tension strut comprise a movable truss allowing the wheel to stroke vertically 22 inches with a shock strut stroke of 9 inches. Fore and aft loads are carried by the truss formed by the drag brace and tension strut. Both the shock strut and drag brace are attached to the tension strut by large spherical bearings. Brake torque is carried through the tension strut to the fuselage. The shock strut is interchangeable left to right.

3.1.3 Main Gear Doors and Actuation

3.1.3.1 Three clamshell doors, one upper and two lower, enclose the main gear wheel well. The main gear and doors are linked together and operate as a single mechanism during extension and retraction. Normal operation is provided by three hydraulic actuators. The gear actuator is attached to the fixed fuselage structure and to the aft torque tube. The downlock actuator is located on the drag brace and operates the gear downlock. The up-lock actuator is attached to the fixed fuselage structure and the up-lock mechanism.

3.1.4 Gear Extension and Downlock

3.1.4.1 On normal gear extension, system hydraulic power is supplied to both the uplock and downlock actuators. The gear is unlocked by the uplock actuators. Power supplied by the gear actuator in the wheel well is transmitted to the gear and forward torque tube by direct linkage. Power from the downlock actuator tends to make the two drag brace members form a straight line. The doors move more rapidly than the gear at the beginning of the extension cycle. This provides clearance for the tire as it moves outboard and forward.

3.1.4.2 After the tire exits, the gear extension motion causes the doors to partially close, and as the gear reaches the extended position, the drag brace members form a straight line. Here the downlock actuator drives the downlock linkage over center against a stop. The linkage is held against the stop by a spring strut, and this forms the gear downlock. Since the doors are attached to the two torque tubes, which in turn are attached to the tension strut, no separate door-open locks are required. The doors remain stationary as the gear strokes on landing. This is accomplished by proper positioning of the link between the tension strut and the forward torque tube. The upper length of the link lies on the strut stroking axis. Since no motion is transmitted to the forward torque tube, the doors remain stationary. Time elapsed during gear extension and locking is a maximum of 15 seconds.

3.1.5 Gear Retraction and Uplock

3.1.5.1 On gear retraction, system hydraulic power is supplied to the gear, operating downlock, and uplock actuators. The downlock actuator moves the downlock off center, and simultaneously, the knee joint moves off center, and the gear begins to move aft and up. Power is being supplied to the aft torque tube by the gear actuator. Door and gear motion on retraction, is just the reverse of the extension motion.

3.1.5.2 The doors initially open further to allow the tire to pass, then close behind the gear. As the gear reaches the retracted position, the uplock mechanism is moved off center from the gear down position by the uplock roller on the aft torque tube. As the uplock is actuated, the gear uplock hook moves in behind the uplock roller on the shock strut and the aft torque tube uplock hook rotates into the up and locked position. The uplock actuator drives the uplock mechanism over center achieving a final up and locked condition.

3.1.5.3 When hydraulic pressure is removed from the system in the up and locked condition, two tension springs hold the mechanism locked until it is unlocked by either hydraulic system pressure, or the emergency release procedure.

3.1.6 Emergency Extension

3.1.6.1 The S-3A landing gear was designed to provide emergency gear extension completely without reliance on hydraulic or electrical systems other than indication of the gear downlock. Emergency extension checkout is possible whether on the ground or in flight. Reversion to normal gear operation is possible. No hydraulic accumulators are provided other than for emergency braking.

3.1.6.2 Since the gears extend forward, a power source is required to extend them. In an emergency, the uplock is released by a cable from the cockpit, and power to extend the gears against the opposing air loads is supplied by mechanical springs and gravity.

3.1.6.3 The gear extension arrangement provides paired beam springs with rollers that act against cam surfaces to generate a moment about the drag brace knee joint to extend and lock the main gear. This arrangement matches the energy available in the spring to the energy requirements for extension.

3.1.6.4 The energy to extend is stored during each retraction cycle. When the gear is extended, the spring force assists the action. Drag brace locking is achieved by a separate spring in the downlock linkage.

3.1.7 Component Configuration (Shock Strut)

3.1.7.1 The main gear shock strut consists of a cylinder and a piston. The cylinder is in two parts, an upper cylinder and a lower cylinder. Shock absorption is accomplished by an air spring and an oil metering orifice and a metering pin. Shock strut rapid extension damping is provided by orifices in the upper part of the piston which meters fluid from the annulus between the piston and the lower cylinder.

3.1.7.2 The shock strut is designed to absorb a maximum vertical landing reaction per main wheel with the aircraft in a 5° rolled attitude at 112,550 pounds. MS 28889 filler valves are incorporated on each end of the strut and this allows the strut to be serviced without jacking the airplane.

3.1.8 Tension Strut

3.1.8.1 The tension strut configuration is a welded assembly consisting of a forged cap, tube, and a forged axle.

3.1.8.2 The material is 300M steel, heat treated to 270,000 psi tensile after welding. Two bronzed bushed lugs are provided for attaching the shock strut, tie-down ring, and door link.

3.1.9 Drag Brace

3.1.9.1 The main gear drag brace configuration consists of an upper and lower link, gear downlock actuator, and two emergency extension springs. The longer upper link is attached to the fuselage by the universal joint. The shorter lower link is attached to the tension strut by a large spherical bearing. Both links are made from 4340 steel, heat treated to 200,000 psi minimum tensile strength.

3.1.10 Main Gear Tire

3.1.10.1 The main tire is a 30×11.50-14.50, type VIII, 24 ply-rating, tubeless tire. Tire weight is 68.7 pounds (each). Static load rating is 25,000 pounds at 245 psi. At this rating, the footprint area is 92.35 square inches. The recommended pressure for operation (at maximum take-off weight) is 245 psi, and the equivalent recommended carrier pressure is 320 psi.

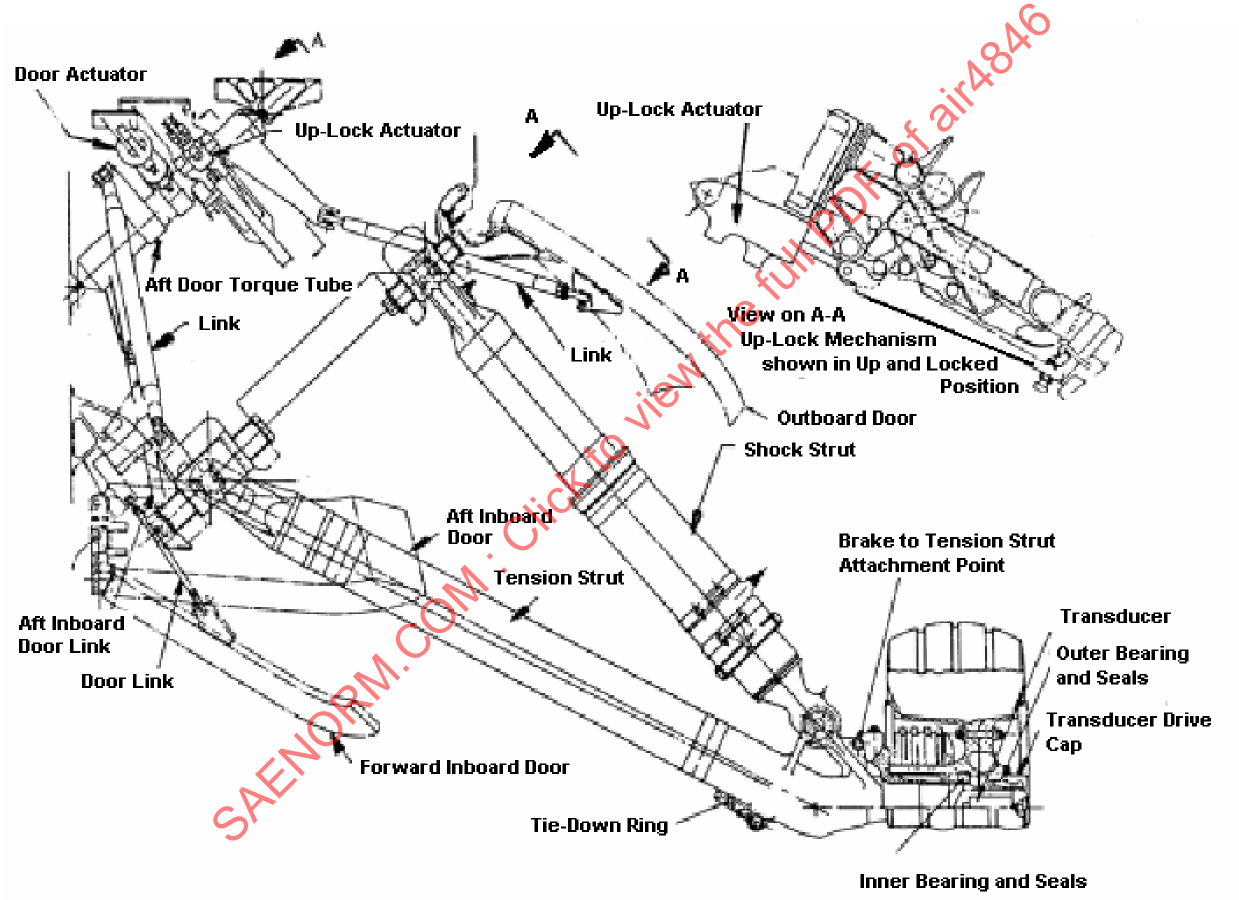

FIGURE 1 - FRONT VIEW S-3A MAIN LANDING GEAR

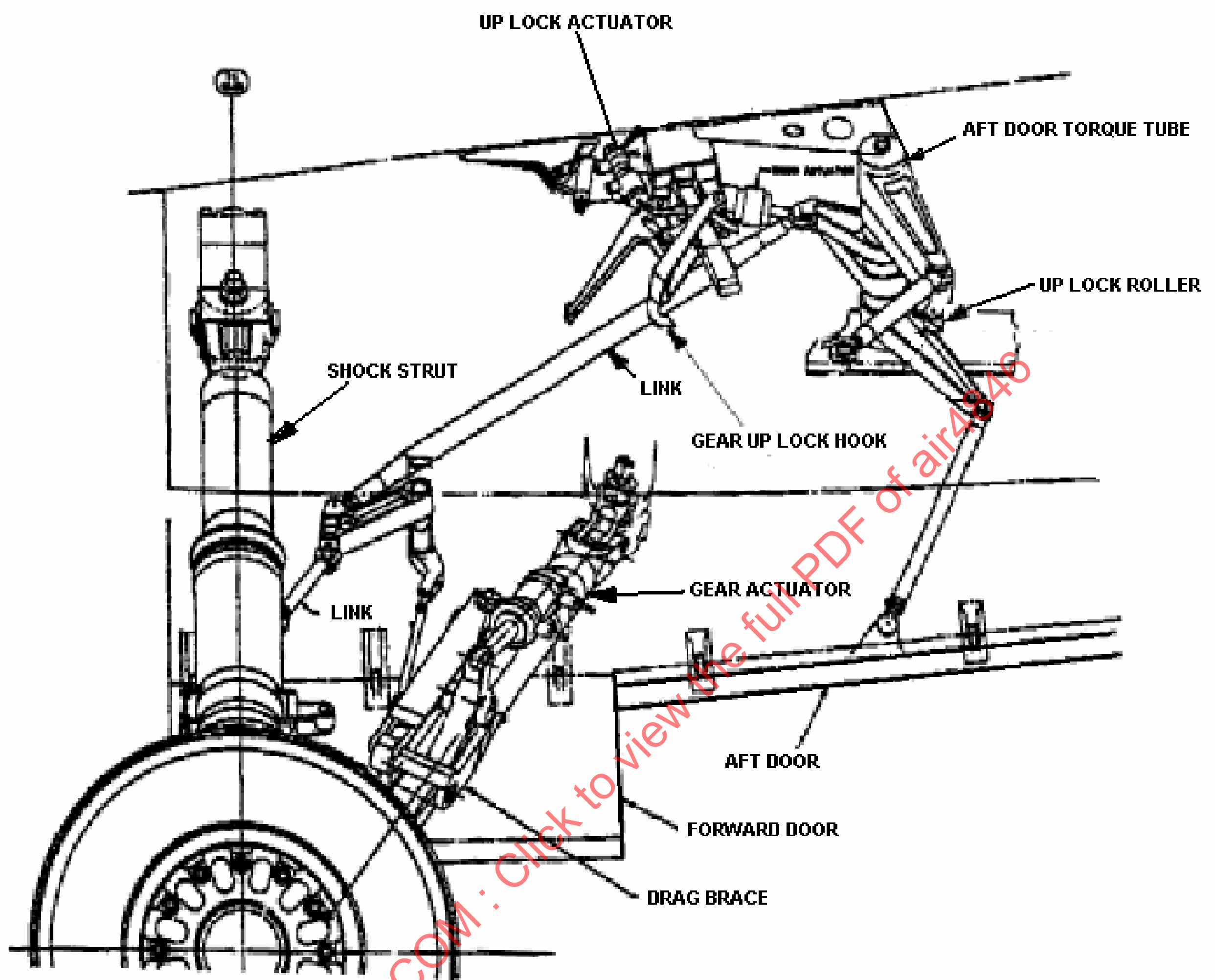

FIGURE 2 - SIDE VIEW S-3A MAIN LANDING GEAR

3.2 C-5A/B Kneeling System Main Landing Gear

3.2.1 The kneeling system on the C-5 enables the airplane to be loaded and unloaded without the use of ground equipment. See Figure 3.

3.2.2 There are three kneeled positions for "drive in" or "truck bed" loading:

a. Forward kneeled for loading through the forward doors.

b. Level kneeled for loading through the forward or aft doors.

c. Aft kneeled for loading through the aft doors.

3.2.3 During kneeling, the wheel axle travel of the main landing gear is the same for all the three kneeled positions. See Figure 4 and 6. The angle of the cargo floor however, is determined by the height of the nose landing gear, the axle travel of which is different for each of the three kneeled positions.

3.2.4 For aft kneeling, the nose gear remains in the down and locked position.

3.2.5 For forward and level kneeling, the nose landing gear retracts into, and is supported by kneeling pads. See Figure 5.

3.2.6 The kneel pads consist of a three position structural mechanism located on the nose gear aft bulkhead. The pads are normally stowed for nose gear extension/retraction and are extended by an electrical actuator for the forward and level kneeled operations. The actuator also operates the folding bulkhead/kneeling door.

3.2.7 The folding bulkhead/kneeling door is retracted for kneeling operations to provide ground clearance for forward and level kneeling. In its normal position it serves as a fairing aft of the nose gear doors.

3.2.8 Operation of the kneeling system is controlled from a panel located at the flight engineer's station. Switches are also located in the fairing forward of the main gear wheel wells, and also in the nose gear wheel well.

The following chart is used to determine the kneeling limitations of the airplane:

TABLE 1

	Kneeling Conditions	Gross Weight	
		Forward Main	Aft Main
		(Gear Kneeled)	(Gear Kneeled)
I	A. No flat tires on unkneeled gears	769,000 lb	732,500 lb
Individual	B. One or more flat tires on side of	769,000 lb	732,500 lb
Main Gear	Aircraft opposite that being kneeled.		
	C. One or more flat tires on unkneeled gear. On side of aircraft being kneeled.	673,000 lb	Prohibited
II	A. No flat tires on unkneeled gear.	769,000 lb	Prohibited
Symmetrical	B. One or more flat tires on either	673,000 lb	Prohibited
Main Gear	Or both main gears remaining		
Pairs	On the ground.		
III	A. No flat tires on unkneeled gear.	Not applicable	Not applicable
Cross Kneeling	(769,000 lb. gross weight).		
(left forward gear	B. One flat tire on either or both	Not Applicable	Not applicable
followed by right	Rears remaining on ground		
Aft gear, or, right	(673,000 lb gross weight)		
Forward gear			
Followed by left			
Aft gear			

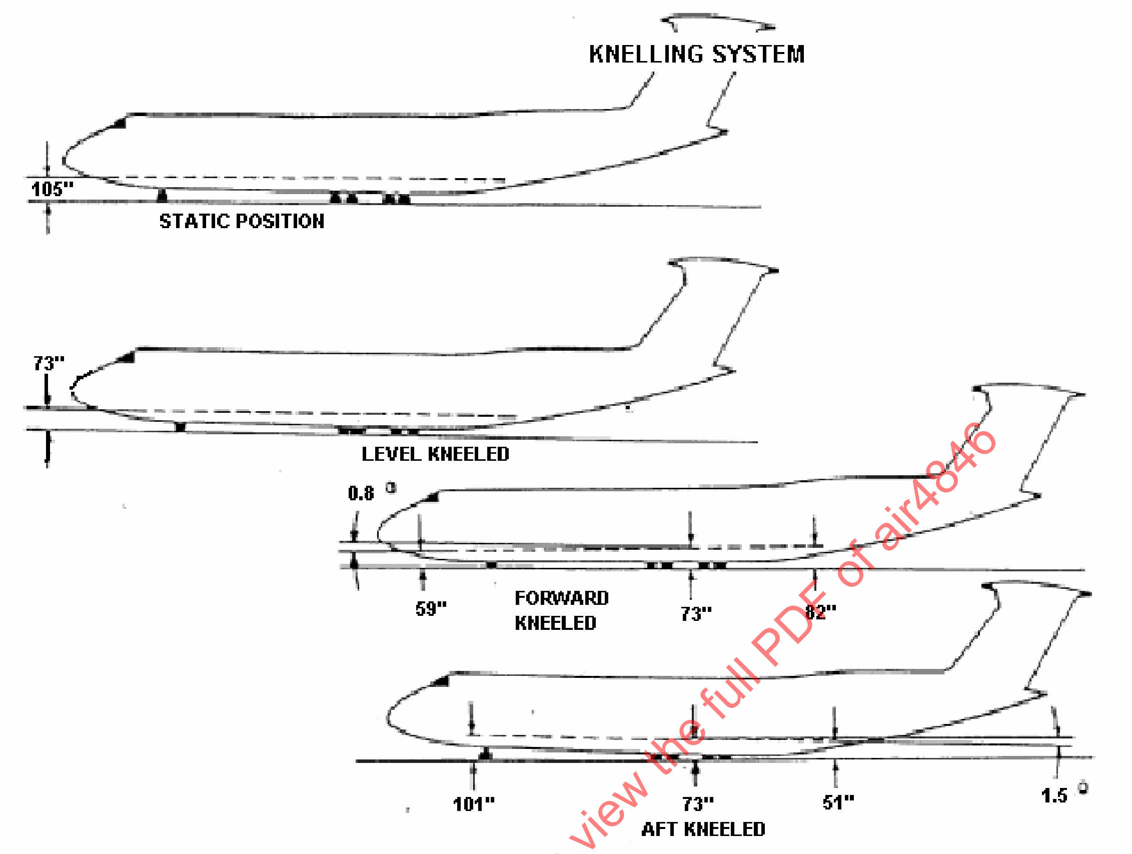

FIGURE 3 - C-5 KNEELING SYSTEM

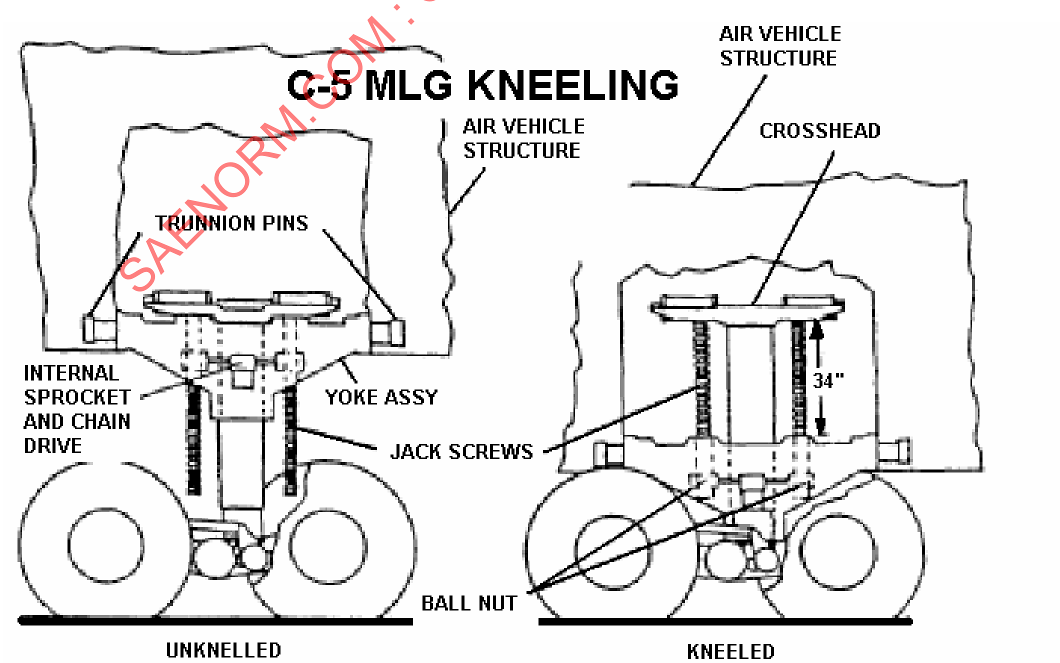

FIGURE 4 - C-5 MLG KNEELING

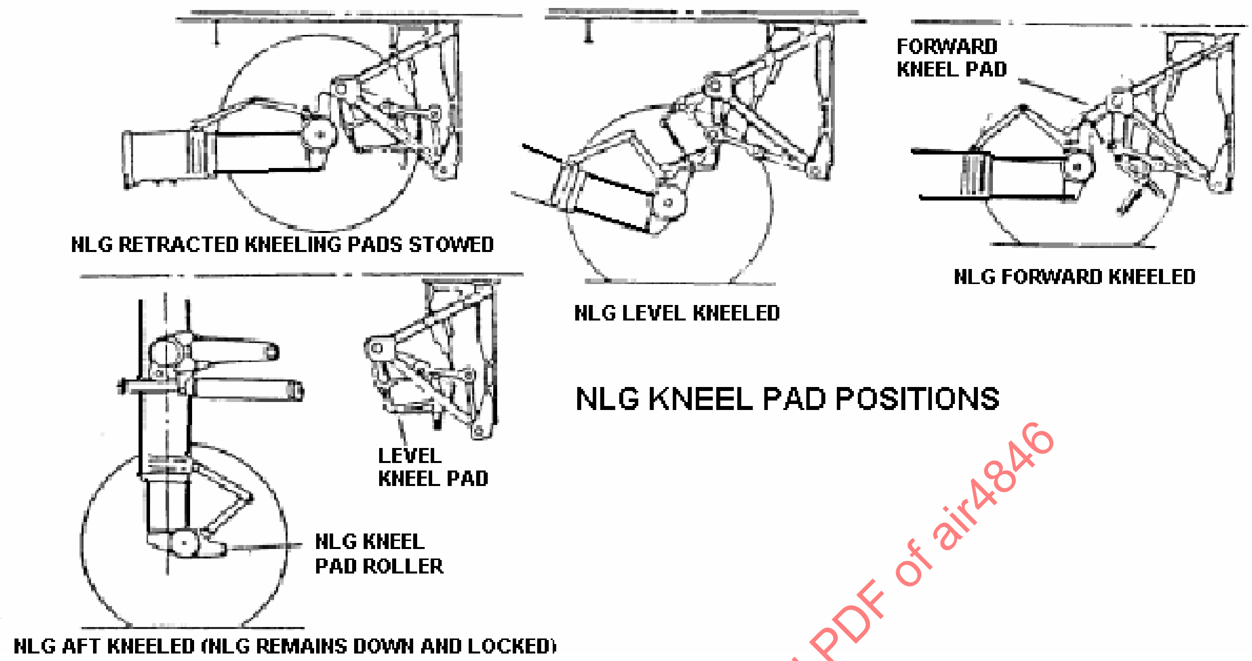

FIGURE 5 - C-5 NLG KNEELING SYSTEM

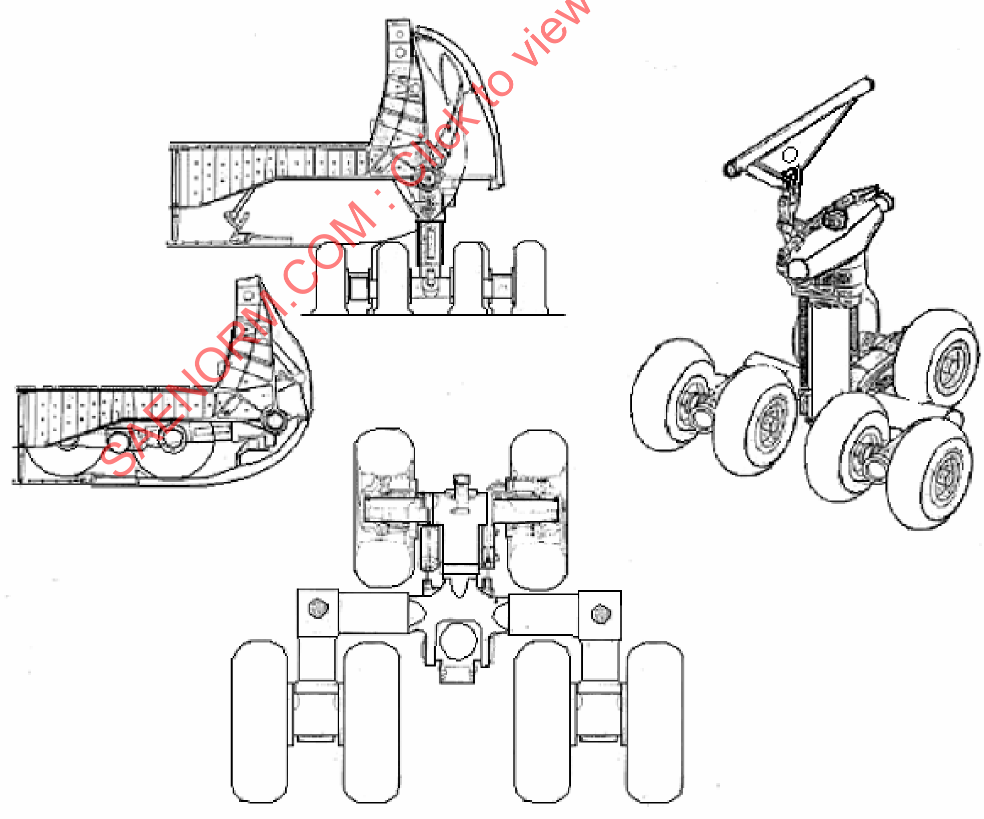

FIGURE 6 - C-5 MAIN LANDING GEAR

3.3 YC-14 Main Landing Gear

Advanced Medium STOL (Short Takeoff and Landing) Transport (AMST) YC-14 was built by Boeing to ultimately replace the C-130. In 1973, Boeing received contracts to build and test two prototypes. The aircraft was designed to use off-the-shelf engines to achieve a Coanda effect to maximize lifting capability. See Figure 7. The program was canceled shortly after flight testing.

FIGURE 7 - YC-14 ADVANCED MEDIUM STOL TRANSPORT

The YC-14 (see Figure 8) uses a levered trailing arm system that is equipped with low-aspect-ratio, high-flotation tires. This levered gear concept has proved extremely reliable on many current transport aircraft. The YC-14 design also provides the following added capabilities:

- Low cargo floor height for ground loading
- Short-field, high-sink-rate landings
- Rough field operation
- Multiple passes on bare soil airfields
- Repeated operation on marginal strength paved runways

The automatic braking and advanced anti-skid control system provides smooth stopping whether the runway is dry, wet, or icy.

These features have all been tested and verified during the YC-14 flight test program.

STOL landing approaches descending at 14.9 ft/s (4.5 m/s) using approach path angles of 6° have been routine, and pilots report remarkable softness in landing gear contacts on both paved and unprepared runways.

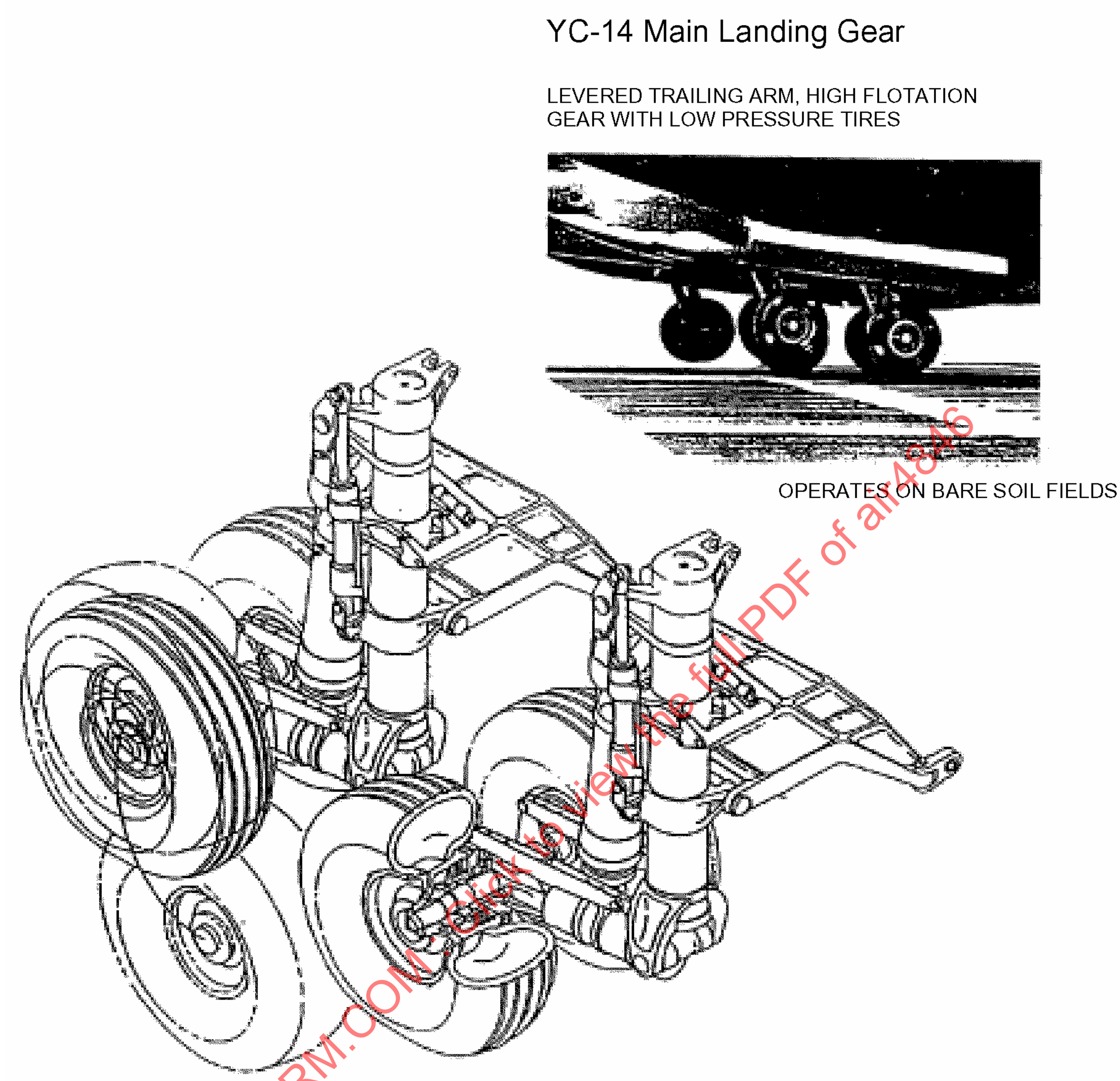

FIGURE 8 - YC-14 MAIN LANDING GEAR

3.4 CF-105 Avro "Arrow" Main Landing Gear

The "Arrow", a supersonic interceptor fighter, was designed and built in the early nineteen fifties by A.V. Roe Canada Ltd., (a division of the Hawker-Siddeley Company of Canada Ltd.). See Figure 9. It was built primarily for the Canadian Government for the national defense of Canada, although it was rumored that other nations were also interested in the project.

A change in the defense philosophy of the Canadian government in 1958, resulted in the cancellation of the complete program, and the destruction of all aircraft and manufactured parts, together with program records and technical drawings produced up to that point. Such destruction was a pitiful loss to the advance of aircraft design technologies that were introduced in the construction of this aircraft, its landing gear providing a significant portion of those technologies.

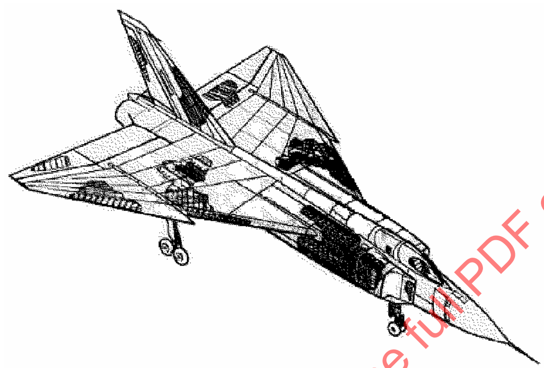

FIGURE 9 - CF-105 AVRO ARROW

Major components of both nose and main gears were manufactured from what was known generally in those days as "ultra-high tensile" steel, a material with considerably higher mechanical properties (260,000/280,000 UTS) than was then in common use. The Arrow program was not the first to utilize this grade of steel for landing gear, but it did contribute to the initial steep learning curve created in the development of this material, and which has resulted in the depth of knowledge of this subject enjoyed to-day.

The main gear executed probably all movements possible during retraction. The gear shortened, twisted, and the tandem truck changed pitch angle. All these motions were made while the gear rotated about a "skew" axis (relative to vertical and horizontal planes).

With the exception of the truck positioner, all power required to perform these movements was provided by the retraction actuator. Low pressure air was used to maintain the truck positioner fully extended in order to ensure the correct truck angle both in the "landing gear down" and "landing gear up" position. Another function of the fully extended truck positioner, (known in those days as the "piece of string"), was to prevent the "slap down" of the front wheel when the rear wheel touched down during landing, giving the gear the characteristics of a trailing arm gear, at least in the early stages of the axle stroke.

In the early days of the flight test program, the main gear only partially extended prior to landing. This has been made public knowledge by means of several articles published in Canada since the program cancellation, but due to the destruction of all the Arrow's flight and service reports, none of these publications have given a full technical explanation for this malfunction, and, in the absence of authentic evidence, all explanations may be speculative.

The shock absorbing unit used in the main gear was of an early liquid spring variety. See Figure 11. Liquid springs have a history of losing extended internal pressure at extreme low temperatures. Environmental requirements of the Arrow (which were to operate inside the Arctic Circle) required the use of a recuperator which was slung under the front brake torque link. Full extension of the shock strut actuators a valve that connects the liquid spring to the recuperator. (As a note, the springs in the system assists the 'lengthening' of the gear leg and was not associated with shock absorption.). See Figure 12.

However, the primary function of the compression springs was to provide full gear extension by negating the gear shortening achieved during retraction.

The speculations which appear most logical are as follows:

1. Liquid Spring did not maintain minimum required internal pressure (at extension) or

2. Support springs failed, or the spring coils became inter-locked (if the springs were not contra-wound)

Assuming either of the above to be true, the shortening mechanism (a chain and sprocket system) would fail. See Figure 10. This mechanism did in fact fail, and was known to be replaced by a continuous bell-crank mechanism. Apart from this mishap, in which no aircraft loss was incurred, the complex but very well integrated gear design features, performed satisfactory, and promised continual improvements in life cycle costs over a reasonable period of time.

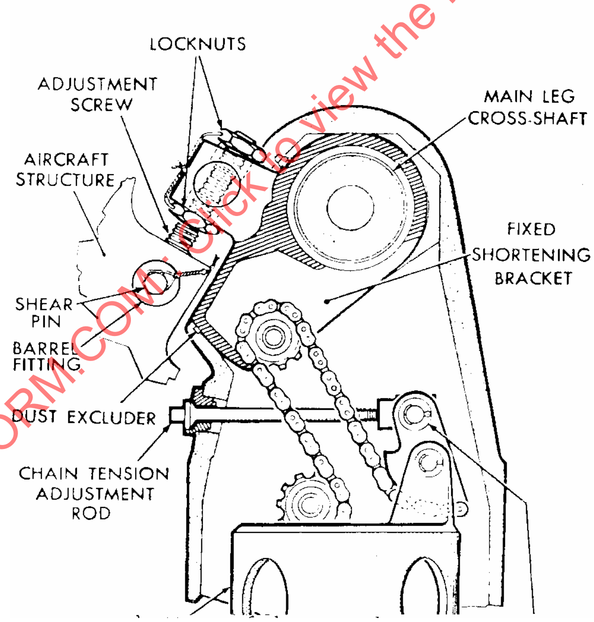

FIGURE 10 - CF-105 ARROW MAIN LANDING GEAR SHORTENING MECHANISM

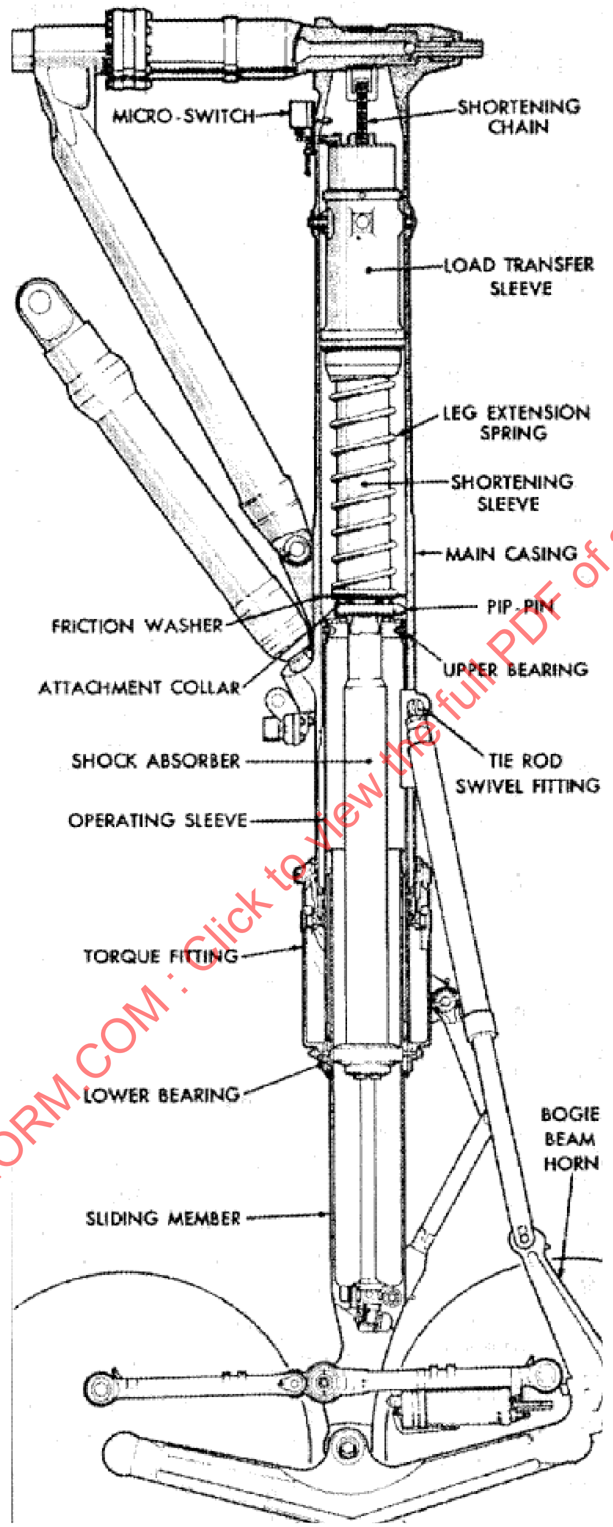

FIGURE 11 - CF-105 ARROW MAIN LANDING GEAR

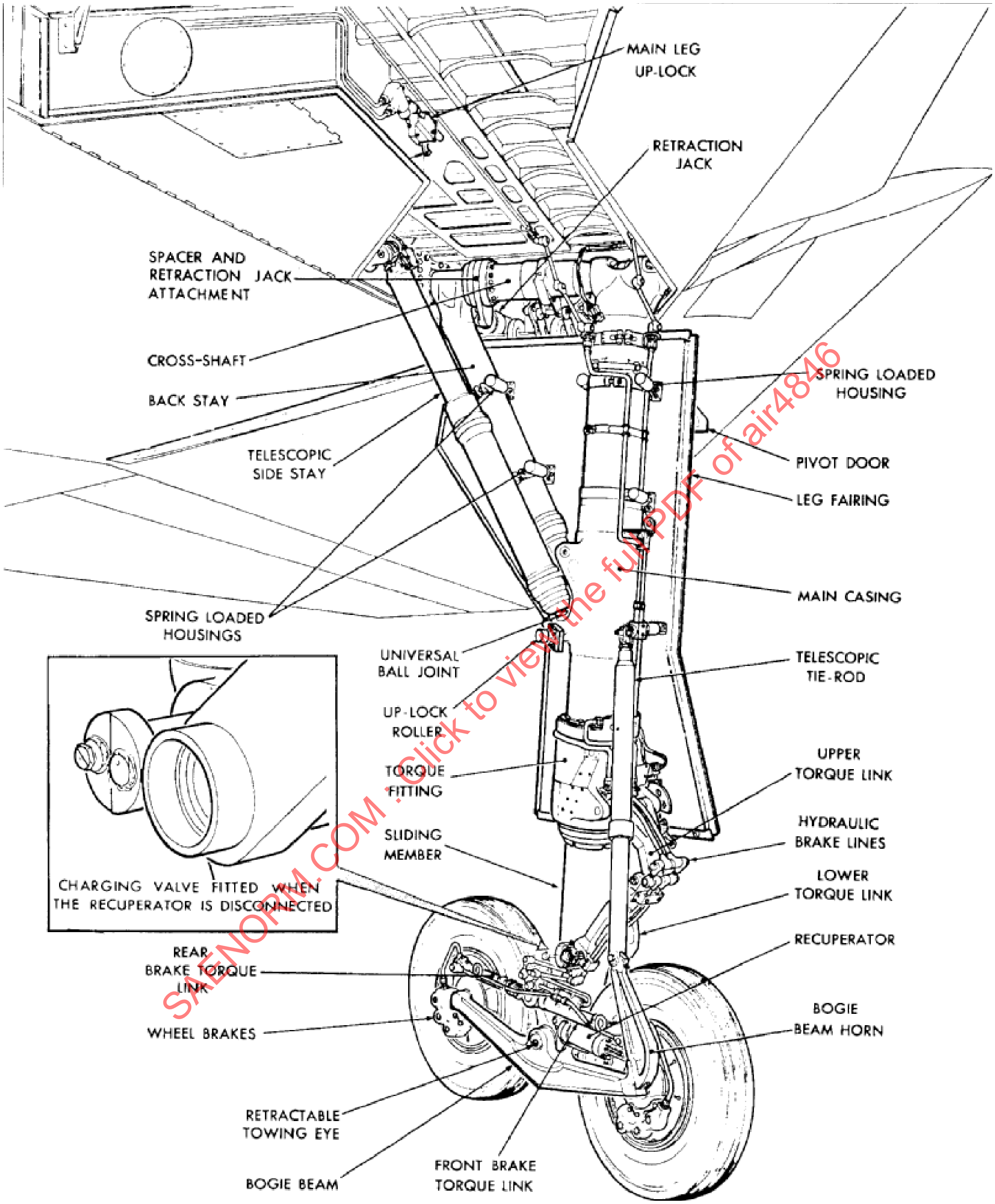

FIGURE 12 - CF-105 ARROW MAIN LANDING GEAR

3.5 V-22 (Osprey) Main Landing Gear

The Bell-Boeing V-22 Osprey is an advanced V/STOL tilt-rotor aircraft developed for the U.S. Navy and Marines. The V-22 combines the efficient flight characteristics of a modern turbo-prop aircraft with the vertical take-off and landing capabilities of a conventional helicopter (see Figure 13).

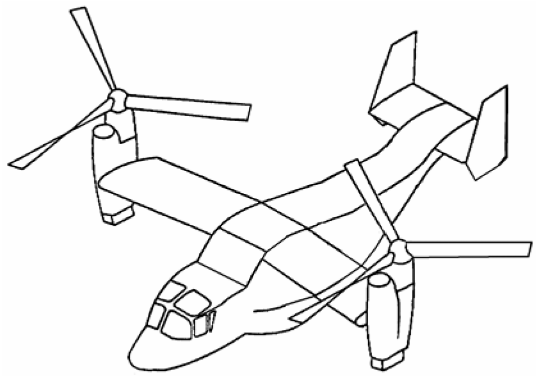

FIGURE 13 - V22

During the loads prediction phase of the gear design, it was found that unique features of the V-22 influenced the gear landing loads. Significant load reductions could be achieved by including the aircraft structural flexibility in the loads analysis and landing gear design (see Figure 14).

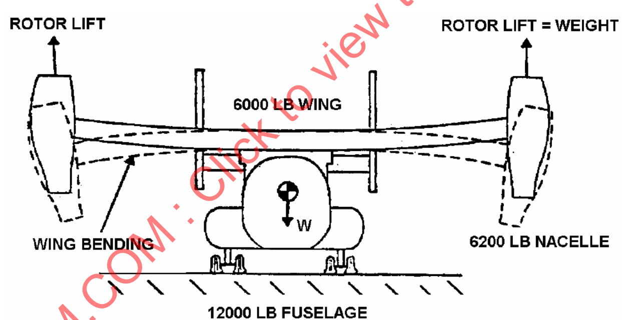

FIGURE 14 - V22 WING BENDING

To take advantage of the load reductions, the aircraft structural flexibility was included in the landing gear drop tests. This was important because typically many of the dynamic elements of the landing gear were redesigned during the drop tests. This was the first time that actual drop tests were performed including aircraft flexibility, although an analytical method for this is outlined in Reference 1. Inclusion of aircraft flexibility involved modification of the drop test rig and drop test procedures.

3.5.1 Overview of Landing Gear Design

The V-22 Main Gear is a twin wheel design using 25.5 × 8.50 -10 wheels and tires with disk brakes. It is a cantilevered type design with longitudinal loads taken as bending in the strut which is reacted by the trunnion pin mounted outer cylinder and drag brace. The drag brace also functions as the retraction actuator and contains two sets of internal segment locks, which serve as the downlock when the actuator is extended, and the uplock when it is retracted (Reference 2).

An isometric view of the left-hand gear is shown on Figure 15. The airframe attachment consists of two trunnion pins in the main fitting, and a drag brace attachment pin. The customer requirement for an "un-handed" gear necessitated the additional drag brace and torque arm lugs. Simplified logistics justified the weight penalty.

The schematic of the V-22 shock strut (Figure 16) illustrates the major components of the two-stage oleo-pneumatic gear. Floating pistons prevent the mixing of oil and gas. Each main gear weighs 233 pounds without wheels, tires and brakes. The main piston diameter is 4.5 inches.

During compression, high pressure oil in the main hydraulic chamber, is forced past the metering pin into the first stage gas spring chamber, and subsequently into the rebound chamber. If the main hydraulic chamber pressure exceeds the second stage pneumatic charge pressure, oil will also flow into the second stage gas spring chamber. The first and second stage charge pressures are 220 psig and 1265 psig respectively. Consequently, compression of the second stage gas spring only begins when the main chamber reaches 1265 psig.

Damping of the second stage is controlled through the second stage fixed orifice. Successful control of the strut during extension is achieved using a metering pin. The total available piston/axle stroke is 15.25 inches. The metering pin profile for the first eight inches is constrained by the 12 ft/s maximum vertical reaction requirement. The next six inches is determined by the 24 ft/s landing case and the profile over the final 1.25 inches is designed to reduce bottoming loads during a flat strut landing.

3.5.2 Loads Analysis

Drop test conditions also included requirements specified by the US Navy, as well as conditions specified in MIL-T-6053C "Tests Impact, Shock Absorber Landing Gear, Impact". There were three landing conditions that were design drivers. The first was the Design Normal Landing of 12 ft/s, 0 knots forward velocity with the aircraft level. This condition was most critical, and was used in the design of the metering pin. Second to this was the Design Hard Landing of 14.7 ft/s, with the aircraft level, and no forward velocity. At this landing speed, there was to be no yielding of the gear. The third condition was the Design Crash Landing of 24 ft/s, with the aircraft level and no forward velocity. During the crash landing, the gear was to remain attached to the backup structure.

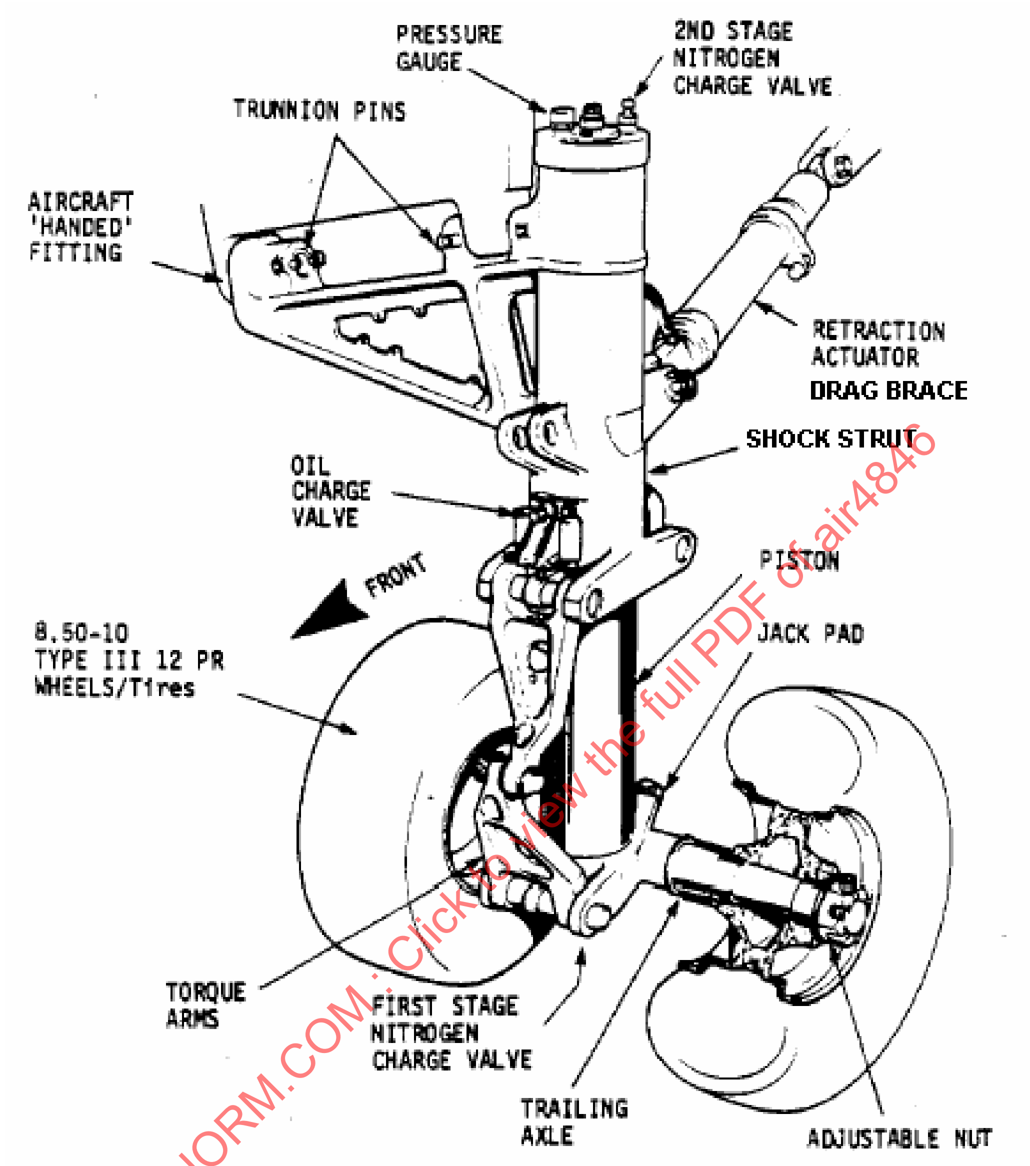

FIGURE 15 - V-22 MAIN LANDING GEAR

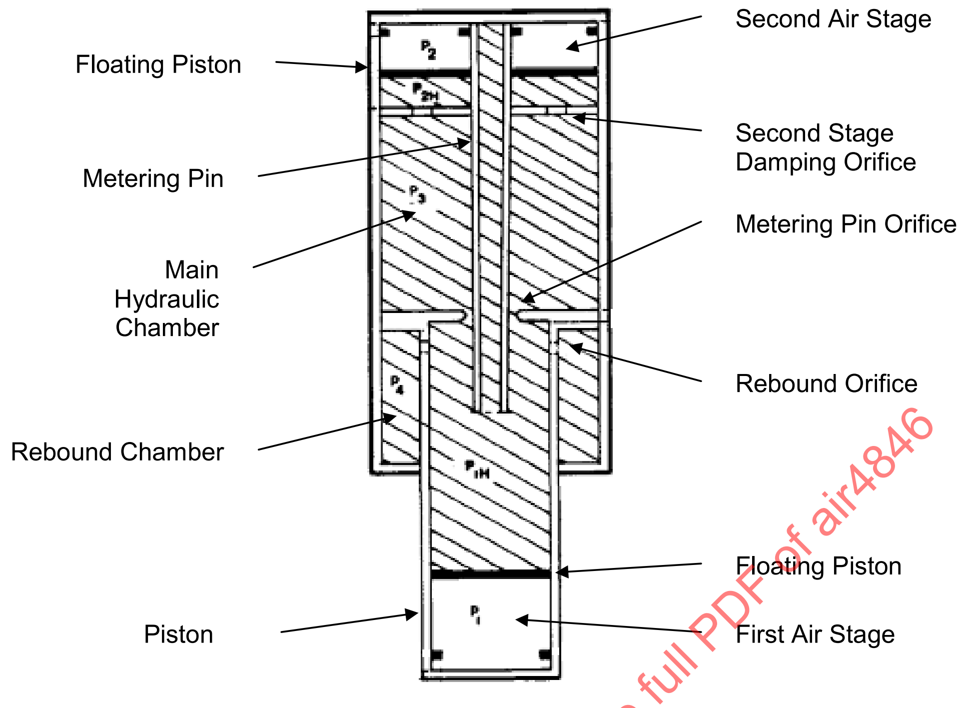

FIGURE 16 - V-22 MAIN GEAR SHOCK STRUT SCHEMATIC

3.5.2.1 Analytical Tools

Computer models of the V-22 and the landing gear were used to calculate the design loads previously mentioned. These tools, described in the following sections, defined the design landing loads, the drop test predictions, and the aircraft modeling in the drop test. These tools were also used to define metering pin characteristics.

The computer analyses are time history models that were created using Continuous System Modeling Program (CSMP) (Reference 3). CSMP takes the model equations of both motion and constraints and numerically integrates them.

3.5.2.2 Dynamic Loads Analytical Model (DLAM)

This model is a full aircraft model of the V-22. A diagram of DLAM is shown in Figure 17. It is a time history model containing up to 30 degrees of freedom. Six rigid body degrees of freedom define the translational and rotational motions of the aircraft. The V-22's single nose gear is modeled with two degrees of freedom, one vertical, and one longitudinal. Each of the two main gears have three degrees of freedom, two vertical, and one longitudinal. Up to sixteen bending modes are included in the analysis. The bending modes are obtained with a detailed Nastran model of the V-22 containing approximately 38,000 elements.

The V-22 main landing gear in DLAM is modeled as close to the real landing gear as possible. The model contains two pneumatic air stages, metering pin damping, rebound damping, and the second stage damping. Bearing friction is modeled. Non-linear tires are modeled using tire tables from the tire manufacturer. The longitudinal stiffness of the gear is also included in order to obtain spin-up and spring-back loads.

3.5.2.3 Single Gear Model

The single gear model as shown in Figure 18 is a time history model of one landing gear. It is used to define the fuselage mass/spring system, and to calculate drop test predictions. The modeling of the main gear is the same as the full aircraft model. The aircraft structure of the V-22 is modeled using two masses separated by a spring. The two masses and spring represent one rigid body mode and one flexible mode of the aircraft. The mass/spring modeling is unusual in landing gear analyses, and the reasons for using it will be explained in the upcoming sections of this document.

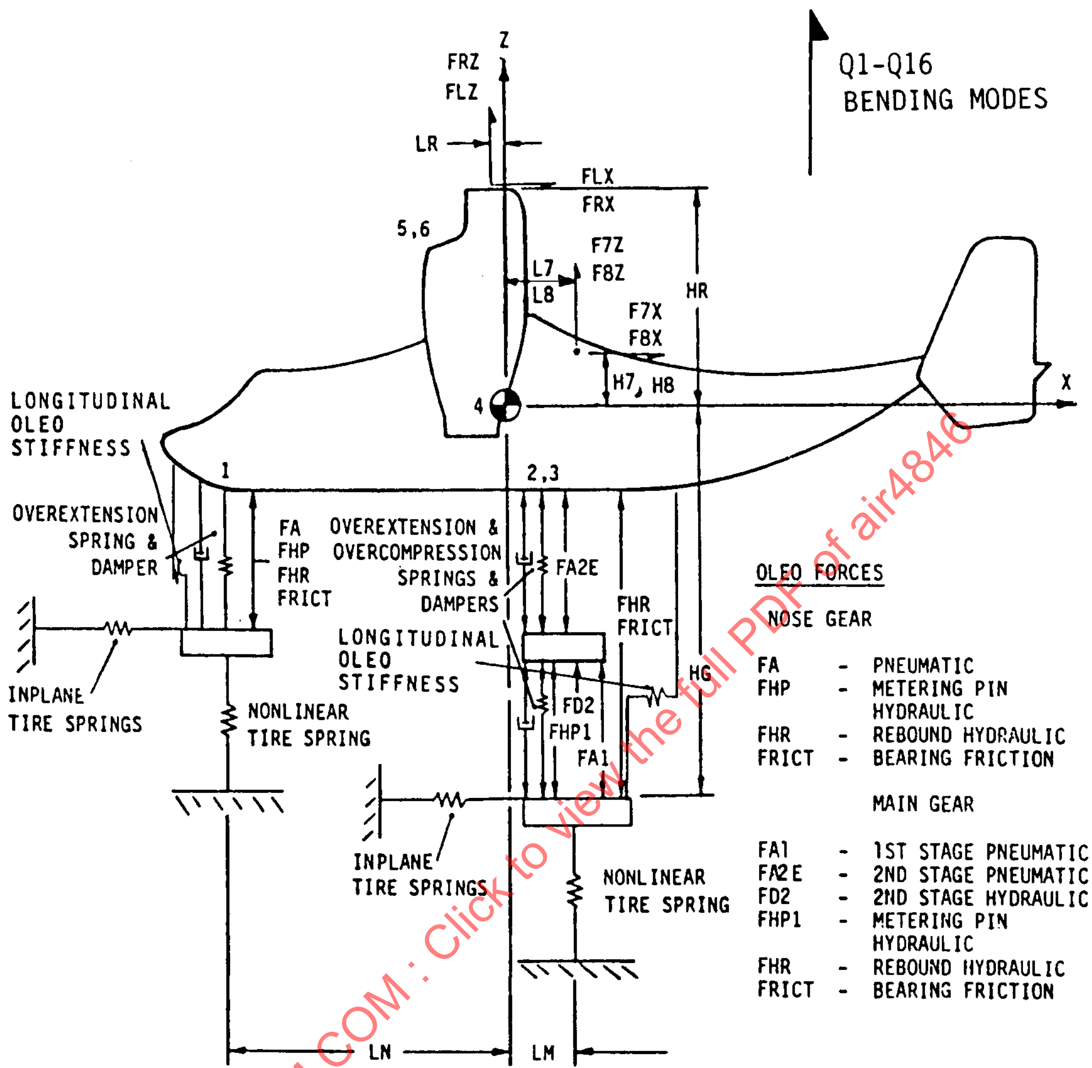

FIGURE 17 - DYNAMIC LOADS ANALYTICAL MODEL (DLAM)

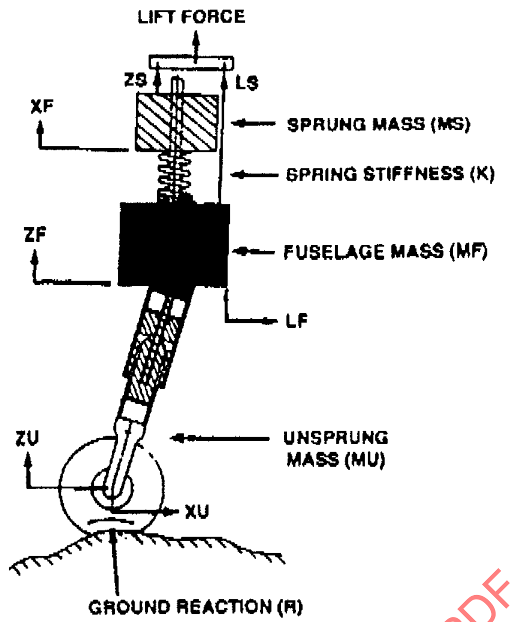

FIGURE 18 - SINGLE GEAR, THREE MASS LANDING, SIMULATION MODEL

3.5.2.4 Analytical Results

3.5.2.4.1 Aircraft Structural Flexibility

When calculating the landing loads, it was discovered that the structural flexibility of the aircraft played a major role in decreasing loads, which consequently affected the metering pin design. The V-22 has a heavy wing relative to the whole aircraft, with rotor nacelles that weigh 6000 pounds at the end of each wing. See Figure 14. Because the nacelles accentuate the behavior of the wing, the symmetric wing bending mode dominates the structural flexibility during landings, with most of the structural energy absorption occurring in the wing. At velocities near the 24 ft/s crash condition, other bending modes become more important, but the symmetric wing bending mode is still dominant. The wing bending mode is shown in Figure 19.

Table 2 shows the effects of including structural flexibility in the analysis. Using the full aircraft model (DLAM), landings of several descent velocities were analyzed with both flexible and rigid aircraft structure. Some of the dynamic elements in the analysis, such as the metering pin and the tire bottoming stiffness, were defined during the drop test. By using these values, Table2 shows the most accurate depiction to date of the loads reduction.

The use of structural flexibility reduced the loads by a significant amount, especially at higher descent velocities. A loads savings of 19,800 pounds (or 26.1%), occurred at the 14.7 ft/s no yield condition. At the crash condition a 60,700 pound load savings was achieved by using structural flexibility. This meant a 31% reduction in load during the crash landing. Because of the large load reductions, the landing design loads were all calculated using structural flexibility.

3.5.2.5 Metering Pin Design

Here, an important fact about the results in Table 2 should be noted. The drop test metering pin was designed with structural flexibility included. The metering pin controls the hydraulic flow in the landing gear, which is the major source of damping during landings. This damping is the largest part of the vertical landing load during the first half of the gear stroke.

If the metering pin were designed assuming a rigid aircraft, the performance of the landing gear when attached to the aircraft would not be optimal. An example of this is shown in Figure 20. The load reductions due to aircraft flexibility would be degraded. Because of this, the metering pin was designed with structural flexibility included.

3.5.2.6 Mass/Spring Model

The metering pin design usually undergoes revisions during the drop tests of the landing gear. In order to simulate the aircraft flexibility during the drop test, the aircraft weight over the gear was modified from the usual single mass to a system of two masses and one spring. The masses and one spring simulate one rigid body and one flexible degree of freedom of the aircraft. This is sufficient to model the aircraft flexibility because of the dominant symmetric wing bending mode. An example of the full aircraft model vs. the single gear model is shown in Figure 21.

A different mass/spring system was defined for each aircraft gross weight, and for each aircraft roll and pitch condition. This was necessary for two reasons. First, the structural response was different for a level aircraft versus a highly rolled or pitched aircraft. Second, the symmetric wing bending mode frequency changed at different aircraft gross weights. Usually the weight change was not as significant as the pitch or roll conditions. Examples of mass/spring systems are defined in the captions of Figures 24 through 26. Defining the mass/spring systems was an iterative procedure; no analytical expression that would define the systems adequately was found.

3.5.3 Drop Tests Analysis and Drop Tests

The following shows how the effects of wing structural flexibility and engine/rotor lumped mass were incorporated into the main landing gear model and drop test rig in order to provide realistic landing gear loads.

The next sections contain a description of the main landing gear model, the drop test arrangement, and a comparison of predicted and drop test landing loads. The results show that a significant reduction in loads can be achieved by using this approach. Jig drop test results of a main gear confirmed the predicted load reductions.

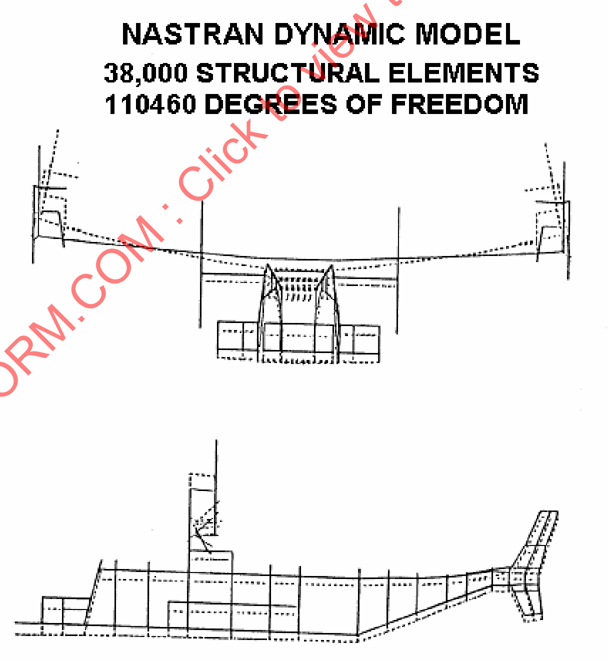

FIGURE 19 - V-22 SYMMETRIC WING BENDING MODE

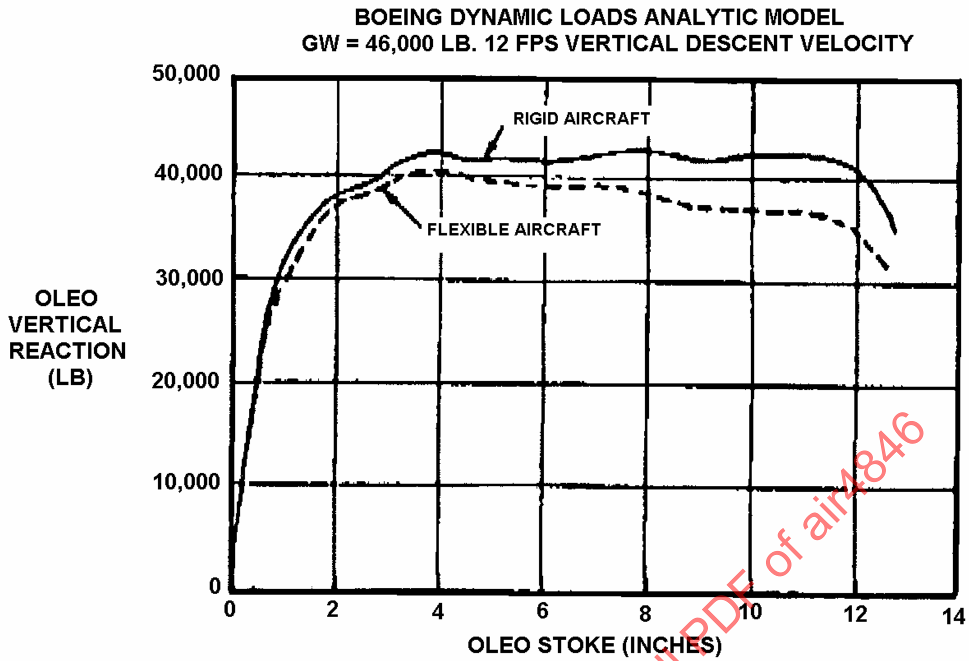

FIGURE 20 - EFFECT OF RIGID VS. FLEXIBLE AIRCRAFT ON LANDING LOADS WITH METERING PIN DESIGNED FOR A RIGID AIRFRAME

3.5.3.1 Analytical Tools

Landing loads are typically obtained using a rigid airframe model and a two mass landing gear model consisting of a fuselage mass and an unsprung mass. To model the significant contribution of aircraft structural flexibility to energy absorption in the V-22 aircraft, a spring and mass is added to the conventional model. The Dynamic Loads Analytical Model Boeing single gear model were used to determine the equivalent masses and spring stiffnesses used to simulate the aircraft loads and motion. This data was then used in the single landing gear model that predicts results for a single gear drop test. The masses of the engine, rotor, and airframe, are referred to as the sprung mass, and the landing gear piston and all rolling stock are referred to as the unsprung mass. Figure 18 shows the three mass landing gear model. Several programs were used in the analysis of the landing gear energy absorption features and the load determination.

An accurate gas spring model capable of handling multistage was developed and applied to numerous landing gear designs. Correlation with test results allowed a model capable of accurate prediction to be developed. It includes empirical corrections from the ideal gas curve , structural strain, friction, and other non linear effects. It is important for energy absorption as well as aircraft handling features that the desired result be obtained in the production hardware.

A computer model of the dynamic single landing gear model was then created using a gas curve which represents the performance of the multi-stage shock absorber. The longitudinal stiffness of the gear which affects the spin-up and spring-back loads is obtained from a finite element model of the gear also used for stress and fatigue analysis of the gear. The dynamic elements of the gear, metering pin and orifices are accounted for in the program. The program was used to predict loads for all specified dynamic requirements using mass/spring data representing the wing symmetric bending mode.

3.5.3.2 Drop Test Set Up and Hardware

Front and side views of the test rig and test vehicle as shown in Figure 22. The drop tests were conducted in a vertical rail type drop machine with the test specimen rigidly mounted in a fixture simulating the method of attachment to the aircraft structure. Rotor/wing aircraft lift was simulated by pneumatic cylinders reacting the carriage weight. The gear was dropped on to a load platform, simulating the required coefficients of friction and slopes. Associated vertical, side and spin-up drag loads are verified. The drag brace load was measured with a load cell and a spin-up machine was used to spin the wheels.

Instrumentation data was acquired and analyzed with a digital computer based test management system with a high sampling rate ensuring that accurate data was obtained. The data was digitally logged, formatted and plotted in a form most suitable for analysis and understanding of the results.

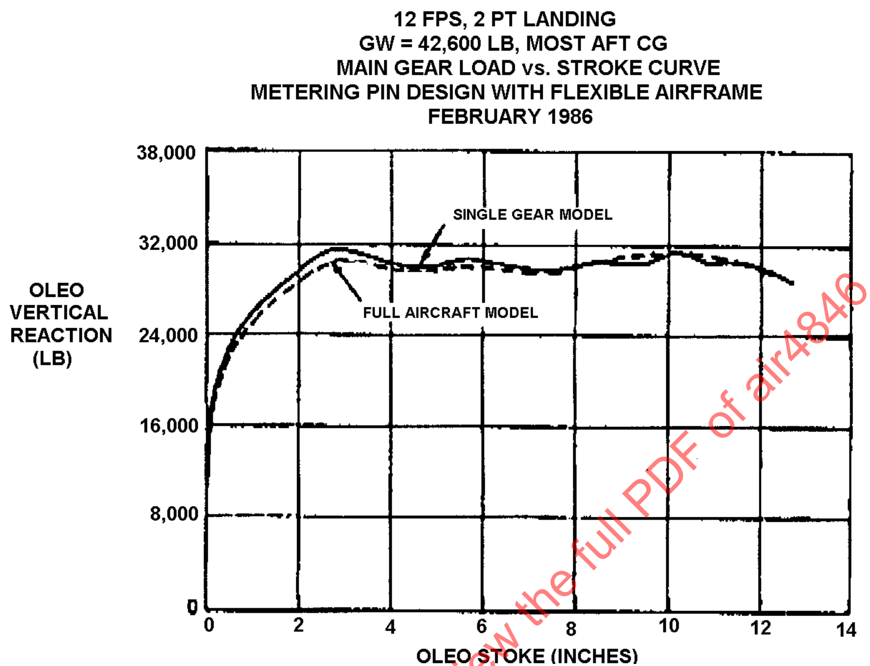

FIGURE 21 - SIMULATION OF FLEXIBLE AIRFRAME WITH SINGLE GEAR MODEL

3.5.3.3 Drop Test Results

Drop tests were required for three basic conditions; Normal landings up to 12 ft/s at weights of 46,000 pounds, 53,000 pounds, and 60,500 pounds. These conditions correspond to the take-off and landing, maximum STOL, and self deployment gross weights, respectively.

The V-22 main landing gear was drop tested using the three mass approach and a few two mass drops. To illustrate the load reductions achieved, two-mass (conventional) predicted results and three mass predictions and test loads are shown in the loads plots. To substantiate the two-mass model, several two-mass drop tests were conducted. The results of the two mass, 12 ft/s landing case (using a weight over gear of 10,590 pounds) are shown in Figure 23. The predicted results are within 2% of the test results for both maximum load and stroke values.

Figure 24 shows a prediction and test result for a 12 ft/s three mass drop test, and (with modified pin to suit two masses) a corresponding two-mass prediction. The results show a maximum ground load of 39,000 pounds for a three mass versus 46,900 pounds of a two-mass prediction (16.8% reduction). This is the case which sets many gear and airframe design values, such as obstruction with side and drag, a critical stress case for landing gear and aircraft structure. This is the prime case for which the metering pin is designed and optimized.

Figure 25 shows similar results for the 14.7 ft/s case, which is the hard landing or reserve energy requirement. The achieved drop test velocity was 14.8 ft/s, and the load reduction was from 74,800 to 50,000 pounds (33%).

The achieved drop test velocity for the Design Crash Landing was 24.35 ft/s, slightly higher than the required 24 ft/s velocity. This case yielded a ground load of 134,000 pounds as shown in Figure 26 for a three-mass versus a 179,000 pound predicted value for a two-mass system, a decrease of 25%. Note that predicted three-mass crash loads fall short of test results. This is attributable to a softer tire bottoming stiffness used in the prediction model than was obtained in the test. However, there is still stroke available. There are some restrictions on optimizing the gas spring for landing alone. These are set by the stability required for on-board deck storage of aircraft. This leads to gas spring stiffness requirements at the positions where the gas is compressed statically when the V-22 is stationary. Taxi bump requirements also define a gas spring maximum load requirement.

Figure 27 shows the relative motions of the fuselage and sprung mass versus time for the reserve energy landing case. The magnitude of the displacement of the sprung mass clearly indicates its energy absorbing capability. About eight inches of sprung mass travel was achieved.

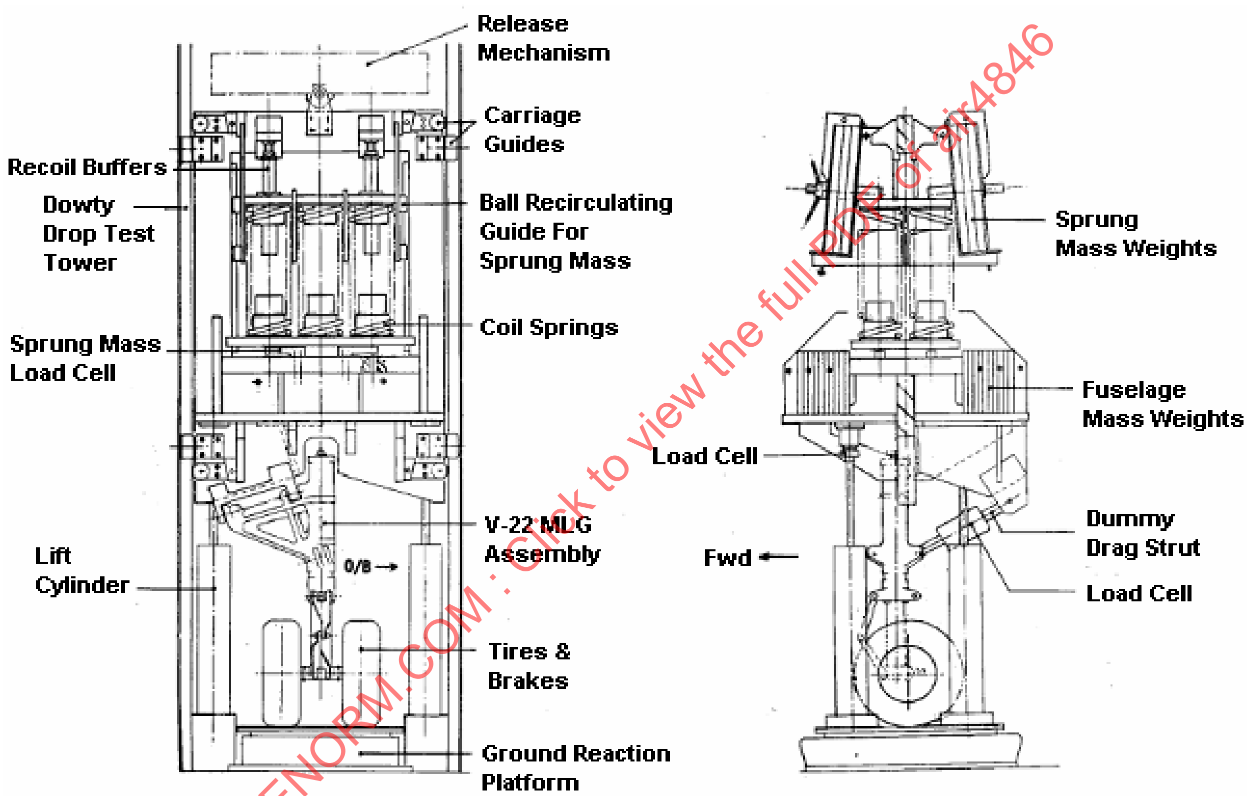

FIGURE 22 - TEST SET UP

3.5.3.4 References

1. Cook, Francis E. and Milwitzky, Benjamin, "Effect of Interaction on Landing Gear Behavior and Dynamic Loads in a Flexible Airplane Structure", NACA Report 1278, 1957.

2. Darlington, Ralph, "Landing Gear - A Complete Systems Approach", Vertiflite, March/April, 1987.

3. Korn, G.A. and Wait, J.V., Digital Continuous - System Simulation, Prentice-Hall, 1978.

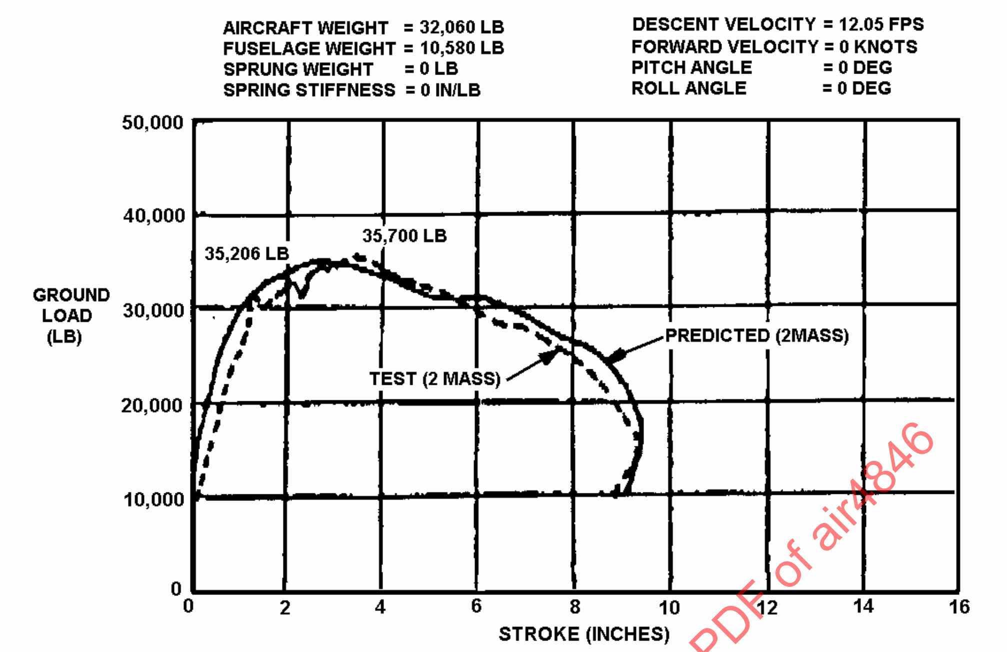

FIGURE 23 - DROP TESTS RESULTS - TWO-MASS SYSTEM

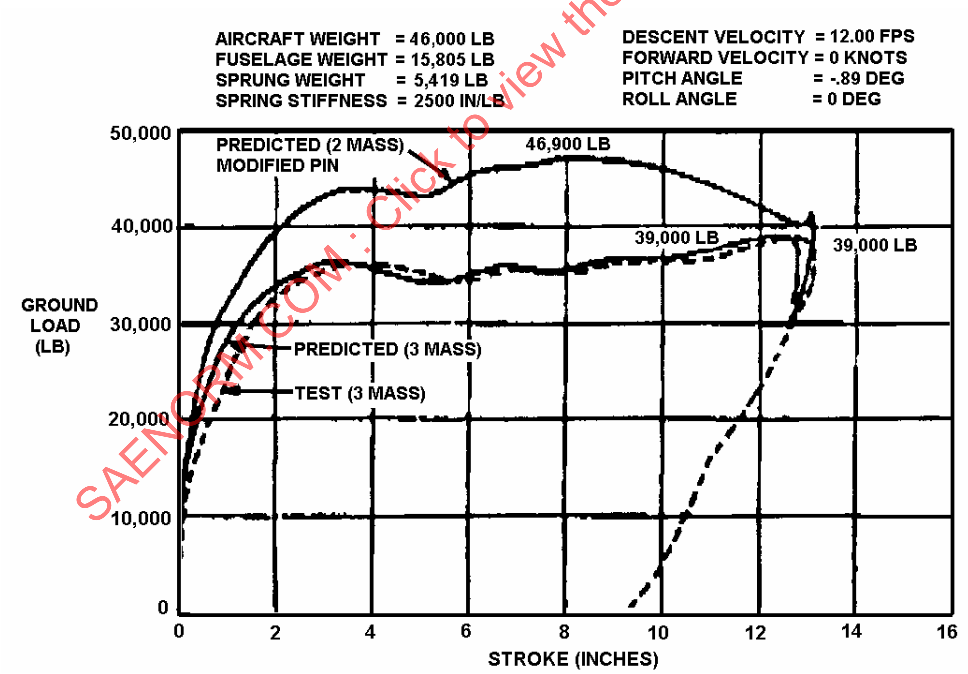

FIGURE 24 - DROP TEST RESULTS - THREE MASS SYSTEM DESIGN NORMAL LANDING

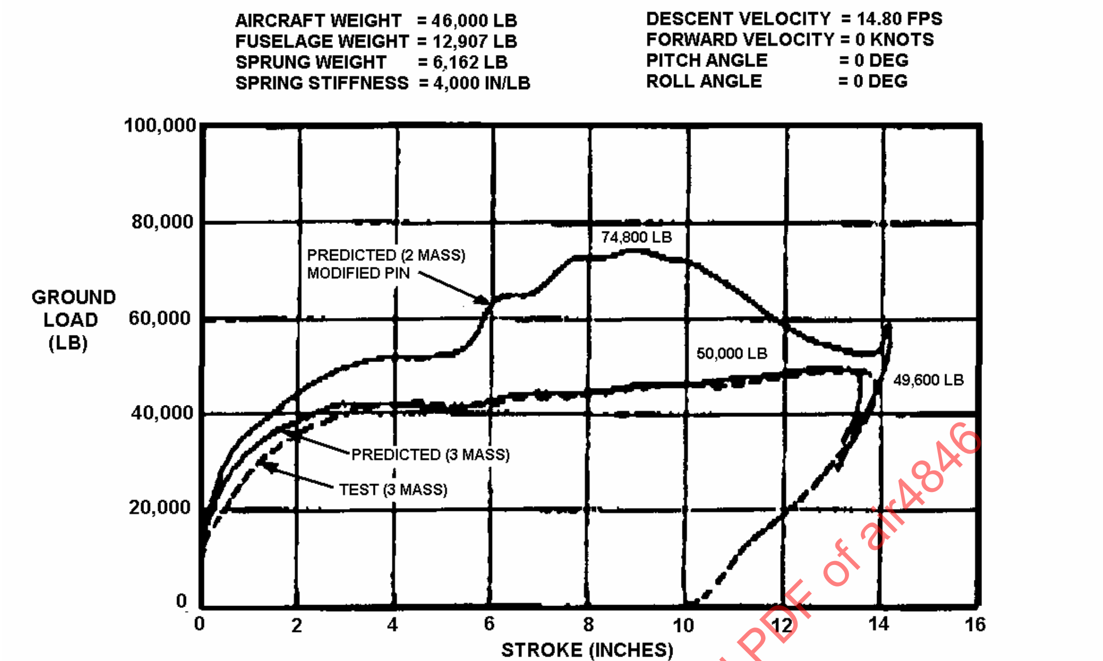

FIGURE 25 - DROP TEST RESULTS - THREE MASS SYSTEM HARD LANDING (RESERVE ENERGY)

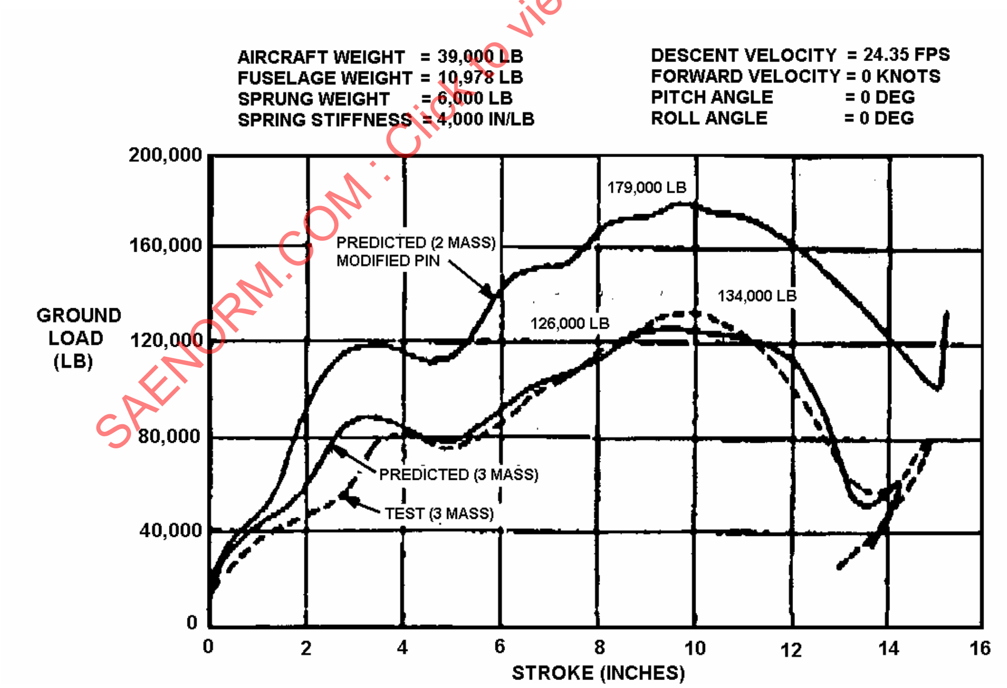

FIGURE 26 - DROP TEST RESULTS - THREE MASS SYSTEM (DESIGN CRASH LANDING)

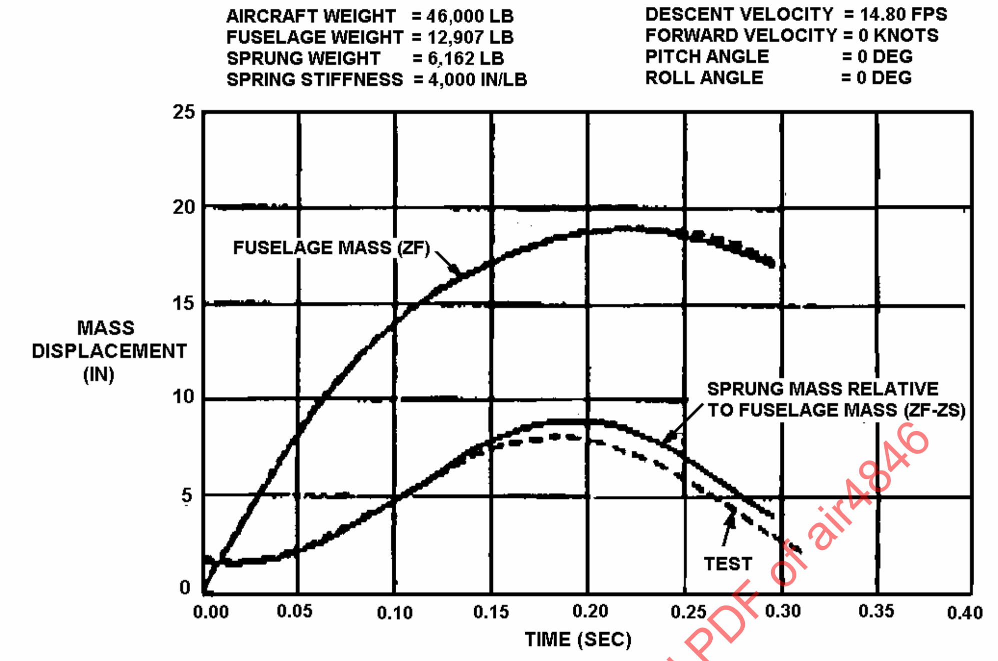

FIGURE 27 - MAIN GEAR DROP RESULTS (RESERVE ENERGY LANDING CASE)

TABLE 2 - V-22 EFFECT OF AIRCRAFT STRUCTURE ON MAIN LANDING LOADS

Dynamics Loads Analytical Model
(Boeing Full Aircraft Model)
Gross weight: 46,000 lb
2 - Point Landing - Level Attitude
Nominal Gear and Tire Servicing
Rotor Lift = Aircraft Weight
Metering Pin Optimized for 12 ft/s
Landing at GW = 46,000 lb
Rotor Lift = Aircraft Weight

Condition	Descent Velocity (ft/s)	Vertical Gear Load Fixed A/C (lb)	Vertical Gear Load Flexible A/C (lb)	Load Difference	% Reduction
Design Normal Landing	12.0	43,200	39,106	4,100	9.5
Design Hard Landing	14.7 No Yield	75,786	55,986	19,800	26.1
Design Crash Landing	24.0	195,706	135,000	60,706	31.0

3.6 C-17 Landing Gear

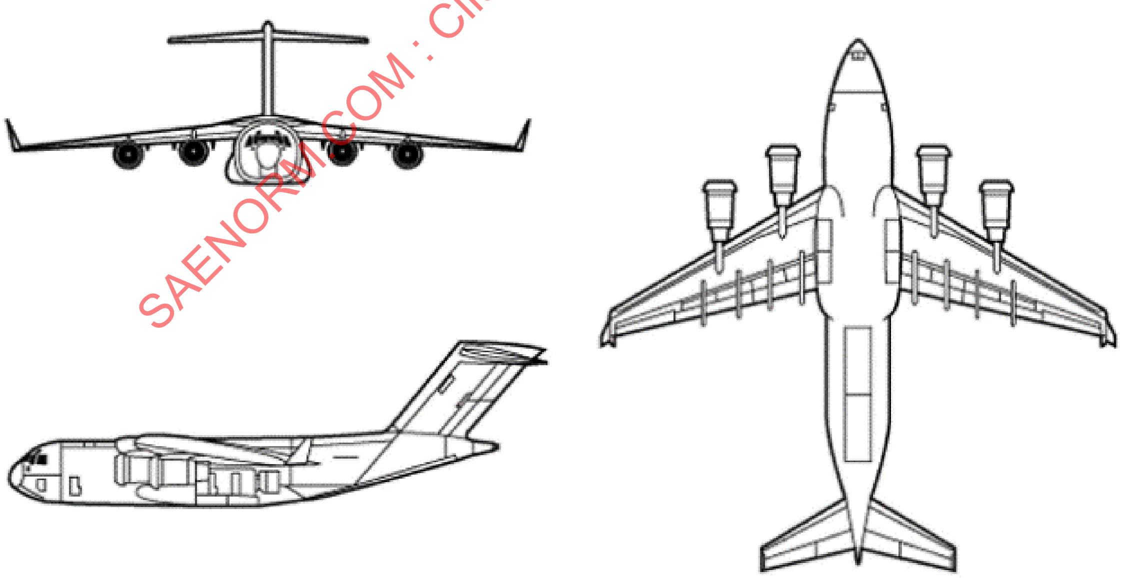

FIGURE 28 - C 17

3.6.1 Main Landing Gear

Each of the main gear "units" (one unit each side of aircraft) consists of two legs (in tandem), each leg having three wheel assemblies. See Figure 29. This amounts to twelve main gear wheels and four posts per aircraft. The fore and aft legs of each "unit" rotate towards each other, during retraction, by approximately 90°. Simultaneously, the inboard wheel, on each leg, moves to an offset position in order to avoid interference with the mating leg. This rotation allows the landing gear pod to have a optimized low frontal area.

Each main leg consists of a trailing arm (articulated) configuration, and hence can cater to the long axle stroke required to absorb the energy created by a maximum sink speed of 15 ft/s.

The main gear tires are 50x12x20 and the brakes are carbon discs.

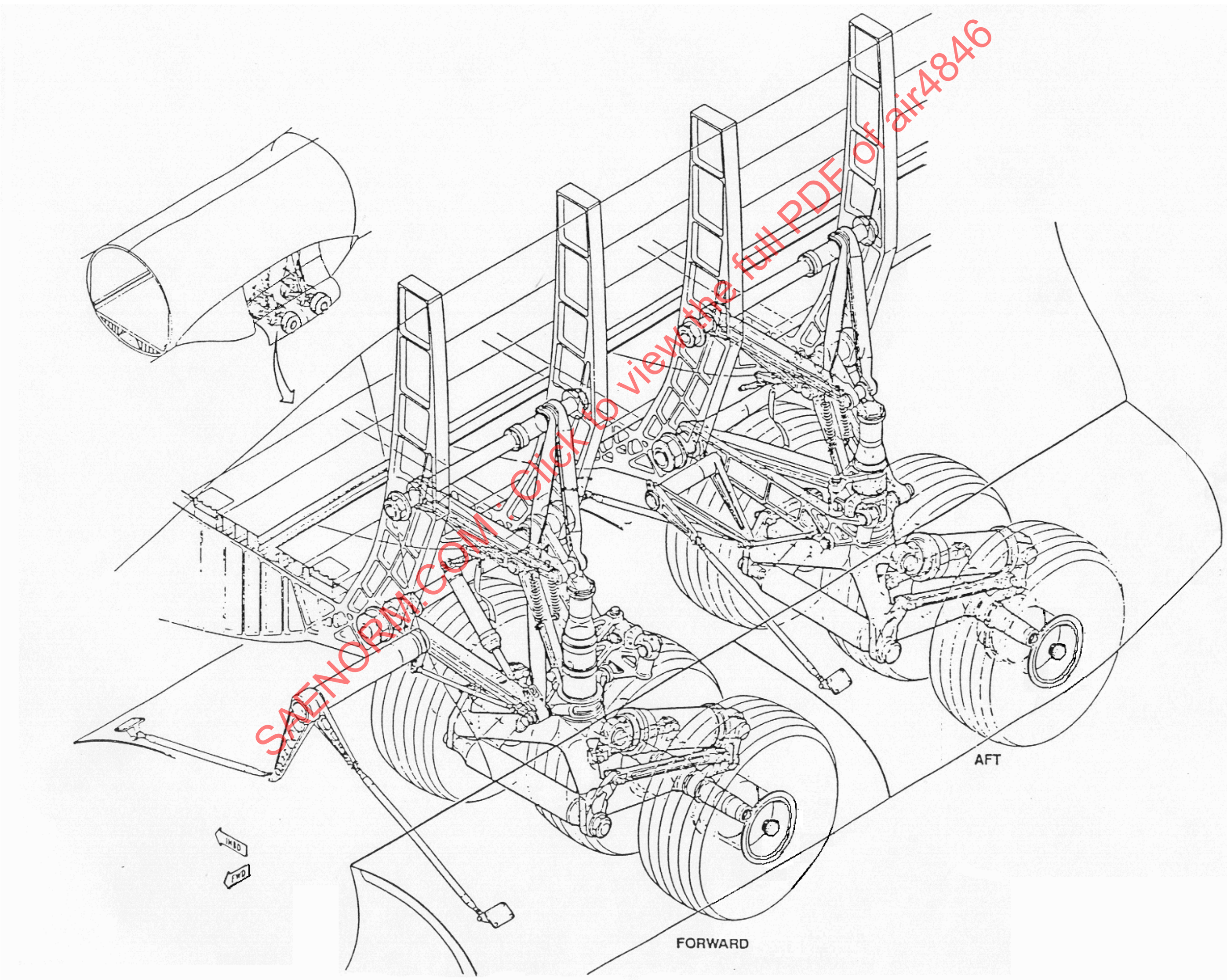

FIGURE 29 - C-17 MAIN LANDING GEAR (LEFT SIDE)

3.6.2 Nose Landing Gear

The nose gear comprises a forward retracting twin wheel strut with a forward sloping rake. An axle stroke of approximately 20 inches deals with high dynamic loads due to high descent velocities. (including pitch over).

3.7 BAe. Andover Kneeling Main Landing Gear

3.7.1 The BAe. Andover is a military variant of the BAe. 748 twin turboprop aircraft. A major feature of its conversion was a new rear fuselage incorporating a loading ramp. As the aircraft is low wing, the floor height from the ground is appreciable and the short length available for the ramp meant an unacceptable inclination of the ramp in the lowered position.

3.7.2 To minimize the ramp angle, a kneeling main landing gear became a requirement. The changed CG geometry meant also that a rearward movement of the main wheels relative to the wing and landing gear attachments had to be accommodated.

3.7.3 The unique solution chosen was a lever suspension with a liquid spring shock absorber in series with a simple oleo having a large effective area. During ground maneuvering, only the liquid spring is deflected but, during landings both liquid spring and oleo close. The oleo has a low compression ratio and the energizing gas is contained in the upper barrel and arms of the main fitting. The gas is separated from the oleo fluid by a floating piston. The nitrogen pre-charged pressure is set at 2100 psig. The kneeling function is achieved by releasing fluid from the oleo to the aircraft's hydraulic system by means of a hydraulic non-return valve being opened by a command signal. The aircraft kneels under the influence of its own weight (see Figures 30 and 32).

3.7.4 The aircraft's hydraulic system working pressure is 2500 psi and this was regulated to 2000 psi in order to recharge the oleo chamber and raise the aircraft back to its normal static position.

3.7.5 For this landing gear, the oleo fluid and the liquid spring fluid are replenished from the aircraft's hydraulic system fluid. The liquid spring is connected to the kneeling piston by a spherical joint. This joint is sealed on its outside diameter and oleo fluid is fed to the surface of the ball. A drilling down the center of the liquid spring piston rod, connects with the fluid chamber of the liquid spring via a recuperating valve, which, under normal static conditions, is maintained firmly closed and sealed, by a spring. Only when the landing gear is fully extended, (aircraft airborn) is the valve allowed to open and cause the oleo and liquid spring chambers to maintain the spring extended pressure at 2000 psi (Figures 31 and 33).

3.7.6 Although the extent of the system utilization is not known, its service life has been satisfactory with no known hydraulic system problems as a result of the main system fluid being used as a shock absorbing medium.

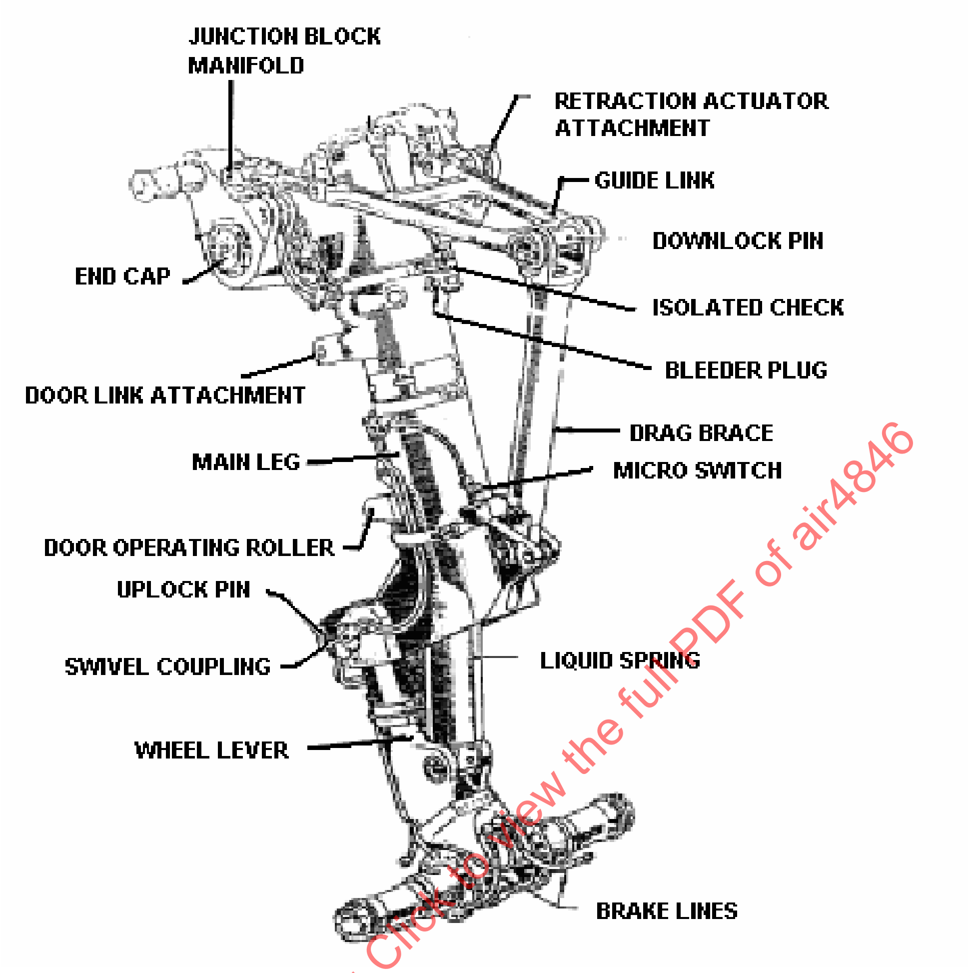

FIGURE 30 - ANDOVER MAIN LANDING GEAR

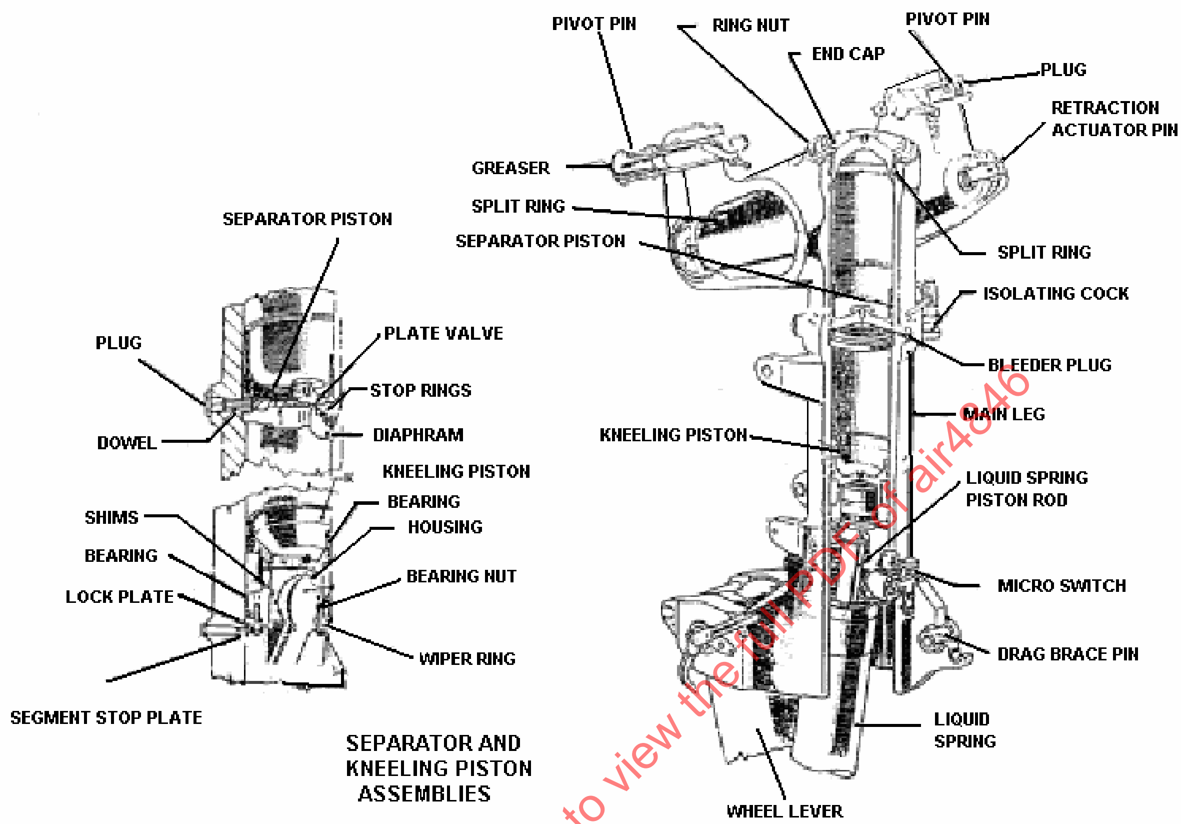

FIGURE 31 - ANDOVER MAIN LANDING GEAR KNEELING MECHANISM

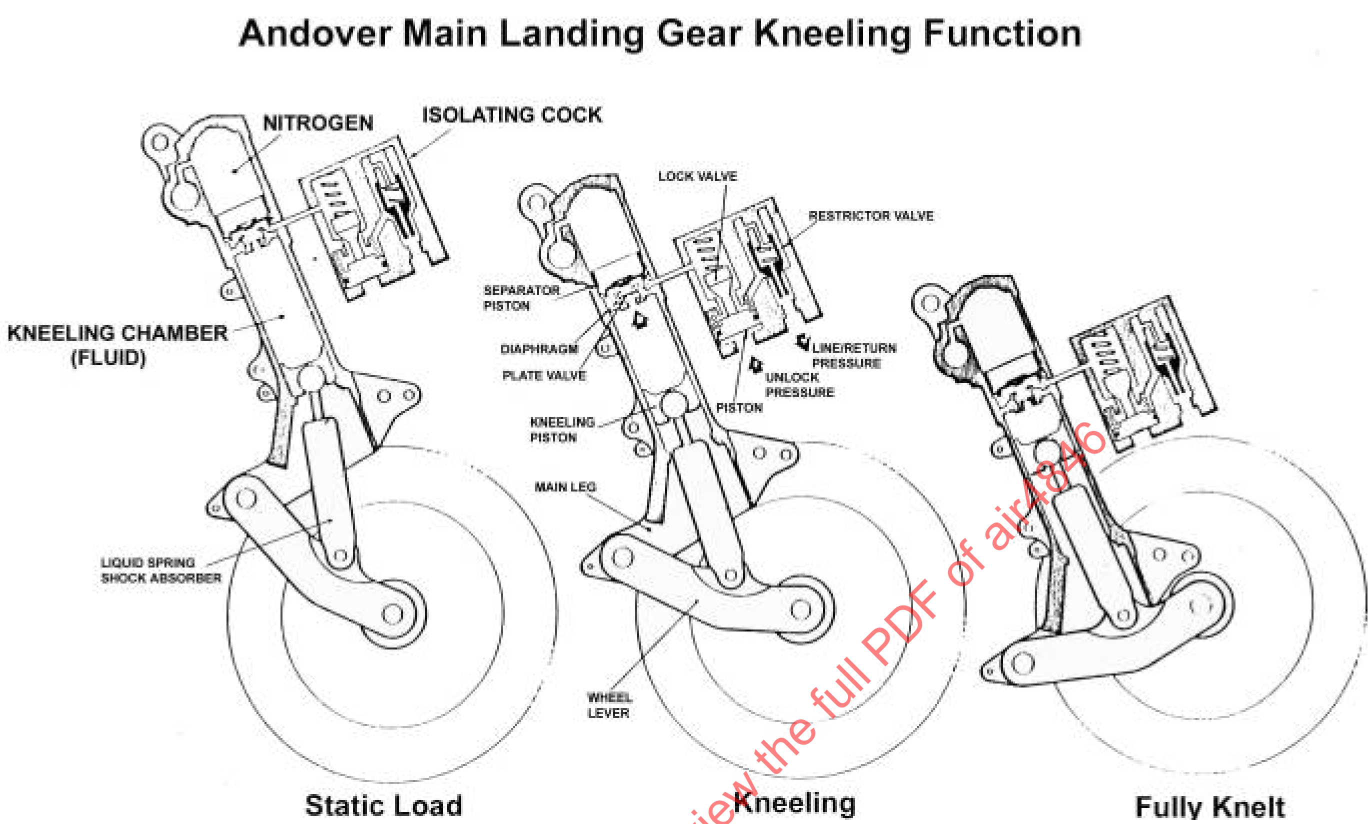

FIGURE 32 - ANDOVER MAIN LANDING GEAR - KNEELING FUNCTION

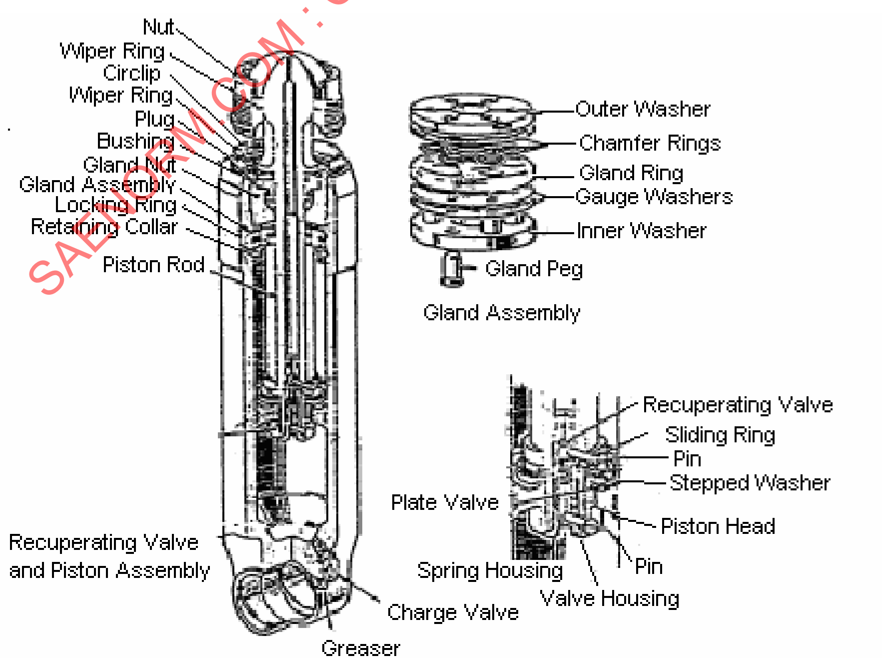

FIGURE 33 - ANDOVER MAIN LANDING GEAR LIQUID SPRING

3.8 BAe. Tornado-Main and Nose Landing Gear

The aircraft is a multi-roll swing wing fighter of a high wing configuration fitted with two RB 190 engines and a gross weight of 60,000 pounds. The aircraft can carry "stores" under its wings, and also a ventral pod.

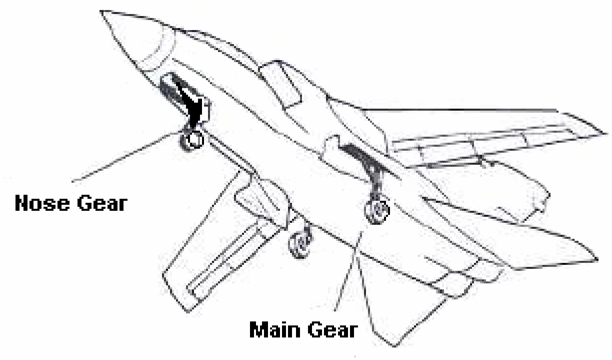

FIGURE 34 - BAE TORNADO

3.8.1 Main Landing Gear

The geometry of the main landing gear was designed to meet three main constraints:

1. The landing gear, being installed in the fuselage, has to provide adequate track in order to meet overturning and roll stability criteria.
2. The landing gear occupies minimum stowed volume
3. The landing gear to be low weight.

The main landing gear design has two axes of rotation in order to retract the wheel into the bay, and to provide a swept path during retraction which does not pass through any of the possible store combinations. See Figure 35.

The strut is a cantilevered type which has a single offset wheel, and a tire (30×11.5-14.5) which is selected for stowage and rough ground operations, instead of twin wheels. The cylinder of the shock absorber is rotatably mounted in a pivot fitting with two bearings which react vertical loads, along with drag and side moments. The pivot housing is mounted to the airframe by a skew axis which places the shock absorber cylinder in its retracted position. The angular position of the wheel, relative to the pivot housing is controlled during retraction by a crank fitted to the top of the shock absorber. The crank is connected to the airframe near the retraction axis by a spherically mounted direction bar with a geometry which positions the wheel in its optimum position within the landing gear bay while clearing all possible combinations of store locations. In the "gear down" position, and weight off wheels, the direction bar provides a small amount of "toe-in", so that when loaded, the tire runs true to minimize wear.

The landing gear is maintained in the down position by a folding drag brace which is attached to the bay inner wall and to the strut pivot fitting by spherical bearings in order to accommodate structural deflections, although at the airframe attachment is pegged so that it is kinematically equivalent to a cardan joint. This controls the locus of the brace center joint during retraction. This type of joint was selected in order to minimize space and weight penalties.

The brace is locked extended by a hammer head lock positioned at the center joint. This type of lock is not affected adversely by local structural deflections which might cause the lock to be unstable in compression under high loads. The lock is sprung to engage automatically, and unlocking is by a small hydraulic cylinder which is pressure sequenced to unlock before a significant load can be applied by the retraction actuator.

Emergency lowering of the landing gears is achieved by a secondary hydraulic power supply which releases the tumbler type uplock (airframe fitted) through a shuttle valve and supplies an alternate lowering chamber of the retraction actuator. Mechanical switches are used for the normal lock and weight on wheels functions, and are duplicated for safety. The landing gear door is operated by a locking actuator.

The materials used are UltTS 300M for the shock absorber structural parts. Structural parts which have stiffness as the prime criterion are of 85 ton UltTS with high strength aluminum alloy used for drag brace members and the main pivot fitting.

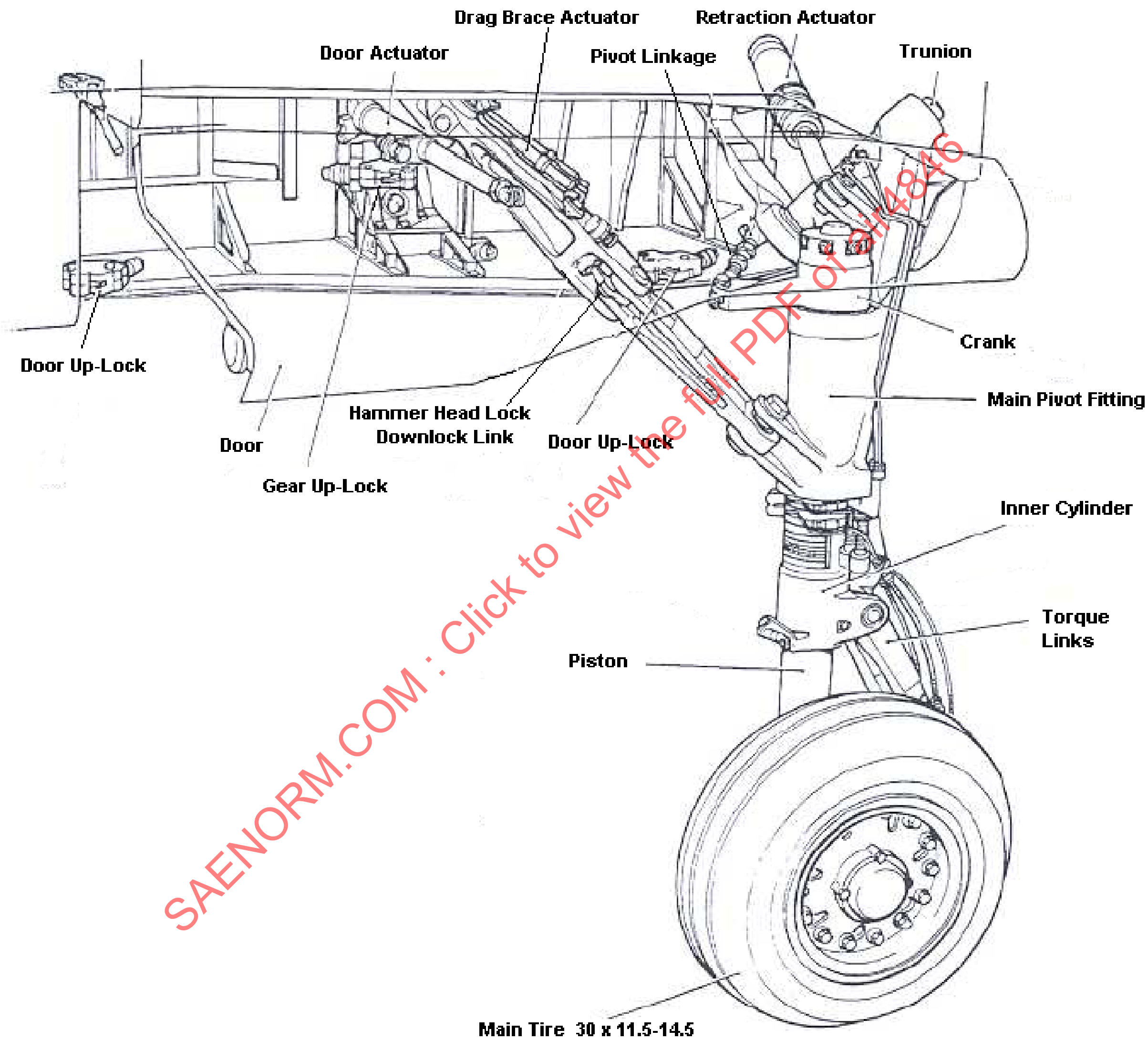

FIGURE 35 - TORNADO MAIN LANDING GEAR

3.8.2 Nose Landing Gear

The nose landing gear is a cantilevered type gear with a forward rake and a geometric trail of the axle. See Figure 36. It has two coaxial wheels (independently rotating) which mount 18 $\times$ 5.5 tires. The strut has a twin chamber shock absorber which rotates in the main cylinder. The shock absorber cylinder has gear teeth located just under the end of the main cylinder, which engage with a pinion on a rotary steering motor.

The steering motor is very similar to that on the F4 Phantom, although it has changes to permit operation on the Tornado's 4000 psi hydraulic system, and to improve life. The motor power source is a high speed vane motor with a double epicyclic speed reduction, and a further reduction by the final spur drive. The high back driving torque, the provision of a moderate back pressure in the return line, together with the strut's mechanical and tire trail, is effective in suppressing shimmy.

360° rotation permits towing and ground handling beyond the normal steering range without disconnection. The steering servo valve, feedback potentiometer, and compensator unit, are included in this installation. The system includes an ECU (electronic control unit) with runaway protection and BIT (built in test). The unit can also accept yaw stabilizing inputs as well as the pilot input with variable gain.

The original design of the Tornado included a hiking feature. See Figure 36. This was achomplished with a shock strut piston being housed inside of a hiking piston, which was extended with the aircraft hydraulic system during takeoffs. Hiking torque links transmitted rotaion to the nose gear piston and wheels. A towing link, extending forward, was connected to the steering collar. A spring pot controled the position of the link. During flight testing it was determined that this hiking feature was not required. The hiking piston was locked off from extending. Later on in the program the nose landing gear was simplied by removing the hiking piston feature. Both configurations are currently in service.

The nose landing gear is locked in the "gear down" position by a folding drag brace which is stabilized by a pair of lock links which connect the center joint with the main cylinder. These links also lock the landing gear in the retracted position by means of the geometry of the retraction actuator which connects to the upper lock link. For retraction, the actuator contracts, rotating the upper link to release the lock maintaining the drag brace in the locked position. During the retraction cycle, the geometry changes to reverse the torque on the upper lock link so that it drives it into the locked position when retracted. The reverse operation occurs during lowering. The lock links are maintained overcenter by two tension springs capable of reacting peak pressures in the return line, causing the actuator to move to an unsafe or unlocked position.

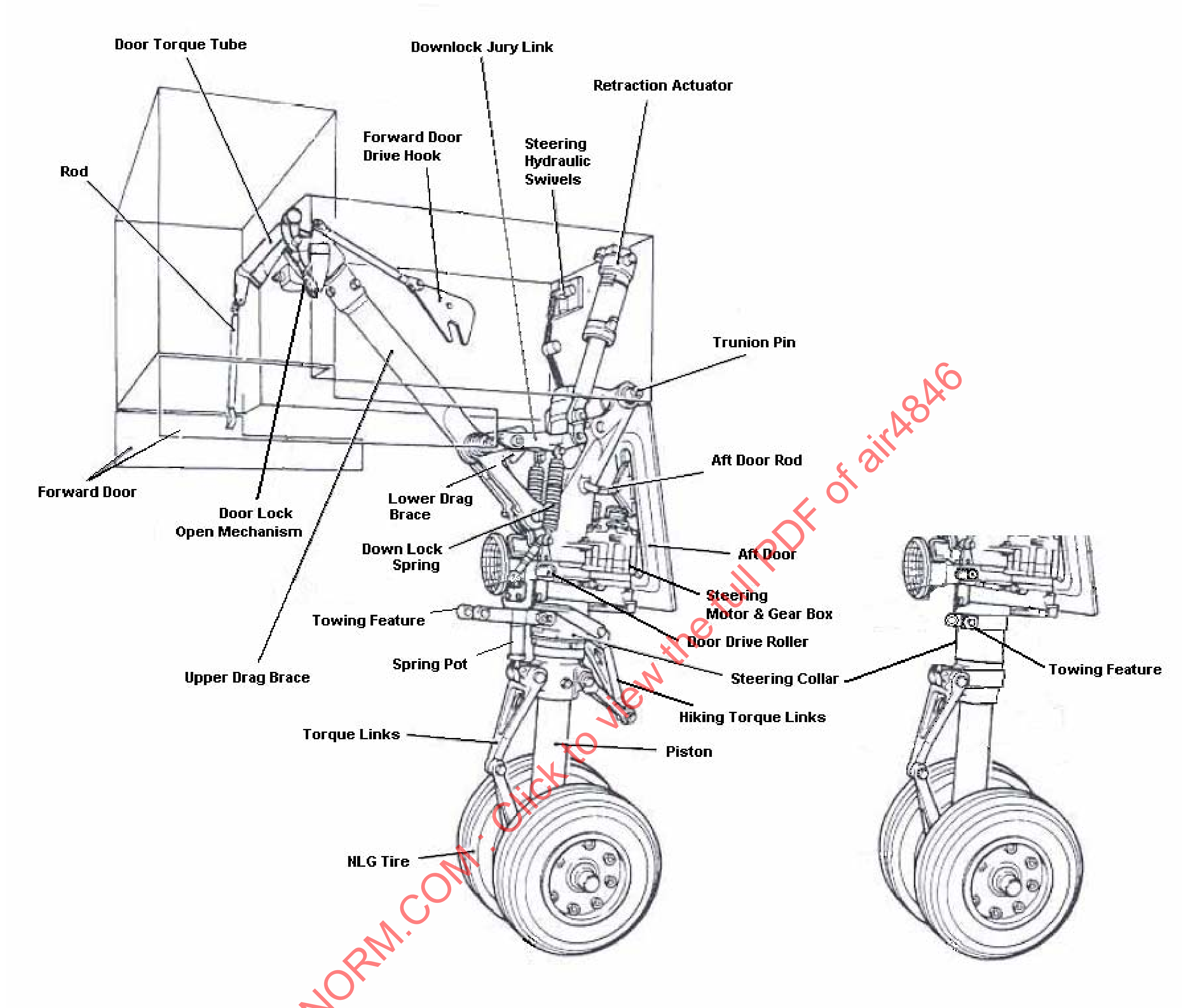

FIGURE 36 - TORNADO NOSE LANDING GEAR

3.9 SB-6 (Seamew) Main Landing Gear

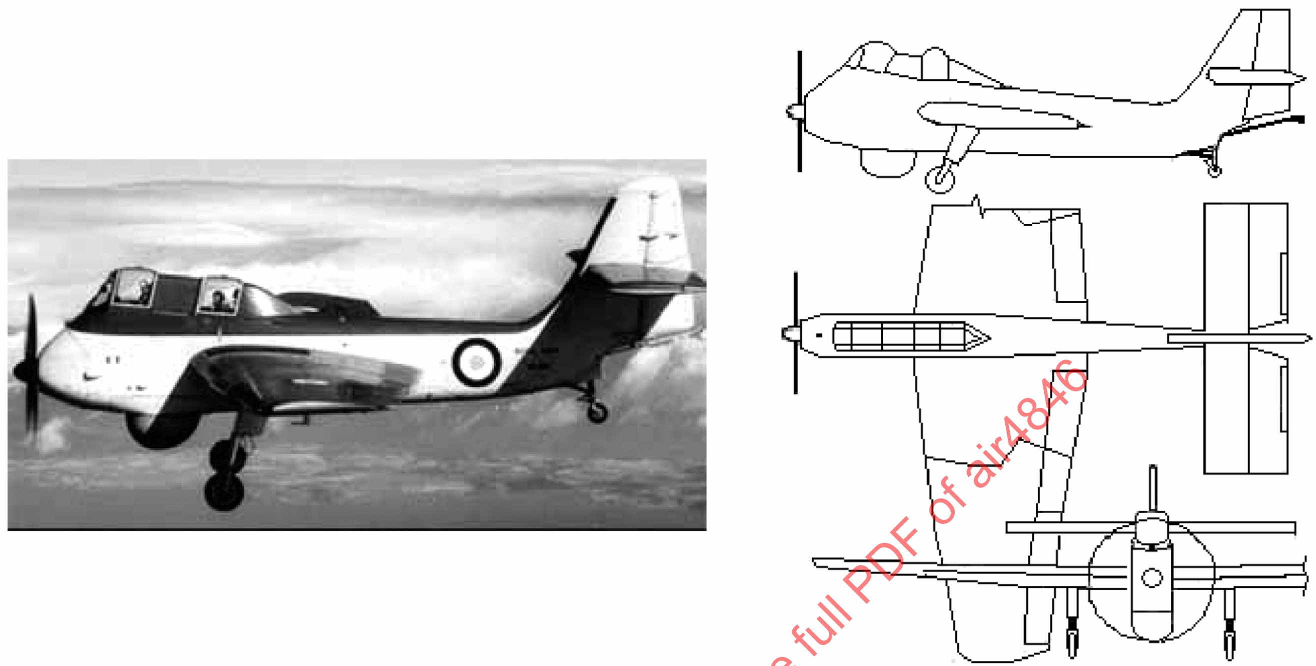

FIGURE 37 - SHORTS SEAMEW SB-6

3.9.1 The Seamew was a propeller driven anti-submarine aircraft designed for use on converted cargo ships. Its weight was only 12,000 pounds. It was designed to be cheap and simple, and had a tail wheel type fixed landing gear, with long strokes in order to absorb the energy inherent because of the high vertical descent velocity requirement.

3.9.2 The solution chosen for the main landing gear was a telescopic unit having a high proportion of its travel as a dash pot, only the second portion of the travel having the effect of a pneumatic spring. The complete main landing gear was ejectable in order to improve survivability when ditching.

3.9.3 The shock absorber solution was a single stage oleo with orifice damping. In the center of the sliding member was an inner piston mounted on a telescopic tie-rod. On the first stage portion of the stroke, fluid displacement was based only on the annular area of the piston, which resulted only in a slowly rising spring force at the ground. At the end of the first stage stroke, the inner piston contacted internal stops in the sliding member, bringing the full area of the sliding member into play in order to activate a gas spring which provided residual travel under static and dynamic conditions.

3.9.4 The shock strut was socketted into two bearings adjacent to the upper and lower wing skins. At the upper end of the strut was a set of lock claws which retained the strut in position on the airframe. An airframe mounted ejector actuator released the lock sleeve, and pushed the shock strut free from the mounting bearings.

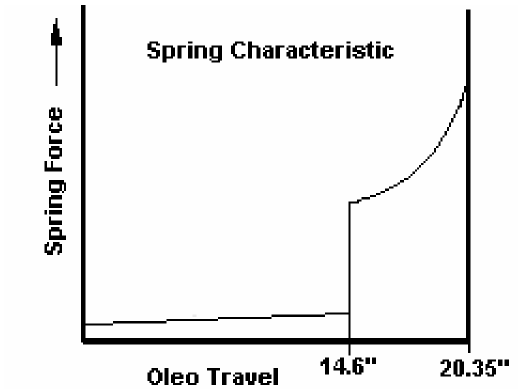

FIGURE 38 - THE SHORT SB-6 SEAMEW

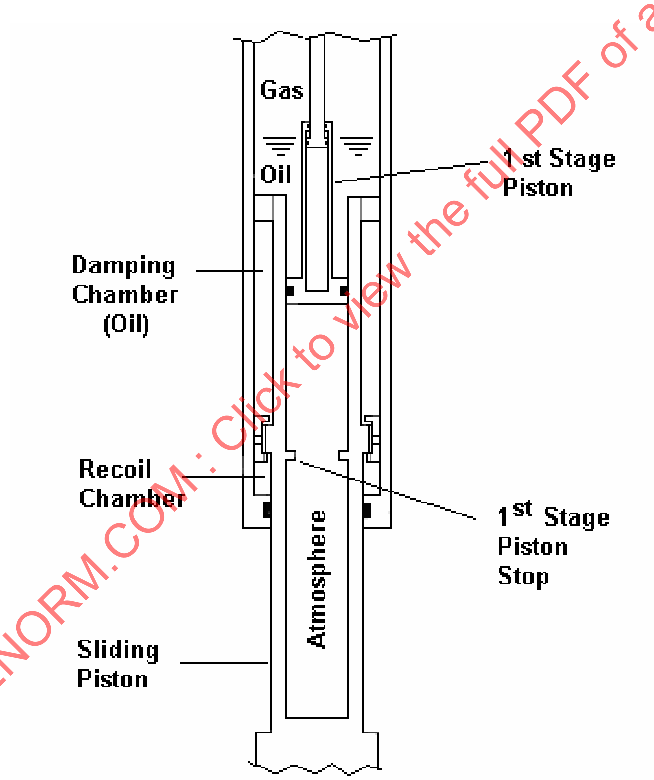

FIGURE 39 - SB-6 SEAMEW MLC SHOCK ABSORBER

3.10 SB-6 Seamew Tail Landing Gear

3.10.1 Like the main landing gear, had the need for a long stroke. However, in this case, the stroke was split 40 to 60% between separate dash pot and oleo, using opposite ends of the same cylinder.

3.10.2 The dash pot is a telescopic (cantilever) unit, and the oleo, (mounted uppermost) is a lever suspension. Before landing, the dash pot extends when its lock is released under the influence of the wheel mass and a force from the oleo spring. On landing, the dash pot closes and the locks close automatically. The remaining landing energy and ground ride is absorbed by oleo closure.

3.10.3 The wheel casters 360°, centering by cam and spring by ±180°, but for landing and take-off, the wheel may be locked central by the pilot.

3.10.4 The upper shock absorber attachment transmits only direct loads into the upper fuselage, with all torque's and the majority of drag and side loads transmitted through the trailing lever.

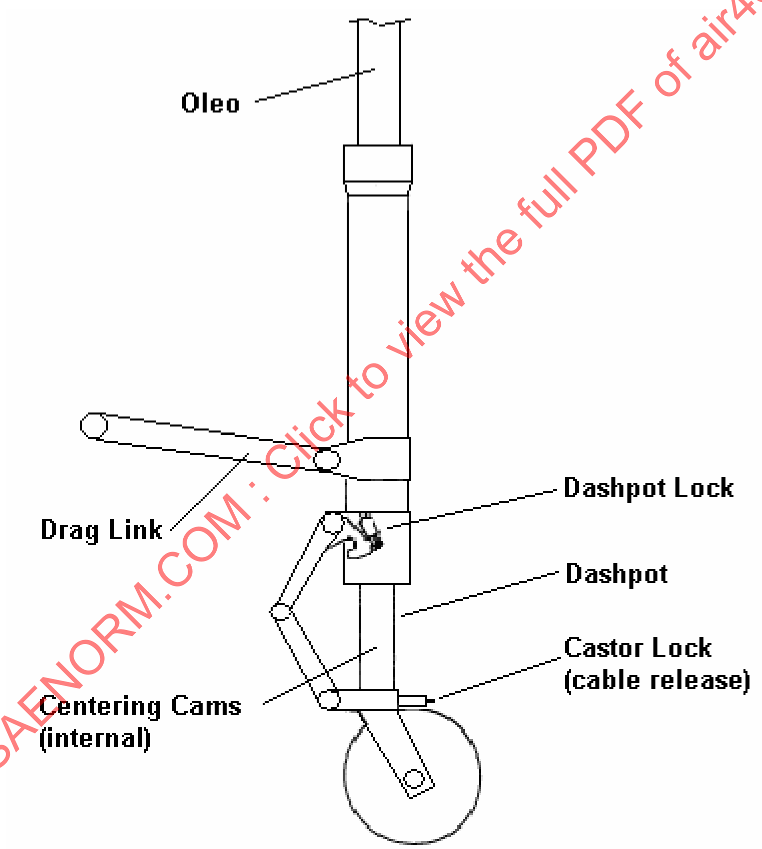

FIGURE 40 - SB-6 SEAMEW TAIL LANDING GEAR - DIAGRAMMATIC

3.11 Piaggio P 180 Main Landing Gear (Tripod)

3.11.1 This equipment can justifiably be described as a "tripod", rather than a side hinging levered suspension since the basic load directions meet (or almost meet) somewhere near the ground, even though the loads pass several different members.

3.11.2 Referring to Figure 41, the particular geometry for this aircraft calls for an extended wheel position forward of the landing gear bay, which is a slot in the fuselage the width of which is equal to that of the retraction pivot. These combine to provide a tripod geometry with acute angles, leading to high loads in the structure and shock absorber, relative to an aircraft gross weight of 10,900 pounds.

3.11.3 Retraction and lever axes of rotation are separate in order to permit a stiff torsional path along the lever, the length of which, combined with the limitation on the bay slot width, results in a high lever ratio for the shock absorber.

3.11.4 The modest retraction angle permits the stay to be used as the retraction means, and the retraction actuator containing internal locks for the extended and retracted positions, acts as a down and uplock for the landing gear.

3.11.5 While simple in concept, as the number of parts are minimal, the design poses several technical problems which have to be over come. The severity of some of these problems depends very much on the stiffness of the aircraft's landing gear support structure.

- The short travel shock absorber has considerable "dead" length.
- Provision of a stiff torsion path for brake and spin-up loads.
- Relative deflection of drag brace and lever assemblies requires spherical joints at the ends of the lower drag brace member, and on the shock absorber.
- The drag brace can be unstable due to high induced loads in the actuator, the value of the loads being dependent on gear and air frame accuracy and stiffness.

Nevertheless, the solution provides a simple, efficient landing gear despite the need for technical expertise and skill greater than is needed for a number of much larger landing gears.

3.12 Piaggio P 180 Nose Landing Gear (Cantilevered)

3.12.1 Electronic Control System for the Piaggio GP 180 Steering is detailed in Figure 42.