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A Study of the CF188 Landing Gear Upgrade

Eric Joseph Grandmont
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Eric Joseph Grandmont entitled "A Study of the CF188 Landing Gear Upgrade." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Peter Solies, Major Professor

We have read this thesis and recommend its acceptance:

Frank Collins, John Muratore

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Study of the CF188 Landing Gear Upgrade

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Eric Joseph Grandmont
May 2009

ABSTRACT

A study was undertaken to assess the effectiveness of the CF188 main landing gear upgrade on reducing Planing Link Mechanism failures. Two main landing gear configurations were studied: the prototype configuration and, for comparison purposes, the current configuration referred to as the baseline. Under this study, the flight test data that was analyzed came from key measurements recorded during maintenance rigging procedures, pilot ground handling quality ratings, and from over 80 landings at different descent rates and aircraft attitudes. Landings consisted of touch and go, full stop, cable overrun and cable engagement. The aircraft that was used through the flight test program had both its main landing gears instrumented. While the prototype configuration had minimal impact on the ground handling characteristics, it demonstrated promising results during maintenance activities as well as loads distribution during landings. The prototype was easier to rig which will allow the use of tighter limits further standardizing the complex maintenance procedure. From both a static and dynamic point of view, the hold down force was significantly increased. Within the scope of this study, it was found that the CF188 main landing gear upgrade will reduce Planing Link Mechanism failures.

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LIST OF SYMBOLS AND ABBREVIATION

lbs	pounds
in.	inches
fpm	feet per minute
KCAS	knots calibrated airspeed
KGS	knots ground speed
sec	second

AETE	Aerospace Engineering Test Establishment
CF188	Canadian Designation for F/A-18 Hornet
EFT	External Fuel Tank
EU	Engineering Unit
FTCR	Flight Test Control Room
FTE	Flight Test Engineer
HUD	Heads Up Display
HQR	Handling Quality Rating
LGAT	Landing Gear Action Team
LH	Left Hand
NWS	Nose Wheel Steering
PIO	Pilot Induced Oscillation
PMA	Planing Mechanism Assembly
RH	Right Hand
RPM	Revolution Per Minute
VSI	Vertical Speed Indicator
WOFFW	Weight Off Wheels
WONW	Weight On Wheels

CHAPTER 1 - INTRODUCTION

From the YF-17 to the F/A-18

In the 1970's, as per Winchester (1) and Crosby (2), the U.S. Air Force had a requirement to complement the F-15 Eagle with a more economical, lightweight fighter aircraft. The U.S. Navy also felt the need to replace some of its fleets with a multi-role aircraft and to complement the expensive F-14 Tomcat. As there was already a competition for the U.S. Air Force lightweight fighter aircraft, Congress directed that the Navy choose one of the contenders, limiting the choice between the Dynamic YF-16 and the Northrop YF-17. Both aircraft, initially designed for the U.S. Air Force, needed a major redesign to meet the U.S. Navy specific requirements. Although the U.S. Air Force decided to choose the YF-16, the U.S. Navy preferred the two engine competitor and decided to go ahead with the Northrop/McDonnell Douglas YF-17 understanding that major redesigns would be required to meet carrier takeoff, arrested landings, range and other specific U.S. Navy requirements. The aircraft designation became the F/A-18. The F/A -18 was a larger aircraft than the YF-17 with wet wings, more powerful engines, more available space for avionics and most importantly, a widened and stronger landing gear to sustain the additional 10,000 lbs, carrier takeoff and arrested landings.

Landing Gear Design

During aircraft design, as in Raymer (3), the landing gear usually gives the most problems to the designers. Depending on centre of gravity location, the distance and the angle with the tip of the tail, and aircraft weight, the tires and shock absorbers must be of a certain size and at a specific location to allow effective takeoff and landings. In addition, if the landing gear is designed to be retracted, the landing gear must retract and fit within the existing structure of the newly designed aircraft. Very rarely would the structure be modified to accommodate the landing gear.

In the case of the F/A-18, the entire landing gear had to be reinforced to sustain the added weight from a light fighter aircraft to a medium fighter aircraft the F/A-18 had become and to meet the Navy requirements for carrier operations. The wheel track, as defined by the distance between the main landing gear tires, went from 6.83 ft. to 10.2 ft (4). The wheelbase, as defined by the distance from the nose landing gear to the main landing gear wheel, only went from 17.2 ft to 17.8 ft. The increase in landing gear size resulted in complications storing the landing gear within the very limited space available in the existing structure of the F/A-18. Basically, during main landing gear retraction, the shock absorber now needed to be shrunk and the main wheel had to be rotated within a specific angle in order to fit within the wheel well. As stated in Roskan (5), these constitute special problems in gear retraction and generally require additional links to be added to the system. The solution to this problem was the complicated, but ingenious Planing Mechanism Assembly (PMA). The PMA consisted of the connecting link, bell crank assembly, planing link, planing arm spring, shrink link and axle lock links. A more detailed description is provided in Chapter 4.

Planing Mechanism Assembly Failure

Although the complex PMA allowed the main landing gear to fit within the limited wheel well size, other problems quickly surfaced. The PMA became a weak part of the landing gear resulting in regular failures. PMA failures usually happened upon touch down or shortly thereafter, and could occur on either the left or the right main landing gear. In general, PMA failures were associated with buckling of the connecting link or the planing link with signs of bell crank assembly contact. During a failure, the axle lock links became unlocked allowing the main wheel to deplane from the landing path resulting in a lost of directional control at high speed. From a pilot perspective, an unlocked axle lock link resulted in a tone and warning light in the cockpit. With a planing link failure tone and warning light, the pilot, if able, was instructed to execute a go-around followed by a cable engagement to alleviate the high speed directional control problem. Throughout the years, numerous PMA failures upon landing resulted in fatal mishaps, hence the importance in finding a solution to this problem.

Possible factors that may have caused PMA failures included but were not limited to: tire pressure and shock absorber servicing, main landing gear rigging during maintenance, bell crank assembly isolation during landing gear stroke, failure of the connecting link buckling under large compression loads or planing link bottoming out, dynamic unlock of the lock links and finally landing profiles. Although multiple theories exist on the cause of the PMA failures, the exact chain of events is still unconfirmed at this time and a specific cause can't be identified.

A Landing Gear Action Team (LGAT) was created to find a solution to PMA failures. The team studied different design enhancements to the main landing gear PMA to make it more resilient to failures. By the redesign of some key parts, as described in Chapter 4, the LGAT aimed at increasing the hold down force to the axle lock links reducing the chances of a dynamic unlock type failure, increasing the bell crank gap to avoid contact during main landing gear stroke, and giving the connecting link a limited stroke capability to reduce buckling potential.

Under a project carried out by the Aerospace Engineering Test Establishment (AETE), the Canadian Air Force volunteered to assist NAVAIR in validating the proposed CF188 (Canadian designation of the F/A-18) modifications by collecting main landing gear data through flight test.

This thesis consists of a complete independent analysis of the data that was gathered under the Canadian flight test program.

CHAPTER 2 – PROJECT AIM AND OBJECTIVES

Aim

The aim of this thesis was to study the effectiveness of the proposed modifications to the CF188 main landing gear in order to reduce the risk of PMA failures.

Objectives

In order to meet the aim, the following objectives were studied by comparing the ground and flight test data from the baseline and the prototype CF188 main landing gear configurations:

1. Assess static hold down force during landing gear rigging;

2. Confirm the increase of the pinhead and bell crank gaps;

3. Assess the aircraft ground handling at various ground speeds; and

4. Assess the loads on the connecting link and planing link during numerous landings including touch and go, full stop, cable overrun and arresting cable engagements.

CHAPTER 3 - LANDING GEAR

Purpose of Landing Gear

The main purpose of the landing gear is to allow the aircraft to be controlled during takeoff, landing and ground operations. Therefore, the landing gear must be able to absorb the loads and associated stresses. It also allows the aircraft to be supported on the ground while keeping the proper clearance between the aircraft and the ground to support external stores such as external fuel tanks (EFT) and weapons. Depending on aircraft requirements, the landing gear may also have to be retractable to limit additional drag during flight or to reduce radar cross section.

During aircraft design, creating the landing gear system is usually very challenging. The landing gear must have the right tire and shock absorber size in accordance with the aircraft weight yet, if retractable, it must fit within the fuselage. It must be at the proper location to allow aircraft rotation without impacting the tail on the ground either on takeoff or during landing. It needs to be stable on landing and provide good steering capabilities that meet design requirements.

Landing Gear Loads

During its operation on the ground, the landing gear is subject to vertical, horizontal, lateral and crush loads. The vertical loads are generally due to the weight of the aircraft and to the normal acceleration during touch down generated from the descent rate and aircraft weight at impact. These loads affect the sizing of the shock absorber and of the tire. Following initial impact at touch down, the weight of the aircraft felt on the landing gear will increase as the aircraft slows down and the lift is decreased. The horizontal loads, also known as drag loads, are generated from the friction between the tire against the landing surface, and by the braking action during the deceleration. Usually this horizontal load is countered with a drag brace. The lateral loads are generated either during turns on the ground or crabbed landings where any roll or/and yaw results in a lateral force component. The lateral force component is usually countered by a side brace. Finally, the crush load occurs when the aircraft runs over a relative sharp object such as an arresting cable for instance (5).

The variables affecting the loads include, but are not limited to: aircraft weight, descent rate, aircraft attitude (in roll, yaw and pitch), deceleration requirements driven by the runway length or distance available post touch down, and finally landing gear maintenance and servicing. Of note, wind and density altitude will affect the above mentioned variables.

Variables such as tire and shock absorbers servicing were tightly controlled throughout this test program and they were considered constant for the purpose of this study.

CHAPTER 4 - EQUIPMENT UNDER TEST

Aircraft

The aircraft under test consisted of a CF188B (T/A-18B) as depicted on Figure A1. The CF188B was a high performance, all weather, supersonic fighter and attack aircraft (6). It was powered by two General Electric F404-GE-400 low-bypass axial flow turbofan engines equipped with afterburner (7). The aircraft was designed with moderate swept mid-mounted wings with Leading Edge Extensions allowing manoeuvrability at high angle of attack and with twin vertical stabilizers inclined 20º outboard from the vertical. The aircraft was equipped with a fly-by-wire hydraulically actuated flight control system including full span leading edge flaps, inboard trailing flaps, outboard ailerons, rudders and differential all moving horizontal stabilizers. The aircraft was equipped with a tricycle landing gear arrangement. The aircraft tail number was CF188907. CF188907 developed by McDonnell Douglas (now Boeing) was an instrumented two seat aircraft.

Aircraft Configuration

As depicted in Table A1, the aircraft configuration for the duration of the test consisted of two wing pylons on stations 3 and 7 and one EFT and pylon on station 5. The total aircraft weight with fuel and two aircrew was approximately 39,650 lbs.

Aircraft Instrumentation

CF188907 was the test aircraft used at AETE. The test aircraft was modified in order to gather analog and digital data, and video images. Both the left and the right main landing gear were instrumented. A telemetry system transmitted the data to the Flight Test Control Room (FTCR) allowing the aircraft and the landing gear parameters to be monitored real time. The video images consisted of the Heads Up Display (HUD), two tail hook cameras, installed to capture images of both main landing gears, and an imagery technician also capturing footage from the side of the runway. A list of parameters recorded during the flight test is available in Table A2.

CF188 Landing Gear

General

The CF188 landing gear was a retractable tricycle type. The landing gear was electronically controlled and hydraulically actuated. The nose landing gear had two wheels in a dual arrangement. A catapult launch bar was installed on the nose landing gear for catapult takeoff during aircraft carrier operation, but was inoperative in the case of aircraft CF188907. The nose landing gear was equipped with hydraulic steering capability providing directional control on the ground through inputs from the rudder pedals. The nose landing gear retracted forward and stored in the main fuselage under the front cockpit. The main landing gear was a levered design with an oleo shock absorber in a single wheel arrangement. The main landing gear was retracted aft and inboard from the down and locked position. During retraction, the shock absorber was shrunk by the shrink link, and the main wheel was rotated 90º by the PMA to fit in the main landing gear wheel well located in the main fuselage under the engine inlets.

Main Landing Gear

As depicted in Figures A2 to A4, the levered main landing gear consisted of a trunnion, side brace, axle lever, shock absorber, and the PMA. The trunnion, the side brace and the connecting link were attached directly to the aircraft structure. The PMA consisted of the connecting link, bell crank assembly, planing link, planing arm spring, shrink link, and axle lock links.

The purpose of the PMA was to rotate the wheel 90º and to compress the shock absorber, shrinking the main landing gear to meet the limited wheel well space requirements during retraction. The connecting link was rigid. It was attached to the aircraft structure at the top and to the bell crank assembly at the bottom. Through the bell crank assembly, it pulled the planing link and the shrink link during landing gear retraction. The planing link had limited stroke capability and was in series with the connecting link via the bell crank assembly. It was attached to the bell crank assembly at the top and to the planing arm and lock links at the bottom. The planing link unlocked the axle lock links, rotated the wheel, held the axle against the planing stop when the main landing gear was retracted, and applied preload to the axle lock links known as hold down force. The shrink link was telescopic and was also attached to the bell crank assembly and to the axle. It pulled on the axle and compressed the shock absorber during retraction. The axle lock links were located on the axle and were driven by the planing link. They rotated the axle and were the over center lock mechanism when the gear was extended and locked. The planing arm spring simply provided additional hold down force to the axle lock links when the gear was extended.

Main Landing Gear Retraction Sequence

The landing gear retraction sequence was initiated by selecting the landing gear handle to the up position. This provided hydraulic pressure to the main landing gear side brace actuator, the retract actuator, the up lock mechanism sequence valve, the doors up lock hook, and the wheel brake and anti-skid system.

First, the brake system stopped the wheel rotation. Second, the side brace became unlocked allowing the initiation of the gear retraction by the retract actuator. As the trunnion rotated aft, the connecting link pulled on the bell crank assembly which then pulled on the shrink link and the planing link. The shrink link compressed the shock absorber while the planing link unlocked the axle lock links rotating the axle 90º to fit in the wheel well. The up lock mechanisms then locked the landing gear in place and the doors closed under hydraulic pressure.

Prototype Parts

The modified parts included a urethane spring added inside the planing link, replacement of the aluminum connecting link cartridge with a collapsible urethane core cartridge, revised geometry for the rigid connecting link, and a shortened dogbone. The modified parts are depicted in Figure A5.

The purpose of the urethane connecting link cartridge was to provide the connecting link with a limited stroke capability (0.070 in.). This limited stroke capability would reduce the potential of connecting link buckling under a large compression load.

The planing link urethane spring was added to increase the stiffness of the planing link and the hold down force. This would decrease the possibility of planing link bottoming out under a large compression load and reduce the chance of a dynamic unlock of the lock links.

The geometry of the rigid connecting link was revised to increase the pinhead gap to decrease the possibility of bell crank isolation failure which would occur when the rigid connecting link would come in contact with the bell crank assembly. The rigid connecting link thickness was decreased from 0.31 in. to 0.21 in., hence increasing the pinhead gap by 0.10 in.

The dogbone was shortened to provide more latitude during rigging of the connecting link and the planing link. The shorter dogbone would also increase bell crank clearance avoiding parts contacting, reducing the chance of load isolation.

Landing Gear Configurations

For comparison purposes, data was gathered using two landing gear configurations. The first configuration was the existing CF188 main landing gear configuration. This configuration was used as the baseline. The second configuration consisted of the modified parts including the urethane connecting link cartridge, planing link urethane spring, revised rigid connecting link, and shortened dogbone.

Cold Lake Airfield

All test flights took place at 4 Wing Cold Lake. The Cold Lake airfield, as depicted in Figure A6, had three primary runways. They consisted of 13L/31R, 13R/31L and 22/04. The runway lengths were 12,600 ft, 10,000 ft, and 8,270 ft respectively and were made of asphalt. For telemetry reasons and for ease of having a dedicated runway during the test flights, the primary runway used was 13R/31L referred to as the Outer Runway. This runway was equipped with a BLISS 500S arresting cable at each end located at 1,360 ft (10). In order to avoid damaging the instrumentation, the runway was bare and dry for every test flight.

CHAPTER 5 - TEST CONCEPT

General

Testing was divided into three phases using a build up approach. The first phase consisted of evaluating the maintenance rigging and to obtain static measurements. The second phase consisted of ground handling quality testing where capture tasks were conducted at different taxi speeds. The third and final phase consisted of different landing profiles including touch and go, full stop, cable overrun and cable arrestment landings. Variables such as aircraft weight, roll angle, yaw angle, and vertical velocity were controlled. The pilot used the HUD information such as the Vertical Speed Indicator (VSI) in ft/min and the flight path angle in order to be on test condition. Aircraft attitude was maintained to touch down, i.e. no landing techniques such as flaring or rounding were used. Aircraft parameters at touch down were monitored real time by the FTCR in order to validate each data point. The FTCR also monitored landing gear status to ensure safe operation.

Phase 1 - Landing Gear Rigging

The purpose of the landing gear rigging was to capture all the adjustments made during the execution of standard maintenance procedures. The measurements were recorded before and after the test flights for both configurations. Of interest, the hold down torques were recorded when the shock absorber was fully compressed, then extended by 4 in., 8 in., 12 in. and fully extended (12.3 in.) while the aircraft was on maintenance jacks. At each test point, the length of the planing link spring was captured. Other measurements included lengths of the connecting link, planing link, shrink link, planing arm spring and bell crank gaps.

Phase 2 - Ground Handling

The purpose of this test was to evaluate the handling characteristics of the prototype configuration compared to the baseline configuration during directional ground manoeuvres. It was also used as a build up approach to takeoff and landing data points. Ground handling tests consisted of centreline capture at low, medium and high taxi speed. Targeted knots ground speed (KGS) were 30 ± 5 KGS, 60 ± 5 KGS and 80 ± 20 KGS respectively. The aircraft was offset from the centreline by approximately 5 and 10 ft during the low and moderate ground speed taxi test and only by 5 ft during the high speed taxi test. Once offset by the required distance, inputs up to ½ rudder with the Nose Wheel Steering (NWS) in low gain were applied to regain the centreline. (Of note, the NWS in low gain was normally used for takeoff and landing operation, allowing the nose wheel to a deflection of up to ± 16º compared to ± 75º in high gain. The high gain was mostly used during tight turns). The desired performance required capturing the centreline within ±3 ft in 3 sec and ±5 ft for adequate performance. The Cooper Harper Rating Scale, depicted in Figure A7, was used to quantify the handling qualities during the capture task. Pilot induced oscillation (PIO) tendency, centreline overshoot and roll/yaw transient were also evaluated.

Phase 3 – Landings

Different landing profiles were evaluated in order to cover most of the aircraft landing envelope and to gather a variety of data points. Landing profiles consisted of touch and go, full stop, cable overrun and cable arrestment landings. The aircraft attitude varied from straight landing without any crab or roll angles, landing with only ±5º of crab angle, landings with only ±5º of roll angle, and finally, landings with ±5º of crab and ±5º of roll in the same and opposite direction. The crab angle was defined as the angle between the longitudinal axis of the aircraft and the ground track while the roll angle was the angle between the horizontal and the lateral axis. For the test point to be valid, the targeted angles had to be within ±2º. Weight of the aircraft varied from 39,000 lbs down to 28,000 lbs and the descent rate from 6 ft/sec to 14 ft/sec in a 2 ft/sec increment. (Of note, the Canadian Air Force did not require 20 ft/sec descent rate landings, as they don't operate from aircraft carriers).

The purpose of the touch and go landings was to gather landing data while minimizing the down time ensuring test efficiency. All the touch and go landings were carried out past the arrestment cable. Positive contact with the runway was established with the NWS indication displayed in the HUD prior to go around. Once airborne, the mission controller, operating from the FTCR, gave the all clear call authorizing the pilot to retract the landing gear. (Of note, unlike U.S. Navy patterns, the landing gear was retracted following every touch and go). This was followed by a closed pattern. During the downwind, the parameters were reviewed and the validity of the data point was determined by the mission controller. The flight test engineer (FTE), occupying the rear seat, then briefed the pilot on the next landing parameters. On final, the pilot aimed to be on condition about 1-2 miles from touch down and maintained that condition to minimize any rates at touch down. Upon touch down, the FTE initiated the tail hook cameras. Unfortunately, the tail hook camera lenses became dirty within the first couple of landings, reducing the quality of images recorded throughout the mission.

Full stop landings were conducted for each of the 6, 10 and 14 ft/sec descent rate series. These landings were all straight without crab and roll. The purpose of the full stop landing was to evaluate the loads on the landing gear created by the braking action.

Cable overrun consisted of landings prior to the arrestment cable allowing the aircraft to roll over the cable. The purpose was to evaluate the crush loads caused by the cable. All these landings were conducted with yaw and roll angles and at 6, 10 and 14 ft/sec descent rate.

The last landing for the 6, 10 and 14 ft/sec descent rate series consisted of an arrested landing. These landings were carried out without any crab or roll angles using a BLISS 500S arresting cable.

For consistency, only three test pilots flew all the missions. Each test pilot first went to the simulator and practised the different landing profiles in different wind conditions.

Risk Assessment

To mitigate the risk associated with such testing, all the modified connecting links and planing links were laboratory tested simulating similar loads to those expected during landings.

To further minimize the risk, the flight test was conducted in a build up approach. The ground handling test had to be conducted successfully prior to the flight test phase. Using the same principle, slow descent rate landings where carried out prior to high descent rate landings and straight landings before roll and crab landings. For safety reasons, every 7^{th} landing was a full stop followed by a quick visual inspection by the maintainers of the landing gear and of the main tires. Furthermore, a crosswind limit of 10 knots was used for every test point. This limit was changed during testing to 5 knots of crosswind for crab away and roll away test points. Finally, any test point that exceeded ±7º of roll or crab angles, or the pre-set safety load for a given component, as indicated in the FTCR by the live telemetry system, resulted in a go-around with the landing gear remaining in the extended position followed by a full stop or cable engagement. A complete maintenance inspection was then conducted. The list of pre-set safety parameters is available in Table A3.

CHAPTER 6 - RESULTS AND DISCUSSION

General

All phases of testing took place at 4 Wing Cold Lake, Alberta, Canada, from 14 March 2008 to 6 May 2008. A total of 271 landings were conducted during 16 test flight missions testing four different configurations. For the purpose of this thesis, the data for 80 landings were reviewed and analysed, comparing the baseline configuration landings to the full prototype configuration landings.

Phase 1 – Landing Gear Rigging

CF188 Rigging Procedures Fleet Survey

A fleet survey of the CF188 was conducted to evaluate the spectrum of key component lengths used during rigging procedures. As depicted in Figures A8 and A9, there was a wide spectrum of connecting link length, pinhead gaps and planing link spring lengths validating the concerns of failures due to main landing gear rigging procedures. As the data shows from these figures, the length of the connecting link had a direct influence on the pinhead gap and sequentially on the planing link. While the connecting link length varied by 0.12 in., the planing link spring length varied by 0.30 in. which was the equivalent of 27% of the total spring stroke (1.125 in.). A connecting link that is too long will result in a smaller pinhead gap which could be more prone to bell crank assembly isolation type failure. In addition, a too long connecting link will result in a smaller planing link, reducing the planing link stroke available, increasing the chances of planing link bottoming out under large compression loads. On the other hand, a too short connecting link will require a longer planing link reducing the hold down force. Rigging of these key components with the right balance while maintaining the required clearances once the gear is retracted is therefore essential to minimize PMA failures. More restrictive limits should be in effect to improve the standard of the rigging procedures used through out the CF188 fleet.

Connecting Link Length

The connecting link lengths were evaluated during rigging procedures of each configuration and after the completion of the flight test. The ideal weight off wheel connecting link length was considered to be 6.55 in. Table A4 shows the difference between the baseline configuration and the prototype configuration connecting length. During the rigging of the prototype configuration, it was reported by the technicians that the shorter dogbone made it significantly easier to set the connecting link length to 6.55 in. The pre-rigging of the connecting link to 6.55 in. maintained a proper bell crank and pinhead gap, while ensuring that the axle stop was engaged when the landing gear was retracted in the wheel well. The shorter dogbone will allow rigging of the connecting link within tighter limits. This will result in reducing the number of variables during rigging procedures, hence further standardizing the rigging procedures.

Pinhead Gap and Bell Crank Gap

The pinhead gap and the bell crank gap were evaluated before and after the test flights for both configurations. Measurements were first taken with weight off wheels (WOFFW) while the aircraft was on maintenance jacks, and then with weight on wheels (WONW). The measurements are summarized in Table A5. In general, the gaps decreased with WONW as the shock absorber was compressed. The most remarkable difference between the two configurations occurred for the pinhead gap. Averaging the difference between the baseline and the prototype configuration, the pinhead gap increased by an average of 0.10 in. with WOFFW and 0.15 in. with WONW. With regards to the bell crank gap, very minor improvements were found. The modified rigid connecting link combined with the shorter dogbone allowed an increase in the pinhead gap by 0.10 in. when WOFFW and by 0.15 in. with WONW. Given that the rigid connecting link was redesigned to reduce the thickness of the inside lug by 0.10 in., it would also imply that the shorter dogbone also contributed to improve the pinhead gap by 0.05 in. with WONW. From a static point of view, this pinhead gap improvement will reduce the chances of bell crank isolation type of PMA failures. Furthermore, it will facilitate rigging of the landing gear by reducing one of the variables.

Planing Link Spring

The planing link spring length was evaluated at different shock absorber strokes. While the aircraft was on maintenance jacks, the landing gear was extended in sequence and measurements of the planing link spring length were taken at 0, 4, 6, 8, 12 and 12.3 in. shock absorber extension (i.e. from fully compressed to fully extended). As depicted in Figure A10, the prototype planing link had initially more compression loads as indicated by the smaller planing link spring length. As the shock absorber compressed, the planing link spring was compressed further. Interestingly, the spring did not compress at the same rate for the two configurations. The baseline planing link spring compressed an average of 0.34 in. while the prototype planing link spring with the urethane spring compressed an average of 0.24 in. This confirmed that from a static point of view, the urethane spring added to the planing link resulted in more stiffness. This improvement of 0.10 in. (29%) will reduce the risk of PMA failures due to the planing link bottoming out.

Static Hold Down Torque

The static hold down torque was measured with aircraft on maintenance jacks (WOFFW). Measurements were taken at different shock absorber extension. The hold down torque was measured as indicated by the torque required to unlock the axle lock links mechanism. The lock links were considered unlocked when it was possible to pull on the feeler gauge only using a small pull force. The feeler gauge was installed between the planing arm stop and the axle lever down stop. In both cases, the hold down torque was greater than the minimum of 56 ft-lbs required during normal rigging.

As depicted in Figure A11 and as expected by the planing link spring length, the hold down torque had a tendency to increase as the shock absorber was compressed and this was more significant for the prototype configuration (slopes were of -1.0 vs -3.4 ft-lbs/in.). The prototype compared to the baseline configuration had an overall 43.8 ft-lbs (52%) increase when the shock absorber was fully compressed and an increase of 13.8 ft-lbs (20%) when the shock absorber was fully extended. This confirmed that the added stiffness by the urethane spring and the prototype PMA configuration resulted in an increase in the hold down torque. The prototype configuration will allow an increase in the hold down force which will reduce the risk of PMA failures due to dynamic unlock of the lock links.

Phase 2 – Ground Handling

The handling qualities of the baseline and the prototype configurations were evaluated on the ground during centreline capture tasks. At different ground speeds; 30, 60 and 80 KGS, and with an offset of 5 and 10 ft, centreline capture tasks were conducted using up to ½ rudder pedal inputs. The centreline capture tasks were conducted from both the left and right using runway 31R. Although some minor inertial effects were felt at higher speed, capturing the centreline within desire performance (±3 ft within ±3 sec) was easy and did not result in any PIO tendency. Essentially, from a pilot point of view, no differences between the two landing gear configurations were noticeable. Handling Quality Ratings (HQR) of 2 and 3 were given to both configurations. HQR results can be found in Tables A6 and A7. Within the scope of this test, the ground handling qualities of the prototype configuration were found similar to the handling qualities of the baseline configuration. Therefore, the prototype configuration did not improve nor negatively impacted the ground handling quality of the aircraft at various ground speeds.

Phase 3 – Landings

Loads During Landing Gear Retraction

Main landing gear retraction loads were evaluated during flight testing. The landing gear was retracted following every takeoff. Of interest, was the transfer of the loads created by the braking action on the wheel onto the planing and connecting links as part of the retraction sequence. Graphics depicting representative loads during gear retraction are presented in Figures A12 and A13. From these figures, the loads from the landing gear retraction can be found when the wheel speed is drastically slowed down, as the braking action on the wheel was one of the first actions to take place after the gear selection handle was put into the up position. For this given baseline configuration example, the maximum compression load transferred to the planing link during the retraction was 425 lbs and 1,097 lbs to the connecting link. The wheel speed was 1,399 revolution per minute (RPM) at the moment of the retraction. For the prototype configuration, the numbers were essentially the same. With a wheel speed of 1,809 RPM, the maximum compression loads on the prototype planing and connecting links were 459 lbs and 1,049 lbs respectively. Of note, the pinhead gap instrumentation could only measured gaps up to 0.22 in. which explains the straight line in Figure A13. Analysing all the compression loads revealed that, first the loads from the braking action as part of the landing gear retraction were not significant and that the loads on the prototype configuration were similar to the loads on the baseline configuration. Analysing all the tension loads revealed that the loads on the prototype and the baseline configuration were similar and consistent. The largest tension load was experienced by the connecting link and was in the 8,000 lbs range where the loads on the planing link were in the 1,500 lbs range. Within the scope of this study, the prototype landing gear did not improve nor deteriorate the load transferred to the PMA during landing gear retraction.

Braking Action Loads

The effect of the braking action on the PMA was evaluated during full stop landings on dry runways. For the purpose of this study, 10 landings were analysed with the baseline configuration and 8 landings with the prototype configuration. Touch downs occurred between 120 and 160 KCAS and braking action were generally applied around 100 KCAS. As depicted in Figures A14 and A15, the braking action had minimal impact on the PMA. The maximum loads to the planing and connecting links occurred at touch down where large compression loads were observed. The braking action resulted in compression loads in the order of approximately 70% of the loads created at touch down. Within the scope of this study, the prototype landing gear did not improve nor deteriorate the loads transferred to the PMA during normal braking action.

Cable Arrestment Landings

The effect of rapid deceleration was evaluated during cable arrestment landings. For the purpose of this study, two cable arrestment landings were analysed with the baseline configuration, and two with the prototype configuration. In general, the aircraft came to a stop within 7 to 9 sec following cable engagement. As an example, data from two landings are depicted in Figures A16 and A17. As shown, the rapid deceleration had no effect on the PMA components. The only large compression or tension loads were once again observed at touch down and during the cable overrun. Within the scope of this study, the prototype landing gear did not improve nor deteriorate the loads transferred to the PMA during cable arrestment landings.

Cable Overrun

The effect of cable overrun was evaluated during touch and go landings and cable arrestment landings, as the aircraft rolled over the cable before the engagement. In all cases, the crush loads transferred to the system from the cable overrun were noticeable as depicted in Figures A18 and A19. For the baseline configuration, the compression load transferred to the planing link was either similar or greater than the touch down loads. However, the loads never exceeded 20% of the available compression load based on the pre-set safety parameter of 5,000 lbs in compression. The loads created by the cable overrun to the connecting link, side brace and the shock absorber were minimal when compared to respective initial touch down loads. This was also applicable to the prototype configuration. However, the compression loads transferred to the prototype planing link were smaller in magnitude. In no cases did it exceed 30% of the initial touch down load, equivalent to 10% of the pre-set safety parameter. The better resistance of the prototype planing link to cable overrun can be explained by the increase in the stiffness provided by the urethane spring. Although it is not suspected that cable overruns could create crush loads to the PMA that could result in failures, the prototype landing gear was more resistant to these loads, and consequentially was an improvement to the existent design.

Touch Down Loads

Loads at touch down on PMA components were evaluated and analysed over 80 landings with different descent rates and different aircraft attitudes. The initial loads created by the touch down were, in general, the largest loads observed through the landing event. Most of the components such as the lock links, planing link, shrink link, connecting link and shock absorber were in compression. The side brace had transient loads in compression but was typically in tension. A representative example of the loads at touch down is depicted in Figures A20 and A21. Of interest from these figures were the side brace and the connecting link being out of phase by 180º, the lock links and the shock absorber loads being in phase and the prototype planing link being in phase with the connecting link loads while the baseline was not.

For the baseline configuration, the maximum loads were normally observed within the first 1 in. of shock absorber compression stroke, as depicted in Figure 22. Cross referring with Figure A11, the static hold down torque was at its minimum when the shock absorber was fully extended. Hence, the maximum compression loads occurred on the PMA when the hold down torque was also at its minimum. When analysing the data for the prototype configuration, it was observed that the maximum compression loads generally occurred when the shock absorber was extended by 5 in. For the prototype configuration, the difference in the static hold down torque between 12 in. and 5 in. of shock absorber extension was approximately an additional 20 ft-lbs. Therefore, the maximum loads on the prototype configuration were occurring at a more convenient moment when comparing with the static hold down torque.

Analysing the data, it was observed that the tension loads in the side brace were in phase with the compression loads in the connecting link. This was true for both configurations. However, only the baseline had the maximum compression connecting link loads essentially at the same time as the maximum tension side brace load. The prototype maximum compression connecting link load occurred 1 to 2 cycles after, suggesting that the side brace had less of an effect on the prototype connecting link. When plotting the maximum connecting link compression load as a function of the maximum side brace tension load, as shown in Figure A23, it can be observed that the loads on the baseline configuration had a tendency to converge towards the connecting link compression safety limit faster than the prototype configuration, even though the initial compression loads were lesser. Although the compression loads on the prototype connecting link were initially greater, they were more constant and did not display the same abrupt conversion towards the safety limit. Further data would be required to ensure that the same abrupt conversion does not exist at greater side brace tension loads for the prototype configuration. Within the scope of this analysis, the prototype configuration would be promising, providing a better safety margin to the connecting link with high side brace tension loads. The prototype PMA would then be more resilient to failures where buckling of the connecting link is the initial cause.

Considering the compression loads on the planing link equivalent in magnitude to the hold down force applied to the lock links, a greater compression load on the planing link would imply better hold down force. As depicted in Figure A24, the compression loads on the prototype planing link were greater when compared to the baseline planing link compression loads. The baseline planing link demonstrated a tendency to level off at 600 lbs in compression loads, although the shock absorber loads where greater (note that shock absorber loads were used in order to capture both the impact of the aircraft weight and descent rate at touch down). Unlike the baseline, the prototype planing link compression loads continuously increased with the shock absorber loads, providing a better hold down force as the load on the landing gear was greater. In addition, the baseline planing link compression loads had a tendency to decrease initially, and then increase again as depicted by the circle on Figure A20. As stated earlier, these compression loads, being proportional to the hold down force, would imply that the decrease in compression would also mean a decrease in hold down force. As the lock links did not have that initial decrease in compression, it could be concluded that this was an important contributing factor to dynamic unlock type of failure. This decrease in compression loads was not observed on the prototype planing link. Therefore, the prototype configuration would be less prone to dynamic unlocks as the planing link did not show that same behaviour.

Finally, the planing link displacements for the prototype configuration were smaller, as depicted in Figure A25, providing a better safety margin with issues such as bottoming out of the planing link in compression. This confirmed that the planing link urethane spring added stiffness to the system. The improvement in planing link displacement will avoid planing link bottoming out in compression, thus decreasing the chances of failure.

Connecting Link Buckling Incident

After the completion of testing one of the partial configurations, which consisted of testing the prototype planing link and shorter dogbone only, the right connecting link was found slightly bent by about 1º. This was not noticeable with the naked eye while the baseline connecting link was installed. The buckle in the connecting link was found during the maintenance activities required to change the landing configuration. Of note, none of the previous landings had resulted in exceeding the pre-set safety parameters, nor triggering the cockpit warning lights and tone associated with a planing link failure. The data also revealed that the lock links remained in the lock position for all the landings during that mission. This resulted in a pause in testing until the safety parameters were reviewed as well as a new risk mitigation developed. Reviewing the data preceding this incident revealed that the maximum compression load applied to the connecting link was - 5,076 lbs during a 758 fpm descent, -1º of roll and -2º of crab (please note that negative roll angle implied left wing down and negative crab angle implied that the nose of the aircraft was pointed to the left, from the pilot perspective). The safety compression load for the connecting link was brought up from - 6,000 lbs to - 4,000 lbs as an additional risk mitigation. A maintenance inspection tool was immediately designed to help detecting slight bent in the connecting link and was used as a pre-flight inspection from that point on.

Based on this incident, one of the theories for PMA failures was then confirmed where the connecting link could be initially failing, hence starting the chain of event. The connecting link may suffer minor buckling without immediately resulting in a planing link failure. This would go unnoticed as the warning lights and tone would not be triggered. The connecting link would then be weakened at that point, especially in compression. The length of the connecting link would also be shortened by that buckling. Because a shorter connecting link will result in a smaller hold down force, then the landing gear will now be more prone to a dynamic unlock situation or suffer more connecting link buckling from another landing. Any of these situations would then result in a PMA failure.

Inspecting the connecting links as part of the daily inspection for all CF188 using the tool that was developed during the test program, will reduce this type of PMA failures, given the aircraft is inspected between the minor buckling and the catastrophic failure. This preventive maintenance should be adopted throughout the fleet.

CHAPTER 7 - CONCLUSION

The aim of this thesis was to study the effectiveness of the proposed modifications to the CF188 landing gear in order to reduce the risk of PMA failures. As the PMA failures were always associated to the unlocking of the lock links as part of the chain of event, it was therefore essential to assess the hold down force from the planing link.

From a static point of view, and as indicated by the torque required to unlock the lock links during maintenance procedures, the prototype planing link offered an important increase in the hold down force. The increase in the hold down force went from 20% with the landing gear fully extended and to 52% with the landing gear fully compressed.

From a dynamic point of view, the hold down force was also greater with the prototype than with the baseline. While the baseline planing link loads levelled up at 600 lbs in compression, the prototype planing link loads where continuously increasing and went up to 1,600 lbs in compression.

Although the prototype planing link compression loads were greater than the baseline, the planing link spring displacement was less, providing better safety margin against planing link bottoming out in compression. In addition, this confirmed that the urethane spring added to the planing link did improve the planing link stiffness. The increase in stiffness was also noticeable against crush loads during cable overrun landings, where the prototype planing link was not as affected by the crush loads when compared to the baseline.

The modifications to the rigid connecting link and the shorter dogbone allowed better clearances for the bell crank assembly gaps, facilitating rigging procedures. This was mostly noticeable for the pinhead gaps. The increase in the pinhead gap will decrease the chances of having bell crank assembly isolation, where greater loads could be transferred to the connecting link potentially resulting in buckling. Therefore, these modifications will decrease the number of planing link failures.

As evaluated during capture task at different ground taxi speed, the handling qualities of the prototype landing gear were deemed similar as the baseline configuration. Within the scope of this study, the prototype configuration did not improve nor negatively impact the ground handling quality of the aircraft on the ground.

The loads created on the landing gear were analysed during touch and go, full stop, cable overrun and arresting cable engagement landings. It was observed that the most important loads occurred upon touch down. A relationship was observed between the side brace and the connecting link loads. Although the compression loads on the connecting link where greater for the prototype, they were more constant and did not display the same abrupt increase as the baseline did when the side brace tension loads were in the 40,000 to 60,000 lbs range.

As experienced with the connecting link buckling incident, the connecting link could some time be the first event of a PMA failure. It could be slightly bent first, go unnoticed for some time, followed by a catastrophic type of failure. This type of failure could easily be avoided by using the inspection tool that was developed during the flight test program as part of the pre-flight inspection to ensure the connecting link was not bent.

The overall performance of the CF188 landing gear upgrade was found acceptable and will decrease the risk of PMA failures.

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APPENDIX

Figure A1. Aircraft CF188907

Table A1. Aircraft Test Configuration

Aircraft Configuration	Station Loading And Suspension								
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Centerline	Empty	Empty	Pylon	Empty	EFT	Empty	Pylon	Empty	Empty

Note: External Fuel Tank (EFT)

Table A2. Flight Test Instrumentation Parameters

Measurand Description	Eng Units (EU)	Approximate EU Range	Sampling Rate (SPS)
Shock Absorber Oleo Lug Load	lbs	-150,000 to +8,000	913.60
Lower Side Brace Load	lbs	-65,000 to +85,000	913.60
Connecting Link Load	lbs	-8,000 to +8,000	913.60
Planing Link Load	lbs	-5,000 to +10,000	913.60
Shrink Link Load	lbs	-1,000 to +10,000	913.60
Inner Lower Lock Link Load	lbs	-25,000 to +5,000	913.60
Outer Lower Lock Link Load	lbs	-25,000 to +5,000	913.60
Planing Arm Angular Displacement	deg	0 to 8	913.60
MLG Axle Lever Nz	g	-100 to +100	913.60
Planing Arm Nz	g	-100 to +100	913.60
Axle Lever Position	deg	0 to 60	913.60
Planing Link Spring Displacement	in.	0 to -1	913.60
Bell-Crank Pinhead Gap Displacement	in.	0 to 0.210	913.60
Trunnion Position	deg	0 to 105	913.60

Table A2. Continued.

Measurand Description	**Eng Units (EU)**	**Approximate EU Range**	**Sampling Rate (SPS)**
Connecting Link Stroke	in.	0 to -0.02	913.60
Shock Absorber Stroke	in.	0 to 12	913.60
Wheel Speed	rpm	90 to 3000	913.60
MLG Brake Temperature	deg F	-40 to +500	488.28

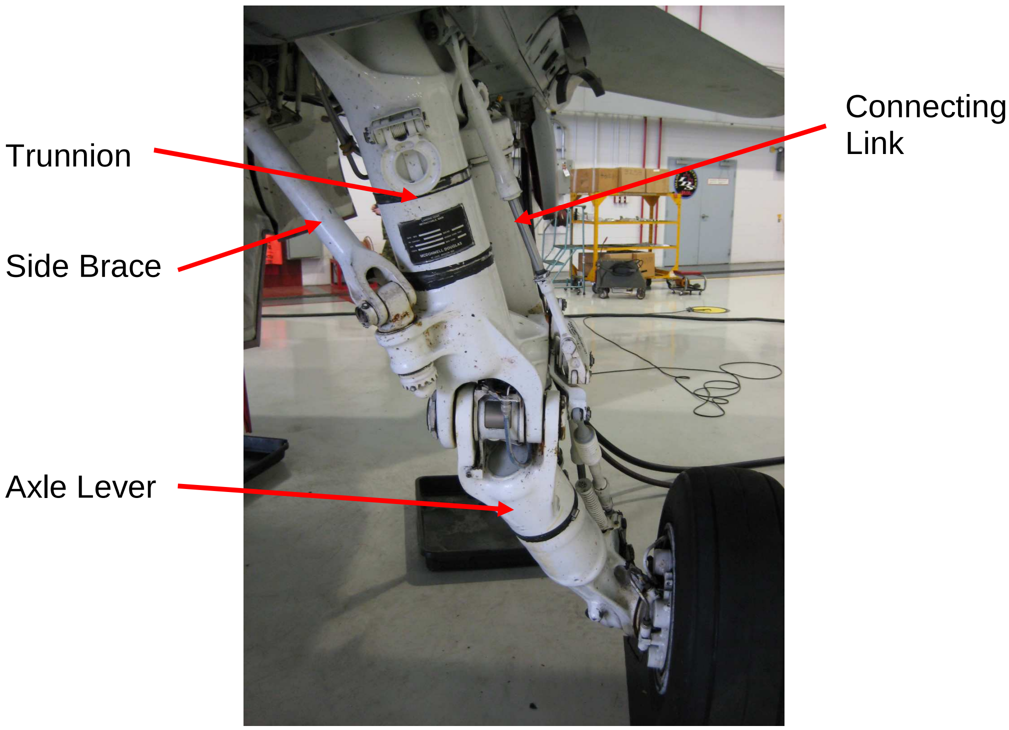


Figure A2. Landing Gear Components (Front View)

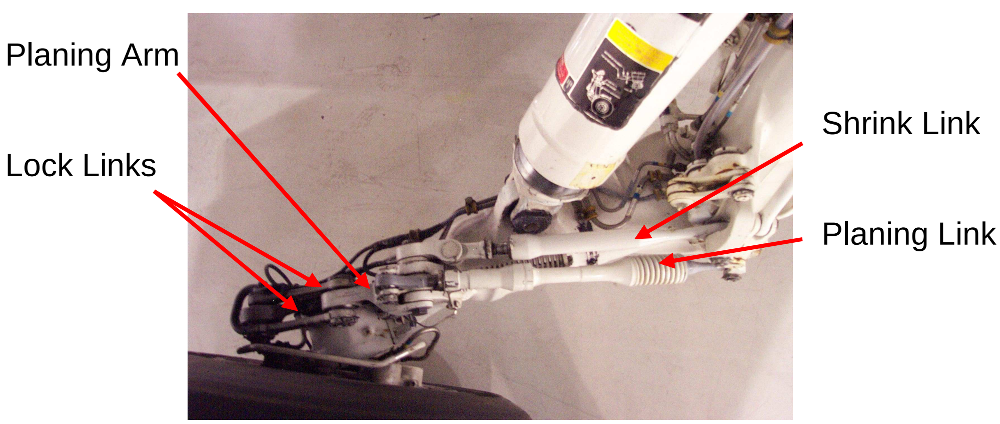


Figure A3. Landing Gear Components (Top View)

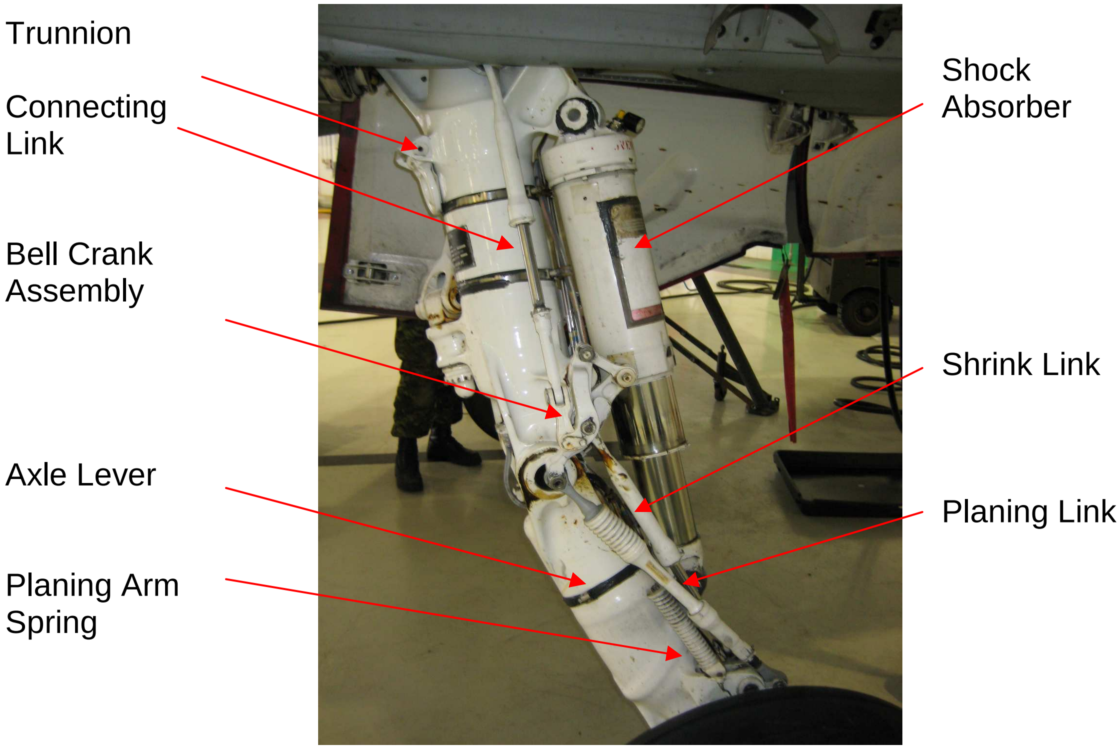


Figure A4. Landing Gear Components (Side View)

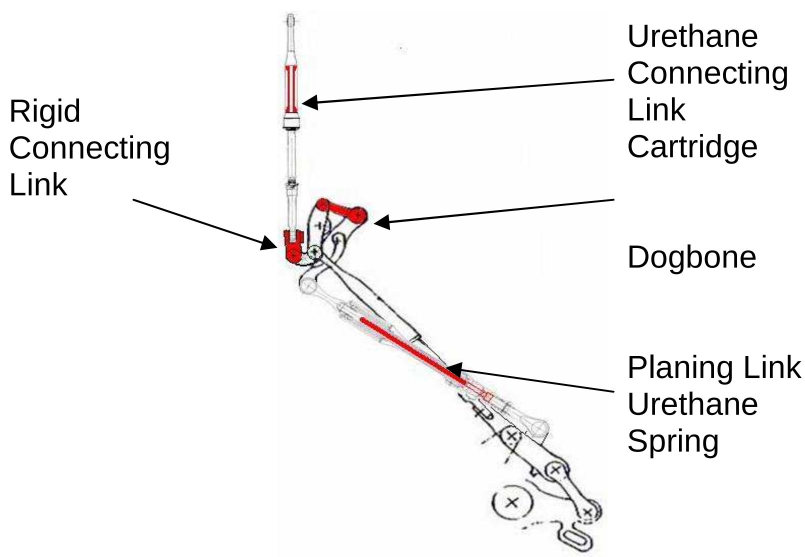


Figure A5. Prototype PMA Components

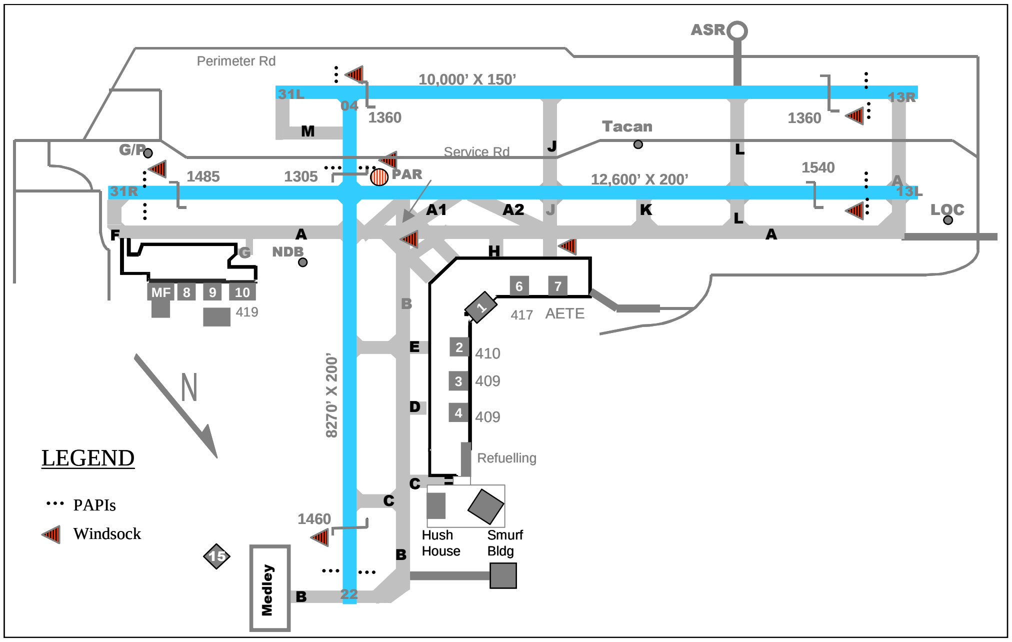


Figure A6. Cold Lake Airfield

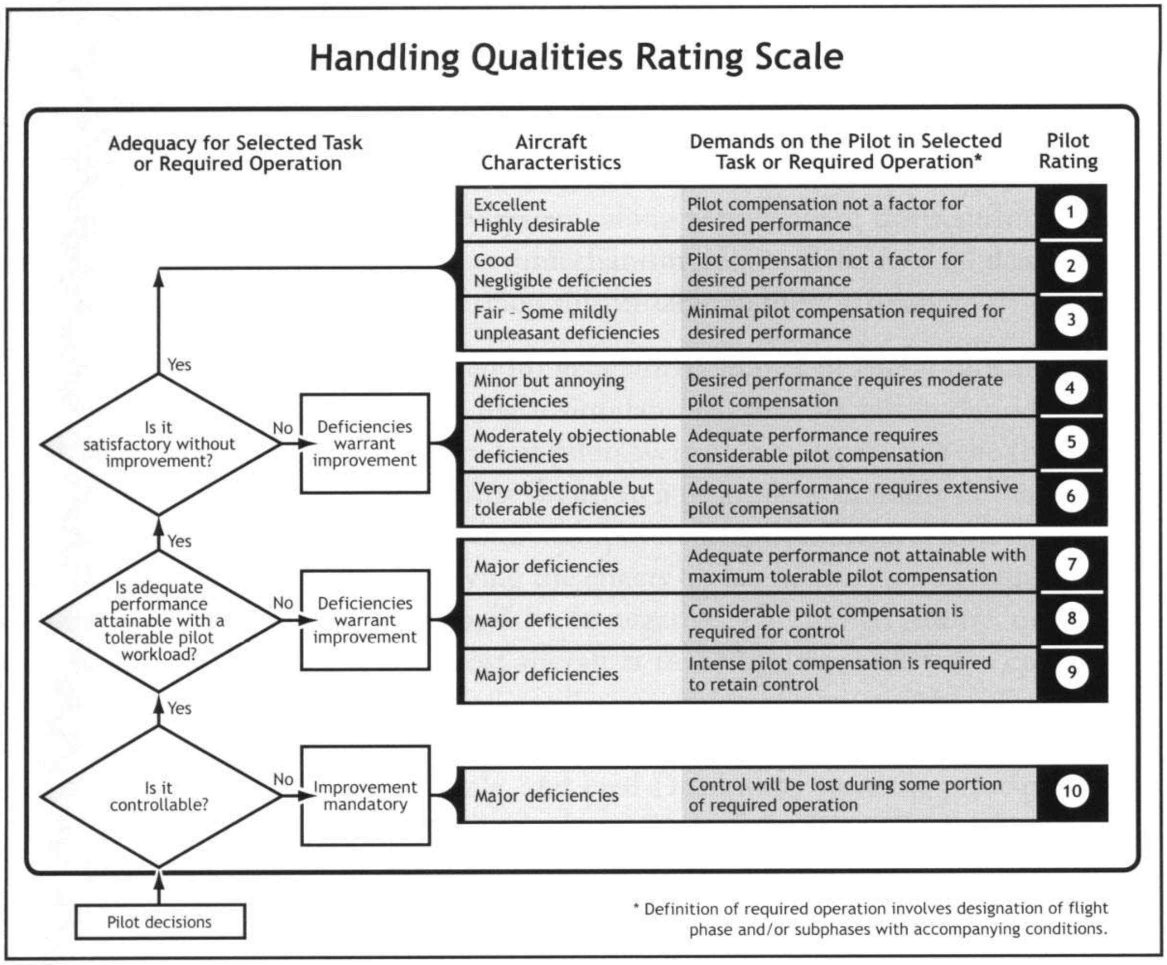


Figure A7. Cooper Harper Rating Scale

Table A3. Pre-Set Safety Parameters.

Parameter	Inspection Limits (lbs)
Planing Link Load	Compression = -5,000
	Tension = +6,000
Connecting Link Load	Compression = -4,000
	Tension = +10,000
Shrink Link Load	Tension = +10,000 Compression = -1,000
Inner / Outer Lock Links Load	Compression = -27,000 per link
	Tension = +7,200 per link
Shock Absorber Load	Compression = -140,000
	Tension = +12,000
Side Brace Load	Compression = -60,000
	Tension = +95,000

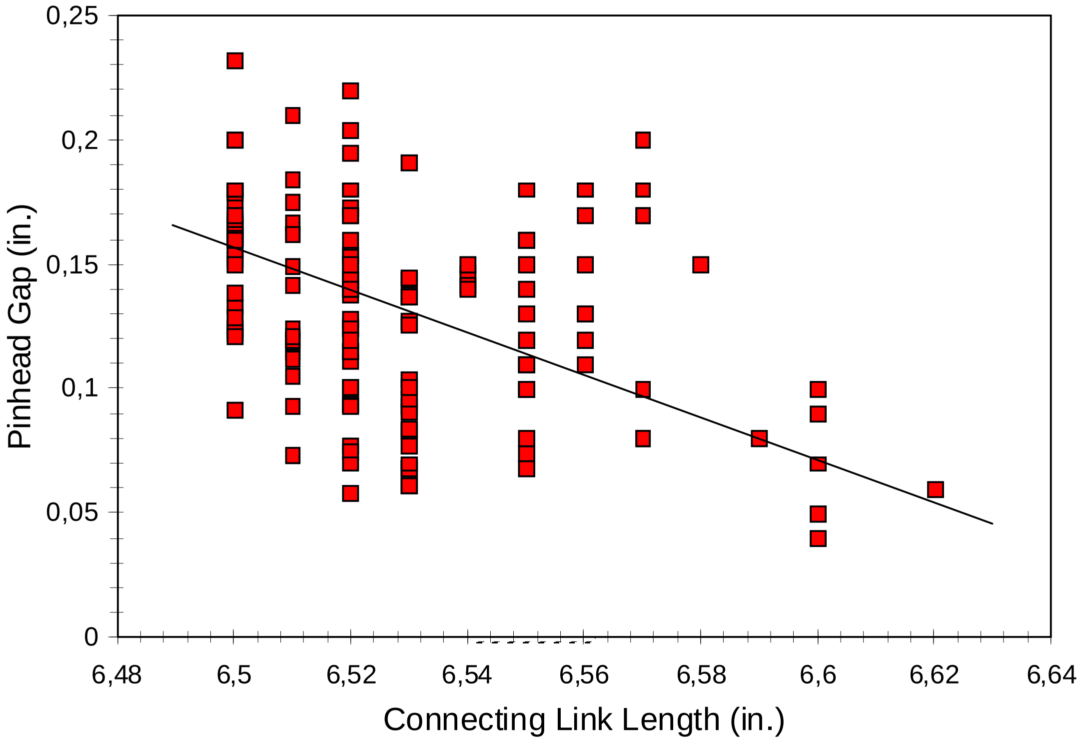


Figure A8. Fleet Survey of Pinhead Gap vs Connecting Link Length

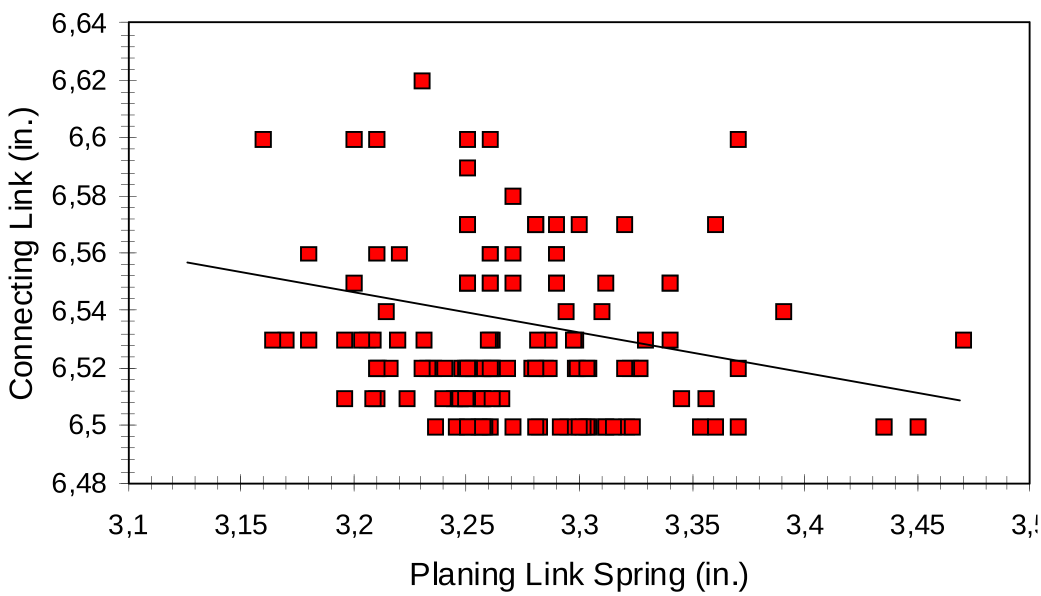


Figure A9. Fleet Survey of Connecting Link vs Planing Link Spring Length

Table A4. Weight Off Wheel Connecting Link Length

Baseline		Prototype Configuration	
Pre Flight Test	**Post Flight Test**	**Pre Flight Test**	**Post Flight Test**
LH / RH (in.)	**LH / RH (in.)**	**LH / RH (in.)**	**LH / RH (in.)**
6.5785/6.5750	6.5785/6.5750	6.5540/6.5595	6.5570/6.5665

Table A5. Baseline and Prototype Comparison of Pinhead Gap and Bell Crank Gap

Parameter	**Baseline**		**Prototype**	
	Pre Flight Test	**Post Flight Test**	**Pre Flight Test**	**Post Flight Test**
	LH / RH (in.)	**LH / RH (in.)**	**LH / RH (in.)**	**LH / RH (in.)**
Pinhead Gap (WOFFW)	0.200/0.1850	0.2750/0.2750	0.3490/0.3585	0.3175/0.3490
Pinhead Gap (WONW)	0.1300/0.1290	0.0950/0.0860	0.2303/0.3115	0.2460/0.2690
Bell Crank Gap (WOFFW)	0.1465/0.1465	0.1400/0.1410	0.1955/0.2105	0.1470/0.1840
Bell Crank Gap (WONW)	0.0950/0.0850	0.0800/0.0850	0.1085/0.1270	0.0870/0.1020
Aircraft Weight	26,900 lbs	29,200 lbs	32,900 lbs	30,600 lbs

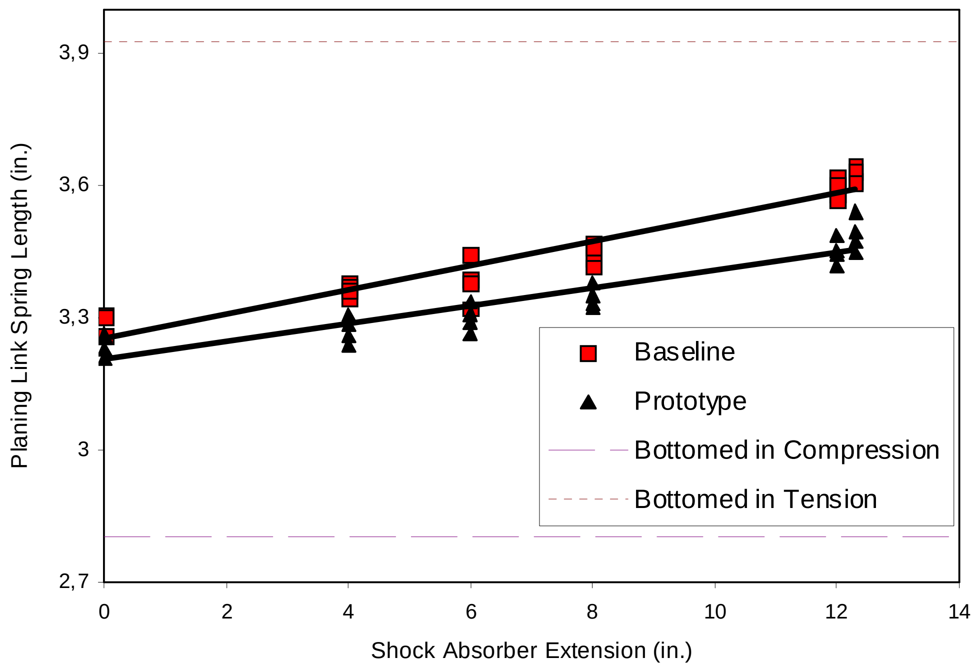


Figure A10. Planing Link Spring Length vs Shock Absorber Extension (WOFFW)

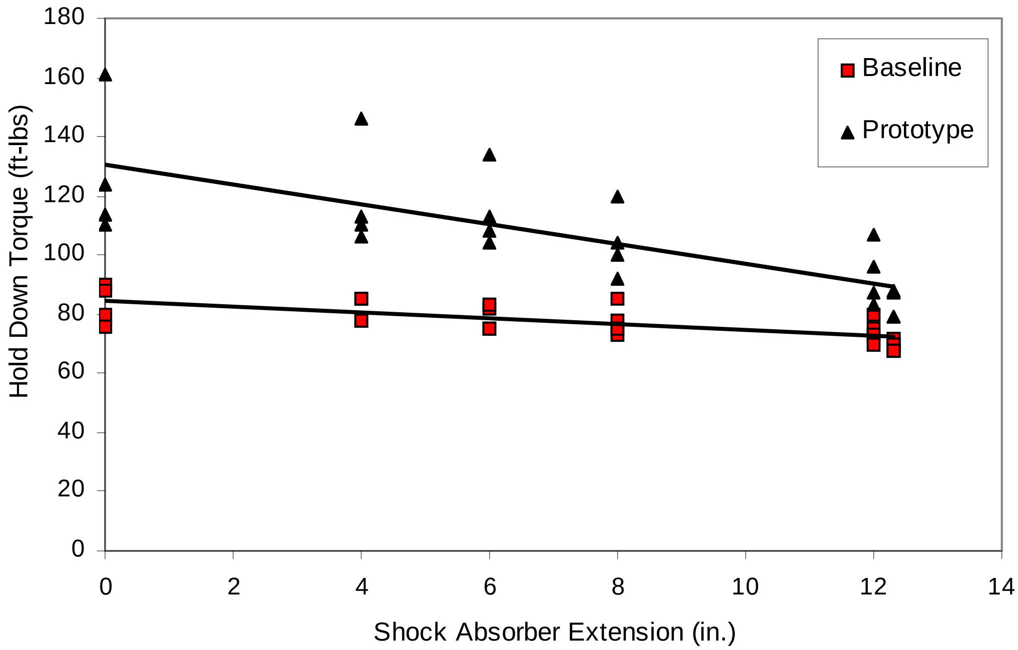


Figure A11. Hold Down Torque vs Shock Absorber Extension (WOFFW)

Table A6. Centerline Capture Task (Baseline Configuration)

Event	Ground Speed (KGS)	Fuel (lbs)	Wind (kts)	HQR
Low Speed Taxi 5 ft & 10 ft	30	11400	110/05	2,2
Med Speed Taxi 5 ft	60	11100	110/05	3,3
Med Speed Taxi 10 ft	60	10900	070/05	3,3
High Speed Taxi 5 ft	80	10800	060/06	3,3
High Speed Taxi 10 ft	80	9800	060/07	3,3

Table A7. Centerline Capture Task (Prototype Configuration)

Event	Ground Speed (KGS)	Fuel (lbs)	Wind (kts)	HQR
Low Speed Taxi 5ft & 10ft	30	11500	350/9	2,2
Med Speed Taxi 5ft	60	11400	350/9	2,2
Med Speed Taxi 10ft	60	11300	350/9	2,2
High Speed Taxi 5ft	80	11000	340/6	3,3
High Speed Taxi 10ft	80	10400	020/5	3,3

Table A8. Measurement Definitions

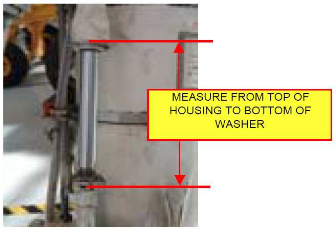
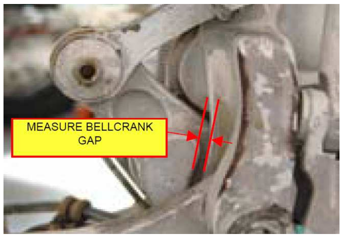
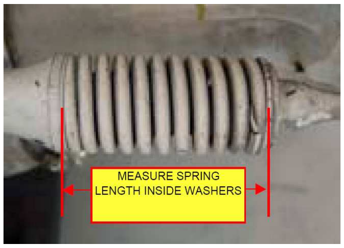
Measurement	Location
Connecting Link Length	
Pinhead Gap	
Gap Between Bell Cranks	
Planing Link Spring Length Inside Washers	
Planing Arm Spring Length From Base Including Retaining Cap	

Table A9. Landing Gear Rigging Measurements (Baseline)

Parameter	Baseline			
	Pre Flight Test		Post Flight Test	
Location	**LH**	**RH**	**LH**	**RH**
Connecting Link Length (WOFFW) (in.)	6,5785	6,575	6,5785	6,575
Pinhead Gap (WOFFW) (in.)	0,2	0,185	0,275	0,275
Gap Between Bell Cranks (WOFFW) (in.)	0,1465	0,1465	0,14	0,141
Planing Link Spring Length Inside Washers (WOFFW) (in.)	3,628	3,5985	3,632	3,61
Hold Down Torque 0" (Fully Compressed) MLG Shock Stroke (ft-lbs)	90	88	80	76
Planing Link Spring Length 0" (Fully Compressed) MLG Shock Stroke (in.)	3,306	3,26	3,3	3,26
Hold Down Torque 4" MLG Shock Stroke (ft-lbs)	85	85	78	78
Planing Link Spring Length 4" MLG Shock Stroke (in.)	3,3775	3,343	3,368	3,36
Planing Link Spring Length 6" MLG Shock Stroke (in.)	3,442	3,388	3,32	3,38

Table A9. Continued.

Parameter	Baseline			
	Pre Flight Test		Post Flight Test	
Location	LH	RH	LH	RH
Hold Down Torque 8" MLG Shock Stroke (ft-lbs)	78	85	73	75
Planing Link Spring Length 8" MLG Shock Stroke (in.)	3,4675	3,433	3,46	3,415
Planing Link Spring Length 12" MLG Shock Stroke (in.)	3,6165	3,578	3,6	3,568
Hold Down Torque 12.3" (Fully Extended) MLG Shock Stroke (ft-lbs)	72	70	68	68
Planing Link Spring 12.3" (Fully Extended) MLG Shock Stroke (in.)	3,646	3,608	3,63	3,605
Pinhead Gap (WONW) (in.)	0,13	0,129	0,095	0,086
Gap Between Bell Cranks (WONW) (in.)	0,095	0,085	0,08	0,085
Planing Link Spring Length Inside Washers (WONW) (in.)	3,23	3,26	3,25	3,26
WONW Aircraft Weight At Time Of Measurement (lbs)	26 900		29 200	

Table A10. Landing Gear Rigging Measurements (Prototype)

Parameter	Prototype			
	Pre Flight Test		Post Flight Test	
Location	**LH**	**RH**	**LH**	**RH**
Connecting Link Length (WOFFW) (in.)	6.5540	6.5595	6.5570	6.5665
Pinhead Gap (WOFFW) (in.)	0.3490	0.3585	0.3175	0.3490
Gap Between Bell Cranks (WOFFW) (in.)	0.1855	0.2105	0.1470	0.1840
Planing Link Spring Length Inside Washers (WOFFW) (in.)	3.4740	3.5395	3.4505	3.4885
Planing Arm Spring Length From Base Including Retaining Cap (in.)	6.8300	6.8500	6.8300	6.8500
Hold Down Torque 0" (Fully Compressed) MLG Shock Stroke (ft-lbs)	114	161	110	124
Planing Link Spring Length 0" (Fully Compressed) MLG Shock Stroke (in.)	3.2295	3.2605	3.2085	3.2545
Hold Down Torque 4" MLG Shock Stroke (ft-lbs)	108 112	145 148	108 104	113 113
Planing Link Spring Length 4" MLG Shock Stroke (in.)	3.2600 3.2475	3.3045 3.2860	3.2380 3.2400	3.2854 3.2760
Hold Down Torque 6" MLG Shock Stroke (ft-lbs)	104 110	130 138	103 104	114 112
Planing Link Spring Length6" MLG Shock Stroke (in.)	3.2875 3.2770	3.3355 3.3145	3.2640 3.2545	3.3080 3.3075

Table A10. Continued

Parameter	Prototype			
	Pre Flight Test		Post Flight Test	
Location	LH	RH	LH	RH
Hold Down Torque 8" MLG Shock Stroke (ft-lbs)	92 108	112 128	96 88	103 105
Planing Link Spring Length 8" MLG Shock Stroke (in.)	3.3245 3.3210	3.3785 3.3545	3.3300 3.2845	3.3510 3.3540
Hold Down Torque 12" MLG Shock Stroke (ft-lbs)	87 104	87 117	84 89	83 83
Planing Link Spring Length 12" MLG Shock Stroke (in.)	3.4435 3.4450	3.4855 3.4825	3.4160 3.4265	3.4500 3.4790
Hold Down Torque12.3" (Fully Extended) MLG Shock Stroke (ft-lbs)	87 87	86 90	79 79	79 79
Planing Link Spring Length 12.3" (Fully Extended) MLG Shock Stroke (in.)	3.4740 3.4805	3.5395 3.5160	3.4460 3.4400	3.4860 3.5125
Pinhead Gap (WONW) (in.)	0.2303	0.3115	0.2460	0.2690
Gap Between Bell Cranks (WONW) (in.)	0.1095	0.1270	0.0870	0.1020
Planing Link Spring Length Inside Washers (WONW) (in.)	3.1860	3.2160	3.1455	3.1710
WONW Aircraft Weight At Time Of Measurement (lbs)	32,9		30,6	

Aircraft: 188907

Source: Flight Test

Fuel Weight: 10,200 lbs

Configuration: Baseline

Phase: Takeoff and Gear Retraction

Time (Local)

Figure A12. Landing Gear Loads During Takeoff and Retraction (Baseline)

Aircraft: 188907

Source: Flight Test

Fuel Weight: 11,000 lbs

Configuration: Prototype

Phase: Takeoff and Gear Retraction

Time (Local)

Figure A13. Landing Gear Loads During Takeoff and Retraction (Prototype)

Aircraft: 188907

Source: Flight Test

Configuration: Baseline

Phase: Full Stop Landing

Fuel Weight: 4,400 lbs

Descent Rate: 668 fpm

Crab Angle: 1.5º

Roll Angle: -1º

Pitch Angle: 2.4º

Time (Local)

Figure A14. Full Stop Landing (Baseline)

Aircraft: 188907

Source: Flight Test

Configuration: Prototype

Phase: Full Stop Landing

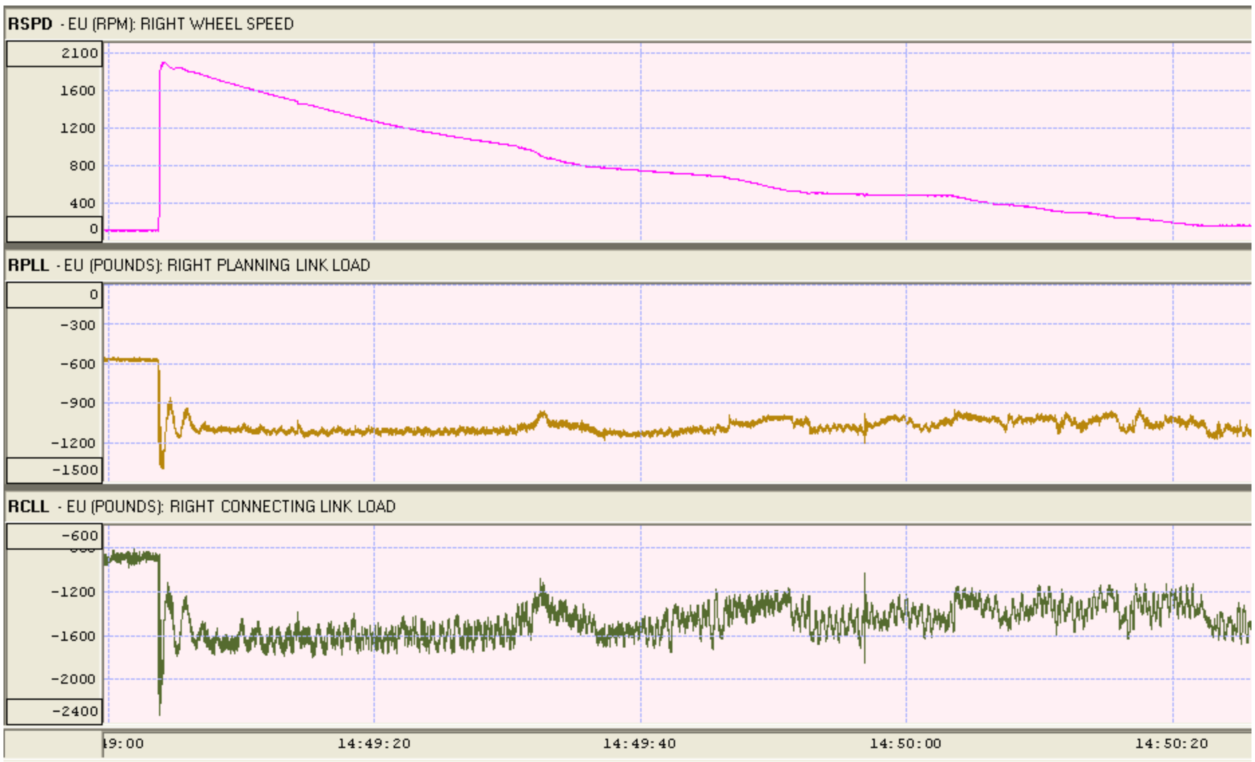
Fuel Weight: 5,100 lbs

Descent Rate: 495 fpm

Crab Angle: 0º

Roll Angle: 2º

Pitch Angle: 4.9º



Time (Local)

Figure A15. Full Stop Landing (Prototype)

Aircraft: 188907

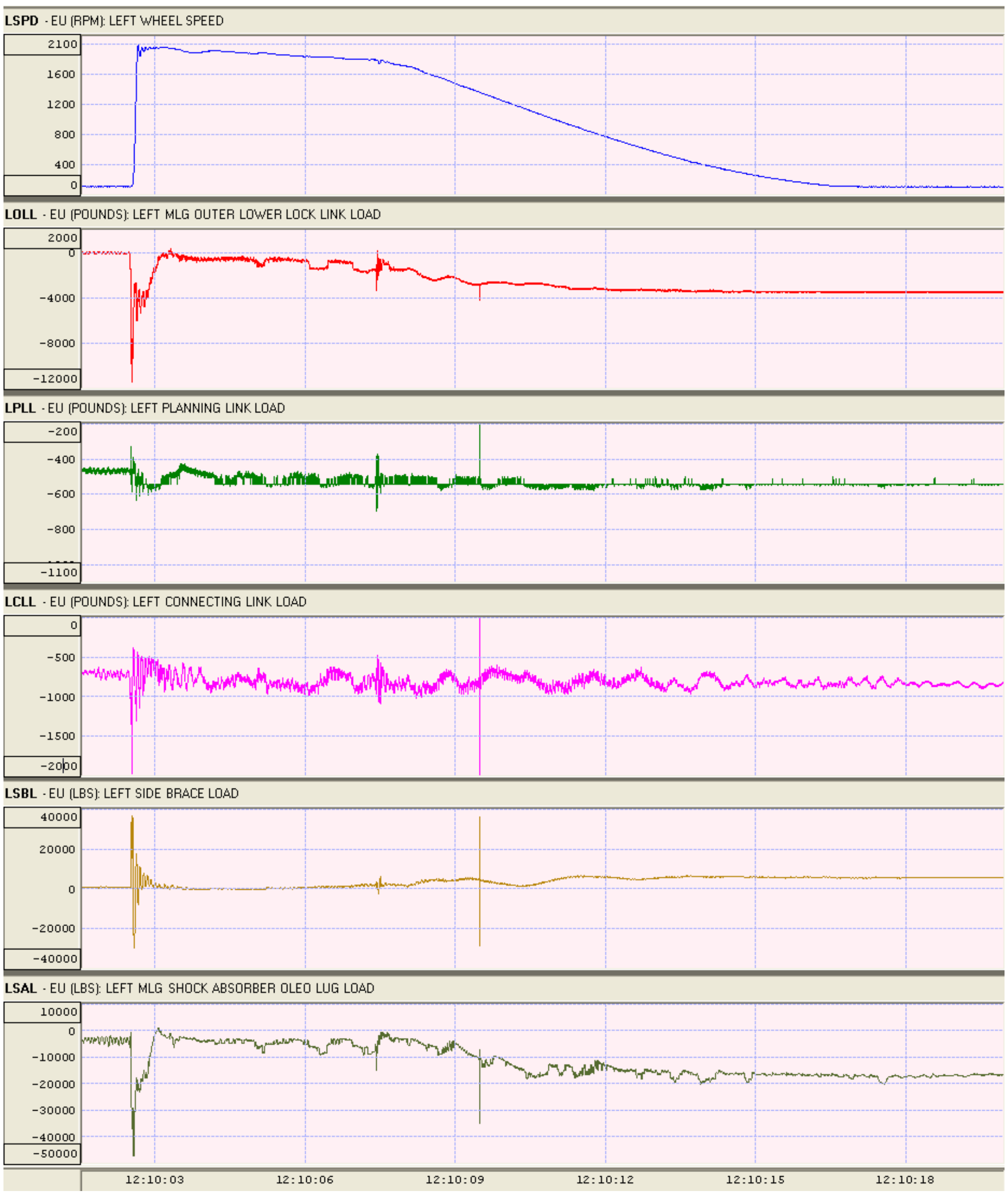
Source: Flight Test

Configuration: Baseline

Phase: Cable Arrestment

Fuel Weight: 2,100 lbs

Descent Rate: 720 fpm



Time (Local)

Figure A16. Cable Arrestment Landing (Baseline)

Aircraft: 188907

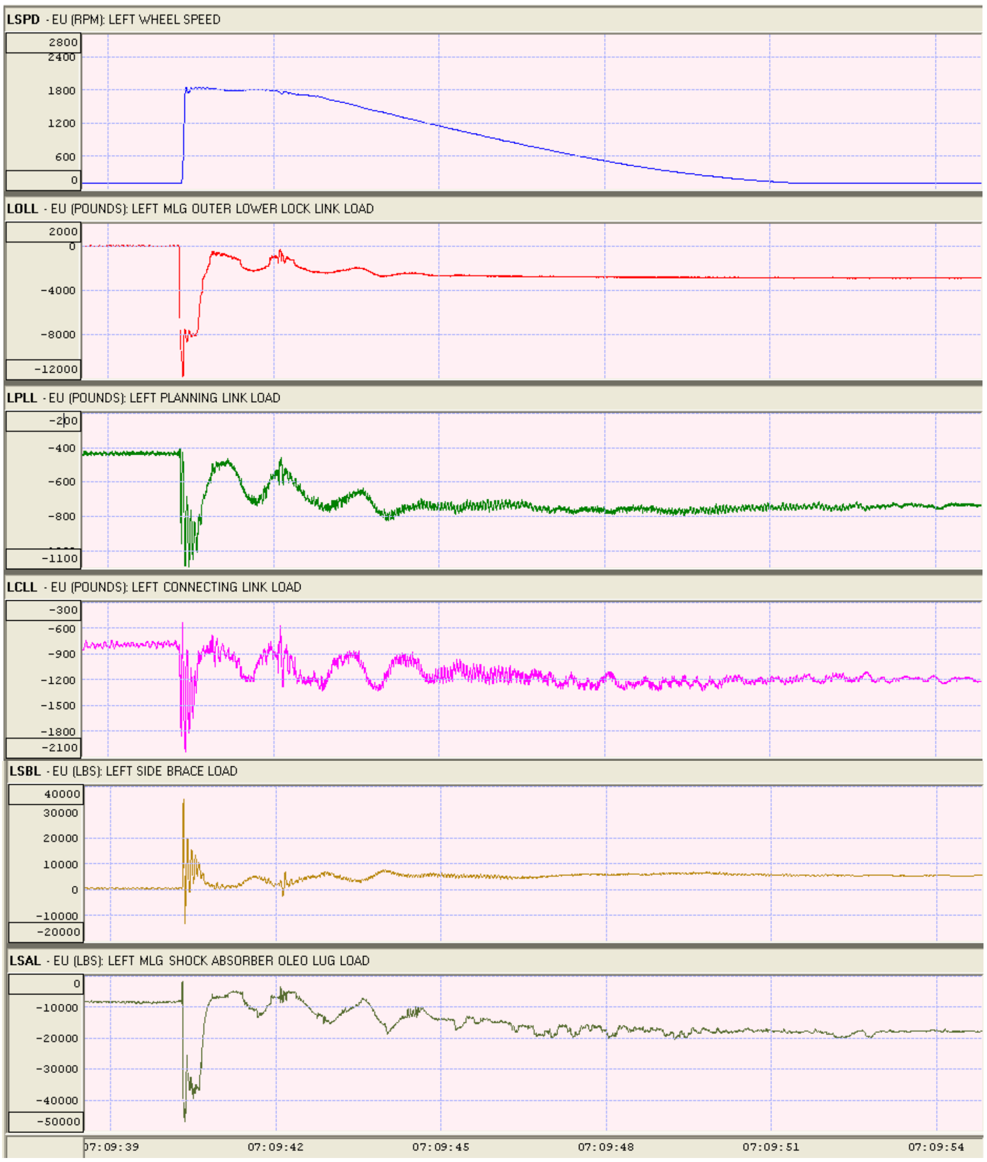
Source: Flight Test

Configuration: Prototype

Phase: Cable Arrestment

Fuel Weight: 3,600 lbs

Descent Rate: 953 fpm



Time (Local)

Figure A17. Cable Arrestment Landing (Prototype)

Aircraft: 188907

Source: Flight Test

Configuration: Baseline

Phase: Cable Overrun

Fuel Weight: 9,200 lbs

Descent Rate: 705 fpm

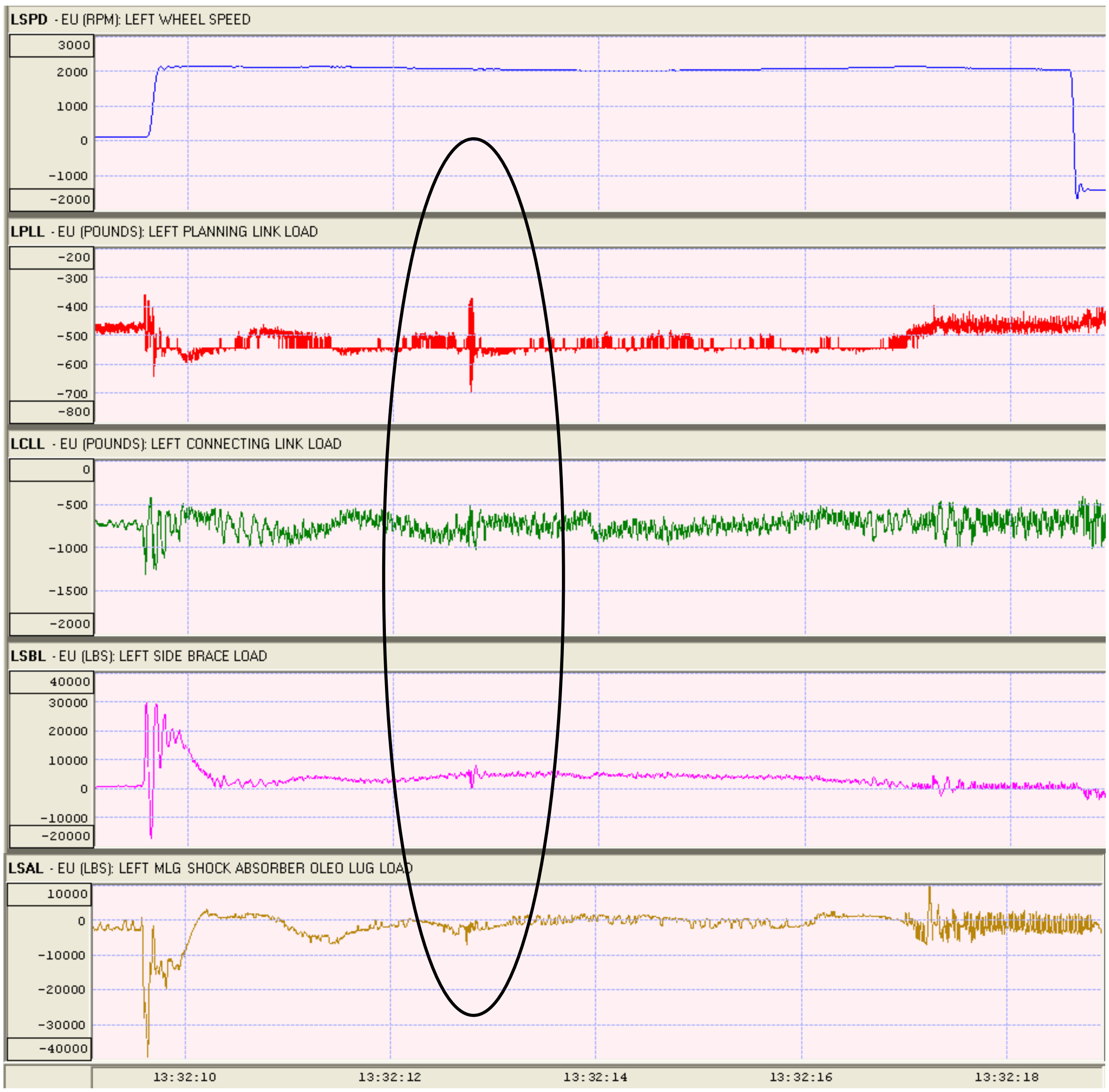


Figure A18. Cable Overrun (Baseline)

Aircraft: 188907

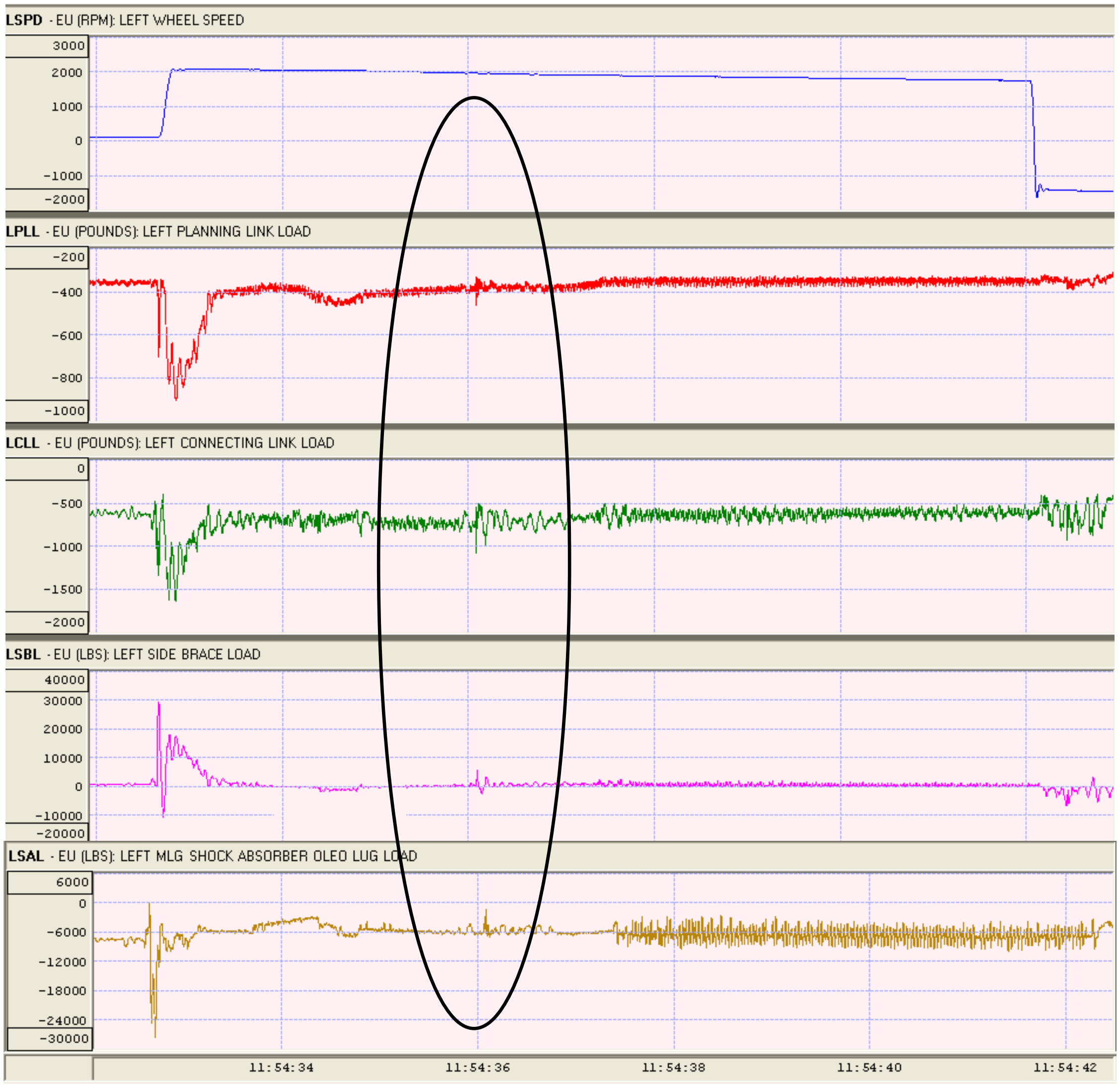
Source: Flight Test

Configuration: Prototype

Phase: Cable Overrun

Fuel Weight: 3,100 lbs

Descent Rate: 638 fpm



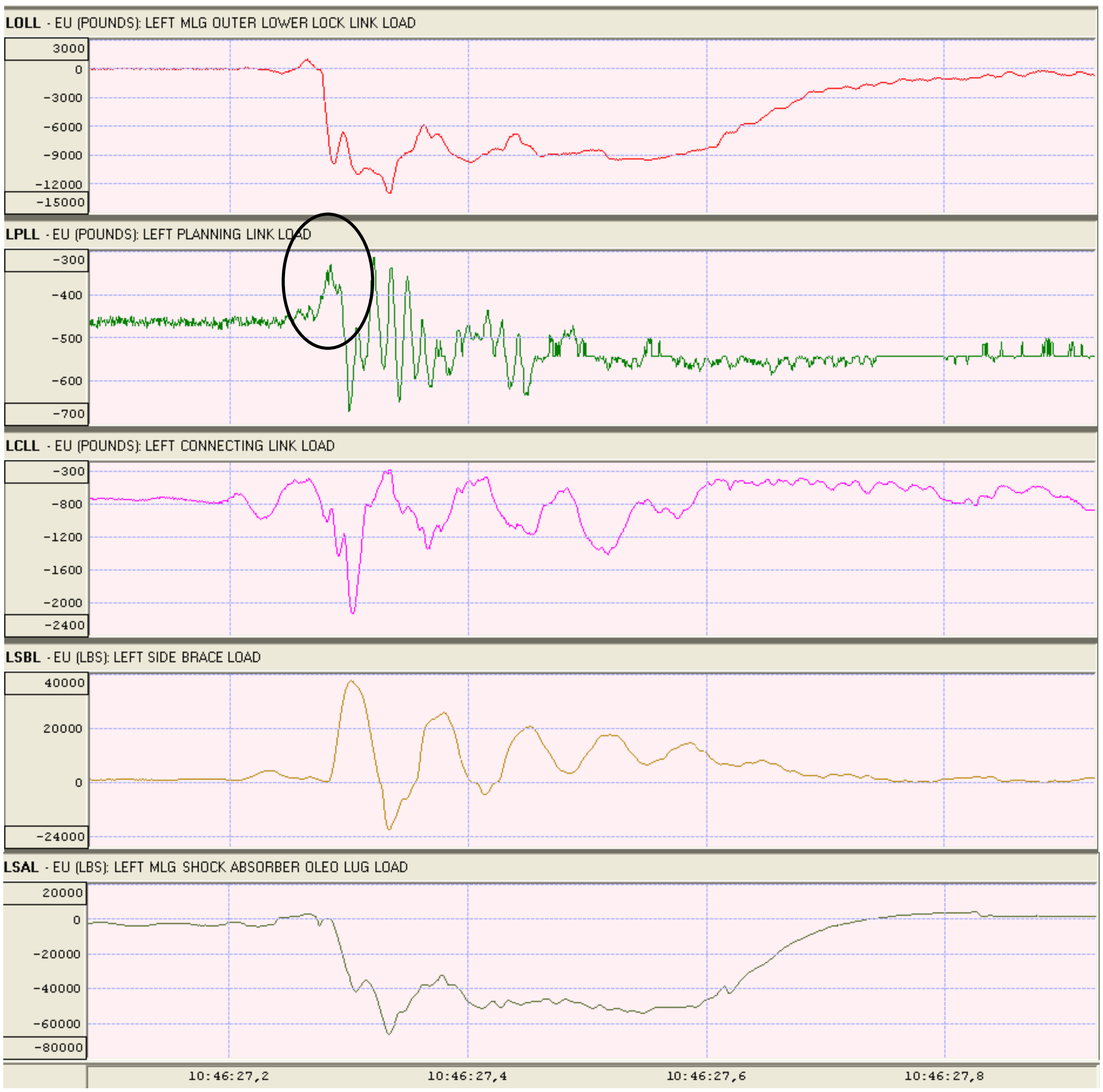
Time (Local)

Figure A19. Cable Overrun (Prototype)

Aircraft: 188907

Source: Flight Test
Configuration: Baseline
Phase: Touch Down

Fuel Weight: 10,200 lbs
Descent Rate: 818 fpm



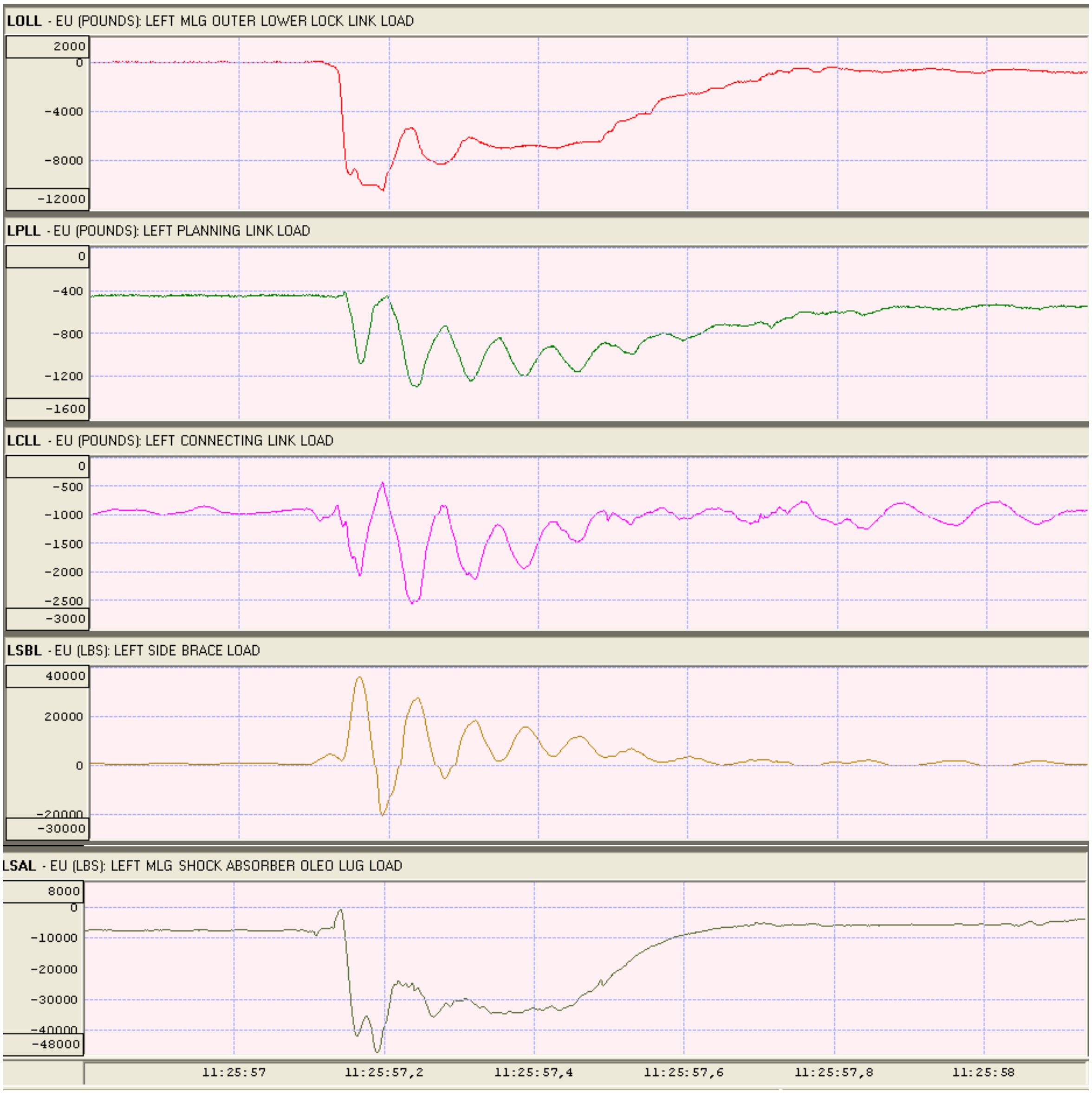
Time (Local)

Figure A20. Loads at Touch Down (Baseline)

Aircraft: 188907

Source: Flight Test
Configuration: Prototype
Phase: Touch Down

Fuel Weight: 5,800 lbs
Descent Rate: 818 fpm



Time (Local)

Figure A21. Loads at Touch Down (Prototype)

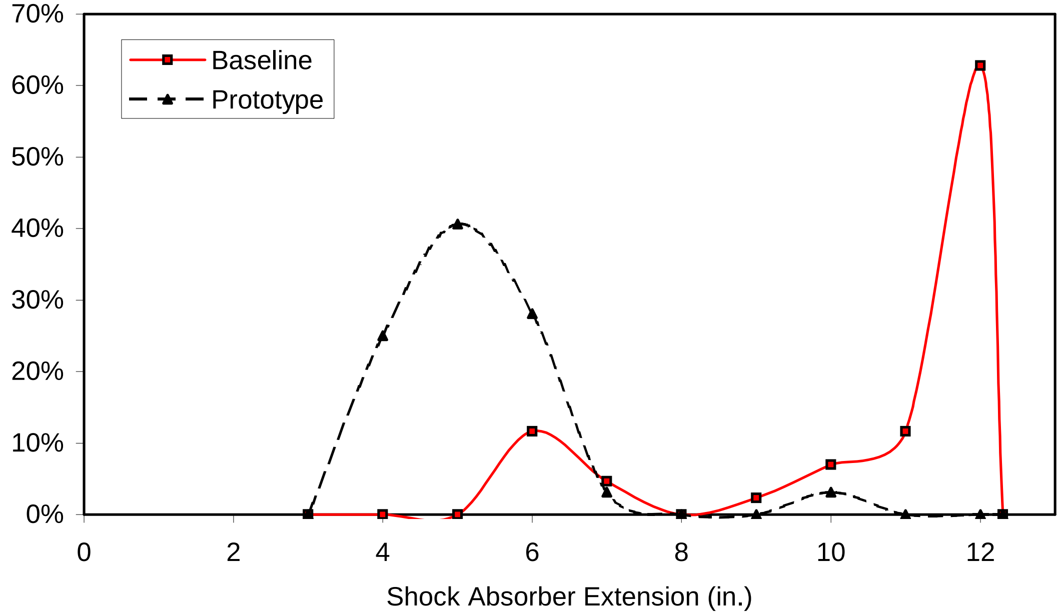


Figure A22. Shock Absorber Extension When Maximum Connecting Link Load

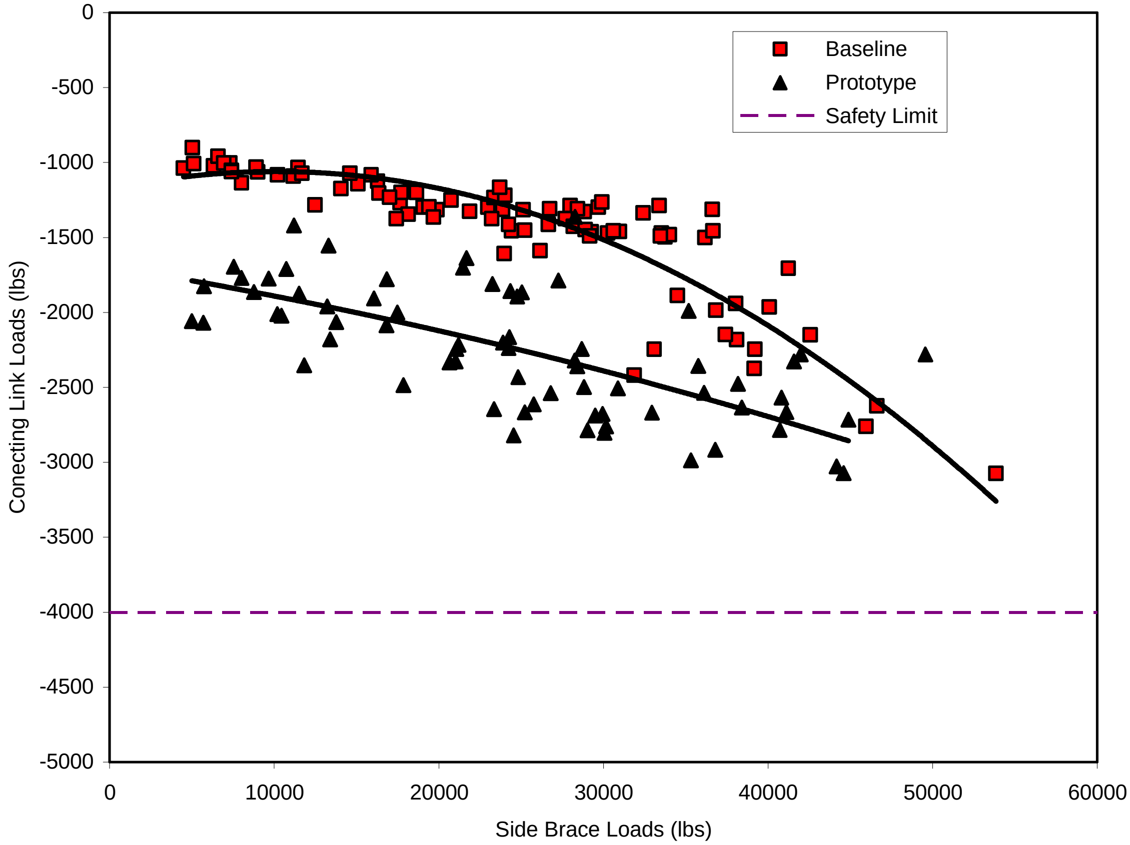


Figure A23. Connecting Link Loads vs Side Brace Loads

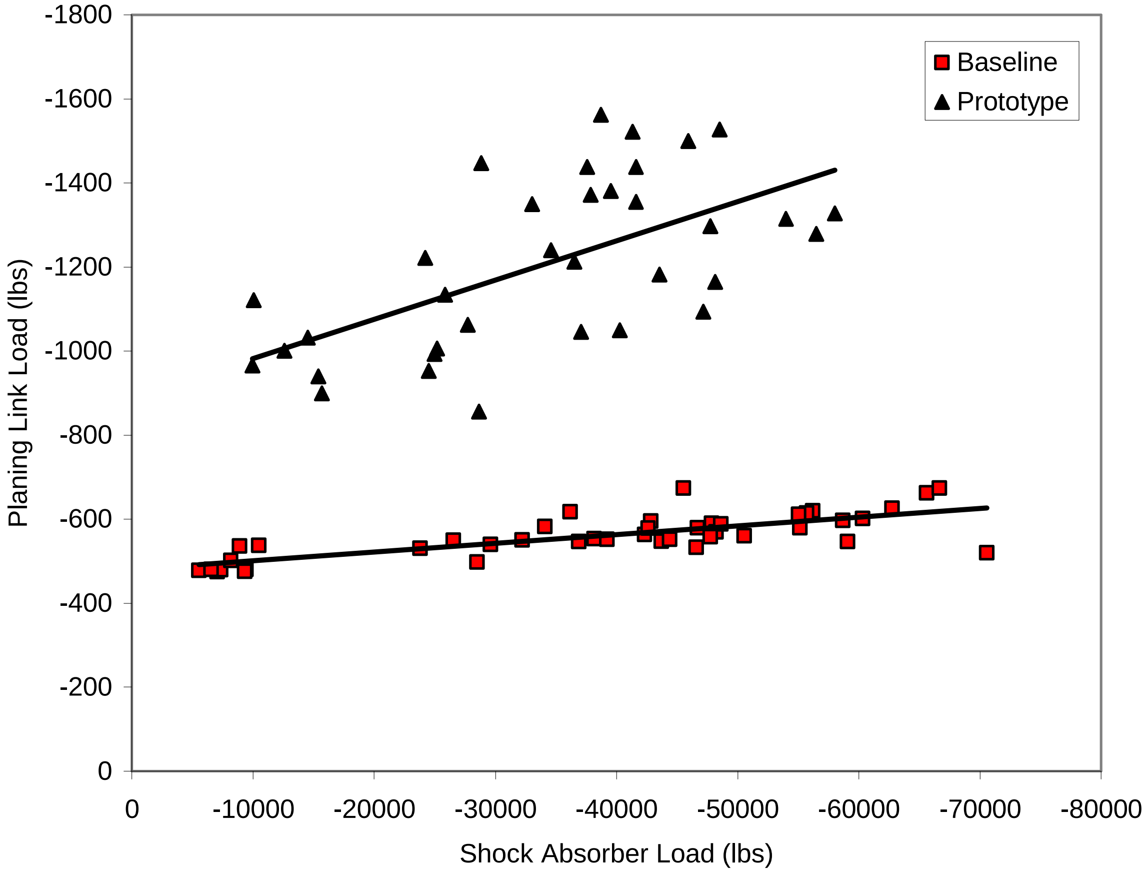


Figure A24. Planing Link Load in Function of Shock Absorber Load

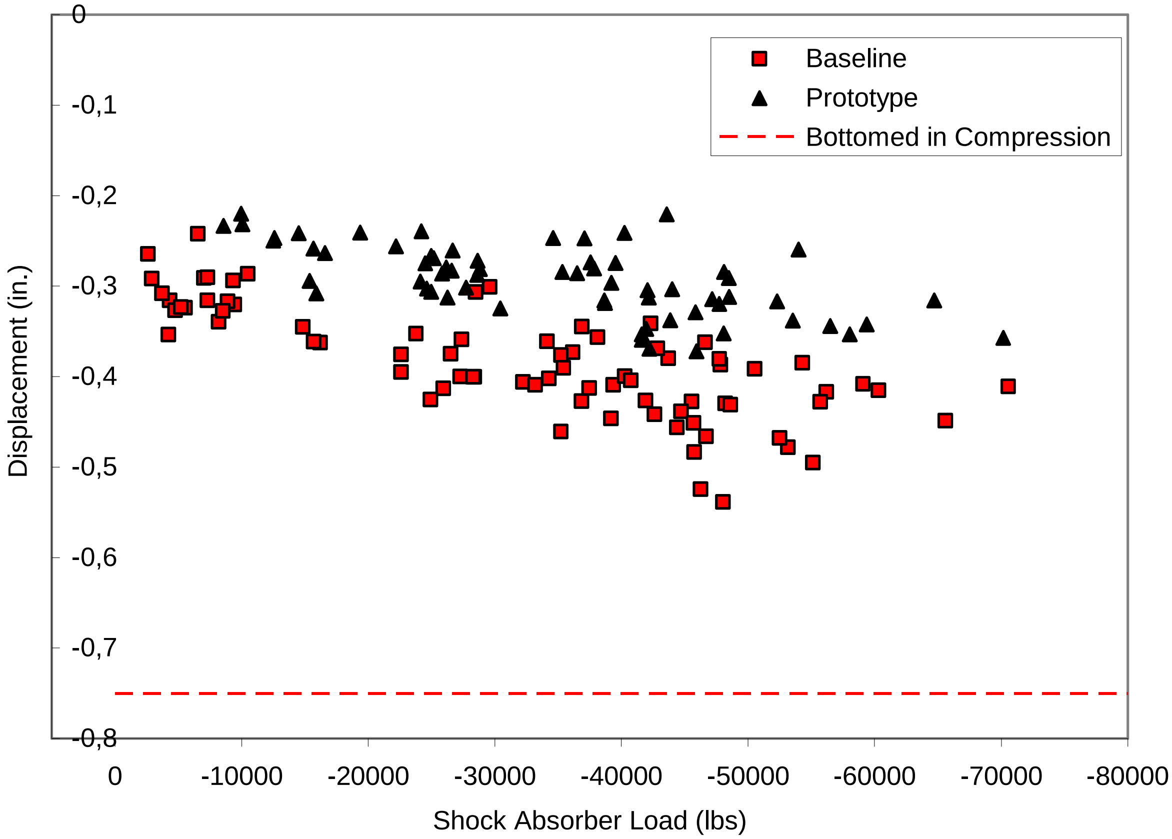


Figure A25. Planing Link Stroke in Function of Shock Absorber Load

VITA

Mr Eric Grandmont is currently working for the Canadian Forces Aerospace Engineering Test Establishment as the Deputy Officer in Charge of Avionics and Crew Systems. During the CF188 landing gear upgrade project, he fulfilled the roles of project officer, flight test engineer and flight test control room mission commander. Mr. Grandmont graduated from the Royal Military College of Canada in 2000 with a Mechanical Engineering Degree. He then graduated from the renowned U.S. Naval Test Pilot School in 2006 as part of Class 129. He has worked on numerous CF188 projects as flight test engineer and on crew systems related projects as the senior crew systems engineer.