Helicopter Ground Stability vs. Undercarriage Geometry, A Numerical Analysis

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Shortly after the Igor Sikorsky developed the first conventional type, the helicopter was seen as the ideal aerial vehicle to operate in a seaborne environment. The helicopter’s Vertical Take-Off and Landing (VTOL) capability meant that little deck space was required to operate them from and the ability to hover was essential for search and rescue operations and resupply missions. This project is aimed at addressing the major issue with helicopter compatibility with naval operations due to undercarriage ground stability using the Eurocopter ARH Tiger as an example. Of particular concern is the generic design of most helicopters that couples a relatively narrow wheel base with a high centre of gravity (CoG) position. Through the numerical analysis of static and dynamic models this project will aim to answer the question; Will a small change in undercarriage parameters result in a major improvement to lateral stability of the helicopter both statically and whilst on a moving deck? From the results of the analysis it was determined that relatively small changes in design geometry can potentially provide significant improvements in lateral ground stability. It was found that in all cases, lateral ground stability is more sensitive to changes in CoG height. It was also found that increasing wheel track, increasing aircraft mass, and changing the stiffness of the main oleos can improve lateral ground stability. Suggestions were made as to how these changes could be implemented into the design of the ARH Tiger and other helicopters. Additionally throughout the research conducted in this project it was found that there was a distinct lack of resources relating to this topic, therefore recommendations were made as to future research topics.

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Introduction

A. Background

Shortly after the Igor Sikorsky developed the first conventional type, the helicopter was seen as the ideal aerial vehicle to operate in a seaborne environment. The helicopter’s Vertical Take-Off and Landing (VTOL) capability meant that little deck space was required to operate them from and the ability to hover was essential for search and rescue operations and resupply missions. The military has seen the benefit of these capabilities, in particular towards naval operations and has utilized helicopters in nearly every operational theatre since the end of WWII. However one major limiting factor has always restricted Seaborne helicopter operations - the lateral ground stability of the helicopter’s undercarriage on a moving deck.

An essential part in preliminary design concepts of fixed wing aircraft is the design and layout of the undercarriage to suit the size and operational requirements of the aircraft. Initially there was little focus on undercarriage design in helicopters as it was seen as an unessential component in the design due to the VTOL capability (Conway, 1958). Many modern helicopter designs still utilize skids as the operational requirements negate the need for wheeled undercarriage. However as issues such as ground resonance and dynamic rollover were better understood and as maritime flying became a major part of helicopter operations, more attention was paid to the layout and design characteristics of helicopter undercarriages (Gessow, 1967).
In modern times we now see helicopters that, from conception, have been purely designed for maritime operations (AgustaWestland AW101 ‘Merlin’, Sikorsky/Westland ‘Sea King’), and others that have been redesigned to create Naval variants (UH-60 ‘Blackhawk’ — NH-60/S-70-B ‘Seahawk’). In these instances the undercarriages have been individually designed to improve lateral ground stability on a moving deck.

As of yet there is no generic undercarriage design criteria to follow during preliminary helicopter design as there is with fixed wing aircraft. What usually occurs is undercarriage is specifically designed and tested to suit one particular helicopter for a specific set of mission parameters.

B. Project Description

This project is aimed at addressing the major issue with helicopter compatibility with naval operations due to undercarriage ground stability. Of particular concern is the generic design of most helicopters that couples a relatively narrow wheel base with a high centre of gravity (CoG) position. This general characteristic of helicopter design results in undesirable lateral tip over criterion. During maritime operations this issue is exacerbated with the rolling and pitching motions of the deck. Using the Eurocopter ARH Tiger as a case study, this project will focus on conducting a numerical study of undercarriage geometry and design parameters and the sensitivity of lateral tip over criterion to the changing of these parameters.

![Figure 1. Example Schematic of ARH Tiger showing high position of major components and CoG](image)

This project will aim to answer the question; Will a small change in undercarriage parameters result in a major improvement to lateral stability of the helicopter both statically and whilst on a moving deck?

C. Project Significance

Whilst at sea, helicopters are required to operate within carefully designated Ship Helicopter Operating Limits (SHOLs) which are defined specifically for each type of helicopter for each particular type of ship. SHOLs cover every aspect of helicopter operations at sea including stowage, lashings, movements around the hangars and deck, launch and recovery procedures, communications, and maintenance (ABR–5419). The primary factor affecting SHOLs is deck movement. Each component of the SHOL is governed primarily by deck pitch and roll limits which have been determined through thorough simulation and flight testing conducted by the Royal Australian Navy’s (RAN) Aircraft Maintenance and Flight Trials Unit (AMAFTU). Any ADF helicopter that is intended to be used in regular operations with RAN ships must first obtain SHOLs from AMAFTU for those ships they intend to operate with.

One of the most restricting elements of any SHOL is the period of time when the helicopter is sitting on the deck, unrestrained, engines running just prior to take-off and just after landing (ABR–5419). Typically it is during this period where allowable deck pitch and roll limits are at their minimum. It is these limits, during those periods of time, which ultimately define the operational capability of all seaborne helicopters. Currently there are several studies underway that are investigating ways to predict deck movement so as to provide optimal windows for launch and recovery during marginal sea conditions. However, the best models only provide a prediction within a few seconds which, is next to useless in any maritime helicopter operations. A much more desirable and reliable solution would be to improve the ground stability of the helicopter. As mentioned before, the typical design of helicopters makes them susceptible to lateral stability issues, thus they are significantly affected by the rolling motion of the deck. Therefore it can be assumed that improving the lateral ground stability of a helicopter will improve the deck motion limits in the SHOLs and overall operational capability of the seaborne helicopter.

Discussions with senior RAN pilots (LCDR B. Mackay, XO-816 Sqn.) and AMAFTU Flight Test Engineers (FTE) (LCDR B. Welling, SFTE–AMAFTU) have revealed that both the RAN and Army would consider any
improvements in the lateral ground stability and thus, the operational capability of current operational helicopters, to be significant. It was also noted that if an improvement was possible with minimal changes to current undercarriage configurations this would be a desirable outcome. Also, the ARH Tiger was chosen to be the case study as it seen as a ‘worst case scenario’ for lateral stability and currently no complete First of Class Flight Trials (FOCFT) or SHOL investigations have been conducted with the Tiger by the RAN. Therefore the results of this thesis study will not only be significant for current and future seaborne helicopter operations of the Tiger and other current designs, but also significant towards future maritime helicopter design.

D. Project Scope
Initially the required scope of the project was to investigate how changes in undercarriage configuration will affect lateral ground stability on a moving deck. But, as mentioned before, from current research and after discussions with AMAFTU Engineers and pilots, it was found that other undercarriage parameters such as Oleo stiffness, tyre pressures, and tyre friction had a significant contribution to lateral tip-over criterion on a moving deck. So therefore the current scope has been expanded to include an investigation as to how changes in some of these parameters also affect lateral stability.

These investigations will be conducted in a series of steps that will look into how changes in configuration and parameters affect static and dynamic lateral stability.

1. Literature Review:
Research how lateral ground stability is defined and what design factors affect lateral ground stability. Also research dynamic ground stability and what parameters affect lateral ground stability in dynamic cases. A review of historical design cases such as the Seahawk and Lynx, will also be conducted to see what methods were used to improve lateral ground stability. Theoretical data obtained from research will then be applied to static and dynamic models for numerical analysis.

2. Static Analysis:
This model will determine initially the static stability of the ARH Tiger in its current configuration. Then it will compare how individual changes in the configuration affect the static stability and determine the best combination of configuration changes. This will determine what dimensional changes can be made to improve the undercarriage stability and these parameters will be applied to the dynamic models.

3. Power-off Dynamic Analysis:
Initially the helicopter will be modelled as a rigid body then modelled as a suspended mass on oleo-pneumatic suspension. The simulated deck motion will be lateral rolling, heave and sway movements that represent the deck movement of a particular ship (LPA) in different sea states. The dimensional parameters that showed improvement in lateral stability in the static analysis will then be applied to both cases. The effects of changing oleo parameters will also be briefly investigated to determine what effect these changes will have to the overall stability. What also will be investigated is how the inclusion of suspension motion affects the magnitude of improvements provided by the particular undercarriage layout changes. Whilst deck pitching motions will not be modelled, the lateral tip over criterion will be determined by changing the rolling vector of the helicopter IRT the rolling axis defined by the undercarriage layout.

4. Power-on Dynamic (time permitting):
This model will finally introduce the forces associated with the thrust moments of the main rotor, tail rotor, and lateral aerodynamic drag, induced by the rolling, heaving and swaying motions of the deck. Unfortunately in the allowable time frame of this project and do the overall complexity of the power-on model this analysis was not conducted as part of this project. However it is strongly recommended that it is considered as a future research project.

The results of the suspended body, power-off dynamic model, in the original configuration, will be compared to results taken from the On-Deck Simulation results obtained by AMAFTU to confirm the validity of the models and simulation.

By applying particular changes to the undercarriage in each model, their effects on the overall lateral stability can be determined by comparing the deck limits of each case. From these results recommendations will be made as to how these changes could be implemented in current designs such as the Tiger or how they can influence future design characteristics.

II. Literature Review.

A. Case Study – Eurocopter ARH Tiger
The Tiger began as a joint French/German project with Eurocopter in the mid 1980’s to look at an armed reconnaissance helicopter to replace the ‘Gazelle’ anti-tank helicopters. Full scale development commenced in 1987 and the Tiger took its first flight in 1993 (Jane’s, 2011). The Australian Army named the ARH ‘Tiger’ as
the replacement platform for the aging fleet of Bell 206B ‘Kiowa’ observation helicopters and the UH-1H ‘Iroquois’ utility/fire support helicopters (Noller, 2003).

Typically the Army operates closely with the RAN during amphibious operations and exercises, regularly using RAN ships for transport and Forward Air Stations (FASs) for their aviation wing. For this reason all Army helicopters are certified to conduct various types of flying operations with particular RAN units. Therefore it was seen as a necessity for the ‘Tiger’ to be certified to operate with RAN amphibious support vessels whilst at sea.

There are several proposed flying operations and requirements that the Tiger is expected to carry out whilst operating with RAN vessels. These include:

- Being transported to and from operational areas and being able to embark and debark unassisted on departure and arrival
- Conduct all reconnaissance/attack/support missions required, utilising the RAN amphibious support units as FASs within the operational area
- Providing air support to amphibious landing parties, and
- Being able to remain stowed below decks for long periods and in any sea state conditions that can be traversed by the supporting ship.

Other seaborne tasks that have been proposed for the Tiger, but not necessarily essential are:

- Reconnaissance and attack missions against surface vessels during Naval operations (e.g. anti-piracy)
- Providing air cover during boarding operations
- Provide air cover for RAN fleet units outside of amphibious operations
- Assist with searching during SAR operations
  (Noller, 2003)

**B. Landing Gear Design**

Historically investigations into undercarriage design focussed primarily on the requirements of fixed wing aircraft. Most work involved tyre and strut characteristics and how to achieve desirable landing and crashlanding performance. Generic rules of thumb were developed for layout parameters that suited the typical take-off, landing, and ground stability requirements of typical fixed wing operations. They also looked into appropriate weight distribution to suit operational requirements.

Conway first noted the ideal lateral tip-over criterion for aircraft to be 55° and it is recommended to not exceed 60°. He stated that undercarriage layout should be configured to meet this parameter. However the primary reasoning behind this was to prevent roll-over during taxiing and during take-off or landing roll. However the USN adopted this criterion into the design requirements of carrier base and seaborne aircraft in the Specification SD-24J, stating that aircraft’s literal tip-over angle must not exceed 54° (Currey, 1988). Both Currey and Raymer briefly discuss this further in their texts.

Lateral tip-over criterion angle can be calculated using the following equation:

\[
\tan(\Psi) = \frac{z_{CG}}{[\text{Wheel Base}\sin(\theta)]} \tag{1}
\]

Where the \(\theta\) is the undercarriage spread angle which can be defined from:

\[
\tan(\theta) = \frac{(\text{Wheel Track}/2)}{\text{Wheel Base}} \tag{2}
\]
There are also brief mentions of helicopter undercarriage design in these texts. However, as Conway states in his text, due to the VTOL capability of helicopters the undercarriage requirements are not as essential as they are with fixed wing aircraft. Until recently this has been the main reason for the lack of investigation into generic helicopter undercarriage design. Typically designers have individually designed the undercarriage for each helicopter as per the mission requirements. One essential component of any helicopter undercarriage design is the ability to attenuate vibrations and reduce the risk of ground resonance (Conway, 1958).

Several papers looked into other factors involved in helicopter undercarriage configuration. Crist conducted an investigation into the characteristics displayed by different configurations during landings, auto-rotation landings and crashes. Rogers developed a computer program that would determine the effect on performance from different configurations.

A recent parametric study conducted by Rik Heslehurst developed a set of lateral stability design charts for a range of undercarriage configurations and CoG locations. The purpose of the charts was to highlight the sensitivity of the lateral tip-over angle and tip back angle to changes in layout geometry ratios (WT/WB vs. xCG/WB). The data obtained from the charts could be used during conceptual design phases to define the optimal undercarriage layout by expressing it as ratios between wheel track, wheel base, CoG height, and longitudinal CoG position. This would provide designers with an overall expression for optimal undercarriage geometry rather than using the highly iterative ‘trial and error’ process that is current used.

C. Related Dynamic Ground Stability Analysis

As mentioned before the preferred lateral tip-over angle for naval aircraft is less than 54°. Many helicopters struggle to meet this due to the narrow, high CoG design. For instance the Tiger has a lateral tip-over angle of 67.5°, which is far outside the USN parameter and well above the maximum recommended angle stated by Conway. Whilst the undercarriage configuration and CoG location may determine this tip-over criterion, they are not the primary factors that lead to roll-over at sea.

The modelling work conducted by Blackwell & Feik, and Noller acknowledges that lateral stability criterion of a helicopter is a considerable limiting factor in on deck stability. However it was found that it was not the primary cause of tip-over conditions. It was found that the inertial forces of the rolling helicopter coupled with the opposing rolling motion of the deck resulted in an undesirable lateral acceleration. Also the lateral displacement of the CoG (IRT earth axis system) is increased by the asymmetric deflection of the main undercarriage causing the aircraft to roll further than the deck. These factors combined would cause the helicopter to tip. It was also found that certain undercarriage configurations and properties caused to helicopter to slide and yaw about the deck in certain conditions which affected the stability and tip-over conditions.

A thesis conducted by LCDR B. Mackay into the condition of dynamic rollover investigated how the combination of poor lateral stability, rolling inertial effects, undercarriage movement, and rotor forces contributed to the condition of dynamic rollover. By using a 2D lateral model of the helicopter he found that the inertial forces, torque, and thrust associated with the turning rotors had a significant effect on the lateral ground stability of the helicopter. He developed a MATLAB script based on the 2D model which produced an output that described the condition of the helicopter. It incorporated a simple sinusoidal function that represented deck rolling motion.

D. Seaborne Operations of ADF Helicopters

Whilst at sea, helicopters are bound to operate within carefully designated Ship Helicopter Operating Limits (SHOLs) which are defined specifically for each type of helicopter for each particular type of ship. SHOLs cover every aspect of helicopter operations at sea including stowage, lashings, movements around the hangars and deck, launch and recovery procedures, communications, and maintenance (ABR–5419). The primary factor affecting SHOLs is deck movement. Each component of the SHOL is governed primarily by deck pitch and roll limits which have been determined through thorough simulation and flight testing conducted by the Royal Australian Navy’s (RAN) Aircraft Maintenance and Flight Trials Unit (AMAFTU).

To help improve the outcome of FOCFTs and to help predict SHOLs of helicopters with particular ships, Defence Science and Technology Organisation (DSTO) were assigned to develop dynamic modelling of the ship/helicopter interface. Mathematical models were developed that described the dynamic characteristics of the components that affect a helicopter’s motion on a moving deck. These models were then developed into computational code using FORTRAN (Blackwell & Feik). This coding was the basis for a DSTO developed simulation software called OnDeck. OnDeck allows AMAFTU and DSTO to develop SHOL estimates for any helicopter/ship interface prior to conducting FOCFTs. DSTO continues to develop dynamic models for particular helicopter/ship interfaces according to ADF requirements or if it is believed that certain operational procedures can be improved.

As mentioned previously the Australian Army regularly conducts amphibious operations with the RAN and also uses RAN capabilities to transport troops, aircraft, and equipment to operational theatre areas. Every helicopter type operational with the Australian Army has been tested with the fleet units that it is expected to
operate with. Therefore it is assumed that the Tiger will operate with future amphibious fleet units. In 2003, ADFA student LT B. Noller conducted a thesis that developed a dynamic model for OnDeck of the Tiger using the mathematical models developed by Blackwell and Feik.

Recently, FTEs at AMAFTU completed their first SHOLs estimate report for the ARH Tiger and LPA Class ship interface. This involved a series of detailed simulations utilising OnDeck to provide a detailed estimate of SHOLs for a varied range of on deck procedures and operations with the Tiger. Whilst the LPA ships have been decommissioned, the results from this report can be used to assist in future FOCFTs with the Tiger on future ship platforms.

Ship motion data for the RAN’s LPA class ships has been obtained from assistant project supervisor, Dr. Matt Garratt, that was used in previous UAV deck landing systems projects. Average parameters for varying sea states will be obtained from this data and implemented into the environmental model being used for the dynamic analysis of this project. Comparing the deck roll limits obtained from these models to those estimated in the above mentioned AMAFTU report, will determine the accuracy of the dynamic models developed in this project.

Further research has found that the French Navy completed FOCFTs with the Tiger on Minstral Class LHDs with extreme weather testing in May 2007; however data from these trials has not been made publicly available outside of the industry.

E. Current Design Examples

There are several cases of helicopters that have had their undercarriage redesigned as part of designing a marinised version. Of particular note are the Lynx and Blackhawk/Seahawk.

When redesigning the Lynx to develop a maritime version, Westland went from a skidded undercarriage to a nose-wheel tricycle configuration. Primarily this was done to achieve better friction on the deck and prevent slipping and sliding. Also the main undercarriage was placed wider apart and incorporated lock-out actuators that cantered the wheels outward. The cantered wheels further helped to reduce the sliding motion and the wider track reduced the lateral tip-over angle (Jane’s, 2011).

With the Seahawk the tail wheel was moved forward to just aft of the rear bulkhead of the fuselage and was made significantly more robust. Initially this would be seen to reduce lateral stability as it increases the lateral tip-over angle (discussed later). However there are several advantages to this configuration. In the case of the Seahawk a large quantity of avionics and mission specific equipment was added to the forward section of the aircraft, increasing the weight on the main wheels. Moving the tail wheel forward provides more even weight distribution and reduces bending moments experience by the fuselage. Also as heavier landings are expected at, a more robust design of the tail wheel would be needed to be withstand the higher dynamic forces and its forward position once again reduces the dynamic bending moments on the fuselage. A further benefit in this design is the reduction of yawing forces on the tail wheel which, when coupled with the increased friction due to increase vertical forces, reduces the risk of the aircraft yawing at larger deck angles. The geometry change also allows for operations using the Recovery Assist, Secure, and Traverse (RAST) system (Janes, 2011). Other changes made include changes to oleo characteristics to help improve the decreased lateral stability due to the increased lateral tip over angle.

The geometric and characteristic changes to the undercarriage configurations to both the Lynx and the Seahawk will be considered as the primary historical examples. The changes incorporated in these designs will be applied to the Tiger models in the project along with other design changes that have determined as significant from the data obtained from the project research.

III. Model Development

A. Tiger Original Configuration

Figure 4 shows the dimensions of the ARH Tiger in its original configuration. These were used for the original configuration parameters in all models of this project. All model cases used the empty weight parameters of the Tiger were the original configuration analysis. The following data is the design parameters of the Tiger for its empty weight configuration:

- Weight: 4162kg
- Long. CoG: 7.195m
- Lateral CoG: 0.002m
- Height CoG: 2.30m
- \( I_{xx} \): 4207kgm²
- \( I_{yy} \): 26712kgm²
- \( I_{zz} \): 23433kgm²
- \( I_{xy}, I_{yx} \): 161kgm²
Ixz, Ixz: 2502kgm²
Iyz, Izy: 26kgm²
(Eurocopter, 2002)

All measurements were taken from the datum reference planes. The station datum plane (for measurements along the X axis) sits 0.54m forward of the nose, the Waterline datum plane (for height measurements) is at a level at which is parallel to the ground plane at a vertical distance equal to the point at which the main undercarriage would sit when fully extended, the lateral datum plane is centreline to the aircraft’s airframe. When the X axis is parallel to the ground plane the undercarriage reference plane is pitched 2.03° forward.

For simplicity and due to the small displacement value, the lateral position of the CoG was assumed to be zero. It was also assumed that the undercarriage is fully extended with the aircraft in the empty weight condition.

When defining the lateral tip over criterion the longitudinal position of the CoG is related to the position of the main wheels and nose/tail wheel. These measurements are defined as Ma and Na respectively. In fig. 3 Na is represented as Xcg or the distance AO, and Ma is the distance OC. For a tail-wheeled aircraft, like the Tiger, these can be determined by the following:

\[ Ma = \text{CoG Long.} - \text{MW Long.} \]  
\[ Na = \text{Wheel Base} - \text{Ma} \]  

For the Tiger Ma and Na were found to be 1.459m and 6.189m respectively.

B. Static Model

For the static tip-over analysis the Tiger was assumed to be a rigid body where the affects of oleo deflection due to movement of the CoG were neglected. This would allow for a much simpler analysis of the lateral tip-over criterion and the effect of implementing undercarriage geometry changes to the design.

To be able to determine at what point the aircraft would tip required the tipping boundary to be defined. This is simply the boundary inscribed by the contact points of the undercarriage of any given aircraft. The point at which the aircraft would tip would be when the aircraft’s centre of gravity would pass over the tip-over boundary.

To be able to analyse when the CoG passes over the boundary, due to lateral roll of the aircraft, the ‘deck’ or ‘aircraft’ rolling axis can either be defined as the along the longitudinal aircraft axis or along one of the tip over boundaries. For the static analysis in this project the deck rolling axis was defined as one of the tip-over boundaries between main and tail wheel. Therefore the roll direction of the helicopter was perpendicular to the selected tip-over boundary. The Earth Axis System was used to determine when the CoG passed over the tip over boundary.

The physical tip-over angle can be found mathematically using the results for Ψ from equation 2.0.

\[ \text{Tip-over angle} = 90° - \Psi \]  

C. Environment Model

Prior to the development of a dynamic model an environmental model for sea and ship deck motions needs to be developed. Modelling real time deck motion can be a complicated process. Typical real sea motion simulations follow a profile where the wave motion is sinusoidal and wave peak height varies according to a
sinusoidal frequency related to the sea state. Simpler models either use a basic constant value sinusoidal motion of constant frequency and peak height. The way a ship reacts to the wave motion is distinctly different for each type of ship and depending on the orientation of ship heading in relation to wave heading.

There are 18 different parameters of ship motion that affects dynamic limits of a helicopter on a deck. The ship motion simulation model used by AMAFTU with OnDeck is simple sinusoidal motion for pitch and roll that considers 8 of these parameters then defines deck limitations by two parameters; pitch and roll. The OnDeck model does not consider the affects of deck heave and yawing motions.

Data has shown that considering heave, sway, yaw, and surge can adversely affect deck limits obtained from typical OnDeck simulations and a more conservative estimate of limits can be obtained. The environment model for this project will consider parameters related to heave, sway, and yaw, so this project will also investigate the inclusion of these parameters provide degraded or more conservative stability results compared to those obtained by AMAFTU. The following are the ship motion parameters that will be considered.

- Roll Attitude, rate, and acceleration
- Heave amplitude, rate, and acceleration
- Sway amplitude, rate, and acceleration
- Slew amplitude, rate and acceleration

Slew represents the horizontal motion of the ship deck from ship yawing motions and sway is the sum of slew and horizontal deck motions from rolling. The environment simulation model used in this project is based on the mathematical model developed by LCDR Mackay for use in MATLAB. The ship deck parameters are for a LPA class ship spot three flight deck, where deck height is 15m above the CoG of the ship. As this project is focusing on the lateral ground stability of the helicopter, only pure rolling motion will be modelled and simulated. This can be achieved by assuming that the wave heading is perpendicular to ship heading.

Physical ship motion data for the RAN LPA class ships was obtained through Dr. Matt Garratt (UNSW@ADFA) and was compared to data available in the AMAFTU report to create estimated values for heave and slew for different maximum roll angles. These were then related to estimated Sea State figures and used in the MATLAB simulation model. The data related to waves heading 270° approaching the right (starboard) side of the ship for an LPA class ship steaming at 20kts. This series of data was used to closely match the data used AMAFTU an LPA class ship steaming at 18kts. Ship motion values were interpolated to provide ship motion estimates for maximum roll angles not covered by the physical and AMAFTU data. It was also determined from the data that the motion periods for all sea states were approximately 10 seconds. Therefore it has been assumed that the motion periods for roll, heave, and slew in all sea states was 10 seconds to maintain simplicity. Amplitude values were also assumed to be constant and equivalent to maximum values achieved during data acquisition periods to provide worst case deck motion model. Appendix A contains detailed data for the deck motion data used in the environment model.

**D. Rigid Body Dynamic Analysis**

The purpose of developing a rigid body dynamic model of the Tiger/ship interface was to gauge whether the geometry changes that provided improvements in stability in the static model, still improved ground stability in the dynamic model. In this model the Tiger is treated a rigid body sitting on a moving deck and the effects of oleo deflection are neglected. Therefore it is assumed that the helicopter is a rigid body rotating about its CoG. Ground stability is defined by the vertical wheel reaction forces and thus deck roll limits are determined by the point where one wheel reaction force equals zero (wheel lift). Also deck roll limits are limited to the maximum recommended lateral tilt limit listed for the Tiger, by the manufacturers, of 12° (AAP7210-018-1, 2010).

A new rolling axis must be defined, because whilst on the ground the helicopter body will roll in a direction perpendicular to the tip-over boundaries as its rolling motion is constrained by the undercarriage layout. Therefore the ground roll axes are defined as two axes that run through the CoG parallel to the tip over boundaries. The rolling axis which the aircraft will roll about is dependent on the direction of deck roll. The Fig. 7 shows how these axes are defined and, like the static model, which direction the Tiger’s body will roll.

The Tiger will roll about the green axis when the deck angle is rolling to the starboard (right) and the red axis when rolling to port (left). The moment of inertia (MoI) about these axes can be determined with the following equation:
\[ I_{Oa} = I_{xx}u_x^2 + I_{yy}u_y^2 + I_{zz}u_z^2 - 2I_{xy}u_xu_y - 2I_{yz}u_yu_z - 2I_{zx}u_zu_x \] (Hibbeler, 2007)

The values \( u_x, u_y, \) and \( u_z \) are the x, y, and z components of the unit vector \( u_a \) that defines the arbitrary axis in relation to the x, y, and z axes. The red and green axis MoI's were found to be 4690kgm\(^2\) and 4788kgm\(^2\) respectively. Once again the earth axis system was used to determine the overall weight distribution, but the aircraft axis system is used to determine the vertical and horizontal reaction forces on each wheel.

A ‘while’ loop is used in MATLAB to determine the rolling moments about each axis depending on the direction of the deck roll. The reaction forces on each wheel was then calculated from these moments using the moment arms of each wheel in relation to the rolling axis. The full MATLAB script used to for the analysis of the rigid body dynamic case can be found in Appendix B.

### E. Suspended Body Dynamic Model

This dynamic model is similar to the rigid body case, however the affects of the suspension deflection are now considered. The purpose of the dynamic simulation of this model is to show how the suspension affects the dynamic ground stability and what effect it has on the improvements provided by undercarriage geometry changes. This model also allows the results from dynamic simulation of the Tiger in its original configuration, to be compared to the un-powered, unrestrained stability results obtained through OnDeck simulation by AMAFTU to confirm the validity and accuracy of the model and simulation.

Ground stability is once again measured by vertical wheel reaction forces, where deck roll limits are defined as when wheel lift occurs. However the roll angle and motions of the deck cause the main undercarriage to be asymmetrically loaded resulting in asymmetric deflection of the main oleos. This results in the aircraft angle of bank (AoB), at times, being greater than the deck roll angle. Therefore the deck motion limits are also determined by the point when the Tiger’s overall AoB exceeds 12\(^\circ\).

A body that is suspended on any suspension system rolls about an axis which runs through a defined ‘roll centre’ (Gillespie, 1992). However during the scope of the research of this project it was found that the methods of determining the roll centre related to mainly motor vehicle suspension systems such as ‘wishbone’ suspension and systems with axles. No literature was found relating to methods of calculating the roll centre for purely pneumatic or oleo-pneumatic suspension, like those in most aircraft. However it was found that an estimate for roll centre could be determined by finding the crossed centre of the suspension deflection limits. A similar method was used by Mackay in his paper. The airframe of the helicopter now rolls about the red or green axes, as defined in the previous section, but they now run through the roll centre parallel to the ground plane.

The MoI for these new red and green axes through the roll centre can be found by applying parallel axis theorem:

\[ \text{Para. } I_{Oa} = I_{Oa} + (\text{Acf. Mass} \times \text{(CoG Arm)}^2) \] (Hibbeler, 2007)

CoG Arm is the distance from the CoG height to the roll centre height. For the Tiger this was found to be 0.415m. The orientation of the green and red rolling axes, ship roll direction, aircraft roll directions and tip over boundaries in the X/Y plane are the same as for the rigid body dynamic model.

The oleo-pneumatic suspension system on the Tiger’s main wheels and tail wheel are two stage systems. Low pressure chambers dominate for suspension deflections less than 0.2073m on the main wheels, and less than 0.1745, for the tail wheel (Noller, 2003). These provide vibration attenuation and reduce dynamic loads to reduce the risk of ground resonance occurring. They also provide cushioning during typical landings. High pressure chambers dominate past these deflection limits to provide energy absorption and prevent the airframe from contacting the ground during hard landings. The high pressure chambers also engage for drop speeds above 2.44 m/s (hard landings). (Eurocopter, 2002)

Oleo parameters for standard oleos can be determined from equations dependant on internal radius, valve orifice design, compression force, drop speed, and deflection. However as the Tiger oleos have two stages the
parameter definition must be conducted for both stages. Noller defined the main and tail wheel oleo parameters as part of the model development of the Tiger in his thesis and determined the following:

For main deflection $< 0.2073m$
\[ \text{Force Oleo LP} = \frac{5.884296}{0.00069609 - (0.003019 \times \text{deflection})} \] (8)

For main deflection $> 0.2073m$
\[ \text{Force Oleo HP} = \frac{48.831343}{0.00118751 - (0.003019 \times \text{deflection})} \] (9)

For tail deflection $< 0.1745m$
\[ \text{Force Tail Oleo LP} = \frac{2.401303}{0.00037812 - (0.001924 \times \text{tail def.})} \] (10)

For tail deflection $> 0.1745m$
\[ \text{Force Tail Oleo HP} = \frac{38.345419}{0.000101127 - (0.001924 \times \text{tail def.})} \] (11)

(Noller, 2003)

Rearranging these equations can provide individual suspension deflection for a given force placed on the oleos. These are then written into MATLAB functions that are called into the main simulation function to determine the suspension heights in each iteration. Changes in tyre deflection were disregarded as only small tyre deflections occurred with the Tiger.

Aircraft AoB can be found by performing trigonometry calculations relating to the main oleo deflections. Forces and moments about the roll centres must now be calculated in relation to the aircraft AoB. Also a further moment about the rolling axes occurs due to the separation of the CoG and roll centre needs to be included into the dynamic simulation calculations. The MATLAB scripts for all functions relating to the suspended body dynamic analysis can be found in Appendix C.

The deck limit results obtained in this model, for the original configuration of the Tiger, can be compared to the AMAFTU results to confirm the model and simulation validity and accuracy. The user selects the maximum sea state prior to wheel lift occurring and then takes note of the deck roll amplitude. This can then be compared to the SHOL plot, obtained by AMAFTU for the Tiger unpowered and unrestrained, where the plot intersects the x axis (roll axis).

F. Considerations for Power-on Dynamic Analysis

While this project was not able to fully analyse the power on dynamic model in the time allocated it is important to describe what considerations need to be made in developing the power-on dynamic model and simulation for future possible projects.

The power-on dynamic model incorporates the same model parameters as the suspended body model, but includes the effects of the main and tail rotors on the dynamic ground stability. It is usually expected that the inclusion of main rotor and tail rotor effects will reduce the dynamic ground stability compared to non-powered cases (AMAFTU, 2011). AMAFTU SHOL results do confirm this, however OnDeck only models the main rotor as a gyroscopic disk and the tail rotor thrust as only that which is produced on a static deck (AMAFTU, 2011). In reality, on a moving deck, the main rotor thrust, torque, and tip path plane (TPP) are constantly changing due to inertial and aerodynamic effects induced by deck motion. Therefore the tail rotor thrust will also be constantly changing to meet the fluctuating torque demands of the main rotor.

In straight, level, un-accelerated, forward flight (SLUFF) there are three main forces that contribute to blade flapping; inertial forces, aerodynamic forces, and centrifugal force. Due to the positive pitch on the main rotor blades, required for forward flight, aerodynamic forces dominate the flapping motions of the blades with centrifugal and inertial forces providing damping (Leishman, 2006). However when on the ground, no or very little control input is given to the main rotor. Therefore aerodynamic forces have a smaller effect on blade flapping and inertial forces dominate, especially on a moving deck. This list briefly describes how particular deck motions affect blade flapping:

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Figure 9. SHOL estimates for the Tiger obtained by AMAFTU.
- Rolling
  o Inertial forces on the blade cause asymmetric flapping
  o Minimal aerodynamic affect, but it slightly worsens asymmetric flap
  o Small changes in torque

- Heaving
  o Inertial forces lead to whole disk flapping up (heave down) or down (heave up)
  o Heaving motion changes angle of attack (α) over whole disk creating aerodynamic forces similar to changing collective input.
  o Large changes in torque

- Sway
  o Inertial forces create similar asymmetric flapping to rolling motion
  o Changes relative wind vector over disk and changes position of advancing blade, leads to flap up at front or rear depending on slew direction and main rotor rotation direction.
  o Moderate changes in torque depending on slew and roll speed

(Leishman, 2006)

The thrust vector produced by the main rotor depends on the orientation of the TPP. Asymmetric flapping to the left or right tilts the TPP adding to rolling moment in that direction. The pitching moment created by the TPP tilting fore or aft can also improve stability when tilting forward or decrease ground stability when it is tilting aft. The collective effect of heaving can also greatly affect dynamic ground stability by changing the overall force on the wheels. There is also a small aerodynamic force induced on the fuselage by the thrust vector which can also have a small contribution to dynamic ground stability.

An obvious side-effect of changing the thrust vector of the main rotor is the change in torque produced. If no control input is provided to the tail rotor to counter this it can lead to yawing motions producing a rolling moment from the tail wheel. If there is control input to counter the torque then there is a coupled rolling moment produced by the tail rotor thrust and tail wheel.

IV. Results and Findings

A. Static Analysis Results

The static model analysis was used to look at how geometry changes affect lateral tip-over criterion. From the research conducted there were several undercarriage geometry configuration changes that deemed necessary to investigate. These were:

- Increasing wheel track
- Decreasing CoG height
- Decreasing Wheel Base

Initial numerical and theoretical analysis showed that it was expected that increasing wheel track and decreasing CoG height would improve lateral ground stability. It was also expected that decreasing the wheel base would degrade lateral ground stability. However changes in wheel base were still investigated to determine whether it showed improvement past a certain point. The effect of combining different configurations was also investigated.

First individual geometry changes were investigated to determine the sensitivity of lateral ground stability to these changes. Each parameter was varied in increments to a point that was deemed to be reasonable in regards to design, capability, and functionality.

- Wheel track: 2.38m to 3.38m at increments of +0.05m
- CoG Height: 2.3m to 1.8, at increments of -0.025m
- Wheel Base: 7.648m to 3.648m at increments of -0.2m

A decrease in lateral tip-over criterion angle represents an improvement in lateral stability.

Initially it can be seen that as expected both increasing wheel track and decreasing CoG height provide improvements in lateral ground stability. Also, decreasing wheel track decreased lateral ground stability. It shows, however that lateral ground stability is most sensitive to changes in CoG height. However, neither decreasing the CoG height nor increasing wheel track, to the reasonable limits defined previously, decreased the
lateral tip-over criterion angle to below the recommend 54° for naval aircraft (Currey, 1988). Increasing the wheel track by 1m though does decrease the tip-over angle to 59.9° which meets the standard for land based aircraft, 60°, defined by Conway.

The next stage of the static analysis process involved combining geometry changes to see if further improvements could be made on lateral ground stability.

The variation iterations for the results in Fig. 11 represent combined increments of each respective parameter. For example: for the combined wheel track and wheel base change, one iteration represents an increase in wheel track of 0.05m and a decrease in wheel base of 0.2m.

The results show that, as expected, combining increases in wheel track and decreases in CoG height provided the only continuous improvement. Other geometry change combinations also show improvements up to a certain point, but begin to degrade due to the exponential gradient of the wheel base changes. It also shows that combining a decrease in CoG height to 1.8m and an increase in wheel track to 3.38m results in a lateral tip-over criterion angle of 53.4° which satisfies the USN requirements defined in Currey’s text.

From these results it is clear that increasing wheel track and decreasing CoG height provided improvements in ground stability. Therefore these will be the geometry parameters that will be investigate further in the dynamic modelling.

B. Rigid Body Dynamic Analysis Results

As mentioned previously the deck roll limits for the rigid body dynamic case were deemed to be when either wheel lift occurred or when the deck roll reached the Tiger’s ground tilt limit of 12°. Therefore the simulation analysis was conducted in two parts. First it was determined what the maximum deck roll amplitude was prior to wheel lift occurring for the Tiger in its original configuration. This was found to be a roll amplitude of 9° which is equivalent to a heavy Sea State 6.

Using the 9° roll amplitude the appropriate geometry changes were applied and the lateral minimum reaction force on the main wheels was found for each change iteration implemented. These values were used to determine improvements in dynamic lateral ground stability. An increase in minimum wheel reaction force was considered an improvement in ground stability.

The second stage of the analysis involved increasing the roll amplitude for each geometry change iteration to determine whether there was any improvement in the maximum deck roll limits. If the simulation stopped due to wheel lift then the previous roll amplitude value was deemed to be the deck roll limit.

The simulation sample time was set to 30 seconds as this period of time would show if there was an unstable trend (increasing peak values) in the results. The simulation output a sinusoidal plot of wheel reaction forces which showed the right hand wheel as having the greatest fluctuation in reaction force. The MATLAB outputs for the dynamic analysis can be seen in Appendix B.

For the first stage of the analysis looked at how geometry changes affected minimum wheel reaction forces for a max deck roll angle of 9°. First the changes to CoG height and wheel track were applied individually. The change increments for each geometry feature are as follows:

- Wheel Track: 2.38m to 3.38m in increments of +0.1m
- CoG height: 2.3m to 1.8m in increments of -0.05m

The minimum wheel reaction forces for each change increment were then taken from the output plots produced by the dynamic simulation and plotted to visually display the improvement trend offered by each
geometry parameter. An increase in minimum wheel reaction forces represents an increase in lateral ground stability.

As it can be seen in Fig. 12, as with the static results, ground stability (min wheel reaction force) is more sensitive to changes in CoG height. The results show an almost linear relationship between CoG height and minimum wheel reaction force with a gradient of about 301N per 50mm decrease in CoG height. Increasing wheel track by 1m provides the best improvement but only at about 206N per 50mm increase.

Following this, the affect of combining the changes in CoG height and wheel track was investigated along with the effect of increasing the Tiger’s mass. The design of the Tiger is such that when mass is added, such as fuel and weapons, the physical height of the CoG decreases. Also the main oleos would compress under the extra weight, lowering the height of the CoG in relation to the ground plane even further. Therefore it was seen as a necessity to investigate the affect of this on ground stability.

The combined changes in wheel track and CoG height produced the best improvement in ground stability. Combining a 0.5m decrease in CoG height with a 1m increase in wheel track increases minimum reaction forces by 49% compared the best result from the individual analysis. It was also found that for about every extra 220kg of mass added, minimum wheel forces increase by about 271N.

As mentioned before the second stage of analysis involved changing the sea state data of the dynamic simulation to determine the affect of the geometry changes on the maximum deck roll limits. This was achieved by increasing the sea state condition for each configuration change until the MATLAB function stopped the simulation due to wheel lift. The previous sea state roll amplitude was then assumed to be the maximum deck roll limit for that design case. This was carried out on the individual design changes and the combined design changes.

The results show that, as with the analysis of minimum wheel reaction forces, maximum deck roll limit is more sensitive to changes in CoG height. It can be seen that the decrease of CoG height by 0.5m can increase the deck roll limit to 11° whereas the increase of wheel track by 1m can increase deck roll limits up to 12°.

The combination of decreased CoG height and increased wheel track provided the best improvement for the maximum deck roll limits. Further improvement past 12° was noted during the analysis however as the manufacturer states the maximum lateral tilt angle to be 12° (AAP7210-018-1, 2010) the maximum possible roll limit was restricted to meet this. Of significance though is the fact that an increase in mass of 1500kg increases the Tiger’s deck roll limit by 1°. This is a significant result as it shows that no physical design changes are required to improve the stability of the Tiger. The importance of this feature will be discussed later.

From the results achieved so far it is initially evident that lateral ground stability is sensitive more sensitive to changes in CoG height. This has so far been the case for the static analysis and rigid body dynamic analysis. It is therefore expected that the same will occur in the suspended body dynamic analysis.

Full results for the rigid body dynamic analysis can be found in Appendix D.

C. Suspended Body Dynamic Analysis Results

The first step as part of the suspended body dynamic analysis was to confirm the validity and accuracy of the models and dynamic simulation. As mentioned previously this is achieved by comparing the suspended body maximum deck roll limit to that estimated through unrestrained, unpowered analysis by AMAFTU.

Therefore, by changing the sea state conditions within the suspended body dynamic MATLAB function, the maximum deck roll limit was determined. This was found to be a maximum roll limit of 7° for the Tiger in its...
original configuration. Now this was compared to the results obtained by AMAFTU which are detailed in Appendix E.

The AMAFTU results show that initial SHOL estimates for the Tiger at empty weight with no cross wind, has a maximum roll limit of about 9.5°. While this is a higher than the 7° estimate for the suspended body case, it must be noted that, as mentioned in section 3.3, if yawing and heaving motions were to be considered a more conservative roll limit would be expected. The OnDeck simulation software used by AMAFTU only considers the deck rolling motions with heave, sway and yaw position. Noting that the environment simulation model in this project considers deck motions from both heaving and yawing (slew), then a lower roll limit estimate is confirmation of the expectation. It also must be noted that the ‘boxed’ estimation of the SHOL defined by AMAFTU has a maximum roll limit of 7°, matching that achieved from the simulation results in this project. It also must be noted that the initial roll limit estimate from AMAFTU analysis closely resembles that achieved in the rigid body case of 9°.

This comparison of the project roll limit results and those obtained by AMAFTU confirms the validity of the models and simulations used in this project. The accuracy of the models is deemed to be satisfactory in the author’s mind as the inclusion of heaving and yawing motions has provided a more conservative roll estimate, which was expected. The roll limit of 7° also matches the final estimated SHOL for the Tiger derived by AMAFTU shown in Appendix G.

An important comparison must be made between the initial configuration results obtained from the suspended body dynamic simulation, and the rigid body dynamic simulation. In the initial configuration the only different between the two models is the height of the rolling axes. In the suspended body case it is 0.415m lower due to the location of the estimated roll centre of the Tiger. This results in the initial deck roll limit being decreased from 9° to 7°. There are two main causes for this, first there is an additional moment created by the displacement of the roll centre from the CoG, second is the fact that aircraft AoB is amplified compared to the deck roll due to the asymmetric deflection of the main oleos. The significance of this finding will be discussed later in this paper.

The analysis of the suspended body dynamic model followed the same two stage process used in the rigid body dynamic analysis. First the minimum wheel reaction forces were analysed followed by deck roll limits. Further to the analysis conducted in the rigid body dynamic case, the suspended body analysis will also analyse the affect of the changes to the overall aircraft AoB and also briefly look into how changing oleo parameters affects ground stability results. The outputs from the suspended body dynamic simulation resembled those in for the rigid body analysis. However as the suspension deflects according to the forces on each wheel, the overall AoB on the helicopter’s airframe differs to the deck roll angle. A further two outputs were produced by the suspended body dynamic function to compare the deck roll angle to the aircraft AoB and to show the deflection behaviour of the main oleos throughout the dynamic simulation. These can be seen in Appendix E.

As with the rigid body dynamic analysis, following the initial condition analysis, the geometric changes are made to the undercarriage and the simulation is run. The minimum wheel reaction forces are obtained from the wheel reaction response plots that are produced. The minimum wheel reaction forces for each configuration case are then plotted to visually display the effects of the geometry changes.

Once again it can be seen that lateral ground stability is more sensitive to changes in CoG height with an almost linear relationship between reaction force and CoG height with a gradient of about 300N per 0.05m decrease. Whilst increasing wheel track by 1m provides the best improvement it only provides about 235N per 0.05m increase. These results are very similar to those achieved in the rigid body dynamic simulation.

As with the rigid body dynamic simulation these geometry changes were combined and analysed along with the effect of increasing aircraft mass. Additionally oleo parameters were altered to determine their affect on lateral ground stability. The oleo parameters were altered by changing the numerator value in Equation 8 to roughly represent changes in oleo internal pressure.

The combined changes results show that combining both decreasing CoG height and increasing wheel track provides the best result with a 36% improvement over the best result achieved by the individual changes. The results for increasing the aircraft mass showed a similar improvement trend as with the rigid body case. The results also showed that from the basic analysis conducted, increasing oleo pressure only provided slight
improvement in ground stability whereas decreasing the pressure degraded stability slightly. More detailed and accurate analysis of ground stability in relation to oleo parameters needs to be conducted.

Due to the asymmetric deflection of the oleos the helicopter airframe will roll further then the deck. This means that deck roll limit is now also restricted by when aircraft AoB reaches 12°. Brief analysis was also conducted on how the geometry changes affected the overall aircraft AoB. Interestingly the results of showed that aircraft AoB is more sensitive to increases in wheel track, whereas decreasing the CoG height provided little change. The affects of combining these changes, along with increasing aircraft mass and changing oleo parameters, on the aircraft AoB was also investigated.

Combining decreased CoG height and increased wheel track provided no significant improvement over the individual geometry changes for aircraft AoB. Increasing the aircraft mass slightly increased the aircraft AoB, mainly due to the increased oleo deflection from the increased weight. Increasing oleo pressure decreases aircraft AoB by about 0.5° for a deck roll amplitude of 7°.

The second stage of analysis, like the rigid body case, involved changing the sea state conditions to find out the deck roll limits for each case. In the suspended body dynamic analysis it can be seen that deck roll limits are not as sensitive to changes in CoG height as they are in the rigid body case. Decreasing CoG by 0.5m only provided an improvement in deck roll limit of 1° and increasing wheel track by 1m only improved deck roll limits by 2°.

Combining geometry changes for the suspended dynamic model provides no further improvement to lateral ground stability than what was achieved from the individual changes. Also whilst increasing mass and increasing oleo pressure provided improvement in terms of wheel reaction force, they do not provide improvement in deck roll limits.

D. Findings

The following is a list of the findings from the static and dynamic analysis conducted on the ARH Tiger ground stability.

1. Decreasing CoG height and increasing wheel track increases lateral ground stability
2. Lateral ground stability is more sensitive to changes in CoG height in both static and dynamic cases
3. Decreasing wheel base worsens lateral ground stability in the Tiger’s case
4. Increasing aircraft mass can provide improvements in ground stability
5. Changing oleo parameters could provide improvement in ground stability on the Tiger.
6. Static estimates for deck roll limits are much greater than estimated dynamic deck roll limits.
7. Rigid Body dynamic analysis can be used to provide estimated improvement factors for geometry changes for suspended body
8. Position of roll centre in relation to CoG has a significant effect on lateral ground stability
9. Aircraft models defined have reasonable fidelity in relation to rolling axes and position of roll centre
10. Environment simulation using basic sinusoidal motion is accurate enough to produce reasonable and comparable results
11. Aircraft AoB is more sensitive to changes in wheel track
12. Considering deck yawing and heaving motions in the environment simulation model does produce more conservative deck roll limit results.
13. The deck roll limits provided by the manufacturer for the Tiger are almost double that estimated by AMAFTU and this project.

V. Conclusions

There are several conclusions that can be made from these results. First in relation to the question asked by the project – ‘Will a small change in undercarriage parameters result in a major improvement to lateral stability of the helicopter both statically and whilst on a moving deck?’ Essentially, yes, a significant improvement can be made in lateral ground stability by making a small change in undercarriage geometry. However it is perception of the reader what is deemed to be a ‘small’ change and what is deemed to be a ‘significant’ improvement.

For example, looking at the results displayed in Fig. 15, for a decrease in CoG height of just 0.4m or for an increase in wheel track of just 0.2m, a 1° increase in deck roll limit is achieved. In relation to the overall size
and design of the helicopter, these are only small variations in geometry, and from the author’s perception the increase of 1° for deck roll limit is significant. As mentioned previously, experienced ADF operators have stated that they would also consider any improvement in deck roll limits as significant. Therefore small changes in helicopter undercarriage geometry can provide significant improvements in lateral ground stability.

The results also showed that other methods, such as increasing aircraft mass and changing oleo parameters could also provide improvements in lateral ground stability. They also showed that the position of the roll centre also has a significant effect on lateral ground stability. From the different types of analysis conducted it can also be seen that basic static analysis of the lateral tip-over criterion can provide an estimate on the affects of changing certain undercarriage parameters in dynamic cases. Also rigid body dynamic analysis can provide accurate estimates of lateral stability improvement trends for real world (suspended) cases.

From the results obtained it can be determined what helicopter undercarriage layout parameters provide the best lateral ground stability. A desirable layout would incorporate a wide wheel track, whilst maintaining a low CoG. Also positioning the main oleos in a manner so that the roll centre is closer to the CoG needs to be considered. Furthermore, having stiffer oleos would reduce aircraft roll and aid to increase overall ground stability. From an operational perspective if measures were taken to increase aircraft weight during maritime operations, dynamic lateral ground stability could be improved further.

From these results and conclusions several design and operational options are available in improving static and dynamic lateral ground stability for current helicopter designs, future helicopter designs, and maritime operations with the Tiger. These suggested methods can be found in Appendix G

VI. Recommendations

A. Best Solutions for Tiger and Current Helicopter Designs

While applying physical geometry changes to undercarriage designs may provide the best solution overall for improving stability, in reality making major modifications to a design is not ideal. Typically the process implementing small design changes can take months to years and cost millions of dollars. Manufacturers will be reluctant to make major changes to working designs if a large market for them doesn’t exist. Operators, most of the time, will not be able to justify outlaying significant costs and time to get aircraft modified, especially if it means that certain levels of operational capability will be lost.

The ideal solution for the Tigers in service in the ADF, along with other in service models, would be one that involved little or no change to the current design and was cheap to develop or add. Therefore the ideal solution would involve some of the non-design changes mentioned in the previous chapter. Already ABR 5419 stipulates that all aircraft in stowage on RAN ships need to have full fuel tanks. This is primarily to reduce risks associated with having air in the fuel tanks, but an added advantage is the increase in weight. Also, as mentioned in Appendix G oleo restraints already exist for the Tiger, therefore it can be assumed that an airworthy variant could easily developed that could be attached the same way.

Another possibility is the development of maritime oleos for the Tiger. As mentioned in Appendix G, a process is already in place for the Tiger for the replacement of the main oleos for transport. Whilst this is an option that would be more costly and time consuming than the other methods, it would not be as costly as completely redesigning the undercarriage. A final suggestion would be to change maritime operating procedures so that fuel reserve limits are increased for flight missions, or make it a requirement that helicopters always carry external fuel tanks during maritime operations. This would increase the weight of the aircraft during the recovery process after returning from flight missions.

B. Best Solutions for Future Concepts

Helicopter undercarriages have a layout and characteristics that suit each particular helicopter design, its operational and mission requirements, and airworthiness requirements. The suggested methods of improving ground stability presented in this project may not be suitable for all helicopter designs. However there are several primary objectives that should be focused on when designing maritime helicopter undercarriage:

- Having as wide as wheel track as possible
- Maintaining CoG as low as possible
- Attempt to have roll centre as close as possible to CoG
- Use oleos that have parameters that reduce aircraft roll and inertial roll during dynamic deck motions.

C. Future Research Topics

During the research for this project it was found that there was a particular lack in material relating to helicopter undercarriage design and naval aircraft undercarriage design. There was also several factors not
considered during the scope of this thesis that need to be investigated further in order to provide more detailed and concise data in relation to maritime operations of the Tiger.

1. A continuation of this project should be conducted to investigate the affects of including main rotor forces and tail rotor forces into the dynamic models of the Tiger. It should also be seen if the results are comparable to those obtained by AMAFTU.

2. A numerical analysis should be conducted into longitudinal ground stability using a similar analysis process to that used in this project. Also looking at how longitudinal motions affect lateral stability and what correlations can be made between longitudinal ground stability and lateral ground stability.

3. If possible a combined numerical analysis simulating deck rolling and pitching motions together should be conducted using the Tiger as an example to see if first a SHOL can be developed for the Tiger similar to those developed by AMAFTU. Then similar geometry changes to those in this project should be applied to the model to determine the overall affect on the entire SHOL.

4. Mathematical models need to be developed to better represent the main and tail rotors in OnDeck. Currently OnDeck only simulates the main rotor and does so by considering it as a gyroscopic disk (AMAFTU, 2011). The main rotor is a more complex system than just a gyroscopic disk and should be modelled as such. As mentioned in section 3.6 there are three main forces that act on the main rotor when it is turning; inertial, aerodynamic, and centrifugal. The dynamic motions of the deck all affect each component differently and thus change the main rotor thrust vector accordingly. A model for the tail rotor also needs to be included which considers how the tail rotor thrust is affected by the fluctuating torque of the main rotor. The rolling moments due to the main and tail rotor thrust need to be included as well.

5. An accurate method of determining the roll centres of different types of aircraft undercarriage needs to be developed. Throughout the research of this project there were no references found in relation to aircraft undercarriage roll centres. Understandably there is a wealth of information relating to methods of determining roll centres of motor vehicle suspension and from these a basic method was formed for the purpose of this project to estimate the roll centre location of the Tiger undercarriage. However a more accurate method of estimating undercarriage roll centre is needed, because, as it was shown in this project, the position of the undercarriage roll centre has a significant effect on aircraft ground stability in dynamic maritime environments.

6. A numerical analysis needs to be conducted on the effect of changing tyre parameters such as lateral and longitudinal spring stiffness, pressure, and friction coefficients, on dynamic ground stability. Blackwell and Feik already developed mathematical models for helicopter tyres in their development of a ship/helicopter interface model. However it seems that little work has been done on what the overall effect of the tyre parameters are on ground stability. Is there a significant change to ground stability modelling results if tyre parameters are included? The models and results in this project could be used for comparison as tyre parameters were disregarded in this project.

7. A proper numerical analysis needs to be conducted on the sensitivity of dynamic ground stability to oleo stiffness, damping, pressures, and other design parameters. The analysis should also look at the benefits of electromagnetically variable shocks or pressure variable oleos.

8. A numerical analysis needs to be conducted into the affect of profile drag due to fuselage design on dynamic ground stability. Looking into methods of reducing profile drag on the fuselage and the sensitivity of ground stability to the implementation of these changes.

9. Conduct research and analysis into the benefits or complexities of angled-deck or cross deck launch and recovery procedures for helicopters at sea. Determine whether they are a viable solution to improving deck stability during maritime operations.

10. Using data from research conducted by Dr. Matt Garratt (UNSW@ADFA) into automated deck landing systems to develop an automated on deck stability control system. Focussing on using control inputs to the main and tail rotors or variably controlling the properties of the undercarriage or combinations of both to improve dynamic ground stability. Also investigate the possibility of incorporating reverse main rotor pitch into the system.

11. Conduct a numerical analysis of aircraft in stowage to determine a method of finding the optimal weight for stowage considering both ground stability issues and dynamic load limits on lashings. Also analyse different lashing types and configurations as well as ways of improving lashing and stowage.

These are the recommended research topics that were determined by the author from the research and results determined throughout this project. It may be possible that there are more research topics that either to be conducted into the topic of helicopter ground stability. The more research that is conducted in the area the more data is available to operators such as the RAN, which can help to improve operational capability and deck safety for all maritime aviation operations. It also helps designers to design helicopters and fixed wing aircraft that have better maritime capabilities.
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