THE IMPLEMENTATION OF THE LANDING CRAFT, AIR CUSHION (LCAC) FULL MISSION TRAINER (FMT) LAND DYNAMICS REACTION TO TERRAIN

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ABSTRACT

The Landing Craft, Air Cushion (LCAC) vehicle is a Naval hovercraft that operates in both a sea and terrain environment. Riding on a 5 foot pressurized cushion of air contained by a skirt system, the craft performance is determined by the nature of the terrain beneath it. The LCAC Full Mission Trainer, produced by Hughes Simulation System, Inc., simulates the craft performance over undulating ground and obstructions on the ground. This paper presents how the terrain database is generated and how the craft cushion dynamics is modeled. A discussion of how the modeling of the craft cushion dynamics uses escape areas between the skirt bottom and the ground, and volumes of air within the cushion to determine airflow and cushion pressures is presented. The coefficient of friction implementation for the type of terrain is also discussed.

INTRODUCTION AND BACKGROUND

In June 1986, the Landing Craft, Air Cushion (LCAC) Full Mission Trainer (FMT) was awarded to Sperry, which after a number of mergers and acquisitions, is now part of Hughes Aircraft Company - Hughes Simulation Systems, Inc., Training and Control System Division, Flight Simulation Operation herein after referred to as Hughes. The LCAC FMT simulation is the first real-time full mission trainer for a hovercraft. The craft dynamics model was subcontracted to the ORI,Inc. who had previously developed non-real-time software and performed test analysis on the JEFF-B, a predecessor of the LCAC. ORI developed the core dynamics algorithms during the first 20 months of the program, at which Hughes became responsible for the integration, refinement, tuning, and testing of the model.

Two separate force and moment models are implemented. One for overland dynamic performance, and another for overwater dynamic performance, both of which use common models for several surface independent dynamic forces and moments. This paper addresses the overland dynamics simulation.

Description of the Craft

The LCAC, as shown in figure 1, is 88 feet long and 47 feet wide riding on a 5 foot high pressurized cushion of air when fully on cushion and is capable of speeds in excess of 50 knots. The cargo capacity of the craft is 150,000 pounds.[1] Four Lycoming TF-40B engines, two on each side, power the craft. On the port and starboard sides, the engines drive an aft mounted ducted propeller and forward mounted double entry centrifugal lift fans using transmission gearboxes and shafting . The two lift fans on each side provide airflow to the air cushion below and the rotating bow thruster above.

The LCAC vehicle has a compartmented flotation hull fabricated of welded aluminum alloy plates and beams forming water tight compartments. The skirt system components, as shown in figure 2, consist of a peripheral skirt with a spray suppressor, a longitudinal stability seal, and two lateral stability seals. The craft has a three compartment cushion defined by the stability seals. The longitudinal stability seal is suspended from attachments and runs along the craft centerline fore-to-aft. The seal goes from the aft peripheral skirt approximately 60 percent of the craft length toward the bow skirt. The longitudinal seal has a double bubble shape when inflated with strakes extending down from the lower bubble to form a blade. Restricting side-to- side movement of the cushion air, the longitudinal stability seal provides increased roll stability.[1]

The lateral stability seals are suspended similarly to the longitudinal seal and extend across the craft between the longitudinal seal at the center to the peripheral skirt at each side. The lateral seals are bag-shaped ending in cone fingers, and restrict airflow between the forward and aft chambers, providing additional pitch stability.[1]

The air for the cushion and seals is supplied by four lift fans through a set of cushion vanes. The air flows into the inner and outer bags which are around the perimeter of the craft, then through feed holes on the bottom of the inner bag into the fingers of the skirt and subsequently into the air cushion. Air for the stability seals is directed from the bag. Air escapes from the cushion under the skirt.

Model Development Background

The core of the dynamics algorithm and preliminary developmental code were realized by ORI, Inc under contract to Hughes. Hughes completed development; then modified and enhanced the model and developmental code during the intensive integration and testing phases of the project.

Interfaces to Other Simulation Systems

The LCAC FMT overland forces and moments model interfaces with several other simulation systems. A major interface is the visual system, which provides terrain contour feedback information under selected craft points. The terrain feedback points are used to define the overland dynamics skirt escape areas and the cushion volumes under the craft. The propulsion simulation system interacts with cushion dynamics by receiving the bag pressure from the dynamics and sending the airflows from the lift fan system.

The weight and balance simulation system provides the overland dynamic model with information about the craft gross weight, mass and the displacement of the craft geometric center relative to the center of gravity. The media simulation system provides the terrain type under the craft and location and size of objects on the terrain plane (derived in correlation with the visual system). The equations of motion simulation system exchanges information with the overland dynamic system. The overland forces and moments are sent to equations of motion system. The craft state including craft pitch, roll, heading, height, speed, and transformation matrices are used by the overland dynamics model.

TERRAIN

Terrain Data Needed by Dynamics

The overland dynamics model requires the height of the terrain under certain points along the craft cushion perimeter and at certain points within the cushion and along the stability seals. The model uses an even spacing algorithm under the craft cushion to compute skirt gaps and cushion volumes. The craft cushion is approximated as a volume of 80 feet by 40 feet by 5 feet.

The height of terrain data points are arrayed in a 5 by 5 matrix in the craft XY body plane, the X axis points being 20 feet apart and the Y axis points being 10 feet apart as shown in figure 3. The middle point of the array (element 3,3) is set at the geometric center of the cushion. The overland dynamics model uses the array arrangement to define the compartments of the cushion by placing the longitudinal stability seal along the aft half of the craft length and the lateral stability seals transversely across the middle of the craft, with the seals meeting at the geometric center point. The model linearly interpolates the terrain data between the points along the peripheral skirt and points of the stability seals for use in cushion volume and skirt gap calculations.

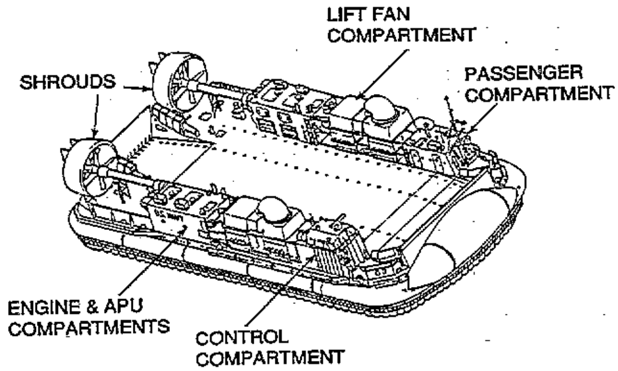
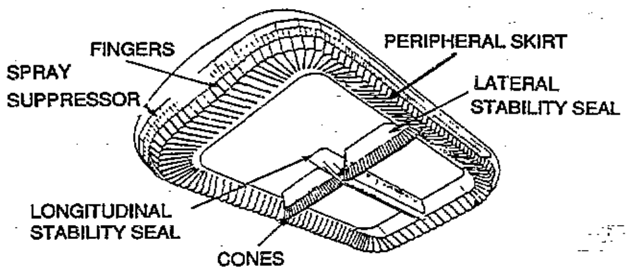
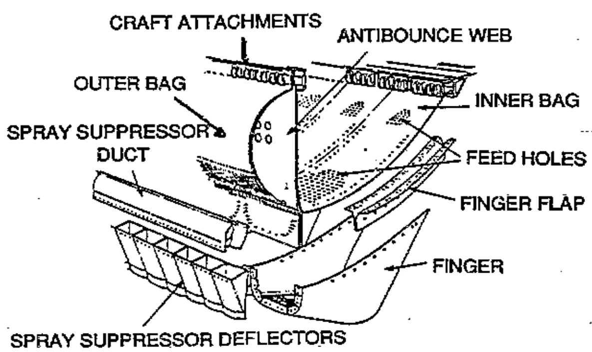


Figure 1. Landing craft, air cushion (LCAC). *Source: SEAOPS*



(a)



(b)

Figure 2. (a) LCAC peripheral skirt system and stability seals, (b) LCAC cross-sectional view of skirt bag and fingers. *Source: SEAOPS*

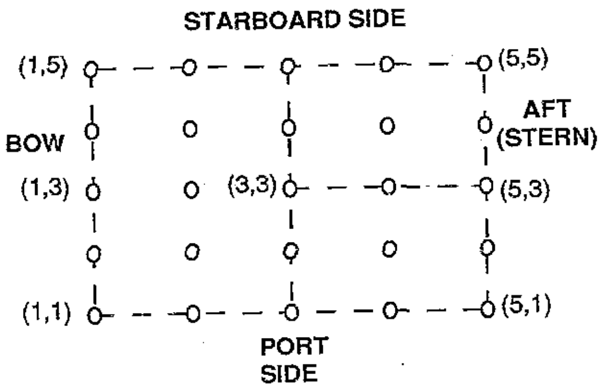


Figure 3. Height of the terrain points relative to craft XY body plane

Elevation Data

The visual system is the source of the elevation data used in the terrain feedback model. Each land polygon represented in the visual system has an equation associated with it from which the visual system computes the elevation of any point on the polygon. Because the LCAC is a slow reacting vehicle (compared with a jet), the visual system computes 5 new elevation points under the craft 50 times per second.

The visual system computes the data at 15 craft points and sends the data to a terrain feedback model which uses the points to determine the other craft points' height of terrain through a weighting function. This provides the overland dynamics with the height of the terrain at the 25 craft points.

Surface Data

The undulation of the terrain feedback data is limited by the computation time and the amount of storage space available to the visual system. The terrain planes that make up the visual database's land are isosceles right triangles which are 41 feet on a side. Since the dimensions of the cushion are 40 feet by 80 feet, it becomes critical to make the vertices of the terrain plane as close together as possible. Due to the image generator processing limitations, the closest they can be is 41 feet. The terrain is a plane between the three vertices of the triangle and is hinged from one terrain plane to the next on a given side.[3]

The visual system shades the various triangles to reflect the type of terrain and the slope of the land. The terrain type changes discretely with the craft movement from one terrain basis set to another. A coefficient of friction is used in overland dynamics in association with each particular terrain type so that the craft dynamics changes as the craft traverses from one terrain type to another. Examples of different terrain types incorporated are: concrete, sand, marshland, and grass.

Objects on the Terrain

Walls, ditches, logs, boulders, and other objects on/ in the terrain plane are features that the craft dynamics responds to and for such purpose, they are modeled as cylinders relative to the terrain plane. The cylinder, with the base on the terrain plane, is placed upright such that the cylinder is in the Down axis in the North-East-Down axes system and as such may be at an angle to the terrain plane if the terrain plane is canted. An object may be defined as a series of cylinders, as long as the cylinders do not overlap. Refer to figure 4 for an example of a special feature model. A data file with information on all the special feature cylinders in the visual database is generated and used to determine which features are within the craft influence region. The distinguishing characteristic of a special feature is whether the craft can dynamically maneuver over the feature. Trees, buildings, and other cultural features are treated as collision volumes and as such are not placed within the special feature database.[3]

For each cylinder, the location (x,y,z) of the cylinder relative to the terrain plane, the radius, the height, and a type index of the cylinder is defined. With the craft cushion defined as 40 feet wide, the special feature cylinder radius must be less than 20 feet so that the overland dynamics algorithm can modify the appropriate cushion volumes and skirt gaps.

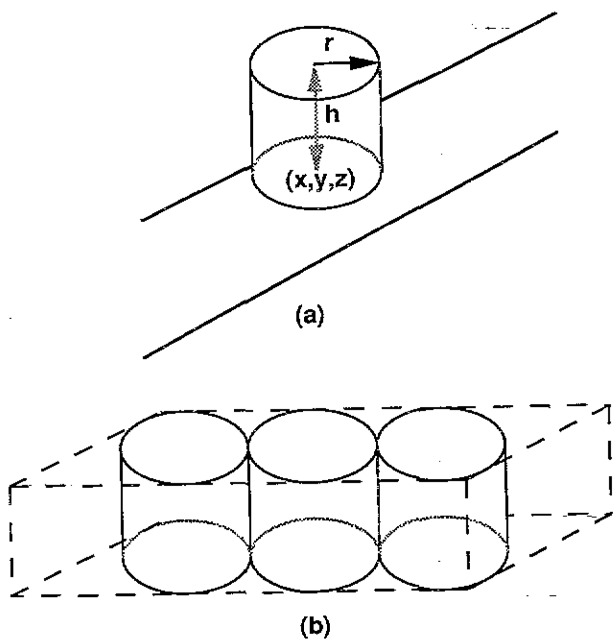


Figure 4. (a) A cylinder on a canted terrain plane, (b) A feature made of multiple cylinders

CRAFT CUSHION DYNAMICS

Overall Approach

The craft moves on a cushion of pressurized air that is supplied by lift fans and escapes under the fingers of the skirt. The actual craft experiences continuous pressure changes and the pressure within the bow bag is probably different than the pressure that is in the side inner bags or the stern bag. There may also be different pressures within a given compartment of the cushion. For developing a program that operates in real-time for training purposes, several limitations and simplifications have been adopted. Spatial pressure variations are neglected, meaning the bag pressure is the same for the bow, sides, and stern. The pressure within a given defined compartment of the cushion is the same through the whole compartment. Airflow to the stability seals is neglected. Varying air densities within the system are not modeled. The skirt bag on the perimeter of the craft is modeled with a constant inflated volume, which means that skirt bag deformation due to contact with external objects and volume changes of the bag are ignored. Reverse airflow, from the skirt bag to the lift fans, is not allowed. The model does not correctly respond to extreme airflow conditions (airflow beyond the capacity of the lift fans).

The equations to define the airflow between the lift fans, the bag, the cushion compartments, and the ambient atmosphere are implemented with steady state solutions. The airflow equations use the pressures within each of the components of the declared airflow system, to define the movement of air. With the steady state solution, the pressures and the airflows balance out. The above airflow equations account for pressure changes due to terrain pumping and craft pumping. Terrain pumping refers to the effect of the changing terrain under the craft. Craft pumping refers to the effect associated with the craft translational and angular velocities.

The continuity equations have many types of flow rate terms.[2]

$$0 = Q_{AE1} + Q_{CP1} + Q_{TP1} + Q_{1-2} + Q_{1-3} + Q_{C1} - Q_{I1} \quad \text{(cushion 1)}$$

$$0 = Q_{AE2} + Q_{CP2} + Q_{TP2} - Q_{1-2} + Q_{2-3} + Q_{C2} - Q_{I2}$$

$$0 = Q_{AE3} + Q_{CP3} + Q_{TP3} - Q_{1-3} - Q_{2-3} + Q_{C3} - Q_{I3}$$

$$0 = Q_F - Q_{I1} - Q_{I2} - Q_{I3} - Q_{CB} \quad \text{(bag)}$$

where;

Q_{AEn} = atmospheric escape flow rate, cushion n, $\frac{feet^3}{second}$ [referred to as ft^3/s] (orifice flow equation)
Q_{CPn} = craft pumping flow rate, cushion n, ft^3/s
Q_{TPn} = terrain pumping flow rate, cushion n, ft^3/s
Q_{m-n} = flow rate, cushion m to cushion n (may be positive or negative), ft^3/s (orifice flow equation)
Q_{Cn} = compressibility flow rate, cushion n, ft^3/s
Q_{In} = flow rate, bag to cushion n, ft^3/s (orifice flow equation)
Q_F = total for inflow rate to bag, ft^3/s
Q_{CB} = compressibility flow rate for bag, ft^3/s

The equations are processed by assuming that for a given equation (not including the bag equation), the solution for the given pressure while holding the intercushion flows constant is reasonably close to the true simultaneous solution.

The orifice flow equation is used to determine the airflow between a boundary of the cushion/bag.[2]

$$Q = A_E C_{OD} \sqrt{\frac{2\delta P}{\rho_a}}$$

where

Q = flow rate, ft^3/s
A_E = escape area, ft^2
C_{OD} = orifice discharge coefficient
δP = pressure differential across orifice, either (bag pressure - cushion pressure), difference between two cushion pressure, or (cushion pressure - atmospheric pressure), lb/ft^2
ρ_a = air density, $slug/ft^3$

Standard orifice flow equation assumes constant fluid density.[2]

Cushion compartment pressures are used to compute the forces and moments that the cushion causes on the craft. Skirt frictional forces and moments are computed based on the terrain type the craft is over.

The cushion escape areas are used in the airflow continuity equations and are computed from the length of the given skirt segment and the height of the terrain beneath the skirt points under consideration and the height of the skirt edge at the points. The height of the skirt edge at a point is determined by using the altitude of the geometric center, the height of the skirt, and the altitude offset associated with the displacement of the point from the geometric center as computed by means of a body to NED transformation matrix. The same formula is used to compute the intercushion areas below the stability seals by using the height of the seal rather than the height of the skirt.

A skirt gap occurs when the skirt edge does not touch the ground. A skirt deflection occurs when the skirt edge is lower than the ground such that the escape area is negative.[2]

The height used for cushion volume calculations is the same as the cushion escape area for the peripheral skirts. For the stability seals, the height is adjusted for the difference between the seal and the peripheral skirt. The height for the cushion volumes for the interior volumes (the point is not under a peripheral skirt or a stability seal) is computed the same as the cushion escape area, including the offset for skirt height. When the cushion volumes are computed, the addition and subtraction of volumes is based on the plane defined by the peripheral skirt bottom, remembering that the skirt height has been treated as a constant height initially.

The cushion escape areas are modified to account for skirt deformations which result in a loss of area. Refer to figure 5. The total escape area for a compartment of the cushion is computed from the individual skirt segments that comprise the compartment. Cushion volumes are computed by multiplying the effective average height by the cushion compartment area. The effective average height is computed from the skirt escape heights using a weighting function.

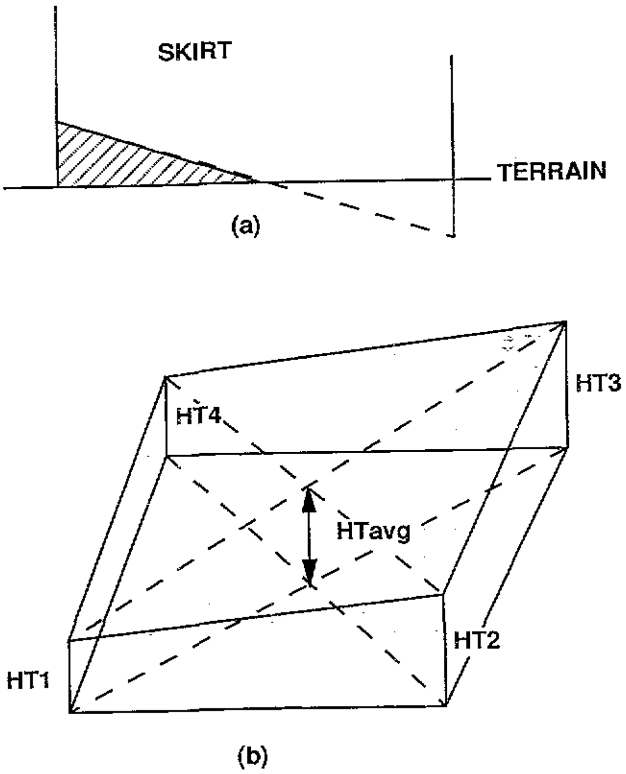


Figure 5. (a) Skirt escape area example, (b) Cushion volume example

Cushion Volumes/Areas

As with any simulation that operates in real-time, the issue of meeting requirements within the restrictions placed on the software by hardware becomes a balancing act. The host computer where the craft dynamics computations are done, is a Gould 32/ 9780 computer with land dynamics operations performed at 30 hertz, at this time. With the craft cushion treated as compartments, a compromise was needed between developing the necessary craft performance integrity and the host computer system time and memory requirements. The compromise reached was the 5 by 5 matrix of craft points. This means that the peripheral skirt is made up of 10 foot segments for the bow and stern - 4 segments each, and 20 foot segments for the port (left) and starboard (right) - 4 segments each. If processing time becomes critical, it may be necessary to reduce the amount of segments on each side, and correspondingly the number of volumes which are in each cushion compartment.

Escape areas between the cushion compartment and the ambient atmosphere is the summation of the escape areas of each segment of the peripheral skirt in the given cushion compartment. The forward cushion compartment is the summation of the eight cushion volumes defined by the 4 segments laterally across the 2 segments longitudinally. Each aft cushion compartment sums 4 cushion volumes defined by 2 segments laterally across 2 segments longitudinally.

The terrain pumping flow rate is computed for each cushion compartment using the cushion compartment area as projected onto the terrain plane and the rate of change of the average height of the terrain under the cushion compartment (including effects of objects on the terrain).

The effects of objects on the terrain (special features) are achieved by increasing or decreasing the appropriate skirt escape areas and cushion volumes. The most tedious part of the algorithm is determining which cushion compartments and escape areas have to be modified and by how much. The actual changes in volume and escape areas are handled when the continuity equations are processed since they represent an influence of cushion airflow and pressure. The volume changes modify the volumes that are used in computing the compressibility flow rate. The escape area change is reflected in the flows out of each cushion using the orifice flow equation.

The compressibility flow rate adjusts for effects associated with the changing pressure within a given cushion/ bag. The flow rate is determined assuming an adiabatic process for a perfect gas to relate density to pressure. The compressibility flow rate for each cushion compartment is computed from the rate of change of the cushion pressure for the compartment, the adjusted volume of the compartment, the ambient atmospheric pressure, and the ratio of specific heats.

Craft pumping is the apparent flow rate due to craft motion. For example, if the craft undergoes a positive roll rate, the starboard cushion pressure increases due to a decreasing volume while the port cushion pressure tends to decrease due to an increasing volume.[2] The craft pumping flow rate is determined for each cushion compartment and involves the craft pitch rate, craft roll rate, craft translational velocities in the body axis system, the location of the cushion centroid, and the cushion compartment area.

Skirt Forces and Moments

The skirt system has skirt auxiliary forces associated with it. While the lift fan system airflow momentum drag and air resistance drag associated with the craft are not discussed in this paper, they are insignificant overland due to the low speeds the craft operates at (they are included in the model since they become significant for speeds overwater). The skirt auxiliary forces are modeled two ways: frictional contact and pressure-related. Frictional contact forces are forces associated with contact through skirt deflection, flutter, turbulence, etc. Pressure related forces are forces associated with jetting airflow.

The skirt frictional force associated with contact is based on the coefficient of friction of the terrain, the craft gross weight, the deflection of the skirt, the deflection rate of change, and the velocity of the craft.

The jetting forces associated with airflow are determined from the escape area of the skirt segment under consideration and the pressure differential between the given cushion and the ambient air. If the craft had zero pitch and roll on a flat surface, the jetting force would then move the craft based on which cushion had a higher pressure: higher aft cushion pressures would move the craft forward, higher port cushion pressure would move the craft starboard (right).

CONCLUSIONS

The Landing Craft, Air Cushion - Full Mission Trainer's (LCAC-FMT) training requirements dictate the need to provide enough different terrain slopes and types to give the crew a wide experience base. The data concerning the terrain representation is visually provided by shading and shape.

Dynamically the craft needs to respond to the changes in terrain and the obstacles on the ground so that the crew learns avoidance techniques. To get the dynamic response, the overland algorithm uses the height of the terrain at given points under the craft and the information for the objects on the ground to determine the various cushion compartment escape areas and cushion volumes, which are used to eventually determine the forces and moments acting on the craft.

In the real world, the craft skirt and the terrain are continuous systems that are complex and interactive (sand will blow out from under the craft, marsh reeds will bend, trees will fall, the craft can be destructively crashed). In the trainer, the complexity has been down-scaled and the interactive nature has been simplified to accommodate the limitations previously presented.

The simulator will be an excellent training tool because it does provide positive initial training as well as refresher training to qualified crews. The representatives from the Navy who have been involved with the testing of the trainer feel the performance that the overland dynamics program has generated will support their training requirements. The crew that train on the LCAC-FMT will be better prepared to take the craft over terrain.

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