THE EVALUATION OF A FIXED-BASE HOVERCRAFT SIMULATOR

by

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Summary

This project is the culmination of the work begun by Band (Ref. 1) and continued by Fraser (Ref. 2). The simulator which they designed was evaluated using hovercraft pilots and non-pilots. A Bell Aerosystems SK-5 hovercraft was simulated in order to provide comparison with a known craft. The non-pilots participated in a lateral tracking task study, while the pilots provided subjective evaluation.

It was found that the simulator was suited for use as a design tool, but that its scope of simulation was limited by the small display size. With a larger display, it was found that the capability of the simulator would be increased.
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Notation

$\text{c}_{yfr}$ Coefficient of side force due to rudder deflection

$D_b$ Body profile drag

$D_m$ Cushion fan inlet momentum drag

$D_{sc}$ Skirt contact drag

$D_{Vx}, D_{Vy}, D_{Vz}$ Coordinates of the operator's eye location in the viewing frame

$e$ Subscript referring to equilibrium values

$f$ Frequency (Hz)

$g$ Acceleration due to gravity

$I_j$ Moment of inertia about $j$ axis

$l_{cf}$ Distance from longitudinal cg. to cushion fan

$L_v$ Scale length of the lateral gust component of artificial turbulence

$m$ Mass of the SK-5

$N$ Resultant external yawing moment

$N_b$ Body yawing moment

$N_{m}$ Yawing moment due to cushion fan inlet momentum drag

$N_{pp}$ Yawing moment due to puff port operation

$N_{pt}$ Power turbine speed (in %)

$N_r$ Yaw damping coefficient

$N_t$ Yawing moment due to tail surfaces

$N_{dr}$ Yawing moment due to rudder deflection

$p$ Roll rate

$q$ Pitch rate

$q_r$ Cushion fan flow rate

$q_s$ Slipstream dynamic pressure
r: Yaw rate
S fr: Total area of fin-rudders
T p: Propellor thrust
T px: Propellor thrust (x body axis)
T xs: Static propellor thrust (x body axis)
u: x-component of velocity of c.g. relative to atmosphere
u o: Mean true airspeed
v: y-component of velocity of c.g. relative to atmosphere
V: Air velocity relative to hovercraft
w: z-component of velocity of c.g. relative to atmosphere
x: Longitudinal body axis
X: Resultant external longitudinal force
X b: Body profile drag (x body axis)
X m: Momentum drag (x body axis)
X sc: Skirt contact drag (x body axis)
X V: Lateral coordinate in viewing frame
XVD: Lateral coordinate in displaced viewing frame
y: Lateral body axis
Y: Resultant external lateral force
Y b: Aerodynamic body side force
Y m: Cushion fan inlet momentum side force
Y pp: Side force due to puff port operation
Y sc: Skirt contact drag (y body axis)
Y t: Aerodynamic tail side force
Y V: Vertical coordinate in viewing frame
YVD: Vertical coordinate in displaced viewing frame
Y or: Side force due to rudder deflection
z: Vertical body axis
\( z_V \) Longitudinal coordinate in viewing frame
\( z_{V_D} \) Longitudinal coordinate in displaced viewing frame
\( \alpha_s \) Air slipstream angle
\( \beta \) Air sideslip angle
\( \beta_p \) Propellor blade pitch angle
\( \Delta j \) Perturbation quantity of variable \( j \)
\( \delta r \) Rudder deflection angle
\( \theta \) Pitch angle
\( \rho \) Density of air
\( \sigma_x \) Standard deviation of the random process \( x(t) \)
\( \phi \) Roll angle
\( \phi_V \) Power spectral density of the lateral gust component of artificial turbulence
\( \psi \) Yaw angle
\( \bar{x} \) Mean value of the random process \( x(t) \)
1. **INTRODUCTION**

This project is an evaluation of the work done by Band (Ref. 1) and Fraser (Ref. 2). Band decided to simulate a hovercraft travelling over a prepared pathway to see if this was feasible from a human factors point of view. With this in mind, he designed a fixed-base simulator having a small display, peripheral display units and various controls in a work station. Although the work station contained many of the controls one would find in a hovercraft, it lacked many of the indicators which are found in many hovercraft. As Band's work was a preliminary feasibility study, the simulator which he designed was simple in nature, but provided enough confidence in the idea that the project was continued. Fraser retained the same concept as Band, but worked on modifications and improvements to the hardware and software of the simulator. A new control wheel was installed, new peripheral display units were designed, and the display generating software was vastly improved. Fraser tested the simulator using an automobile lateral tracking task. This provided a good test for the peripheral display units and the simulator as a whole, but did not provide information as to how good the simulator was for hovercraft simulation. The purpose of this project was to provide that final evaluation.

One of the reasons for the construction of the simulator was that there was a general lack of hovercraft simulators in existence. A literature survey and inquiries to government and industry turned up one previous hovercraft simulator. Bell Aerosystems had simulated some hovercraft in their simulation facility, but have not simulated any hovercraft recently. A need was perceived for a versatile hovercraft simulator at relatively modest cost.

In performing an evaluation of a simulator of this type, the original reason for building the simulator must be kept in mind. It is very easy to hypothesize on how much better the simulator would be, say, if the display were larger, or if indicators were installed in the simulator. A brief chronology of this project follows, indicating the steps which were taken in the evaluation.

The initial step was a search for appropriate equations of motion for the simulation. The derivation of equations of motion for a hovercraft was beyond the scope of this project, so a survey of the literature was undertaken. In order to make the evaluation easier, it was decided to look for a set of equations of motion for an existing hovercraft with known handling characteristics. This provided a real reference case with which to compare the simulator. An attempt was made to locate a full set of equations having six degrees of freedom. Although there are such sets available, they are general in nature and are lacking the stability derivatives for any particular hovercraft. Most reports dealt with three degrees of freedom, the most common being pitch, roll and heave. The equations which were finally used were those contained in Ref. 3. These were the overland equations of the Bell Aerosystems SK-5 hovercraft having three degrees of freedom, longitudinal and lateral translation, and yaw.

The procedure for the evaluation involved two phases of testing. The first of these was the performance of subjects on a lateral tracking task. The subjects had to track down the centre of a roadway in the presence of a crosswind gust disturbance which simulated atmospheric turbulence. This
task was carried out with the hovercraft moving at constant speed, and only rudder and puff port control available. A high disturbance level was used in order to make the task challenging. The subjects who took part in the tracking task experiments had no previous experience operating hovercraft. This was judged to be a disadvantage, but for this type of experiment experienced hovercraft pilots were not available. The second phase of the testing was the subjective comments of two hovercraft pilots on the effectiveness of the simulator.

Throughout the reading of this report, it should be remembered that the simulator was designed as a research tool to be used for pilot controllability studies. The main thrust was to keep costs as low as possible, yet still retain an effective simulator.

2. THE SIMULATOR

Details of the design and construction of the simulator can be obtained in Refs. 1 and 2. A short description of the simulator will be given in this section. The simulator is shown in Figs. 1 and 2. It consists of three main parts; a work station outfitted with a display and controls, a PACE TR-48 analog computer, and a Hewlett Packard 2100A digital computer. The analog computer was used to program the equations of motion of the Bell SK-5 hovercraft, and the digital computer was used to generate the visual display which is described below. The control flow of the simulator is shown in Fig. 3. The subject sits in a seat facing an 8-inch by 10-inch CRT display. The display is a wire frame drawing of a horizon line and a roadway lined with utility poles. The poles move past the vehicle according to the velocity of the hovercraft. Two peripheral display units carry images of the utility poles through the subject's peripheral field of vision in order to enhance the forward motion cue. The controls provided in the work area are control wheel, rudder pedals, thumb switches and throttle levers. The seat is fully adjustable to provide correct eye position in relation to the display and comfort for the subject.

Because of the small size of the CRT, certain restrictions were placed on what could actually be simulated. The most important restriction was that the display was limited to ± .27 radians of yaw. The reason for this limitation was that beyond .27 radians, the vanishing point as calculated by the perspective program was off the screen. In a real life situation, if the hovercraft yawed beyond this limit then the operator would shift his gaze out of one of the side windows in order to retain his aiming point down the road.

One major and three minor changes were made to the display generating programs used by Fraser (Ref. 2). Fraser assumed that the operator's eyes were in the same position as the vehicle centre of gravity, and suggested that this simplification be used routinely. As can be seen from the location of the operator's work station in the SK-5 (Fig. 4), the operator's eye position does not coincide with the centre of gravity of the hovercraft. A study was carried out in order to determine the magnitude of the effect on the display of moving the operator's eye position away from the centre of gravity.
A sample result of this study is shown in Fig. 5. The location of the centre of gravity was assumed to lie on the longitudinal axis of the hovercraft, 20.6 feet from the bow and 4 feet above the ground level when the vehicle was on full cushion. It was assumed that when he was sitting at the work station, the operator's eyes were located 10 feet in front of and 8 feet above the centre of gravity. In Fig. 5, a comparison was made between perspective views with the operator's eye position at the work station and at the centre of gravity. In this example, the hovercraft is located at the centre of the road and has a yaw angle to the right of 0.1 radians. The display shown in heavy lines is that with the operator's eye position in the work area. As can be seen, there is a large difference between this view and the view seen if the eyes were located at the centre of gravity, which is shown by the fine lines. Because of the differences in generated displays, it was decided that it was important to retain the eye offset from the centre of gravity. For this reason, an extra transformation was incorporated into the perspective display program, which is contained in Appendix A. This was done allowing the coordinates of the operator's eye position to be entered as input parameters in order to provide flexibility in simulating different vehicles. The eye displacement from the centre of gravity is taken care of by a simple transformation in the $F_V$ frame of reference (see Fig. 6).

\[
\begin{bmatrix}
  x_{V_D} \\
  y_{V_D} \\
  z_{V_D}
\end{bmatrix} = \begin{bmatrix}
  x_V - D_{V_x} \\
  y_V - D_{V_y} \\
  z_V - D_{V_z}
\end{bmatrix}
\]

In this case, $x_V$, $y_V$ and $z_V$ are the coordinates in the viewing frame, $x_{V_D}$, $y_{V_D}$ and $z_{V_D}$ are the coordinates in the displaced viewing frame, and $D_{V_x}$, $D_{V_y}$ and $D_{V_z}$ are the coordinates of the subjects' eyes as measured from the centre of gravity in the viewing frame. An explanation of the different viewing frames can be found in Ref. 2. This change in the perspective program is the major change referred to above.

The minor changes were a direct result of complaints from the subjects who participated in the tracking task experiments. Each subject found that the display flickered several times per minute, and all felt that the flickering distracted them from performing the tracking task. Because of this, an attempt was made to remove the flicker. The refresh rate for the oscilloscope was changed from once every 40 milliseconds to once every 23 milliseconds. This aided the problem slightly but did not completely stop the flickering. The program which calculated the locations of the points in the wire frame display was modified to increase the speed with which it performed these calculations. This decreased the time between updates of information by 10 milliseconds from 45 to 35 milliseconds. This reduced some of the jerkiness in the display but it did not remove the flicker. It was finally found that due to the hardware configuration of the HP 2100A computer, it was possible for the peripheral display units to interrupt the oscilloscope. Every time this happened the display would flicker. This problem was remedied by changing the computer hardware to give the oscilloscope higher priority than the peripheral display units.
The Bell Aerosystems SK-5 hovercraft was chosen for the simulation partly by default in that these were the only equations of motion found for a particular craft which had the required degrees of freedom. The equations were obtained from Ref. 3 and were modified to suit this simulation. As presented in that report, the equations of motion were nonlinear. This would have required a large number of specialized computing components on the analog computer for the simulation of the equations. Due to the fact that this was beyond the computing capacity of the TR-48 computer, it was decided to simplify the equations in order to be able to model them.

The equations of motion were simplified by linearization about an arbitrary set of equilibrium conditions. In order to justify this step, the conditions being simulated were examined. Firstly, the situation being simulated was flight down a straight road. This meant that a set of equilibrium conditions could be picked which would be valid over the chosen test run period of three minutes. Secondly, as outlined previously, the hovercraft was limited to a maximum yaw angle of 0.27 radians from the direction of the roadway. Thus it was felt that small angle approximations could be used to linearize the equations without a large loss in accuracy. Another factor involved was the large change in coefficients due to changes in airspeed and cushion gap. It was therefore decided to limit the speed of the hovercraft to within ±10% of the equilibrium speed chosen. The derivation and linearization of the equations of motion are given in Appendix B. Geometric and inertia parameters for the SK-5 are contained in Table 1.

Once the equations had been linearized, the calculation of the coefficients was computerized in order to provide the capability to quickly change equilibrium conditions. This computer program was written in BASIC and calculated the coefficients of the equations of motion, scaled the equations for modelling on the analog computer and calculated the potentiometer settings for the analog computer. The BASIC computer program and a sample output are given in Appendix C. The accuracy of this program was checked by comparing the analog solution to a digital time solution. This latter solution was obtained using the program RKGIL in the UTIAS computer library.

The solution to a step rudder input calculated by the analog computer and RKGIL differed by less than 1% at the end of a three-minute test run. With the BASIC program, the equations of motion could be linearized about any set of equilibrium conditions having a zero yaw rate from the vehicle at rest to operation at full speed. There were two reasons for choosing BASIC as the computer language for this program. The first was that BASIC is an easy language to understand and use, and can be quickly learned by someone familiarizing himself with the simulator. Secondly, BASIC allows on-line modification of the program. This was judged to be particularly important in a research simulator. What this means is that the programmer can modify the equations of motion while sitting at a terminal and get an immediate printout of new pot settings for the analog computer. This would allow the programmer to change the configuration of the hovercraft, for example, by adding a fin to the rear of the craft, and he would be able to quickly get a subjective response to this change from the pilot in the simulator.

Once the coefficients of the equations of motion were obtained, the equations had to be set up on the analog computer. A diagram showing the
programming for the full set of linearized equations is shown in Fig. 7. This setup is for the most general case, and the equations can be programmed to take into account a steady crosswind with controls initially trimmed to keep the hovercraft flying down the centre of the road. There were four controls available to the operator: throttle, propellant blade pitch control, rudder control and puff port control. This covered most of the situations one would want to simulate.

In order to make the tracking task challenging, a disturbance had to be put into the system. To do that, the regime in which the hovercraft was operating had to be carefully examined. Because the simulation was confined to overland operation there was no need to consider wave motion as is encountered on water. The most important effects in terms of disturbance to the flight of the hovercraft were those of atmospheric turbulence. Thus the disturbance signal used was a lateral gust disturbance approximating atmospheric turbulence. The formula for the power spectrum of the disturbance input was obtained from Ref. 4. The power spectral density of the lateral gust disturbance at the vehicle centre of gravity is given by

\[ \phi_v(f) = \frac{\sigma_v^2 L_v u_0}{1 + \left( \frac{2 \pi L_v}{u_0} f \right)^2} \]

The parameters which apply to atmospheric turbulence near the surface of the Earth were obtained from Ref. 5. It was assumed that the mean true airspeed of the hovercraft was 46 feet per second. The wind was assumed to be a headwind in order for there to be no steady state crosswind, but the effect of the headwind on the ground velocity of the hovercraft was ignored. The lateral gust disturbance was put into the system as a yaw torque using a simple gain transfer function. This disturbance was equivalent to a root mean square yaw torque of 3700 ft-lb with a mean value of 100 ft-lb typically. The disturbance signal used was white noise filtered by a single pole low pass filter having a cutoff frequency of 0.8 Hz. This frequency was obtained using a true airspeed of 46 feet per second and a lateral scale length of 10 feet. The disturbance input used was essentially a simplification of the real case, but it was felt that since the SK-5 was so massive, the effect of the wind on the side velocity of the hovercraft would be very much smaller than its effect on yaw.

The preceding section describes the system which was devised for the testing of the simulator. Due to practical hardware limitations and some problems which were foreseen in the use of inexperienced subjects, the simulation had to be further simplified. These changes to the basic model are presented in the following section.

4. MODIFICATIONS TO THE SK-5 SIMULATION

The SK-5 simulation outlined above was modified for several reasons. The first of these was a lack of computing space on the TR-48 analog computer. This required a reduction in the number of amplifiers and potentiometers used in simulating the equations of motion. On examining the task to be performed, it was decided that the easiest way to reduce the number of computing components was to restrict the equilibrium conditions to flight down the centre of a straight
roadway with no constant crosswind. This meant that all of the coefficients which had the equilibrium air sideslip angle $\beta_e$ as a factor could be eliminated, as $\beta_e$ is zero in this case.

The next modification was the elimination of the throttle and propeller blade pitch controls from the simulation. One of the reasons for this was the lack of computing space. It was also felt that over a three-minute run the subject would not have to use these controls. Due to the linearization of the equations of motion, the throttle and pitch settings could only be varied over a narrow range and it was felt that the effects of these changes would not be noticeable to the subjects. Due to the inexperience of the subjects, it was felt that providing them with four controls to handle an unfamiliar vehicle would be too much of a strain, and that the removal of the two controls would simplify the task.

The final change in the equations of motion was also the result of an anticipated difficulty on the part of the subjects to control the hovercraft. For this reason the effects of the rudder and the puff ports on the motion of the vehicle were uncoupled. As presented in the equations of motion, both the rudder and the puff ports produce side force and yawing moments. In order to simplify the task for the subjects, these effects were uncoupled. The rudder control was set up so as to provide yawing moments only. It was decided to couple the two puff ports on each side of the hovercraft together to provide a sideforce, and the adverse yawing moment generated was ignored. The puff ports were controlled by one double throw switch mounted on the control wheel.

The net result of all these changes can be seen in Fig. 8. This is a diagram of the programming that was actually used for the tracking task experiments. It should be noted that the forward velocity, $U_e$, stays constant at the equilibrium speed selected for the simulation.

The other major modification to the system was a change to the way in which the disturbance signal was input to the equations of motion. Originally, bandwidth limited white noise was recorded on an Ampex SP300 tape recorder. The cutoff frequency for the white noise was 30 Hz. This signal was filtered by a single pole low pass filter having a cutoff frequency of approximately 0.8 Hz and the filtered signal was put into the system of equations as a yaw torque. Before being filtered, the signal from the tape deck was put through a bias removing circuit because of a d.c. offset imparted to the signal by the tape deck. It was found that the mean level of the disturbance input signal varied considerably from run to run, and this made proper scoring of the tracking task impossible. It was found that the three-minute record length being used was too short in comparison to the time constant of the bias removing circuit to effectively remove the d.c. At this point the tracking task experiments were already in progress, and in order to determine the strength of the disturbance signal in absolute terms, it was decided to see what the open loop yaw response of the SK-5 was, due to the disturbance signal alone. When these measurements were taken, it was found that there was no correlation between the rms level of the disturbance signal input and the rms level of the hovercraft yaw angle output. Upon examination, it was found that the reason for this was that the SK-5 itself was acting as a low pass filter with a cutoff frequency which was lower than that of the disturbance signal. The measuring circuit for the disturbance signal measured the high frequency content of that signal, but the high frequencies were filtered out by
the hovercraft. Because the high frequency content differed from one run to
the next, there was little correspondence between the rms levels of the noise
input and yaw output signals.

In order to correct the problem with the disturbance signal, the
following steps were taken. The disturbance signal was put through a bias
removing circuit and a low pass filter which had a cutoff frequency of 0.12
Hz. This cutoff frequency was determined by the transfer function of the
hovercraft relating yaw torque input to yaw angle output without the pilot
in the loop. The equilibrium conditions were a true airspeed of 46 feet per
second, a throttle setting of 95% and a propellor blade pitch angle of 12°.
This filtered signal was recorded on a Revox A77 tape recorder which had a
lower d.c. drift than the Ampex tape recorder. The tape was divided into
three-minute records, and for each record a d.c. level was measured. This
d.c. level was removed using a bias potentiometer on the analog computer, and
this time the disturbance signal was put into the system of equations as a
yaw angle having a mean square value of 0.02 radians and a mean value of zero
radians typically. This disturbance signal was an approximation to the
response of the vehicle due to turbulence, and thus was somewhat removed from
the artificial turbulence model of Ref. 4. With the new disturbance input,
proper normalization of the tracking scores was achieved.

5. TRACKING TASK EXPERIMENTS

The task chosen for this study was a straight line tracking task.
The subjects were required to track down the centre of a straight road in the
presence of atmospheric turbulence. The turbulence was modelled as a random
crosswind disturbance.

An initial decision had to be made on the parameters to be used for
the display. Because the SK-5 hovercraft is 23 feet wide, it was decided to
make the roadway 50 feet wide, allowing the centre of the hovercraft to
deviate 13.5 feet either side of the road centreline before the side of the
hovercraft reached the side of the road. The distance of the utility poles
from the road sideline was arbitrarily chosen to be 10 feet, and the poles
were made 25 feet high. The pole spacing was put at 100 feet between poles,
and only poles up to 700 feet away were displayed. The reason for choosing
these figures was that it made the display look like a real road, and thus
motion cues were easier to perceive than if the road had been set up differ­
ently.

The equilibrium conditions for the motion of the hovercraft were
selected as follows. The equilibrium airspeed of the hovercraft was nominally
chosen as 44 feet per second. This speed was selected because it was near the
midpoint of the operating region of the SK-5. It was felt that at lower
speeds the poor lateral stability of the vehicle would be too much for the
subjects to handle, while at higher speeds the response of the vehicle would
be too sensitive to control movements. In order to simplify the simulation,
any headwind effect on ground speed was ignored, so that the ground speed
was the same as the true airspeed. The steady state throttle setting was
95%, which is close to full cushion, and the propellor blade pitch was set
at 12°.
The scoring method used in this study will now be outlined. Each run consisted of a three-minute and ten-second record, the last three minutes of which were used for scoring. For each run, the mean and rms levels were recorded for the deviation of the vehicle position from the centre of the roadway, the deviation of the vehicle yaw angle from the zero position (straight ahead) and the disturbance input signal. The analog programming for the signal processing is shown in Fig. 9. The scoring method used was based on the standard deviation of the side position error $\sigma_{Ty}$. This quantity was normalized by the standard deviation of the noise signal $\sigma_n$. The standard deviations were obtained in the following way:

Consider a variable $x = \bar{x} + \Delta x$.

The mean square of $x$ can be expressed as

$$\overline{x^2} = \frac{1}{T} \int_0^T (\bar{x} + \Delta x)^2 \, dt$$

$$= \frac{1}{T} \left[ T \bar{x}^2 + 2 \bar{x} \int_0^T \Delta x \, dt + \int_0^T \Delta x^2 \, dt \right]$$

By definition the middle term is zero, therefore

$$\overline{x^2} = \bar{x}^2 + \frac{1}{T} \int_0^T \Delta x^2 \, dt$$

Now the standard deviation, $\sigma_x$, is given by

$$\sigma_x^2 = \frac{1}{T} \int_0^T \Delta x^2 \, dt$$

From the signal processing on the analog computer $\overline{x^2}$ and $\bar{x}$ were obtained. Using these, the standard deviation was easily calculated.

The four subjects chosen for the tracking task studies were all graduate students at the University of Toronto Institute for Aerospace Studies. None of the subjects had any previous experience operating hovercraft. This was judged to be a major disadvantage in a study of this type because one generally relies on the comments and performance of the subjects in order to evaluate the simulator. In actual fact, the results of the tracking task experiments alone were of little value, but when taken in combination with the comments of the experienced hovercraft operators, they provided a good indication of the value of the simulator. In order to partially overcome the problem of inexperience, aircraft pilots were sought as subjects. It was felt that subjects with flying experience, knowing the effects of turbulence and sideslip on aircraft, would find it easier to adjust to a hovercraft simulation and would have better performance than non-pilots. Of the four subjects who took part in the tracking task experiments, two were licensed private pilots. All of the subjects were licensed automobile drivers, ensuring that each had experienced the control problem of keeping a vehicle on a roadway. Initially, three of the subjects were asked to take part in the experiments.
Two of these three were the licensed pilots. The purpose of the experiment, namely to test the controllability of the SK-5 hovercraft travelling down a roadway, was explained to each subject before the tests began. Each subject was shown a front view, side view, and plan view of the hovercraft as well as the geometric and inertia parameters, in order that they would have a better understanding of the hovercraft they were flying. The location of the pilot work station in the hovercraft and its displacement from the centre of gravity of the vehicle were also shown to the subjects.

Each subject was given a chance to get used to controlling the hovercraft before the tests actually began. It took each subject between thirty and sixty minutes to become sufficiently familiar with the simulator so that the actual tests could be conducted. In the first group of tests, a low level disturbance was put in as a yaw torque. A graph for a typical run showing the disturbance input, vehicle side position and control movements is shown in Fig. 10. It was during this first set of tests that the problems with the disturbance signal were discovered. Testing was suspended until the problems could be corrected. In this period, one of the subjects had to drop out of the program because of other commitments. A fourth subject was recruited to take the place of the one who dropped out.

After the problems were rectified, a second set of tests was performed using the three remaining subjects, this time using a high level of disturbance input. The level of the noise signal was equivalent to a standard deviation of 0.13 radians in vehicle yaw angle. The subjects all had difficulty in controlling the vehicle in this case.

A plot of performance against run number for the high level test was made to see if the subjects improved with experience. This is shown in Fig. 11. Subjects 1 and 2, who had performed 20 test runs and 30 test runs respectively on the low level test, had erratic scores. Their performance reflects the difficulty they experienced in controlling the vehicle. During the task, it was not uncommon for the subjects to fly the hovercraft off the roadway and into the utility poles. Subject 3 was given twice as many runs as the others because he had not previously flown the simulator. A learning curve can be seen for this subject. His performance improved over the first ten runs, and the final thirty runs can be used for test purposes. This subject's performance was also erratic over the experiment. In order to explain the widely varying scores, it was decided to compare the standard deviation of the disturbance input for each run. The results of this are shown in Fig. 12. A general trend of increased tracking score due to increased noise level can be seen, but there is quite a variation of tracking scores at noise levels above 0.13 radians (expressed as standard deviation in vehicle yaw angle). Part of this is due to the fact that the task assigned to the subjects was difficult, and it took great effort on the part of the subjects to control the hovercraft. This erratic performance may also be due to the way in which the subjects controlled the hovercraft. A separate display, showing the same view as seen by the subjects, was used to monitor their performance. The subjects would try to control the hovercraft in a manner similar to the way in which they would control an automobile in the same situation. When a change in heading angle occurred due to turbulence, the subjects would try to damp it out. If a deviation in the side position of the vehicle was detected, then they would select a heading to return the hovercraft to the centre of the road. In some cases, the subjects overcompensated for the correction and setup oscillations with the vehicle which
were difficult to damp out. As will be seen in a comparison with the experienced hovercraft pilots, the student subjects' problems stemmed from both the task presented and their inexperience in operating this type of vehicle.

The subjects who took part in the tracking task study were asked for their subjective opinions of the simulator. The main criticism of the simulator concerned the display. They found it difficult to detect side motion due to the small field of view of the display. All subjects commented that they thought the task would be easier to perform if there were a road centreline included in the display. This provides an extra piece of information, but it was felt that if this was included in the display, the subjects would tend to try and keep the centreline in the middle of the screen rather than keeping the hovercraft in the centre of the road. One of the subjects felt that it would make the simulation more realistic if a mask was put on the CRT screen to simulate the front of the hovercraft and thus provide a better reference point. This was judged to be too difficult to do with such a small display but might well be applicable to larger displays. Interestingly, all of the subjects felt that the simulation was realistic, and each said that he could project himself into the task, that is, each could imagine that he was flying a hovercraft down a road.

6. PILOT EVALUATION OF THE SIMULATOR

Perhaps the most severe test of the simulator was its evaluation by actual hovercraft pilots. This evaluation of the simulator was assisted by two hovercraft pilots from the Air Cushion Vehicle Division of the Coast Guard Ship Safety Branch of Transport Canada. One of the pilots had logged over 1500 hours in various hovercraft and had operated them recently. The other pilot had logged 25 hours but had not operated a hovercraft in the past eight years.

The first hovercraft pilot has had operating experience in the British Hovercraft Corporation SR.N5 and SR.N6 and the Bell Aerosystems Voyageur and Viking hovercraft. He felt that the SK-5, which is essentially an SR.N5, was one of the best air cushion vehicles to simulate because its operation required a high level of pilot skill. The purpose of the simulator was explained to the pilot in advance, so that he would not have any false expectations.

The first pilot was given two tasks to perform. The first task was to track down the roadway with no wind, and the second task was to track down the roadway with the same high level disturbance as was used in the previous study.

Before the testing was started, the pilot noticed some aspects of the simulation which differed from the real case:

(1) Hovercraft are normally operated in a steady state condition with yaw angles up to 45°, whereas this simulation was limited to yaw angles of 15°. It was pointed out by the experimenter that for the purposes of the task presented, the hovercraft should not require more than 15° of yaw, and this point was agreed to by the pilot.
(2) The pilot pointed out that the puff port setup used in the simulation was not used in the actual flying of the hovercraft, that is, the two puff ports on the same side of the hovercraft were never used simultaneously. The puff ports were either used individually or in diagonally opposite pairs to generate a yawing moment. If both puff ports on one side were used simultaneously, a large rolling moment would be generated by the reduced cushion pressure on that side. Because of this inaccuracy, it was decided to provide rear puff port capability only for the simulation tested by the pilot. The puff ports were put into the equations to give a yaw moment, and the adverse side force produced was ignored. The rear puff ports were controlled by the same thumb switch as was previously used.

(3) The most serious deficiency in the simulation was the situation being simulated. The terrain over which the SK-5 hovercraft is normally operated is water, open land or marsh. The hovercraft is not operated along a pathway as narrow as a fifty foot roadway, and it is not operated at high speed over land in the presence of obstacles.

Despite the faults found by the pilot, he found that the display was realistic and he could easily project himself into the task. The pilot used a different procedure for controlling the hovercraft than the students who had participated in the tracking task studies. The pilot would first determine a heading which would take the vehicle down the centre of the roadway. This heading was maintained even though the vehicle might have drifted away from the centreline. When the hovercraft reached the side of the road, a new heading was selected which would take the vehicle back to the centre of the road. This new heading again was not altered until the vehicle reached the other side of the road. Thus the hovercraft would be directed in a zigzag course down the roadway rather than trying to maintain a position at the centre of the roadway at all times. When the pilot tried to perform the tracking task with a disturbance input, he kept running off the roadway. The pilot commented that he missed the propellor blade pitch control, as he wanted to reduce the speed of the hovercraft in order to make its handling more manageable. He also noted that on windy days, one did not operate the hovercraft on full cushion. When asked about the control "feel", the pilot thought that the rudder control was too sensitive, and that the puff ports had the right force but reacted too quickly to control movements. After the gain on the rudder pedals was decreased and a first order lag with a time constant of 1.25 seconds was put into the puff port response, the pilot thought that the controls felt "right". The pilot commented that he also missed the high level of background noise which is present in hovercraft. The pilot's overall assessment of the simulator was that it was a very good simulator, but as far as controllability was concerned, the hovercraft was being simulated in the wrong conditions.

The second pilot, although he had not operated a hovercraft in the past eight years, had operated the British Hovercraft Corporation SR.N5 before. This pilot had great difficulty in adjusting to the simulation. He could not project himself into the task, and thus ended up trying to fly the road rather than the hovercraft. The vanishing point of the display was used as his aiming point, and this allowed the hovercraft to wander off the road. In order to try and correct this, the pilot was instructed to change his aiming point to a location two thirds of the way down the road, but even then he was unable to control the hovercraft. When asked to comment, the pilot said that he found the display confusing, not knowing exactly where the vehicle was. He also
found that the display moved in the opposite direction to that which he expected in response to control movements. This situation was useful in that it showed that not everyone can adjust to the simulator. As will be seen in the next section, a change in the simulator made a large improvement in the simulation from the point of view of this pilot.

7. LARGE DISPLAY EVALUATION

The simulation evaluation performed by the hovercraft pilots was also tried using a larger display than the 8-inch by 10-inch oscilloscope. The large display consisted of a television picture of the oscilloscope display projected onto a 7-foot (diagonal) screen by an Advent Model 1000A television projector. A television camera with a 1:1.8 lens was placed where the operator's eye would be in relation to the oscilloscope and the pilots were placed 8 feet from the screen, giving a viewing angle of 20° rather than 15°. This gave a 1:2.4 total distortion in the display as seen by the pilots. The controls available to the pilots were two momentary-on double throw switches, giving partial rudder control and rear puff port control. Because of the distortion in the display, the large display evaluation was just a simple qualitative check using the comments of the hovercraft pilots. For a more thorough evaluation, the perspective program would have to be modified to take into account the display size, pilot position in relation to the screen and the magnification of the television camera.

The pilots found that the large display was much better than the small one. They found that it was easier to visualize the large display as being the outside world, and therefore less effort was required to control the hovercraft. The second pilot overcame his problems with display confusion, and was able to fly the hovercraft without running off the roadway.

8. CONCLUSIONS

The results of the evaluation of the simulator were mixed. Five of the six people who tried the simulation found that the display was realistic and that they could easily project themselves into the situation, yet one found the simulation confusing. For a simulator of this type to work, one must choose subjects who can easily adapt themselves to smaller outside world displays.

The results of the tracking task studies showed that all of the subjects had difficulty in controlling the vehicle. This was in agreement with the assessment of the experienced hovercraft pilot, that the conditions presented were too severe for the Bell SK-5 hovercraft. Even though they experienced difficulty, the subjects all gave the simulator a good subjective evaluation. The tracking task study has shown that the poles were placed too close to the hovercraft flight path to be easily avoided. The hovercraft simulated would require a wider roadway with utility poles farther away to be operated at high speed in high wind conditions.

The simulator was found to be good for the task for which it was designed. There are also other tasks which can be simulated quite well. These include straight line tracking tasks with or without wind for the hovercraft used in this simulation, or for other hovercraft with different handling characteristics. The simulation of atmospheric turbulence can be expanded from the
headwind case that was used in this study to a steady wind coming from any
direction relative to the hovercraft. It is also possible to change the wind
strength or direction during the simulation. The simulator is not confined to
the straight line case, for shallow curves can be programmed into the road.
The simulator does not have to be used with the pilot in the loop. Information
about the response of a hovercraft to many varied conditions can be obtained
using the simulator, giving a visual as well as a mathematical set of results.
Although the simulator was designed for hovercraft simulation, it has been used
as an automobile simulator (Ref. 2), and as a simulator for the remote manipulator
system of the NASA space shuttle (Ref. 6).

The large display was found to make a big improvement to the simulation.
The reason for this is that large outside world displays look more like the actual
scene than small ones, and the subject requires less effort to imagine that he
is in the scene. With a larger display and the proper placement of the subject,
a wider field of view can be used. This is important from the point of view
of hovercraft simulation because these vehicles are normally operated with large
yaw angles. Also, sharper curves will be able to be programmed into the roadway.
An increase in the computing capacity of the analog computer would enable non-
linearities to be handled.

The experienced hovercraft pilot noticed the lack of background noise
in the simulator. The introduction of noise and vibration into the simulator
would enhance the realism of the simulation.

In conclusion, the simulator was found to be good for the conditions
presented. If a simulator is to be used for general hovercraft simulation, it
is recommended that the larger display be incorporated.
# REFERENCES

1. **Band, D.**

2. **Fraser, A. J.**

3. **Bell Aerosystems**

4. **Reeves, P. M. et al.**

5. **Teunissen, H. W.**

6. **Reid, L. D.**

7. **Etkin, B.**
BIBLIOGRAPHY


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SIMULATOR
VIEW OF WORK STATION

FIGURE 1

SIMULATOR
COMPUTING EQUIPMENT

FIGURE 2
Simulation Control Flow

FIGURE 3
(FROM REF. 2)
PLAN VIEW, FRONT VIEW AND SIDE VIEW OF THE BELL AEROSYSTEMS SK-5 HOVERCRAFT

FIGURE 4

(FROM REF. 3)
COMPARISON OF VIEWING TRANSFORMATIONS

EYE POSITION - AT WORK STATION, HEAVY LINES
- AT CENTRE OF GRAVITY, FINE LINES

SIMULATION CONSTANTS

ROAD WIDTH 50 FT
DISTANCE FROM POLES TO ROAD SIDELINE 10 FT
DISTANCE TO FARthest POLE 700 FT
POLE SPACING 100 FT
POLE HEIGHT 25 FT
Ψ = 0.1 radian

CENTRE OF GRAVITY LOCATION ON LONGITUDINAL AXIS
- 20.6 FEET FROM BOW
- 4 FEET ABOVE GROUND

WORK STATION LOCATION ON LONGITUDINAL AXIS
- 10 FEET AHEAD OF C.G.
- 8 FEET ABOVE C.G.

FIGURE 5
Axis Transformation

FIGURE 6

(FROM REF. 2)
BELL SK-5 SIMULATION ANALOG PROGRAMMING
FIGURE 7
Three of these circuits were used for $n$, $T_y$, and $\psi$.

**FIGURE 8**

**FIGURE 9**
TIME TRACE OF TRACKING TASK PERFORMANCE

FIGURE 10
NORMALIZED TRACKING SCORE vs. RUN NUMBER

FIGURE 11

TRACKING SCORE vs. DISTURBANCE LEVEL

FIGURE 12
APPENDIX A

C***** PERSPECTIVE 23 SEP 76 INTERIM (MCTR)
C
COMMON IBUF(8), IBUFA(2000), IBUF(2000)
C
C***** SIMULATION CONSTANTS
C
WRITE(2,200)
200 FORMAT("UPDATE RATE? -")
READ(1,*) UPDAT
WRITE(2,201)
201 FORMAT("RW,WP,HP? -")
READ(1,*) RW,WP,HP
WRITE(2,202)
202 FORMAT("SP,REFXP? -")
READ(1,*) SP,REFXP
WRITE(2,203)
203 FORMAT("TYMAX,VMAX? -")
READ(1,*) TYMAX,VMAX
WRITE(2,204)
204 FORMAT("EYE CO-ORDINATES (X,Y,Z)? -")
READ(1,*) DXV,DVY,DVZ
UPDAT=UPDAT/10.
XP1=REFXP
CALL STIME(IUPDT)
CALL BUF(A(IBFA1,IBFA2)
CALL PLTIN
CALL MPIN
C
C***** SAMPLING
C
10 CALL SAMP
CALL TIME(NPASS)
CALL SREG(NPASS)
IPT=0
C
C***** SCALING
C
PHI=0.1*FLOAT(IAND(IBUF(1),177700B))/32704.
THETA=0.1*FLOAT(IAND(IBUF(2),177700B))/32704.
PSI=0.3*FLOAT(IAND(IBUF(3),177700B))/32704.
TY=TYMAX*FLOAT(IAND(IBUF(4),177700B))/32704.
TZ=36.*FLOAT(IAND(IBUF(5),177700B))/32704.
V=VMAX*FLOAT(IAND(IBUF(6),177700B))/32704.
DELT=FLOAT(NPASS)*0.01
C
C
C***** HORIZON LINE CALCULATION
C
XSI=0.
XSI=255.
YDUM1=127.-576.*THETA
YDUM2=160.*PHI
YS1=YDUM1-YDUM2
YS2=YDUM1+YDUM2
CALL POINTS(XS1,YS1,XS2,YS2,IP1,IBFA1)
C
C
C***** VANISHING POINT CALCULATION
C
XSVP=(PHI*THETA-PSI)*460.8+127.
YSVP=127.-((THETA+PHI)*PSI)+576.
C
C
C***** ROAD SIDE LINE CALCULATIONS
C
P10=-10.*PSI
T10=-100.*THETA
RY1=RY+TY
RY2=RY-TY
XS1=(P10+RY2-TZ*PHI+DVX)*460.8/(10.+DVZ)+127.
YS1=(T10+RY2+PHI+TZ+DVY)*576./((10.+DVZ)+127.
YS1=(T10+RY2+PHI+TZ+DVY)*576./((10.+DVZ)+127.
CALL POINT (XSVP,YSVP,XS1,YS1,IP1,IBFA1)
C
C
C***** CONTROL POLE CALCULATION
C
P1=-100.*PSI
T1=-100.*THETA
RY=RY+TY
RY=-RY-TY
HZ1=HZ+TZ
HZ2=HZ+TZ
P1L=(T1-WY1*PHI-HZ2+DVY)*576./((100.+DVZ)+127.
P1L=(P1-WY1-TZ+DVX)*460.8/(100.+DVZ)+127.
P3L=(T1-WY1+PHI+TZ+DVY)*576./((100.+DVZ)+127.
P3L=(T1-WY2+PHI-HZ2+DVY)*576./((100.+DVZ)+127.
P3L=(P1-WY2-TZ+DVX)*460.8/(100.+DVZ)+127.
P3L=(T1-WY2+PHI+TZ+DVY)*576./((100.+DVZ)+127.
C ****POLE DISTRIBUTION

XP=XP1
IPASL=0
IPASR=0

80 CONTINUE
AK=(XP-100.)/XP
XS1=AK*(XSVP-PBLX)+PBLX
YS1=AK*(YSVP-PBLY)+PBLY
XS2=XS1
YS2=AK*(YSVP-PTRY)+PTRY
IF(IPASL)30,30,45
30 IF(-172.-XS1) 40,40,32
32 IF(XS1+2359.) 40,40,34
34 IPASL=1
XS2=(-20.50*XS1-3519.94)/e513.82-XS1)
NDAL=-1680.*+3208.6*ATAN(XSP/9.)
GO TO 45
40 NDAL=1750
45 CONTINUE
CALL POINT (XS2,YS2,XS1,YS1,IPT,IBFA1)
XS1=AK*(XSVP-PBRX)+PBRX
YS1=AK*(YSVP-PBRY)+PBRY
XS2=XS1
YS2=AK*(YSVP-PTRY)+PTRY
IF(IPASR)50,50,65
50 IF(XS1-426.) 60,60,52
52 IF(2613.-XS1) 60,60,54
54 IPASR=1
XS2=(-8727.7+20.5*XSP)/(259.8+XSP)
NDAR=-1680.*+3208.6*ATAN(XSP/9.)
GO TO 65
60 NDAR=1750
65 CONTINUE
CALL POINT (XS2,YS2,XS1,YS1,IPT,IBFA1)
XP=XP-SP
IF(XP)85,85,80
85 CONTINUE
86 XP1=XP1-V*DELT
IF(XP1-(REFXP-SP))90,90,95
90 XP1=XP1+SP
95 IF(XP1-(REFXP+SP))100,100,97
97 XP1=XP1-SP
100 IBFD=IBFA1
IBFA1=IBFA2
IBFA2=IBFD
CALL PTIME
CALL PLOT (IPT,IBFA2)
ITL=1
ITR=-1
CALL MCNTR (ITL,ITR,NDAL,NDAR)
GO TO 10
END
APPENDIX B

1. Derivation of the Equations of Motion of the Bell SK-5

The linearized equations of motion of the Bell SK-5 were developed from the three degree-of-freedom set (longitudinal force, lateral force and yaw torque equations) presented in Ref. 3.

The aerodynamic equations of motion in body axes (Ref. 6) are,

\[ x - mg \sin \theta = m(\dot{u} + qw - rv) \]  
\[ y + mg \cos \theta \sin \phi = m(\dot{v} + ru - pw) \]  
\[ N = I_z \ddot{\phi} - I_{zx}(\dot{\theta} - qr) - (I_x - I_y)pq \]

For the case of three degrees-of-freedom, some of the variables can be set to zero. In this study, \( p, q, w, \theta \) and \( \phi \) can be set to zero. The three equations will now be considered separately.

2. Longitudinal Force Equation

Eliminating \( q, w \) and \( \theta \) from (B.1.1), we obtain,

\[ x = m(\dot{u} - rv) \]  

This can be rearranged to give an acceleration equation,

\[ \ddot{u} = rv + \frac{1}{m} X \]

The external forces acting on the vehicle are:

(a) Propellor Thrust \( (T_p) \)
(b) Cushion Fan Inlet Momentum Drag \( (D_m) \)
(c) Body Profile Drag \( (D_b) \)
(d) Skirt Contact Drag \( (D_{sc}) \)

The \( x \)-components of these forces will be referred to as \( T_{px}, X_m, X_b \) and \( X_{sc} \). The values for these forces were obtained from Ref. 3.
The static propellor thrust was found to be

\[ T_{xs} = (180 + 3323 \beta_p) \left( \frac{N_{pt}}{100} \right)^2 \text{ pounds} \quad \text{(B.2.3)} \]

The change of thrust due to forward speed is accounted for in the following equation:

\[ T_{px} = T_{xs} - 5.2V \cos\beta \text{ pounds} \quad \text{(B.2.4)} \]

The cushion fan inlet momentum drag is

\[ D_m = \rho Q_f V \]

where

\[ Q_f = -560 + 43N_{pt} \]

The x-axis momentum drag is

\[ X_m = D_m \cos\beta = \rho Q_f V \cos\beta \text{ pounds} \quad \text{(B.2.5)} \]

The x-component of the body profile drag is given by

\[ X_b = (0.082 - 0.000833\beta)V^2 \quad \text{(B.2.6)} \]

Skirt contact drag occurs when the power turbine setting falls below 75%. It is given by

\[ X_{sc} = (400 - 5.32N_{pt})u \quad \text{(B.2.7)} \]

In the above equations it was assumed that the throttle was variable from zero to 100%, and that 1100 horsepower was available from the engine at full throttle.

3. Lateral Force Equation

Eliminating \( p, w, \theta \) and \( \phi \) from (B.1.2) we obtain

\[ Y = m(\dot{v} + ru) \quad \text{(B.3.1)} \]

This can be rearranged to give an acceleration equation,
The external forces (Y) acting on the vehicle are:

(a) Aerodynamic body side force (Yb)
(b) Aerodynamic tail side force (Yt)
(c) Cushion fan inlet momentum side force (Ym)
(d) Side force due to rudder deflection (Ysr)
(e) Side force due to puff port operation (Ypp)
(f) Skirt contact drag (Ysc)

The aerodynamic body side force is a function of the air sideslip angle $\beta$ and varies as the square of the velocity. It is given by the following equation for air sideslip angles between zero and 40°.

$$Y_b = 0.00933\beta v^2 \quad \text{(B.3.3)}$$

The aerodynamic tail side force is largely determined by the propellor slipstream velocity and angle. For angles between 0° and 20°, the aerodynamic tail side force is given by

$$Y_t = 0.04S_{fr} q_s \alpha_s \quad \text{(B.3.4)}$$

The subscript 's' in the above equation refers to the slipstream.

The cushion fan inlet momentum side force is the $y$-component of the momentum drag of the fan intake. It is

$$Y_m = D_m \sin\beta = \rho Q_f V \sin\beta \quad \text{(B.3.5)}$$

For rudder deflections between 0° and 20°, the coefficient of side force due to rudder deflection is

$$c_{y\sigma r} = 0.0283/\text{degree}$$

The sideforce due to rudder deflection is

$$Y_{sr} = c_{y\sigma r} S_{fr} q_s x \cdot \sigma r \quad \text{(B.3.6)}$$
The SK-5 uses twin rudders which form a part of an NACA 0009 airfoil section with the tail.

Each of the four puff ports on the SK-5 produces 250 pounds of side force. When a puff port is used, air is removed from that portion of the skirt and this causes an adverse roll to occur. Because of this, the side-force produced by a puff port is reduced from 250 to 138 pounds.

The skirt contact drag in the y-direction for throttle settings below 75% is given by,

\[ Y_{sc} = (400 - 5.32N_{pt})v \]  (B.3.7)

4. Yaw Torque Equation

Eliminating \( p \) and \( q \) from Eq. (B.1.3) we get

\[ N = \frac{1}{I_z} \cdot r \]  (B.4.1)

This equation can be rearranged to give the acceleration equation

\[ r = \frac{1}{I_z} \cdot N \]  (B.4.2)

The external yawing moments for overland operation consist of the following:

(a) Body yawing moment \( (N_b) \)
(b) Yawing moment due to cushion fan inlet momentum drag \( (N_m) \)
(c) Yawing moment due to tail surfaces \( (N_t) \)
(d) Yawing moment due to rudder deflection \( (N_{\delta r}) \)
(e) Yaw damping coefficient \( (N_r) \)
(f) Yawing moment due to puff port operation \( (N_{pp}) \)

The body yawing moment is a function of the air sideslip angle \( \beta \), and varies with the square of the velocity of the vehicle. It is given by the following equation:

\[ N_b = 0.0217\beta v^2 \]  (B.4.3)

The yawing moment due to cushion fan inlet momentum drag is the product of the side force due to the fan inlet momentum drag and the distance of the fan inlet from the centre of gravity of the vehicle.
\[ N_m = D_m \sin \beta \cdot l_{cf} \]
\[ = \rho Q_f V \sin \beta \cdot l_{cf} \quad (B.4.4) \]

The yawing moment due to the tail surfaces is given by the product of the side force produced by the tail surface and the distance of the tail surface from the centre of gravity of the vehicle. The yawing moment due to rudder deflection is similarly obtained. If the distance from the centre of pressure of the fin-rudder combination to the centre of gravity of the vehicle is used, the following equations are obtained.

\[ N_t = 18.4Y_t \quad (B.4.5) \]
\[ N_{gr} = 18.4Y_{gr} \quad (B.4.6) \]

The yaw damping coefficient for low speed operation was estimated to be

\[ N_r = 0.26 \times 10^5 \text{ ft lb/rad/sec} \]

The yawing moments due to puff port operation were obtained by multiplying the puff port side force by its longitudinal distance from the centre of gravity and neglecting any loss due to adverse roll.

\[ N_{pp} = 8.0Y_{bow} - 10.0Y_{aft} \]

5. **Linearization of the Equations of Motion**

The equations of motion were linearized in the following way. All variables were rewritten as the sum of a steady-state part and a perturbation quantity, e.g.,

\[ u = U_e + \Delta u \]
\[ T_p = T_{pe} + \Delta T_p \]

These new variables were substituted into the equations of motion, and a steady state equation and a perturbation equation were obtained for each degree-of-freedom.

The three steady-state equations were solved simultaneously, so that a steady state forward speed was obtained for a particular throttle and propeller
blade pitch setting. Once the steady state values for all variables were found, they were substituted into the perturbation equations to give the equations of motion which were used in the simulation.

A sample linearization will be performed on the lateral force equation. Starting with Eq. (B.3.2), the variables are replaced by steady state and perturbation components to obtain

\[ \dot{(V_e + \Delta V)} = - (Re + \Delta r)(U_e + \Delta u) + \frac{1}{m} (Y_e + \Delta Y) \]  

(B.5.1)

The steady state equation is obtained when all of the perturbation quantities are set to zero.

\[ \Delta \dot{V_e} = - (Re)(U_e) + \frac{1}{m} Y_e \]  

(B.5.2)

Equation (B.5.2) is then substituted into the left hand side of Eq. (B.5.1) to yield

\[ \Delta \dot{V} = - U_e \Delta r - Re \Delta u - \Delta r \Delta u + \frac{1}{m} \Delta Y \]  

(B.5.3)

Second and higher order products of perturbation quantities can be eliminated because by definition, these quantities have a small magnitude. Also, because of the limitations of the simulation, it was decided that there should be no steady-state yaw rate, that is, \( Re \) was set to zero. Thus, the perturbation equation becomes

\[ \Delta \dot{V} = - U_e \Delta r + \frac{1}{m} \Delta Y \]  

(B.5.4)

The external forces acting on the vehicle are

\[ Y = Y_b + Y_t + Y_m + Y_\delta r + Y_{pp} + Y_{sc} \]  

(B.5.5)

This equation is also linearized to yield

\[ Y_e + \Delta Y = (Y_{be} + \Delta Y_b) + (Y_{te} + \Delta Y_t) + (Y_{me} + \Delta Y_m) + \]  

\[ + (Y_{5e} + \Delta Y_{5r}) + (Y_{pp} + \Delta Y_{pp}) + (Y_{sc} + \Delta Y_{sc}) \]  

(B.5.6)

Separating the forces into steady state and perturbation components
\[ Y_e = Y_{be} + Y_t + Y_m + Y_{6r} + Y_{pp} + Y_{sc} \quad (B.5.7) \]

\[ \Delta Y = \Delta Y_{b} + \Delta Y_t + \Delta Y_m + \Delta Y_{6r} + \Delta Y_{pp} + \Delta Y_{sc} \quad (B.5.8) \]

Equation (B.5.8) can now be substituted into the right side of (B.5.4).

Each of the external forces must now be linearized. An example is shown for the aerodynamic body side force. Starting with the equation

\[ Y_b = 0.00933 \, V^2 \quad (B.5.9) \]

variable substitution gives

\[ Y_{be} + \Delta Y_b = 0.00933 \left( \beta_e + \Delta \beta \right) (V_e + \Delta V)^2 \quad (B.5.10) \]

Expanding the right side gives

\[ Y_{be} + \Delta Y_b = 0.00933 \left( \beta_e + \Delta \beta \right) (V_e^2 + 2V_e \Delta V + \Delta V^2) \quad (B.5.11) \]

After eliminating double products, the steady state and perturbation forces can be written as

\[ Y_{be} = 0.00933 \beta_e \, V_e^2 \quad (B.5.12) \]

\[ \Delta Y_b = 0.00933 \left( 2V_e \beta_e \Delta V + V_e^2 \Delta \beta \right) \quad (B.5.13) \]

The other forces in the lateral force equation were linearized in the same manner, and the various components of the forces were linearized until each force was reduced to a steady state equation and a perturbation equation in terms of \( \Delta r \), \( \Delta N_{pt} \), \( \Delta \beta_p \), \( \Delta V \), \( \Delta \beta \) and \( \Delta \delta r \).

The longitudinal force equation and the yaw torque equation were linearized in a way similar to the lateral force equation.
APPENDIX C

10 REM SK-5 POT SETTING CALCULATIONS
95 REM**********************************************************************
96 REM*** VEHICLE PARAMETERS ***
97 REM**********************************************************************
100 LET M=465
110 LET R=2.36000E-03
115 LET L=6.5
120 LET A=61.4
125 LET I=32600
130 LET C0=2.83000E-02
135 LET N=-26000
136 REM**********************************************************************
137 REM*** SIMULATION CONSTANTS ***
138 REM**********************************************************************
140 PRINT "INITIAL VELOCITY ";
150 INPUT V0
160 PRINT "INITIAL AIR SIDESLIP ANGLE ";
170 INPUT B0
175 LET B0=3.14159/180
180 PRINT "INITIAL TURBINE SETTING ";
190 INPUT N0
200 PRINT "INITIAL PROPELLOR BLADE PITCH ANGLE ";
210 INPUT BI
215 LET BI=3.14159/180
220 PRINT "INITIAL RUDDER DEFLECTION ";
230 INPUT R0
235 LET Q0=-560+43*N0
240 LET T0=(-5.2*V0* C0S(B0))
245 LET V1=V0*C0S(B0)*Y6/Y7
250 LET S1=V0*SIN(B0)*Y6/Y7
255 LET S2=(C180+58* BI)*2*N0/10000
260 LET S3=58*(N0/10000)^2*Y2/Y0
265 LET S4=-5.2*C0S(B0)-R*Q0*V0*C0S(B0)
270 LET S4=S4*(8.2000eE-02-B.33000E-04*B0)*V0
275 LET S4=S4*Y3/(M*Y0)
280 PRINT "STEERING RATIO ";
290 INPUT S
300 REM**********************************************************************
305 REM THE FOLLOWING ARE CALCULATIONS FOR THE POT SETTINGS ***
310 REM FOR THE LONGITUDINAL EQUATION OF MOTION. ***
315 REM**********************************************************************
320 LET S6=(-V0*C0S(B0)+ABS(N)/(18.4*M))*Y6/Y7
325 LET S2=(C180+58* BI)*2*N0/10000
330 LET S3=58*(N0/10000)^2*Y2/Y0
335 LET S4=-5.2*C0S(B0)-R*Q0*V0*C0S(B0)
340 LET S4=S4*(8.2000eE-02-B.33000E-04*B0)*V0
345 LET S6=S6*(8.2000eE-02-B.33000E-04*B0)*V0
350 LET S6=S6*Y3/(M*Y0)
355 LET S6=S6*Y7/(M*Y0)
360 REM**********************************************************************
365 REM THE FOLLOWING ARE CALCULATIONS FOR THE POT SETTINGS ***
370 REM FOR THE LATERAL EQUATION OF MOTION. ***
375 REM**********************************************************************
380 REM**********************************************************************
385 REM**********************************************************************
390 REM**********************************************************************
395 REM**********************************************************************
400 REM**********************************************************************
LET I4 = C0*A*R0*R1*C4
LET I5 = C1*V2*SINCB9) + C1*V0*SINeE9)*COSeB9)*5.2*C2
LET G4 = Z4*Y6/Y1
LET I5 = 4.00000E-02*A*A0*R*V0 + 1J2*COSeE9) - V3*C2*5.2*COSB9)
LET G5 = Z5*Y6/Y2
LET G6 = Z6*Y6/Y3
LET S9 = e2*9.33000E-03*V0*B0 + 15 + R*Q0*SIN(39) + I6)*Y3/eM*Y7
LET I7 = C1*V2*V0 + V0*V2*coseB9» - 5.2*CI*eV0*SINCB9»2*C2
LET G8 = Z8*Y6/Y5
REM********************************************************
REM THE FOLLOWING ARE CALCULATIONS FOR THE POT SETTINGS ***
REM FOR THE YAW-TORQUE EQUATION OF MOTION ***
REM********************************************************
PRINT "DELTA;VAP", F2, F7, G4
PRINT "DELTA;VA", F4, F9, G6
PRINT "DELTA; BA", F5, F8, G7
PRINT "DELTA; RUD", "G4, G8"
PRINT "DELTA;PP", "G2, G9"
PRINT "COMPUTER COEFFICIENTS (SCALED)"
PRINT "DELTA; R", S1, S6, Z3
PRINT "DELTA;NPT", S5, S7, Z4
PRINT "DELTA; BA", S5, S8, Z7
PRINT "DELTA; RUD", "Z1, Z8"
PRINT "DELTA;PP", "Z2, Z9"
PRINT "K0=150/(Y5*S)
PRINT "K1=V0*SIN(B9)/Y7
PRINT "K2=V0*COS(B9)/Y8
PRINT "K3=COS(B9)*Y7/Y8
PRINT "K4=Y9/X0
PRINT "K5=SIN(-B9)*Y7/X0
PRINT "K6=(V0*COS(B9)*SIN(-B9)+V0*SIN(B9)*COS(-B9))X1/X0
PRINT "X7=COS(B9)*Y9/Y3
PRINT "K9=SIN(B9)*Y8/(V0*Y4)
PRINT "K9=K9*180/3.14159
PRINT "L0=COS(-B9)*Y7/(V0*Y4)
PRINT "L1=SIN(-B9)*Y9/Y8
PRINT "L2=(V0*COS(-B9)-V0*SIN(-B9))X1/Y8
PRINT "L3=Y8/Y9
PRINT "L4=B9/X1
PRINT "L5=Y6/X1
FOR THE FOLLOWING VARIABLES, ENTER MAX. ABS. VALUES.

U 75
UET55
NPT 710
This project is the culmination of the work begun by Band (Ref. 1) and continued by Fraser (Ref. 2). The simulator which they designed was evaluated using hovercraft pilots and non-pilots. A Bell Aerosystems SK-5 hovercraft was simulated in order to provide comparison with a known craft. The non-pilots participated in a lateral tracking task study, while the pilots provided subjective evaluation.

It was found that the simulator was suited for use as a design tool, but that its scope of simulation was limited by the small display size. With a larger display, it was found that the capability of the simulator would be increased.