A FACILITY FOR DYNAMIC TESTING OF MODELS OF AIRBORNE VEHICLES WITH GROUND EFFECT

by

Jaan Liiva

OCTOBER, 1961

UTIA Technical Note No. 53
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A feasibility study has been carried out of the testing of self-powered models of vehicles with ground effect, on a circular track of 20 ft. diameter. Preliminary testing of a GETOL model with a wing of aspect ratio 3.5 and 17 inch wingspan was performed by flying over ramps in the groundboard of the track. The motion of the vehicle was recorded by filming with a motion picture camera. A theoretical study of the cable derivatives introduced by the harnessing and of their magnitudes relative to the aerodynamic derivatives was made. Problems associated with the model construction and performance are outlined and experimental test results are presented.
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**NOTATION**

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<td>( J )</td>
<td>momentum thrust</td>
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<td>( \ell_1 )</td>
<td>distance from centrepost to point of action of total cable drag</td>
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<td>( L^* )</td>
<td>additional rolling moment due to cable</td>
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<td>( m )</td>
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<td>( M^* )</td>
<td>cable restoring moment due to perturbation pitch angle displacement ( \theta )</td>
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\[ \theta \] perturbation angle of pitch
\[ \mu' \] viscosity of air at S. T. P.
\[ \mu \] mass parameter of vehicle
\[ \lambda \] characteristic wavelength
\[ \rho \] atmospheric density at S. T. P.
\[ \tau \] characteristic time
\[ \psi \] perturbation angle of yaw
\[ \rho_c \] cable linear density in lbs/ft
\[ \Omega \] angular velocity of model around centrepost
\[ (\quad)^* \] cable forces and derivatives
I. INTRODUCTION

Much work has been completed on the statics of GEM and GETOL aircraft, but so far little is known about the dynamics of these vehicles. To study the dynamic behaviour of models of such vehicles, a circular track facility has been built at UTIA.

The concept of using flying models on a circular path, controlled by a pilot through lines to the centre is not new. It has been in use by "U-Control" model fliers for years. The quality of power plants used for the models has been greatly improved. Consequently, there are glow-plug engines now available with horsepower ratings sufficient to power models for most testing purposes.

Testing by this method was proposed by Braun (Ref. 2) in 1949, using models of conventional type aircraft on a 150 foot radius tether. Some of the difficulties that he outlined are not relevant to aircraft of the groundcushion type, where the testing is carried out on a horizontal table at the largest diameter of the testing sphere. The testing sphere is defined as that surface which the tether from the centrepost to the centre of gravity of the vehicle will trace out. Variations in the model's height above groundboard are a small percentage of the radius of the testing sphere. Braun's results show that with the constraint of lines whose weight is small in comparison to vehicle weight, the short-period longitudinal pitching mode can be obtained directly, but that for the long-period mode (the Phugoid) the constraints must be carefully considered.

Rotating-arm devices have been considered, but not used due to the interference of the arm on the derivatives (see Ref. 10).

In wind tunnel testing the "effective" shape of the ground encountered by the peripheral jet depends on the boundary layer on the groundboard. With a Reynold's number that produces a turbulent boundary layer, the ground surface is effectively one of unknown roughness and distance from the jet face.*

In free flight model testing the pilot in control does not have an absolute knowledge of the attitude of the model when the controls are activated for a response test. Responses of the vehicle could be telemetered to the recording equipment, but the resulting model to house this would then be quite large and heavy. On a circular track one can harness the model to suppress any undesirable modes such as roll and yaw. Continuous recording of flight attitude is possible by the simple arrangement described in this report.

* The concept of an effective ground surface may actually prove to be inadequate as a representation of the complicated interaction between the jet sheet and the boundary layer.
The test data obtained from the track is easy to read and process by direct hand calculation or by automatic analogue and digital computation. Transfer functions and stability derivatives can in principle be obtained by methods similar to those already developed for flight test work.

II. TESTING TRACK

2.1 Construction and Specifications

The track consists of a level annular table of 9.0 foot radius from the centre of track to centrepost (see Fig. 1). Eighteen pieces of 1/2" thick plywood form the horizontal table, each subtending an angle of 20 deg. at the centre. The effective table width is 2.5 feet. The framework to support the table is made from Dexion angles for ease of assembly, and also to facilitate adjustment of height when levelling. The bottom of the Dexion framework is fastened to the concrete floor with Ramset bolts and each frame is cross-braced to the two adjacent ones. This combination of interconnected frames, fastened securely to the floor produces a very strong and stiff structure. One of the 18 plywood boards is hinged for access to the interior. The horizontal table is 30 inches above the floor to provide sufficient room for observers to remain inside the track during test runs.

2.2 Flight Recording

During flight the vehicle was photographed by a 16 mm. Bolex movie camera, with an electric drive. The filming speed was 32 frames per second. The camera is fixed rigidly at the centre of the testing track to the structure which overhangs the track (see Figs. 1 and 2). The optical path from the camera to the model is completed with a mirror, mounted at an angle on a sleeve. This sleeve is fitted with two ball bearings to the top of the centrepost. The lines from the model swing the sleeve and mirror in such a way that the mirror is always aimed at the model; consequently, the model is always in the camera's range of vision.

To obtain quantitative results, there is a vertical background of horizontal lines spaced one inch apart. The background board is 20 inches high, to permit continuous photography of transition to flight outside ground effect.

Floodlights on every second post light the model and background for photography.

To prevent discoloration of the grid and to provide protection against solution of the glues which bind the plywood, the whole structure was covered with several coats of butrate dope.
There are three reference points on the aircraft; a double rectangle on nose and tail and a post on the wingtip closer to the camera, as shown in Fig. 8. By conducting a frame-by-frame analysis of the film from a test run, the relative heights above groundboard and distances from each other of these points can be determined. Arithmetic operations, performed either by hand calculating machine or electronic digital computer, will yield the angles of pitch, roll and yaw against frame number. The camera filming speed is calibrated by filming the second hand of an electric clock. This procedure gives an accurate measure of time. Centre of gravity position of the model along the track is obtained from the angle of orientation of the track within the film frame. As the model proceeds along the track, the track rotates in the camera frame due to the arrangement of stationary camera and rotating mirror.

The model points were read from the film by using one of two methods.

1) For very accurate results the commercial comparator available at UTIA was used. This procedure is very time-consuming.

2) For quicker but less accurate results the pictures were enlarged by projecting onto a screen at a convenient magnification, such as half, full, or double size. The accuracy of reading is consistent with track construction accuracy and frame magnification. By aligning a sheet of graph paper with the grid lines on the backboard, the model points were directly plotted against frame number.

2.3 Centrepost

The centrepost shown in Fig. 2 consists of a three-legged frame to hold a 3/4 inch diameter steel rod with set-screws for adjustment of height. The rod is fitted with two ball bearings at the top, and an aluminum sleeve is pressed on the outer races of the bearings. Since the models are self powered it was decided to make the inertia and bearing drag of the rotating part of the centrepost as small as possible. This prevented direct mounting of the camera to the centrepost and the mirror arrangement described in part 2.2 was used instead. The mirror arrangement had the added advantage that distance along the track could be directly obtained as an angular displacement from a reference radius, such as that at the ramp.

The lines to the model are fastened to two nylon-coated steel wires that run through tubular guides and attach to a bell crank. The guides provide a restoring moment to the mirror mount if the vehicle tends to lead or lag. On the model wingtip there is a bell crank the height of which is adjustable by a set-screw. There is no additional rolling-moment introduced by the tether, if the lines are adjusted to the height of the vehicle c.g.
One control can be introduced to the vehicle through the control lines. By linking cables from the elevator or engine throttle to the bellcrank on the wingtip of the vehicle, it can be controlled from the outside. This mechanical control through the bellcranks was intended for use as a throttle control for the GETOL model, but since no suitable throttle for the engine was found, the control was not used.

Other controls could be provided by using stepping relays or servos, electrically fed through the control lines and slip-rings on the centrepost, operated from a control-centre outside the test track.

2.4 Starter

An engine starter is indispensable for efficient operation of the test track. In the beginning of the program much time was spent trying to start the engine by hand; the starter subsequently made this a simple operation. Figure 9 shows the starter which consists of an automobile starter motor, a 6 volt battery and charger. The model engine is pressed against a rubber hose fastened to the motor shaft, while the needle valve on the engine is adjusted for proper fuel flow, as indicated by the sound of the exhaust. Final adjustment can then be made with the engine removed from the starter. Power for the glowplug is obtained from one of the three cells in the battery. While 1.5 volts for the glowplug is recommended by the manufacturer, it was found that 2 volts made starting easier with occasional burnout of plugs.

III. MODEL

3.1 Structure

The model used for preliminary feasibility tests was based on a Vertol design (Figs. 3 to 8). It was made from balsa wood covered with polyester resin. The internal surfaces of the nacelles and ducting were also covered with the resin to provide a smooth surface. The combination of balsa covered with resin makes a strong structure, but it has a tendency to crack. These cracks occurred at many of the joints and had to be repaired by using a layer of glass cloth with resin to bond it to the surface of the model.

3.2 Specifications

The wing is of NASA 4418 cross-section with a 6" chord at the root, tapering to a 3" tip chord outboard from the nacelle structures. The wing aspect ratio is 3.5—a compromise chosen to provide both a good ground cushion and a more efficient wing for forward flight than the circular planform, which is more efficient as a GEM. The wing span is 17". The horizontal tail aspect ratio is 4.5, with a tail moment arm of almost 13.0". The long moment arm to the high aspect ratio horizontal tail provides a neutral point at 52% chord (Ref. 1).
This is sufficient to accommodate the shift of the centre of pressure from the midpoint of the wing during hovering, to the more conventional aerodynamic centre near 1/4 chord for forward flight. The C.G. of the vehicle has to be at the midpoint of the wing to provide trim, since the centre of pressure is at the midpoint of the planform enclosed by a peripheral jet during hovering. It may be possible to compensate for a C.G. forward of midchord point during hovering, if the centre of pressure can be shifted by having jet slots of different width at the front and rear of the wing.

The weight of the finished model together with power plant, fans, pulleys, belts and empty fuel tank is 2.4 lbs. Variation of C.G. position and of the moment of inertia can be effected by adding or subtracting lead weights to the tail, nose and wingtips.

The jet slot width can be changed by taping over part of the present opening of .40 inches or by making new bottom covers for the wing with the desired jet slot opening.

3.3 Nacelles, Fans and Ducting

The two forward-facing intakes each have a fan driven by a common engine mounted inside the fuselage. There is a twin pulley on the crank-shaft of the engine. A belt to each fan pulley provides the power transmission. The intake nacelles have built-up lips to prevent separation during hovering. Fixed stator blades behind the fan straighten the flow.

The air supplied by the fans can be directed to either or both of two openings. It can all be used to provide the ground cushion by exhausting the air through the slot around the periphery of the wing, i.e. the hovering mode. Fixed turning vanes inside the nacelle, located at the upper wing cover, turn the air into the wing. At the moment no information is available on their effectiveness in our model (see Fig. 6). For forward flight, part of the air is used to provide a forward thrust. The back of each nacelle has a set of 4 slots which can be opened or closed to provide various amounts of forward thrust.

The fans are mounted on the shafts with two ball bearings and a thrust bearing each, and are removable. There are commercial fans available to suit model engines of all power ratings. These fans are made to power models of jet aircraft with air passing straight through the body, and were not designed to work against the high internal resistance encountered in our model.

Two types of fans were tried unsuccessfully, since neither allowed the engine to speed up to its full 15,000 r.p.m. and thereby develop its full 3/4 horsepower.
Fair results were obtained from the smaller fan after reducing its solidity by 50\% by cutting away six of its twelve blades.

Due to the extremely bad matching of fans to engine and model ducting when the wing bottom cover was on, the hovering heights obtained were small, of the order of .04 to .06 h/\dot{c}. With the bottom cover removed and the model running as a simple plenum chamber heights of over 3" were obtained during portions of the run.

3.4 Engine

Installed in the model is a .35 cubic inch displacement Fox Combat Special glowplug engine delivering 3/4 horsepower at 15,000 r. p. m. This engine has a ball-bearing mounted crank-shaft and a tap on the crank-case for pressurizing the fuel supply. The pressurized supply operated satisfactorily, giving a constant fuel feed and facilitated starting. There was no throttle control on the engine. Two types of butterfly valves were tried on the carburator, but neither operated satisfactorily. (For efficient control of speed a combination of throttle and exhaust valves can be used. These were not installed on our engine). Runs were therefore taken at full speed, as set by the needle valve on the fuel supply.

Many flexible and springloaded motor mounts were tried unsuccessfully. Not one of them provided enough tension on the belts to prevent slippage. The present mount attaches the engine solidly to the model with four screws and locknuts. The tension to keep the belts tight is provided by the cantilevered fan shafts, fastened into the stator section. Belt tension can be adjusted with shims underneath the engine mounts.

Engine cooling was critical in the preliminary hovering tests. Runs of only a few seconds were obtained before the engine overheated. Glowplug engines are normally cooled by the slipstream from the fan or propeller. In our installation of two fans driven by belts, there was no slipstream cooling of the engine. An ejector was constructed, using the high-velocity exhaust gases from the engine to induce cool air over the cylinder head. During hovering the ejector interfered with the inflow into the fans. With forward flight around the track there was sufficient cooling without the ejector for runs of a few minutes duration. The ejector was discarded, since it added to the weight and did not perform as expected.

The engine performed much better after being thoroughly broken in by running it on a bench stand for several hours with a rich mixture of fuel and added castor oil.

More serious difficulty was caused by the castor oil, which sprayed from the exhaust over pulleys and belts during the runs. This oil caused slippage of the belts after five or six circuits around the track. This slippage could clearly be heard from the change in engine tone. Most of the data was taken on the first three circuits. Between runs the belts and pulleys were cleaned with a commercial window cleaning solvent.
IV. MODEL HARNESSING CHARACTERISTICS

4.1 Cable Properties

The harnessing arrangement selected consists of two dacron lines from the bellcrank on the centrepost to the wingtip bellcrank. The distance between the lines is 2 inches. Figures 7 and 2 show wingtip and centrepost arrangements. The dacron lines have the following properties:

- maximum safe tensile stress per line is 11 pounds
- average diameter $d_c$ is $1.51 \times 10^{-3}$ feet
- average lineal weight $p_c$ is $8.56 \times 10^{-5}$ lb/ft.

4.1.1 Cable Tension

Cable tension for the unbanked and unyawed vehicle in level circular flight around the track is

$$T = \frac{W V^2}{g R} \quad (4.1)$$

If the vehicle is banked, or if control surfaces are deflected, the tension will not be given exactly by equation 4.1, but if the speed of the vehicle is greater than 10 ft/sec the error will be less than 3% for angles of bank up to 5 degrees.

4.1.2 Cable Sag

To enable the vehicle to fly with its wings level at any given speed, the height of the centrepost is adjustable to compensate for cable sag.

From Ref. 21 the differential equation of the cable, and the boundary conditions are (see Fig. 10a)

$$\frac{d^2 y}{dx^2} = \frac{1}{T_0} \int_{c}^{c} \quad y \bigg|_{x=0} = \frac{dy}{dx} \bigg|_{x=0} = 0 \quad (4.3)$$

$T = T_0$ at $x = 0$ and the horizontal component of tension at any point in the cable is assumed to be constant over the length of the cable. This equation neglects the centrifugal force on the cable and gives a pessimistic answer for cable sag. This assumption is good provided the total cable mass is small compared to that of the airplane model, which is the case in the present tests.
Solving Eq. 4.3 gives

\[ y_h = \frac{1}{2T_o} \rho_c R c^{-2} \]  

(4.4)

Using the values for our line the sag is only $5.69 \times 10^{-3}$ inches at 30 ft/sec testing speed, and decreases rapidly with increasing speed.

4.2 Harness to Wingtip

The pair of lines to the model are harnessed to the wingtip as described in Sec. 2.3, to keep yawing and rolling to a minimum. We are mainly interested herein in obtaining the longitudinal derivatives of the vehicle. The procedure for defining the derivatives is as outlined in Ref. 1, except as otherwise noted. The cable derivatives are compared to the vehicle aerodynamic derivatives to show their relative magnitudes. The comparison will be carried out for the vehicle described in Section II.

4.2.1 Cable Drag Coefficient $C_D^*$

Assuming straight lines to the model, and that the drag coefficient for an infinite cylinder can be approximated by

\[ C_{D\ell} = C_D^{\alpha} Re_{\ell} \]  

(4.5)

$C_D$ and $\alpha$ can be found from a log, log plot of $C_D$ vs. $Re$ e.g. Refs. 22, 23 or 24, reproduced here for convenience in Fig. 17.

\[ Re_{\ell} = \frac{\rho V\ell d_c}{\mu} \]  

(4.6)

The drag on one wire is then

\[ D^\ell = \int_0^{R_c} C_{D\ell} \frac{1}{2} \rho V_c (\frac{r}{R_c}) d_c \cdot dr \]  

(4.7)

where \[ V_c = V_c \left( \frac{r}{R_c} \right) \]  

(4.8)

Substituting for $C_{D\ell}$ from Eq. 4.5, using Eq. 4.8 and integrating

\[ D^\ell = C_D^{\alpha} Re_{\ell} \frac{1}{2} \rho V_c \int_0^{R_c} \left( \frac{r}{R_c} \right)^{2+\alpha} d_c \]  

(4.9)

\[ D^\ell = \frac{C_D^*}{3+\alpha} \left( R_c d_c \right) \frac{1}{2} \rho V_c^2 \]
The drag acts at a distance \( l_i \) from the centrepost, where \( l_i \) is given by

\[
\ell_i = \frac{1}{D^*} \int_0^{R_c} \frac{1}{2} \rho V_c^2 \left( \frac{r}{R_c} \right)^2 d_c \cdot r \cdot dr
\]  

(4.10)

Integrating we get

\[
\frac{\ell_i}{R_c} = \frac{3+a}{4+a}
\]  

(4.11)

Setting up a co-ordinate system as shown in Fig. 10e, we see that by taking moments about the centrepost, the drag component of the cable tension at the wingtip is

\[
\Delta D^* R_c = \ell_i D^*
\]  

(4.12)

\[
\Delta D^* = D^* \frac{\ell_i}{R_c} = D^* \frac{3+a}{4+a}
\]

This component must be added to the vehicle drag; it produces a yawing moment and a drag force on the vehicle.

The effective additional drag coefficient is then

\[
C_D^* = \Delta D^* \frac{1}{\frac{1}{2} \rho V_c^2 S}
\]

(4.13)

Since two wires are used in the harness

\[
C_D^* = 2 C_{Dv} \frac{3+a}{4+a} \left( \frac{1}{2} \rho V_c^2 S_c \right) \frac{3+a}{4+a}
\]

\[
= 2 C_{Dv} \frac{S_c}{4+a} \left( \frac{R_c}{R} \right)^2
\]

(4.14)

we have used

\[
V_c = \Omega R_c
\]

(4.15)

\[
V = \Omega R
\]

(4.16)
Additional drag occurs in the centrepost bearings. This drag is assumed to be small in comparison to vehicle and cable drag.

To find the angle $\alpha$ (Fig. 10e) that the cable tension makes with the radius from the centrepost to the end of cable at vehicle, we use Eq. 4.3, but substitute $D^*(x)$ for $\rho^c$ using the assumptions of small cable weight compared to vehicle weight

$$\frac{d^2y}{dx^2} = \frac{D^*(x)}{T_0}$$

where $y$ is now the displacement in the horizontal plane. Using Eq. 4.5 and

$$\mathcal{L} = \mathcal{\Omega}$$

we get

$$\frac{d^2y}{dx^2} = \frac{1}{T_0} C_{D_1} \left( \frac{\rho d_c \Omega x}{\mu'} \right)^a \frac{1}{2} \rho x^2 d_c$$

Integrating we get

$$\frac{d^2y}{dx^2} = \frac{1}{T_0} C_{D_1} \frac{1}{2} \rho x^2 d_c \left( \frac{\rho d_c \Omega}{\mu'} \right)^a \frac{x^{3+a}}{3+a} + C_1$$

and

$$y = \frac{1}{T_0} C_{D_1} \frac{1}{2} \rho x^2 d_c \left( \frac{\rho d_c \Omega}{\mu'} \right)^a \frac{x^{4+a}}{(3+a)(4+a)} + C_1 x + C_2$$

The boundary conditions are:

$$y = 0 \text{ at } x = 0$$
$$y = 0 \text{ at } x = R_c$$

whence it follows that $C_2 = 0$ and

$$C_1 = -\frac{1}{R_c T_0} \left. C_{D_1} \frac{1}{2} \rho \left( \frac{\Omega R_c^2}{\mu'} \right) d_c \left( \frac{\rho d_c \Omega R_c^2}{\mu'} \right)^a \frac{R_c^2}{(3+a)(4+a)} \right|_0$$

using Eqs. 4.15, 4.6, 4.9

$$C_1 = -\frac{D^*}{T_0 (4+a)}$$
\( \alpha \) at \( x = R_c \) is then found from Eq. 4.20

\[
\alpha = \left( \frac{dy}{dx} \right)_{x = R_c} = \frac{D^*}{T_o} \left[ 1 - \frac{1}{4 + a} \right] \tag{4.22}
\]

\[
= \frac{D^*}{T_o} \frac{3 + a}{4 + a} = \frac{\Delta D^*}{T_o}
\]

This result can also be deduced directly from Fig. 10e.

### 4.2.2 The Cable Derivative \( C^*_Z \)

Assuming straight, level, horizontal flight with small perturbations, we see that the vertical force due to the cable is (Fig. 10b)

\[
\mathbf{z}^* = -T \varphi = - \frac{T h}{R} \tag{4.23}
\]

\( \varphi \) is approximately the angle of bank \( \phi \) for the vehicle with wingtip tethering, if wire sag can be neglected as shown in Sec. 4.1.2. Substituting from Eq. 4.1 for \( T \)

\[
\mathbf{z}^* = -m \frac{V^2 h}{R R} \tag{4.24}
\]

\[
C^*_z = -m \frac{h V^2}{R^2} \frac{1}{\frac{1}{2} \rho \frac{V^2 S}{}} \tag{4.25}
\]

\( m \) is non-dimensionalized as in (Ref. 1), i.e. let

\[
\mu = \frac{m}{\rho S \frac{V^2}{2}} \tag{4.26}
\]

then

\[
C^*_z = -\mu \frac{h}{R} \tag{4.27}
\]

Non-dimensionalizing \( h \) by dividing by \( \ell \),

\[
\frac{h}{\ell} = H \tag{4.28}
\]

and

\[
\frac{\partial C^*_z}{\partial H} = C^*_{zh} = -\frac{\mu \ell^2}{R^2} \tag{4.29}
\]
4.2.3 The Cable Derivative $C^*_m \theta$

If the vehicle's angle of pitch varies by an angle $\theta$ from $\theta_0$, then a restoring moment is set up as shown in Fig. 10c.

$$M^* = -\frac{I d \theta}{2} \cdot \frac{d}{Rc}$$  \hspace{1cm} (4.30)

Non-dimensionalizing by using Eqs. 4.1 and 4.26, we get

$$C^*_m = -\frac{\mu d \theta}{4 R R_c}$$
$$\frac{dC^*_m}{d \theta} = C^*_m \theta = -\frac{\mu d \theta}{4 R R_c}$$  \hspace{1cm} (4.31)

4.2.4 The Cable Derivatives $C^*_n \psi$, $C^*_x \phi$

To show that the roll and yaw response will tend to be small, $C^*_n \psi$ is calculated for the vehicle in section 2 with wingtip harness attachment as shown in Fig. 7. Figure 10d gives the relevant parameters

$$N^* = T \ell = TR \psi$$  \hspace{1cm} (4.32)

$$\sin \frac{\psi}{b/2} = \sin \frac{(-\psi)}{R_c} \text{ or } \psi = -\frac{\psi \cdot b/2}{R_c}$$  \hspace{1cm} (4.33)

$$N^* = -T \frac{\psi \cdot b}{2 R_c}$$
$$C^*_n = -\frac{\mu \cdot b}{2 R_c} \psi$$

$$\frac{dC^*_n}{d \psi} = -\frac{\mu \cdot b}{2 R_c} = C^*_n \psi$$  \hspace{1cm} (4.34)

Similarly

$$\frac{dC^*_x}{d \phi} = C^*_x \phi = -\frac{\mu \cdot b}{2 R_c}$$  \hspace{1cm} (4.35)

These derivatives are large, compared to conventional aircraft derivatives, as will be shown in Section 4.3.
4.3 Comparison of Vehicle Aerodynamic and Cable Derivatives

The calculations will be performed for a 2.0 lb. vehicle at h = .25 inches and forward speed of 30 ft/sec. The following are quantities used in the computations:

- \( R_C = 8.29 \text{ ft.} \)
- \( R = 9.00 \text{ ft.} \)
- \( h = 0.25 \text{ in.} \)
- \( V = 30.0 \text{ ft/sec} \)
- \( W = 2.0 \text{ lbs.} \)
- \( \rho = 2.38 \times 10^{-3} \text{ slugs/ft}^3 \)
- \( \mu_\text{lateral} = 1.16 \times 10^2 \)
- \( \mu_\text{long.} = 1.78 \times 10^2 \)
- \( \Re_V \approx 3.00 \times 10^2 \)
- \( \mu' = 3.73 \times 10^{-7} \)
- \( \bar{c} = 5.56 \text{ in.} \)
- \( \bar{b} = 17.0 \text{ in.} \)
- \( S = 91.2 \text{ in}^2 \)
- \( d_c = 1.51 \times 10^{-3} \text{ ft.} \)
- \( d = 2.00 \text{ in.} \)
- \( \rho_c = 8.56 \times 10^{-5} \text{ lbs/ft} \)
- \( \frac{\partial \bar{c}}{\partial h} \)

4.3.1 Drag of Cable

\[
C_D^* = \frac{2 \, C_D \, S_c \, (\frac{R_c}{R})^2}{4 + \alpha \, \frac{S}{S_c} \, (\frac{R_c}{R})}
\]

\[
= 0.0115
\]

We can see that the cable drag is a significant fraction of the total drag and must be carefully considered in derivative analysis.

4.3.2 Lift

For equilibrium flight

\[
Z = W
\]

By the most optimistic theory (in sense that \( \frac{\partial Z}{\partial h} \) is largest) we have \( Z = \frac{W}{h} \) for the cushion. Hence cushion derivative is

\[
\left( \frac{\partial Z}{\partial h} \right)_\text{cushion} = -\frac{W}{h^2} = -\frac{W}{h}
\]
also \( \frac{\partial \zeta^*}{\partial h} = -\frac{T}{R} - \frac{W \cdot V^*}{R} \) from Eq. 4.14

Therefore the ratio \( \frac{(Z_h)_{\text{cushion}}}{Z_h^*} \) is:

\[
\frac{R \cdot \frac{q}{V^*}}{h \cdot 2} = \frac{q}{900 \times 12} 
\]

hence in our case

\[
\text{ratio} = \frac{81 \times 32 \times 12}{900 \times 25} \approx 140 
\]

This ratio, for the same height \( h \), falls to 10 when the speed of the vehicle is about 100 ft/sec.

In regimes where the vehicle has little inherent stability in heave, i.e. \( (Z_h)_{\text{cushion}} = \lambda \) the cable derivative would be the predominant one.

4.3.3 Pitch

Artificial pitch stability is provided by \( C_{m\theta}^* \):

\[
C_{m\theta}^* = -\frac{\mu \cdot d}{4R \cdot R_c} = -0.0165
\]

This value of \( C_{m\theta}^* \) is small, but enough to provide some stability in pitch if vehicle is neutrally stable. By variation of \( d \), a limited range of pitch stability can be provided. This stabilization increases rapidly with \( d \) since it is squared in the equation.

4.3.4 Roll and Yaw

\[
C_{\psi}^* = C_{n\psi} = \frac{\mu \cdot b}{2R_c} = -5.07
\]

Typical values of \( C_{n\psi} \) are .05, therefore the roll and yaw response of the vehicle should be extremely small during flight, i.e. the wingtip harness has the effect of suppressing the roll and yaw degrees of freedom.

4.3.5 Cable Dynamics \( (1) \)

The speed of propagation of a wave in a cable with tension \( T \) is

\[
\omega = \sqrt{\frac{T}{R_c}}
\]

The characteristic time for this wave to travel the length of the cable and return is:

\[
\tau = \frac{2 \cdot R_c}{\omega} = 2 \cdot R_c \sqrt{\frac{R_c}{T}}
\]

\( (1) \) This analysis is due to Prof. B. Etkin.
substituting for \( T \) and assuming \( R_c \approx R \)

\[
\tau_1 = 2 R \sqrt{\frac{p_c R}{m V^2}}
\]

The time to complete one cycle in pitch or heave is

\[
\tau_2 = \frac{\lambda}{V}
\]

where \( \lambda \) = one wavelength

The ratio of these times is

\[
\frac{\tau_1}{\tau_2} = \frac{2 R V}{\lambda} \sqrt{\frac{m_c}{m V^2}} = \frac{2 R}{\lambda} \sqrt{\frac{m_c}{m}}
\]

We can see that the ratio of the characteristic times depends only on the length of the cable, the wavelength of an oscillation and the mass ratio of cable and vehicle.

Substituting the values which occurred in the experiments into the equation we get

\[
\frac{\tau_1}{\tau_2} = \frac{2 \times 9}{6} \times \sqrt{\frac{9 \times 8.56 \times 10^{-5}}{2}}
\]

\[
= 3 \times 19.6 \times 10^{-3}
\]

\[
= 58.8 \times 10^{-3}
\]

For the cable to adjust instantly to conditions at the end, the ratio of the above times must be small. If the ratio approaches one there may be dynamic interactions between the motion of the cable and that of the model. In the present case it is evident that such interaction can be neglected.

V. TESTING AND RESULTS

Initial hovering tests with an engine of half power indicated that severe mismatch of fan and load existed, so the engine shown in Figs. 7 and 8 was installed. Hovering heights of .25 to .75 inches were achieved with the larger engine. Since there was no cooling for the engine without forward motion, as described in Section 3.4, hovering tests were limited to a few seconds before the engine overheated.

The vehicle was tethered to the centrepost and testing on the track began. A ramp was made by raising one edge of the door in the track to the required height. Values of .125, .25, .50 and .75 inches were used. The resulting ramp was set at the required height and the vehicle traversed it during each subsequent pass.
The accuracy of the results was limited by the camera shutter speed. With the electric motor drive the maximum filming rate of the camera was 32 frames per second. The shutter speed of the camera was fixed and proportional to the filming rate. While the filming rate was adequate to record and define the motion, the shutter speed was not fast enough to produce a clear and well defined picture of the reference points on the model. At the testing flight velocity of approximately 30 ft/sec, the background reference lines were fan-shaped, with both ends one inch blurs at the frame edge, due to the fixed camera and rotating mirror arrangement.

Three fan configurations were tested. On all fans the outside diameter of 3.5 inches and hub diameter of 1.5 inches were kept constant. The first fan had 12 fibre blades of .75 inch chord. The results from tests indicated that back pressure on the fan was too great to allow the engine to accelerate up to full speed (12,000 to 15,000 r.p.m.). With the bottom cover of the wing removed, the vehicle hovered at a height of .25 inches.

The second fan tested was of identical construction to the first, except that the blade chord was .50 inches. In the peripheral-jet configuration the hovering heights obtained were very small, but in the plenum chamber configuration the model performed better. A graph of the test run with .50 inch high ramp is given as Fig. 13.

The reference point height and angle of pitch $\theta$, were calculated from test records similar to the ones in Fig. 11 and 12. With the model on the ground the zero angle of pitch $\theta_0$ is defined by the tailpoint height: 2.375 inches, and nosepoint height: 1.905 inches above the ground. The reference point used for the calculations and shown on Figs. 13 to 16 is midway between these two points: 2.240 inches above ground, vertically up from the midchord of the wing at the centreline of the vehicle. Horizontal separation of nose and tail points is 14.25 inches. The wingtip point is 2.406 inches above ground when model's angles of pitch and roll are zero. Because the nose and tail points are on the side of the vehicle the straight line joining them is 1.015 inches out from the centreline of the aircraft toward the camera, at wing midchord (perpendicular to X, Z plane, as defined in Ref. 1 or 20).

The centre of gravity of the aircraft was fixed at 54.5% chord for the runs shown in Figs. 14 to 16. The pitching moment of inertia was .0123 slugs-ft$^2$.

Corrections were made for parallax of the readings due to displacement of the vehicle reference points from the backboard. Yaw and roll angles were calculated but not plotted because the variation was no more than $\pm$ 0.8 degrees. Collisions of the leading and trailing edge of the wing with the groundboard were frequent and have been indicated on all "reduced" graphs of test records.
The solidity of the fan was further decreased by cutting away 6 of the 12 blades from the fan with .50 inch cord. As a result the vehicle's flight in the plenum chamber configuration was highly unstable. Heights of wing bottom above the ground of 3 inches were reached during some of the runs. In the peripheral jet configuration the flight was more stable in height, with .25 to .50 inches ground clearance. Figures 14 to 16 are results from test flights over .125, .25 and .50 inch ramp heights, obtained from frame by frame analysis of the test film. The tests were performed in the peripheral jet configuration with one half of the lower slot on the back of each nacelle open for forward thrust. It was found experimentally that this gave the highest flight above the groundboard without substantial loss of forward velocity. The traces suggest a highly damped heave oscillation and a very lightly damped pitch oscillation, as expected, since the annular jet formed by the wing has little stability in pitch due to the relatively large aspect ratio.

The track was carefully levelled during construction, but due to the butrate dope which was applied for protection against engine fuel, the boards had buckled at the joints. A few runs were taken with no ramp in the track. Two unreduced test records are shown in Figs. 11 and 12. The results indicate frequent hits of both leading and trailing edges of the wing with the ground. The pitching mode is very lightly damped, if not unstable. Centre of gravity height is nearly constant, indicating a steady flight height.

A test was performed to see if the wake would linger on the track and disturb the model on subsequent passes. One piece of track was amply equipped with wool tufts on the groundboard, over the background grid and around the edges of board and light fixture. From visual observations, it was seen that the wake was lost through the cracks between backboard and groundboard, and no motion of the tufts was evident after the model had progressed 120° from the tufted section.

VI. CONCLUSIONS

It can be concluded from the theoretical analysis of cable restraints, and experimental track testing, that this method can be used for testing of vehicles with ground effect, from hovering, through transition, to full forward flight. Longitudinal stability, trim and control effectiveness can be investigated. Additional synthetic stability can be introduced by suitably harnessing the model (e.g. Sec. 4.2.3). Response to gusts and turbulent air could be studied by installing fans at various places around the track.

From the experience gained during this phase of testing it appears that future development of the facility should proceed along the following lines:
1) Design of a suitable one-fan vehicle of the GETOL type. The vehicle should be designed as an integral unit of fan, powerplant and fuel supply. To this unit planforms of various aspect ratios and shapes could be fastened for testing.

2) Instrumentation of models to enable outputs of flight results to be directly processed during test runs by analogue equipment.

The photographic method should be improved as outlined in this report, and retained as an absolute check on instrumentation accuracy and response.
REFERENCES


11. Various Authors. In this report are contained nearly all references to early work on Ground Effect Phenomena.

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FIG. 1 CIRCULAR TRACK WITH MODEL, CAMERA SUPPORT AND CENTREPOST
FIG. 2 CENTREPOST AND FILMING CAMERA ARRANGEMENT

- Camera with Electric Motor Drive
- Mirror
- Adjustable Centrepost
- Guides for Lines to Bellcrank
FIG. 3 FRONT VIEW OF MODEL AND FANS

FIG. 4 MODEL WITH SMALL ENGINE INSTALLED. FAN AND ENGINE PULLEYS CAN BE SEEN. SNAP-ON CAB IS REMOVED.
FIG. 5 TOP AND SIDE VIEW OF GETOL MODEL. SLOTS ON REAR OF NACELLES ARE OPEN.

FIG. 6 BOTTOM OF MODEL WITH WING COVER REMOVED. THE AIRFOIL SECTIONS THAT TURN AIR INTO WING, AND SUPPORT POSTS FOR LOWER COVER CAN BE SEEN.
FIG. 7 MODEL ON TRACK. NEW HIGH-POWER ENGINE HAS BEEN INSTALLED; LIPS ON NACELLE INTAKES, AND SPINNERS FOR THE SIX-BLADED FANS HAVE BEEN ADDED.

FIG. 8 MODEL AS SEEN BY CAMERA FROM CENTRE-POST. THE FRONT AND REAR CHECKERS AND WINGTIP POINT CAN BE SEEN CLEARLY.
FIG. 9 FRONT VIEW OF ENGINE STARTER ARRANGEMENT WITH MOTOR, SWITCH, BATTERY AND CHARGER ON A MOVABLE DOLLY.
FIG. 10 (a) CABLE SAG PARAMETERS

FIG. 10 (b) CABLE DERIVATIVE $C^*_z H$
FIG. 10 (c) CABLE DERIVATIVE $C_{mg}^*$
FIG. 10 (d) CABLE DERIVATIVE $C_n^*$
FIG. 10 (e) DRAG COMPONENT OF CABLE TENSION
FLIGHT ALONG LEVEL TRACK WITH NO RAMP

NACELLE SLOTS OPEN

HOT FUEL

VELOCITY 27.0 Ft/Sec

DISTANCE BETWEEN WING TIP AND NOSE POINT

• NOSE POINT, ZERO HEIGHT IS 1.905 IN.
• WINGTIP POINT, ZERO HEIGHT IS 2.400 IN.
• TAIL POINT, ZERO HEIGHT IS 2.375 IN.

FIG. 11 UNREDUCED RECORD TAKEN FROM FLIGHT ALONG TRACK WITH NO RAMP INSTALLED.
FIG. 12 UNREDUCED RECORD TAKEN FROM FLIGHT ALONG TRACK WITH NO RAMP INSTALLED.

FLIGHT ALONG LEVEL TRACK WITH NO RAMP

BOTTOM NACELLE SLOTS HALF OPEN

HOT FUEL

VELOCITY 26.6 Ft/Sec

- NOSE POINT, ZERO HEIGHT IS 1.905 IN.
- WINGTIP POINT, ZERO HEIGHT IS 2.400 IN.
- TAIL POINT, ZERO HEIGHT IS 2.375 IN.

DISTANCE BETWEEN WING TIP AND NOSE POINT

FRAME NUMBER — 1/32 SECOND
FIG. 13 FLIGHT IN PLENUM CHAMBER CONFIGURATION OVER 0.50 INCH RAMP IN TRACK.
WITH MODEL ON TRACK REFERENCE POINT HEIGHT IS 2.240 INCHES VERTICALLY ABOVE MID-CHORD OF WING

HOT FUEL

BOTTOM NACELLE SLOTS HALF OPEN

O PITCH ANGLE
• REFERENCE POINT

VELOCITY 26.5 Ft/Sec

FRAME NUMBER — 1/32 SECOND

FIG. 14 FLIGHT IN ANNULAR JET CONFIGURATION OVER .125 INCH RAMP IN TRACK.
WITH MODEL ON TRACK REFERENCE POINT HEIGHT IS 2.240 INCHES VERTICALLY ABOVE MID-CHORD OF WING

NOT FUEL

BOTTOM NACELLE SLOTS HALF OPEN

○ PITCH ANGLE  
● REFERENCE POINT

VELOCITY 26.5 Ft/Sec

RAMP

LEADING EDGE HIT

FRAME NUMBER — 1/32 SECOND

FIG. 15 FLIGHT IN ANNULAR JET CONFIGURATION OVER .25 INCH RAMP IN TRACK.
WITH MODEL ON TRACK REFERENCE POINT HEIGHT IS 2.240 INCHES VERTICALLY ABOVE MID-CHORD OF WING
BOTTOM NACELLE SLOTS OPEN

HOT FUEL

○ PITCH ANGLE
● REFERENCE POINT

TRAILING EDGE HIT

FRAME NUMBER — 1/32 SECOND

VELOCITY 26.5 Ft/Sec

FIG. 16 FLIGHT IN ANNULAR JET CONFIGURATION OVER .50 INCH RAMP IN TRACK.
Drag = $C_D \times \frac{1}{2} \rho V^2 S_c$

$S_c = d_c \times R_c$

$d_c$ - CABLE DIAMETER

$R_c$ - CABLE LENGTH

Reynolds Number = $\frac{\rho V d_c}{\mu}$

FIG. 17 DRAG COEFFICIENT FOR TWO-DIMENSIONAL FLOW AROUND A CYLINDER